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A population synthesis study of the MS+WD population in the SDSS

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Abstract. Detached white dwarf + main sequence (WD+MS) systems represent the simplest population of post-common envelope binaries (PCEBs), and their ensemble properties carry important information about common-envelope phase. However, most population synthesis studies do not fully consider the effects of the observational selection biases of the samples used to compare with the theoretical simulations. We present a set of detailed Monte Carlo simulations of the population of WD+MS binaries in the Sloan Digital Sky Survey (SDSS) Data Release 7, which allows us to make a sound comparison with the available observed data. We find that our simulations correctly reproduce the properties of the observed distribution of WD+MS PCEBs. This includes the distribution of orbital periods and of masses of the white dwarf and main sequence stars. These distributions can be correctly reproduced for several choices of the free parameters, although models in which $\leq 10\%$ of the internal energy is used to eject the common envelope, and in which a small common envelope efficiency ≤ 0.3 seem to fit the observational data better. We also find that systems with He-core white dwarfs are over-represented in the observed sample, because of selection effects.

1. Introduction

Close-compact binaries deserve close scrutiny, as they provide explanations for several interesting astrophysical phenomena. Examples of these systems are cataclysmic variables, low-mass X-ray binaries, or double degenerate binaries – to mention only some important and well-studied ones. Also their statistical distributions are crucial to understand the evolution during a common envelope (CE) episode. Actually, the vast majority of close-compact binaries are formed through at least one CE episode. This occurs when the more massive star fills its Roche lobe during the first giant branch or the asymptotic giant branch. Even though the basic concepts of the evolution during a CE phase are rather simple, the details are still far from being well understood. Binary systems formed by a white dwarf (WD) and a main sequence (MS) companion are intrinsically one of the most common, and structurally simplest, populations of Post-Common Envelope Binaries (PCEBs). Thus, their statistical properties provide the crucial observational input that is needed to improve the theory. However, until now, detailed population synthesis studies have failed to constrain the free parameters involved in the formulation of the CE phase, owing to an utter lack of observational data. Recently, this situation has changed with the advent of the Sloan Digital Sky Survey (SDSS). Here we describe the results of a detailed population synthesis study of WD+MS PCEBs in the Galaxy, aimed at constraining the theories of CE evolution.

2. The population synthesis code

We expanded an existing Monte Carlo simulator which has been extensively described in previous works (García-Berro et al. 1999; Torres et al. 2002; García-Berro et al. 2004). Thus, here we only summarize its most relevant inputs, and we refer the reader to Camacho et al. (2014) for an extensive description of the code. We randomly chose the galactocentric coordinates of each synthetic star within ~ 5 kpc from the Sun, following the SDSS DR7 spectroscopic plate directions. We assumed a percentage of binaries of 50%, and we normalized our simulated systems to the local disk mass density. We drew two more random numbers for the mass on the MS of each simulated primary – according to the initial mass function of Kroupa et al. (1993) – and for the time when each star was born – assuming a constant star formation rate. The adopted age of the Galactic disk was 10 Gyr. We used three initial mass ratio distributions – a flat distribution $n(q) = 1$, with $q = M_2/M_1$ the mass ratio, a distribution that depends inversely on the mass ratio, $n(q) \propto q^{-1}$, and a distribution proportional to the mass ratio, $n(q) \propto q$. Orbital separations were drawn according to Nelemans et al. (2001). Finally, the eccentricities were chosen according to a thermal distribution (Heggie 1975). Then, each of the components was evolved. We did that using the analytical fits to detailed stellar evolutionary tracks of Hurley et al. (2000). For those binary systems in which the primary had enough time to evolve to the WD stage, three situations can be found. For detached systems in which no mass transfer episodes occur, we adopted the initial-to-final mass relationship of Catalán et al. (2008). When the mass transfer was stable we employed the procedure detailed in Hurley et al. (2002), while if the mass transfer was unstable, i.e. if the system underwent a CE phase, we employed the α formalism. For He-core WDs, we adopted the evolutionary tracks of Serenelli et al. (2001). For C/O WDs, we used the tracks of Renedo et al. (2010), while for O/Ne WDs, we adopted the cooling sequences of Althaus et al. (2007) and Althaus et al. (2005). All these cooling tracks correspond to WDs with pure hydrogen atmospheres. The next step consisted of applying to the Monte Carlo sample a set of color cuts (Rebassa-Mansergas et al. 2013), a spectroscopic completeness filter (Camacho et al. 2014), another filter that takes into account the intrinsic binary bias of the real sample (Rebassa-Mansergas et al. 2011), and an orbital detection probability function (Nebot Gómez-Morán et al. 2011). With all these ingredients we could then meaningful compare our samples with the observed one (Rebassa-Mansergas et al. 2012), which consists of 53 WD+MS PCEBs from the SDSS DR7 catalogue. In this sample 49 of the 53 PCEBs have mass determinations for the WD, and 14 contain a He WD, 23 a C/O WD, and 2 an O/Ne one.

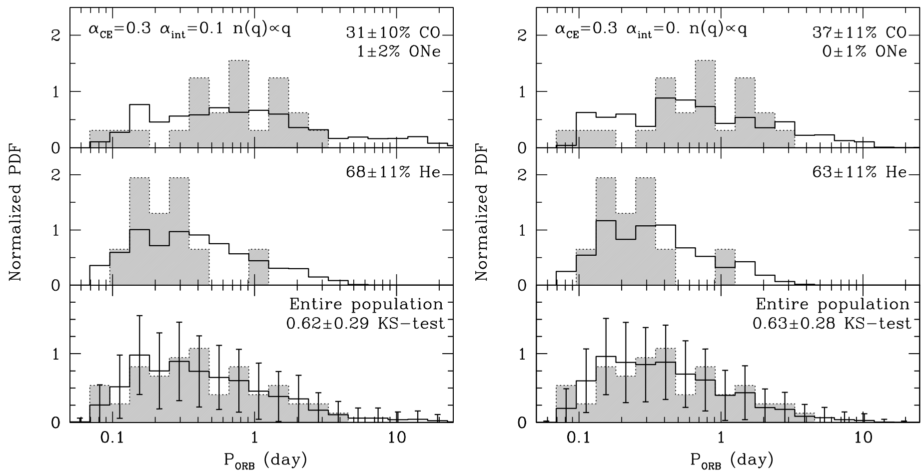

Figure 1. Period histograms (normalized to unit area) of the distribution of present-day WD+MS PCEBs for two of our best models (black line) compared with the observational distribution (dotted line, gray histogram).

3. Results

We found that the selection criteria produce a dramatic decrease in the total number of simulated WD+MS PCEBs, independently of the adopted model. In particular, the final simulated population is smaller than 0.1% of the initial sample in all the cases. The most restrictive selection criteria are the color cuts and the spectroscopic completeness filter. Only ∼ 7% of the objects in the input sample pass the cuts in color and magnitude, while the spectroscopic completeness filter eliminates ∼ 97% of those that survive the first filter. If only these two filters are applied, the total population of potentially observable systems decreases drastically down to 0.2 – 0.3% of the unfiltered sample. We thus conclude that the observed sample is severely dominated by the selection criteria. Nevertheless, our results can still be compared with the observed distributions. For such a purpose we performed a Kolmogorov-Smirnov (KS) test to compare the observed and the theoretical period distributions. We only selected those models with a KS value greater than 0.6, with a percentage of WD+MS PCEBs with He-core WDs below 70% (Rebassa-Mansergas et al. 2011), and a small fraction ($< 6\%$) of O/Ne WDs, in accordance with the observed sample. Additionally, we required that the theoretical models had statistical properties similar to those of the observed sample. These included a similar average period, as well as maximum and minimum period, and an assessment of the morphology of the global distribution of periods.

In Figure 1 we compare the distribution of periods of two of our best models ($\alpha_{\rm CE} = 0.3$ and $n(q) \propto q$) including and disregarding internal energy ($\alpha_{\rm int} = 0.1$ and 0.0, respectively) with the observed one. Additional models which fit the observed distribution equally well can be found in Camacho et al. (2014). We show the period distributions for the entire sample of WD+MS PCEBs (bottom panels) but also separately for systems containing He WDs (middle panels) and C/O or O/Ne WDs (top panels). In general, our Monte Carlo simulations agree closely with the observed period distribution for the entire population. However, the still large observational error bars preclude drawing definite conclusions. This indicates that the selection criteria

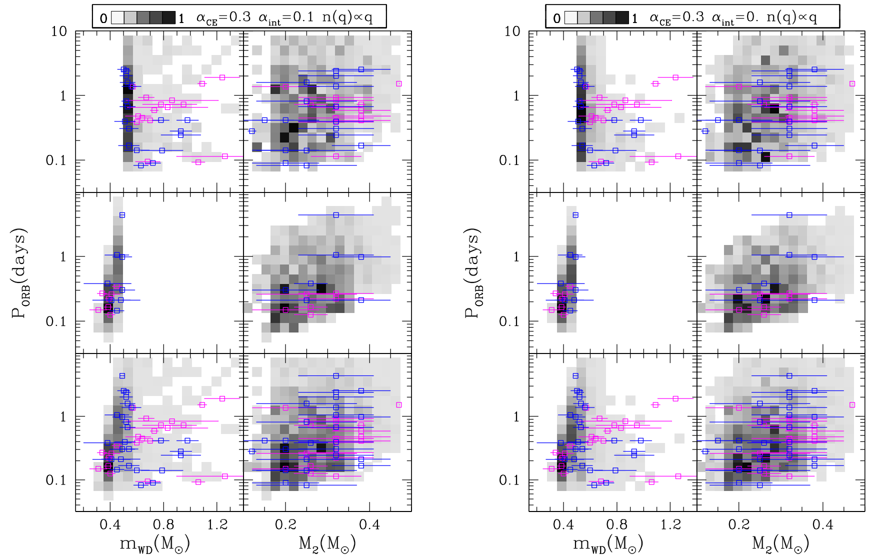

Figure 2. Period-mass density distribution of present-day WD+MS PCEBs for two of our best models (gray scale) compared with the observations (magenta and blue squares). The blue squares denote those systems for which the effective temperature of the WD is lower than 12 000 K, in which case the mass determination of the WD could be problematic. The top panels show the population of WD+MS PCEBs containing C/O or O/Ne WDs, middle panels are for systems containing a He WD, and the bottom ones show the entire population of simulated WD+MS PCEBs.

dominate the final observational distribution. Nevertheless, we emphasize that those models with non-zero internal energy present slightly extended tails in the long-period end of the distribution, in agreement with observations.

Figure 2 shows the period-mass distributions of the simulated sample for the same models of Fig. 1. Clearly, our simulations match the observed distribution remarkably well. Note that the WD+MS binary systems containing a He WD occupy a narrow strip in WD masses and, moreover, the periods of these systems cluster around 0.2–0.3 days. All this is in excellent agreement with the properties of the observed sub-population of WD+MS PCEBs with He WDs. For those WD+MS binaries containing C/O or O/Ne WDs, the distribution of WD masses is considerably broader. Our simulations also predict that WD+MS PCEBs containing an O/Ne WD are possible, although these systems should be rare. This is again consistent with the observed sample, where only two systems contain an O/Ne WD. The periods of WD+MS PCEBs with C/O or O/Ne WDs also span a wider range, with typical periods ranging from $\leq$ 0.1 to about four days, also in good agreement with the observations. When all the WD+MS PCEBs with available period and masses are considered, the agreement with the observed distribution is excellent.

4. Conclusions

We found that, in general, in our models the percentage of He WDs is larger than that found observationally, but compatible within the error bars. We judge that this is an interesting feature that might be real, and deserves to be further explored. Also, a low value of the CE efficiency ($\alpha_{\rm CE} \leq 0.3$) is required to reproduce the observed number of PCEBs containing He-core WDs. Additionally, we found that models with a variable binding energy parameter seem to fit the observed distribution of periods better than models in which the binding energy parameter is assumed to be constant. Our calculations also show that high values of $\alpha_{\rm int}$ are ruled out by the observations, although the ensemble properties of the population of WD+MS PCEBs do not allow us to discard low values of $\alpha_{\rm int}$, say less than ~ 0.2. We also compared the distribution of orbital periods as a function of the mass and found excellent agreement with the observational data. Our simulations are able to reproduce not only the distribution of orbital periods, but also the observed period distribution as a function of the mass of the WD if low values for the CE efficiencies and a detailed prescription of the binding energy parameter are assumed.

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