Binary population models of CVs: post thermal timescale mass transfer CVs

MSc Thesis

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February 28, 2013

Abstract

Context. Recently the white dwarf (WD) mass distribution of cataclysmic variables (CVs) has been found to dramatically disagree with the predictions of the standard CV formation model. The high mean WD mass among CVs is not imprinted in the currently observed sample of CV progenitors and can therefore not be attributed to selection effects. The standard CV formation model might thus miss an important ingredient that can explain the discrepancy between the WD masses among CVs and their progenitors. Two explanations have been put forward: either the WD grows in mass during CV evolution or the CV formation is preceded by a (short) phase of thermal timescale mass transfer (TTMT) in which the WD gains a sufficient amount of mass from its companion.
Aims. Here we investigate if and under which conditions a phase of TTMT prior to the CV formation, which has been considered a rare channel in previous works, can become a typical channel of CV formation and if the problem with the high WD masses can be solved in this way.
Methods. We perform binary population synthesis models using the Binary_C code to simulate the present intrinsic CV population. We use different models to investigate how several key aspects of CV evolution can influence the effect of a TTMT phase on the WD mass distribution. We carry out a statistical analysis on the characteristics of each model and compare these with the characteristics of a sample of observed CVs.
Results. We are able to produce a large number of massive WDs if we assume significant mass loss due to wind from the surface of the WD. The models that include this wind predict that two-thirds of the intrinsic CV population had a phase of TTMT and produce a mean WD mass that agrees with the observed value. The most convincing agreement between observations and model predictions is reached if, in addition to the TTMT wind, mass loss during nova cycles is taken into account.
Conclusions. The high WD masses among CVs can be explained by a preliminary phase of TTMT if such a TTMT wind exists. An accurate prescription for the adiabatic mass-radius exponent and corresponding critical mass ratio is of crucial importance for the formation of WDs with a mass of $\sim 0.8\,\mathrm{M}_\odot$. Our models predict that the majority of massive WDs among CVs have experienced TTMT.

Key words. accretion, accretion discs – instabilities – stars: novae, cataclysmic variables – stars: binaries: close

Contents

1. Introduction

The class of compact binaries comprises a great diversity of stellar objects and phenomena in the galactic zoo. They are very important probes of our comprehension of stellar evolution in general and mass transfer in particular. Cataclysmic variables (CVs) are compact binaries consisting of a white dwarf (WD) and a low-mass main sequence (MS) star, which transfers mass to the WD due to Roche lobe overflow (RLOF). CVs have been investigated for several decades, but their formation and evolution is still not fully understood. It is generally accepted that CVs result from wide binaries evolving into a common envelope (CE) structure, from which the core of the giant remains as a WD and the companion has spiralled inwards by means of drag forces within the envelope (Paczyński 1976). After the envelope is expelled, the orbit of the detached post-common-envelope binary (PCEB) is further reduced through the loss of orbital angular momentum via gravitational radiation (GR) and magnetic breaking (MB). When the orbit is sufficiently close, the accompanying MS star fills its Roche lobe and if the resulting mass transfer is stable, a CV is born.

According to this CV formation scenario, the distribution of WD masses in the newly formed CVs should be similar to the mass distribution of single WDs, if not shifted towards lower masses due to an early expulsion of the envelope, thus prematurely terminating the mass growth of the giant's core. This naive expectation of on average small WD masses has been confirmed by binary population models of CVs, e.g. Politano (1996) predicts a mean white dwarf mass of $0.49\,M_{\odot}$ for the primaries of CVs. Measurements of WD masses in CVs have been in the range of [0.8-1.2] $M_{\odot}$ (e.g, Warner 1973, 1976; Ritter 1976; Robinson 1976), i.e. significantly higher than predicted. This discrepancy between the observed and expected mean WD mass in CVs has been successfully interpreted as a selection effect by Ritter & Burkert (1986). Simply speaking, the idea is that the larger the WD mass, the more energy is released per accreted unit mass and the more extended is the accretion disk around the WD. Thus, CVs with massive WDs are (on average) significantly brighter and much easier to be discovered. However, recently Zorotovic et al. (2011) showed that this old explanation does no longer hold. They showed that the observed WD mass distribution of faint CVs (dominated by the emission from the WD instead of the accretion disk) should be biased towards low mass white dwarfs while, as shown by Littlefair et al. (2008), the measured mean WD mass for these systems still remains to be $\sim 0.8\,M_{\odot}$.

Thus the standard model of CV evolution might miss an important ingredient. Zorotovic et al. (2011) suggest two possibilities. The first is that the WDs in CVs gain mass through accretion of transferred matter and the second explanation is that a large number of CVs could descend from binaries with initially more massive secondaries[1]. This implies a previous phase of thermal timescale mass transfer (TTMT) in which the mass of the WD grows due to stable hydrogen burning on its surface (Schenker et al. 2002). At that stage, the system might be observed as a supersoft X-ray source (SSS, Kahabka & van den Heuvel 1997). Indeed, a small sample of UV observations has shown 10-15 % of CVs accreting CNO processed material, indicating that the companion has been stripped of its external layers due to a preliminary phase of TTMT (Schenker & King 2002; Gänsicke et al. 2003). These companions therefore appear to be more evolved than a single MS star of the same mass.

While binary population models of new-born CV with evolved donor stars have been performed in the past (e.g. de Kool 1992; Baraffe & Kolb 2000; Podsiadlowski et al. 2003; Kolb & Willems 2005), a systematic study of the impact of TTMT on the white dwarf mass distribution of CVs is missing. Here we fill this gap by using updated binary population models including TTMT and investigate whether a large number of CVs descending from SSSs might explain the large masses of CV primaries.

2. The code

Our method is to simulate the evolution of a large number of binaries and select those systems that evolve into a CV within the age of the Galaxy. Then we quantitatively investigate their characteristics and the evolutionary channel by which they have formed. We use the population nucleosynthesis code *Binary_C* of Izzard et al. (2004, 2006, 2009) based on the binary star evolution code of Hurley et al. (2002).

In order to simulate CVs, the characteristic aspects of their evolution have to be taken into account. In particular, the implementation and treatment of the stability of mass transfer, the mass-radius relation of the donor star, MB

[1] The mass transferring donor star in the CV is defined as the seconday, i.e. the initially least massive star.

and the fate of the transferred matter have to be considered carefully. We will therefore adress them in detail below.

2.1. Stability of mass transfer

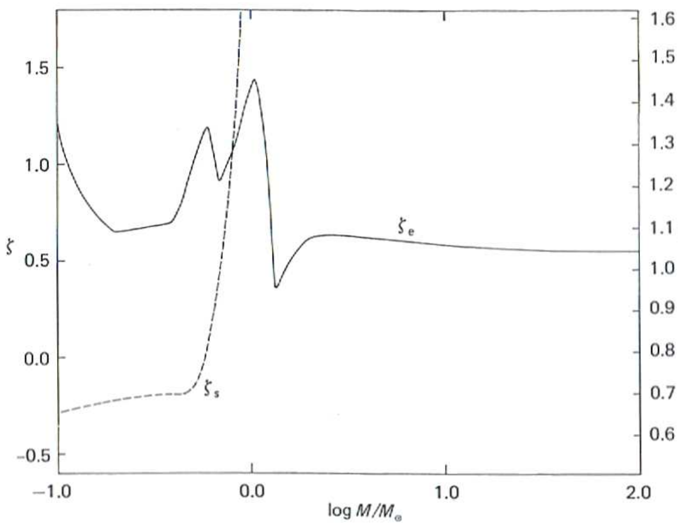

Figure 1. The adiabatic (dashed) and thermal (solid) mass-radius exponent as a function of mass for zero-age MS stars of solar composition. The corresponding critical mass ratio is depicted on the right-hand axis. This mass ratio only holds for conservative mass transfer. Taken from Pringle & Wade (1985).

The stability of mass transfer is determined by the change of the radius with respect to the Roche lobe. If the adiabatic response of the donor radius is unable to retain the star within its Roche lobe, mass transfer will occur in a dynamically unstable way and will probably lead to a CE. However, if the star is able to restore hydrostatic equilibrium, mass transfer is determined by the thermal readjustments of the star. If the new thermal equilibrium radius is also smaller than its Roche lobe, the binary is stable against mass transfer and mass transfer is driven by angular momentum loss or nuclear evolution. Otherwise mass transfer is driven by readjustments of the star on the thermal timescale. The mass-radius exponents and corresponding critical mass ratios that determine the stability of mass transfer are shown in Fig. 1. The adiabatic mass radius exponent is determined by detailed model calculations of Hjellming (1989) and the thermal mass radius exponent is from Webbink (1985). The adiabatic mass-radius exponent for low-mass MS donors is very sensitive to the depth of their convective envelope. For MS stars $\lesssim 0.7\,\mathrm{M}_\odot$ the envelope is deeply convective and the donor star is no longer able to restore hydrostatic equilibrium in response to mass loss. Therefore, the adiabatic mass-radius exponent decreases steeply around $0.7\,\mathrm{M}_\odot$.

Instead of the standard prescription for the critical mass ratio for dynamically unstable mass transfer in *Binary_C*, a constant $q_{\rm cr}$ of $\frac{2}{3}$ for $M_2 \lesssim 0.7\,\mathrm{M}_\odot$, we use the analytic fit from Politano (1996) for stars that are defined as deeply convective, low mass MS stars ($\lesssim 0.7\,\mathrm{M}_\odot$) in the code:

$$q_{\rm cr}(M_2) = \begin{cases} \frac{2}{3} & M_2 \leq 0.4342\,\mathrm{M}_\odot \\ 2.244(M_2 - 0.4342)^{1.364} + \frac{2}{3} & 0.4342 \leq M_2 \lesssim 0.7\,\mathrm{M}_\odot \end{cases} \quad (1)$$

in which M_2 is the mass of the donor star and the mass ratio is defined as $q \equiv \frac{M_2}{M_{\rm wd}}$. This prescription for the critical mass ratio is valid for conservative mass transfer. For typical CVs with stable mass tranfer, mass is only lost from the binary by instantaneous nova outbursts on the surface of the WD. Between two nova outbursts, all mass is transferred to the WD and mass transfer can be considered conservative.

Semi-detached binaries which reside in the upper right corner of Fig. 1 ($\zeta > \zeta_{\rm e}$) experience TTMT, while semi-detached binaries below the adiabatic and thermal mass-radius exponent are typical CVs. Since *Binary_C* does not follow the thermal mass-radius exponent (Hurley et al. 2002, section 2.6.3) and mass transfer might not be conservative during TTMT, we use the mass transfer rate to dinstinguish between CVs and SSSs, i.e. binaries with TTMT. We identify a binary as a SSS if the primary is a WD (helium, carbon-oxygen or oxygen-neon), the donor is a MS star and the mass transfer rate is higher than the limit for stable hydrogen burning, as described in Meng et al. (2009). Furthermore, the mass of the WD has to increase by at least $0.01\,\mathrm{M}_\odot$ during the TTMT, otherwise we do not define the emerging CV as a post SSS system. Likewise, if the mass transfer rate is below this limit, the primary is a WD and the donor is a MS star, we identify the system as a CV.

2.2. Fate of the transferred mass

A crucial and precarious question is how to treat the transferred matter, both when the binary is a SSS and a CV. We discuss both cases separately in what follows.

2.2.1. Thermal timescale mass transfer

When the mass transfer rate is within the limits of stable hydrogen burning, all transferred hydrogen-rich matter is processed into helium and accreted on the WD. If the mass transfer rate exceeds this limit, hydrogen will be accreted faster than it can be processed into helium. Two scenarios for this situation have been proposed in the literature. The first is that the redundant hydrogen-rich matter is accumulating on the surface of the WD and will form a red-giant-like envelope (Nomoto et al. 1979). Consequently, the WD will be observed as a giant-like star.

The other scenario is that the burning of hydrogen may cause a very strong wind (Hachisu et al. 1996). This wind ejects part of the accreted matter and tends to stabilize the mass accretion on the WD, thus preventing the formation of a new giant-like envelope. The WD will still accrete a certain amount of matter, $\dot{M}_{acc}$, depending on the mass accumulation efficiency of hydrogen burning, $\eta_{\rm H}$, and the mass accumulation efficiency for helium-shell flashes, $\eta_{\rm He}$ on the surface of the WD. It can be expressed as:

$$\dot{M}_{acc} = \eta_{\rm H}\,\eta_{\rm He}\,\dot{M}_{\rm tr} \quad (2)$$

where $\dot{M}_{\rm tr}$ is the rate at which mass is transferred from the donor to the WD. The efficiency parameters $\eta_{\rm H}$ and $\eta_{\rm He}$ depend on the mass transfer rate (Meng et al. 2009). We will refer to this wind as the *Hachisu* wind.

2.2.2. Nova outbursts

When the mass transfer is below the limit of stable hydrogen burning, the accreted hydrogen is compressed on the surface of the WD and is subsequently ignited under highly degenerate conditions. This leads to unstable hydrogen shell burning and flashes, i.e. novae. How much mass is lost during these nova outbursts, has been subject of debate for several decades. The longstanding paradigm has been that nova eruptions in CVs expell the majority of the mass that has been accreted prior to the nova outbursts and probably even more (Prialnik 1986; Prialnik & Kovetz 1995; Townsley & Bildsten 2004; Yaron et al. 2005). However, recent models have shown that CO WDs, in particular low mass, can grow in mass and only eject a small fraction of the accreted matter if no mixing with core material is assumed (Starrfield et al. 2012; Williams 2013).

Although there is a general consensus that the WD loses some of the accreted mass, it is uncertain how much mass is lost during a nova outburst and if the mass of the WD can actually grow. Both mass loss and mass growth during nova outbursts can significantly alter the WD mass distribution in the CV population, whether or not a phase of TTMT occurred. The standard assumption for our models is that none of the transferred matter is accreted on the WD, but we will also investigate the influence of both mass loss and mass growth on our models.

2.2.3. Accretion onto HeWD

It is uncertain if and when a thermonuclear explosion is induced by the accretion of helium onto a HeWD. The accretion of helium can occur either directly or through stable hydrogen burning on the surface of the WD. Models from Woosley et al. (1986) have shown that a detonation due to the accretion of helium at a rate of $2 \times 10^{-8} \mathrm{M}_{\odot}\mathrm{yr}^{-1}$ can occur when the star reaches $0.66\,\mathrm{M}_{\odot}$, while previous models by Nomoto & Sugimoto (1977) found a limit of $0.78\,\mathrm{M}_{\odot}$ for the accretion of hydrogen at the same rate. Nomoto & Sugimoto (1977) furthermore found that the mass at detonation depends strongly on the mass accretion rate, where a lower mass accretion rate implies a higher detonation mass. Since there is currently no clear stringent limit on the mass of HeWDs, we have adopted the default maximum mass of a HeWD from *Binary_C*, i.e. $0.7\,\mathrm{M}_{\odot}$.

2.3. Mass-radius relation for CV donors

As discussed above, mass transfer can force the donor star out of thermal equilibrium when the timescale of mass transfer is smaller than the thermal timescale of the donor. In the case of low mass donors, the mass transfer is driven by the loss of angular momentum, which is caused by MB and/or GR.

MB is supposed to be active until the donor star becomes fully convective (Rappaport et al. 1983). For single ZAMS stars this occurs when the mass is $\sim 0.35\,\mathrm{M}_{\odot}$ and MB is probably reduced in a disruptive manner. This disrupted MB scenario is used to explain the observed gap between 2 and 3 hours in the orbital period distribution of CVs (Spruit & Ritter 1983; Schreiber et al. 2010). In semi-detached binaries at the upper edge of the period gap, the angular momentum loss is high enough to force the MS donor out of thermal equilibrium, which causes the radius of the donor star to exceed its thermal equilibrium radius. Due to this bloating and readjustments of the donor on relatively long thermal timescales, the stellar structure of the donor corresponds to the stellar structure of a more massive single star on the MS. The proper mass of the bloated donor star is smaller than the value that would be inferred if the donor star were on the MS (Knigge 2006; Howell et al. 2001). In other words, the mass of the donor is smaller than that of a main sequence star with the same radius and stellar structure. Therefore the mass transferring donor in a CV becomes fully convective at a smaller mass than its main sequence counterparts in detached binaries or single stars and the dynamo mechanism responsible for MB remains active for donor masses $\gtrsim [0.2 - 0.26]\,\mathrm{M}_{\odot}$ (McDermott & Taam 1989; Howell et al. 2001; Patterson et al. 2005).

The mass-radius relation of the donor star is therefore of crucial importance for the proper simulation of the standard model of CV evolution. Not assuming an increased radius above the gap, would not allow to simulate the orbital period gap seen in the observed distribution of CVs. Consequently, we would not be able to separate systems below and above the gap, which, as we will see later, might be crucial to understand the WD mass distribution in CVs. In order to account for the larger radius when the donor is out of thermal equilibrium, we implemented the mass-radius relation for low mass MS donors in CVs, as deduced by Knigge et al. (2011). To establish a smooth transition between the equilibrium radius ($R_{2,\mathrm{eq}}$) given by *Binary_C* and the increased radius for CV donor stars ($R_{2,\mathrm{CV}}$), we define the factor by which the radius is increased compared to its thermal equilibrium value, each timestep, as:

$$f = \frac{R_{2,\mathrm{CV}}}{R_{2,\mathrm{eq}}} \tag{3}$$

and let the radius grow exponentially with time towards the fully inflated value (i.e. $R_{2,\mathrm{CV}}$) given by Knigge et al. (2011). The equilibrium radius excess (f_{exc}) and current radius (R_2) as a function of time are thus given by:

$$f_{\mathrm{exc}}(t) = f + (1-f)e^{\frac{t}{\tau}} \tag{4}$$

$$R_2(t) = f_{\mathrm{exc}}(t) R_{2,\mathrm{eq}} \tag{5}$$

where t is the time since the donor filled its Roche lobe and τ is the timescale for angular momentum loss in CVs, typically 10^7 years (Davis et al. 2008).

When the donor detaches from its Roche lobe and moves into the gap, the radius of the donor relaxes to its equilibrium value and we decrease the radius in a similar manner. In this case, we use Eq. (3), replace $R_{2,\mathrm{CV}}$ with the radius the star had just before it detached and $R_{2,\mathrm{eq}}$ with the radius as described in Knigge et al. (2011) for donors below the period gap. We assume that donor stars whose initial mass is $\leq 0.35\,\mathrm{M}_{\odot}$, do not experience efficient MB, analogous to single ZAMS stars. Therefore, we do not inflate the radius for these donors, but only use the radius for CV donors below the gap. As is pointed out by Knigge et al.

(2011), the power-law approximation for the mass-radius relation of MS donors breaks down for masses $\leq 0.05\,\mathrm{M}_\odot$. We therefore only consider CVs with a secondary more massive than 0.05 $\mathrm{M}_\odot$.

The slighly more physical alternative to implementing the mass-radius relation from Knigge et al. (2011) would be to couple the increase of the radius to the mass transfer rate, e.g. Howell et al. (2001), which, however, would lead to nearly identical results.

The reinitiation of mass transfer below the gap is determined by the radius, and thus mass, of the donor star in the gap. The lower the mass, i.e. radius, of the donor star in the gap, the shorter the orbital period at which mass transfer is reinitiated. The mass of the donor star in the gap thus determines the orbital period at which the binary reappears as a CV. The location of the lower edge of the period gap is better defined than the location of the upper edge (Gänsicke et al. 2009). Taking these argument together with the mass in the gap provided by Knigge et al. (2011), we place the boundary for donors in CVs to become fully convective at $0.20\,\mathrm{M}_\odot$. This value provides the best reproduction of the lower edge of the period gap in our simulations.

Accordingly, we assume MB is disrupted at $0.20\,\mathrm{M}_\odot$. We use the prescription of Hurley et al. (2002) for MB and calibrate for the angular momentum loss rate at the upper edge of the period gap by multiplying this prescription with a factor of 0.19 (Davis et al. 2008). Furthermore, we subtract the angular momentum loss due to MB directly from the orbit, assuming the orbit and spin are coupled.

2.4. Mass transfer rate

The rate at which mass is transferred onto the accretor, $\dot{M}_{\mathrm{tr}}$ given in $\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, is calculated with (Hurley et al. 2002):

$$\dot{M}_{\mathrm{tr}} = F(M_{\mathrm{d}})[ln(\frac{R_{\mathrm{d}}}{R_{\mathrm{L,d}}})]^3 \tag{6}$$

where R_{d} is the radius of the donor star, $R_{\mathrm{L,d}}$ the Roche lobe radius of the donor star and $F(M_{\mathrm{d}})$ a numerical factor to ensure that the mass transfer is steady, see Eq. (59) from Hurley et al. (2002). Since the mass transfer rate is computationally not coupled to the inflation of the donor radius, the factor $F(M_{\mathrm{d}})$ is too small to let the star follow its Roche lobe within a few per cent. In other words: the mass transfer rate is too small to be self-regulating. To prevent the star from overfilling its Roche lobe by more than a few per cent, we multiply $F(M_{\mathrm{d}})$ with a factor of 1000 if the mass-radius relation from Knigge et al. (2011) is applied to the donor star. This allows the mass transfer rate to be self-regulating, but increases the possibility of numerical instabilities in the calculation of the mass transfer rate. Fortunately, we did not have any problems with that.

2.5. General modelling

We generate a three-dimensional grid with M_1, M_2 and the separation as free initial parameters. Our resolution is 150 for each parameter, thus for each model we simulate $\sim 3 \cdot 10^6$ binary systems. We let the initial mass of the primary, M_1, range from 1 to 9 $\mathrm{M}_\odot$, in order to let the primary evolve into a WD within the Hubble time. The initial mass function (IMF) of the primary is given by Kroupa et al. (1993). For M_2 we assume an initial mass ratio distribution which, given M_1, is proportional to the mass ratio q. Hence binaries with equal masses are preferred (Popova et al. 1982). The distribution for M_2 serves to illustrate, and increases, the effects of the evolutionary scenario under consideration in this paper, since massive secondaries increase the probability of TTMT. The initial mass of M_2 ranges from 0.08 to 3.5 $\mathrm{M}_\odot$ to maximize the number of MS donor stars. Both M_1 and M_2 are picked from their initial mass distribution with a logarithmic spacing. This means that we select more primaries and secondaries with a lower mass, because these systems are most typical for the evolutionary channel of CVs. Therefore, each binary in the grid is given an individual formation probability, depending on the assumed distribution of the initial parameters and taking into account the logarithmic spacing in mass. The initial orbital separation a is assumed to be flat in log a (Popova et al. 1982; Kouwenhoven et al. 2007) and ranges from 3 to 10^4 $R_\odot$ to cover the whole space of binaries that will interact within the Hubble time. We furthermore assume circular orbits and solar metallicity for all binaries. We set the common envelope efficiency parameter, α_{ce}, equal to 0.25, in accordance with the range of values determined by Zorotovic et al. (2010). A small α_{ce} is required to keep the number of low mass WDs small, as is observed. The binaries are formed with a constant star formation rate by randomly assigning them a lifetime between 0 and 13.5 Gigayear, our assumed age of the Galaxy (Pasquini et al. 2004).

The above assumptions constitute our reference model. We furthermore assume in our reference model that a giant-like envelope is formed when the mass transfer rate exceeds the limit for stable hydrogen burning and none of the accreted mass remains on the WD when the mass transfer rate is in the nova regime.

2.6. Parameter study

For reasons that will become clear when the results of the reference model are discussed, we will investigate three other models in which we use additional assumptions. Apart from the above assumptions, the stabilizing Hachisu wind during TTMT and mass loss or mass growth during nova outbursts are the remaining parameters that can be tested. The Hachisu wind appeared to be fundamental to produce large numbers of post-TTMT CVs and we therefore included it in the additional three models. In the third and fourth model, we furthermore tested how respectively mass loss and mass growth during novae affect the WD mass distribution. The treatment of mass loss and mass growth in model 3 and 4 is discussed below.

2.6.1. Treatment of mass loss

We used m_{acc} and m_{ej} from Table 2 in Yaron et al. (2005) to construct an interpolation table with efficiencies for mass 'accretion' during nova cycles, which we implemented in *Binary_C*. The amount of mass loss, i.e. 'accretion efficiency', depends on the mass of the WD, the mass transfer rate and the core temperature of the WD. The core temperature of the WD is derived from its mass and luminosity (Mestel 1952).

2.6.2. Treatment of mass growth

In the case of mass growth, we assume that a fraction of 10 % of the transferred mass remains on the WD after a nova eruption. This is an arbitrary but conservative fraction, since it is likely that still a significant amount of the accreted matter is lost in a nova, as discussed in section 2.2.2.

The four models can thus be summarized as follows:

1. The reference model as described in section 2.5.
2. The reference model including a wind from the accreting WD that stabilizes mass transfer and prevents the formation of a giant-like envelope (section 2.2.1).
3. Model 2 including mass loss during nova outbursts (section 2.6.1).
4. Model 2 including mass growth during nova outbursts (section 2.6.2).

3. Results

We will first discuss the results of our reference model. Subsequently we address the effects of the additional assumptions with respect to the reference model.

3.1. Reference model

Figure 2 shows the binaries that are identified as a CV at the present epoch according to our definition, given in section 2.1. The distribution of both the orbital period (bottom) and WD mass (left) are shown, as well as their combined probability distribution in the 2-dimensional plane. The dashed lines mark the upper (3.18 hr) and lower edge (2.15 hr) of the observed period gap (Knigge 2006). The solid line marks the region in which mass transfer will become dynamically unstable, assuming $q_{\rm cr}$ is given as in Eq. (1). The dotted line marks the extension of this region if one assumes a constant $q_{\rm cr}$ of $\frac{2}{3}$ for $M_2 \lesssim 0.7\,{\rm M}_{\odot}$. These lines are calculated by equating the radius of the donor star with its Roche lobe radius. The vertical line on the right side corresponds to a donor mass of $0.7\,{\rm M}_{\odot}$, while the curved left side corresponds to the critical mass ratio.

The orbital period distribution shows a clear spike at the period minimum, corresponding to very low mass secondaries ($M_{\rm sec} \lesssim 0.08\,{\rm M}_{\odot}$). This spike agrees with the observed period distribution from Gänsicke et al. (2009), where CVs also seem to accumulate towards lower periods. Likewise, as in Gänsicke et al. (2009), the majority of CVs in the reference model is currently below the period gap, albeit only 42.4 % of the current CV population was born in or below the gap. Since the mass transfer rate below the gap is smaller than above the gap, the evolutionary timescale is shorter above the gap than below by a factor of 10 to 100. Therefore, one would also theoretically expect more binaries at lower periods, see e.g. Kolb (1993).

The absence of CVs, in particular with low mass WDs, at long orbital periods has been predicted by previous models (de Kool 1992; Kolb 1993; Howell et al. 2001; Davis et al. 2008), although a fair number of CVs have been observed at the upper edge of the period gap (Ritter & Kolb 2003; Gänsicke et al. 2009). This absence can be explained as follows: mass transfer becomes dynamically unstable for CVs whose mass ratio exceeds the critical value given by Eq. (1). This will happen within the region marked by the solid line in Fig. 2. CVs are thus not able to evolve towards lower periods through this region without experiencing dynamically unstable mass transfer and merging. This means that CVs with a WD $\lesssim 0.7\,{\rm M}_{\odot}$ and $log(\frac{P_{\rm orb}}{\rm days}) \lesssim -0.8$ have to be born there. The majority of HeWDs therefore resides below the gap.

The WD mass distribution shows 3 peaks. The peak at $0.55\,{\rm M}_{\odot}$ corresponds to binaries that evolved into a CE when the primary was on the asymptotic giant branch (AGB). These WDs have a carbon-oxygen (CO) core with a lower mass than expected for single WDs due to the earlier expulsion of the envelope. The second peak at $0.4\,{\rm M}_{\odot}$ consists of WDs with a helium (He) core, for which the mass growth of their core was terminated when they were on the first giant branch (FGB). The steep decline after the peak for CO WDs is in agreement with the observed mass distribution of single WDs (Kepler et al. 2007).

However, the reference model shows a third peak at $0.93\,{\rm M}_{\odot}$, which is atypical for the mass distribution of single WDs and which is also not predicted by previous models of CVs from e.g. de Kool (1992) and Politano (1996). This peak consists for more than 70 % of CVs that have experienced TTMT. Thus these CVs initially resided at longer orbital periods and were accompanied by more massive secondaries. de Kool (1992) and Politano (1996) both rejected these CVs from their models, because they did not include CVs that experience TTMT. The third peak therefore clearly demonstrates the consequences of our initial assumptions and how sensitive the model is to them. For instance, it would be absent if one assumes a constant value for $q_{\rm cr}$, instead of Eq. (1). The region in which mass transfer becomes dynamically unstable for a constant $q_{\rm cr}$ of $\frac{2}{3}$ for $M_2 \lesssim 0.7\,{\rm M}_{\odot}$ is then extended by the dotted line in Fig. 2. In this case, all CVs with a WD $\lesssim 1\,{\rm M}_{\odot}$ and $log(\frac{P_{\rm orb}}{\rm days}) \gtrsim -0.6$ would eventually merge. The third peak would also be absent if one assumes an initial distribution for the mass of the secondary that is flat in q. In that case, the majority of the secondaries would not be massive enough to initiate a phase of TTMT. The WD mass distribution and average WD mass would then be similar to the distribution derived by de Kool (1992) and Politano (1996).

The deficiency in the WD mass distribution at $0.8\,{\rm M}_{\odot}$ in the simulation is in sharp contrast with the distribution as derived by Zorotovic et al. (2011), which shows a peak at $0.8\,{\rm M}_{\odot}$ (their Fig. 6). More general, the WD mass distribution predicted by our reference model disagrees drastically with the observed distribution. Not only is the mean WD mass of $0.61\,{\rm M}_{\odot}$ in the reference model much lower than the mean mass derived by Zorotovic et al. (2011), i.e. $\langle M_{\rm WD} \rangle = 0.83 \pm 0.02$, but also the shapes of the distributions are different. As shown by Zorotovic et al. (2011), the high WD masses derived from observations can not be explained by observational biases. We therefore conclude that our reference model is missing an important feature of CV formation and/or evolution.

Our key focus is the treatment of TTMT in the code. In the reference model, 14.3 % of the CVs have undergone TTMT prior to evolving into a CV. If only those CVs that contain a WD more massive than $0.8\,{\rm M}_{\odot}$ are considered, the fraction of CVs that have undergone TTMT increases to 70.5 %. However, there are few CVs with such massive

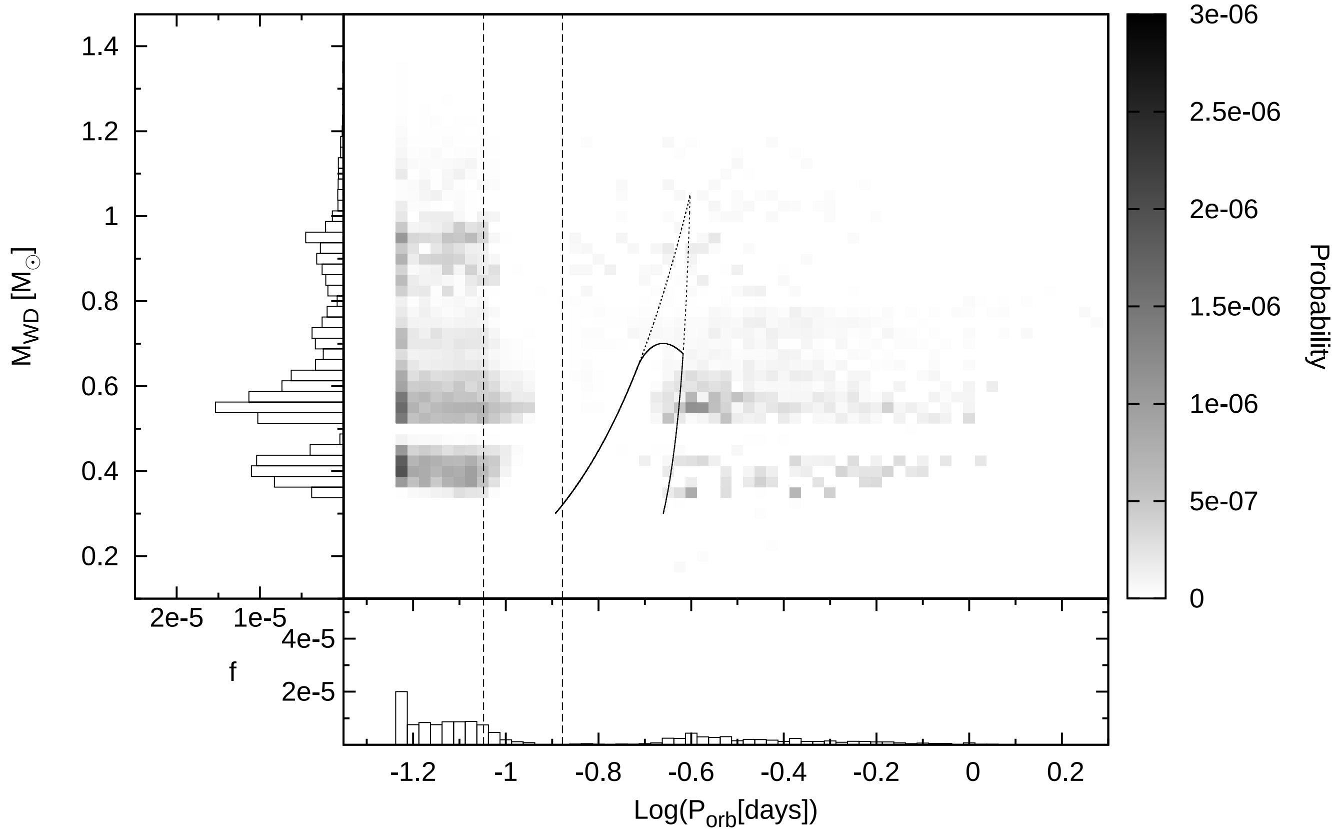

Figure 2. *Center*: 2-dimensional histogram of the orbital period and WD mass distributions in CVs for our reference model. The color intensity represents the sum of the formation probabilities of all CVs residing in that 2-dimensional bin. The dashed lines mark the upper (3.18 hr) and lower edge (2.15 hr) of the observed period gap (Knigge 2006). The solid line marks the region in which mass transfer will become dynamically unstable, assuming $q_{\rm cr}$ is given as in Eq. (1). The dotted line marks the extension of this region if one assumes a constant $q_{\rm cr}$ of $\frac{2}{3}$ for $M_2 \lesssim 0.7\,{\rm M}_\odot$. *Bottom panel*: orbital period distribution of the CVs in our reference model. The dashed lines mark the upper (3.18 hr) and lower edge (2.15 hr) of the observed period gap (Knigge 2006). *Left panel*: WD mass distribution of the CVs in our reference model.

WDs in the reference model. This is due to the formation of a giant-like envelope in these systems, when the transfer rate of hydrogen-rich matter exceeds the limit for stable hydrogen burning. Consequently, He WDs evolve into FGB stars and CO and ONe WDs into AGB stars. Thus these binaries no longer meet the definition of a CV and will eventually evolve into a CE and merge.

It seems that the limits for the mass transfer rate, between which hydrogen burning on the surface of the WD is stable, define a range that is too small. The mass transfer rate is either too high or too low and therefore these CVs respectively merge or the WD does not gain a sufficient amount of mass. CVs with a TTMT phase can therefore not provide a serious contribution to the WD mass distribution in the reference model. In the second model we will discuss the implementation of the theoretical *Hachisu* wind that prevents the WDs from forming a new giant-like envelope in the case of TTMT. This wind thus serves as a tool to investigate the consequences of extending this small range to higher mass transfer rates, i.e. extending the parameter space that leads to SSSs.

3.2. Hachisu wind

We incorporated the *Hachisu* wind described in section 2.2.1 and the corresponding WD mass (left) and orbital period (bottom) distributions are shown in Fig. 3. As in Fig. 2, the dashed, solid and dotted line represent respectively: the orbital period gap and the region in which mass transfer becomes dynamically unstable, depending on the prescription for $q_{\rm cr}$. As can be seen from the orbital period distribution, assuming a larger range for the mass transfer rate that allows for stable hydrogen burning more than doubles the number of CVs with respect to the reference model. This can be ascribed to the contribution of the CVs with a massive WD ($\gtrsim 0.7\,{\rm M}_\odot$), which in the reference model evolved into a giant-like star. The distribution for $M_{\rm wd} \lesssim 0.7\,{\rm M}_\odot$ is practically the same as the distribution of the reference model in Fig. 2 and so are their evolutionary paths.

The influence of the description used for $q_{\rm cr}$ is even bigger for the second model. The WDs with masses between $0.7\,{\rm M}_\odot$ and $1\,{\rm M}_\odot$would not be present if one assumes a constant $q_{\rm cr}$ of $\frac{2}{3}$, because they would experience dynamically unstable mass transfer when they evolve through the dotted region, see Fig. 3. In that case, the WDs in CVs with a mass around $0.8\,{\rm M}_\odot$ below the gap, would already have to be this massive when they evolve out of the CE. This requires an initial mass $\gtrsim 3\,{\rm M}_\odot$ and therefore they have a relatively small formation probability compared to less massive WDs, depending on the IMF of the primary and the CE efficiency. However, Eq. (1) allows CVs with

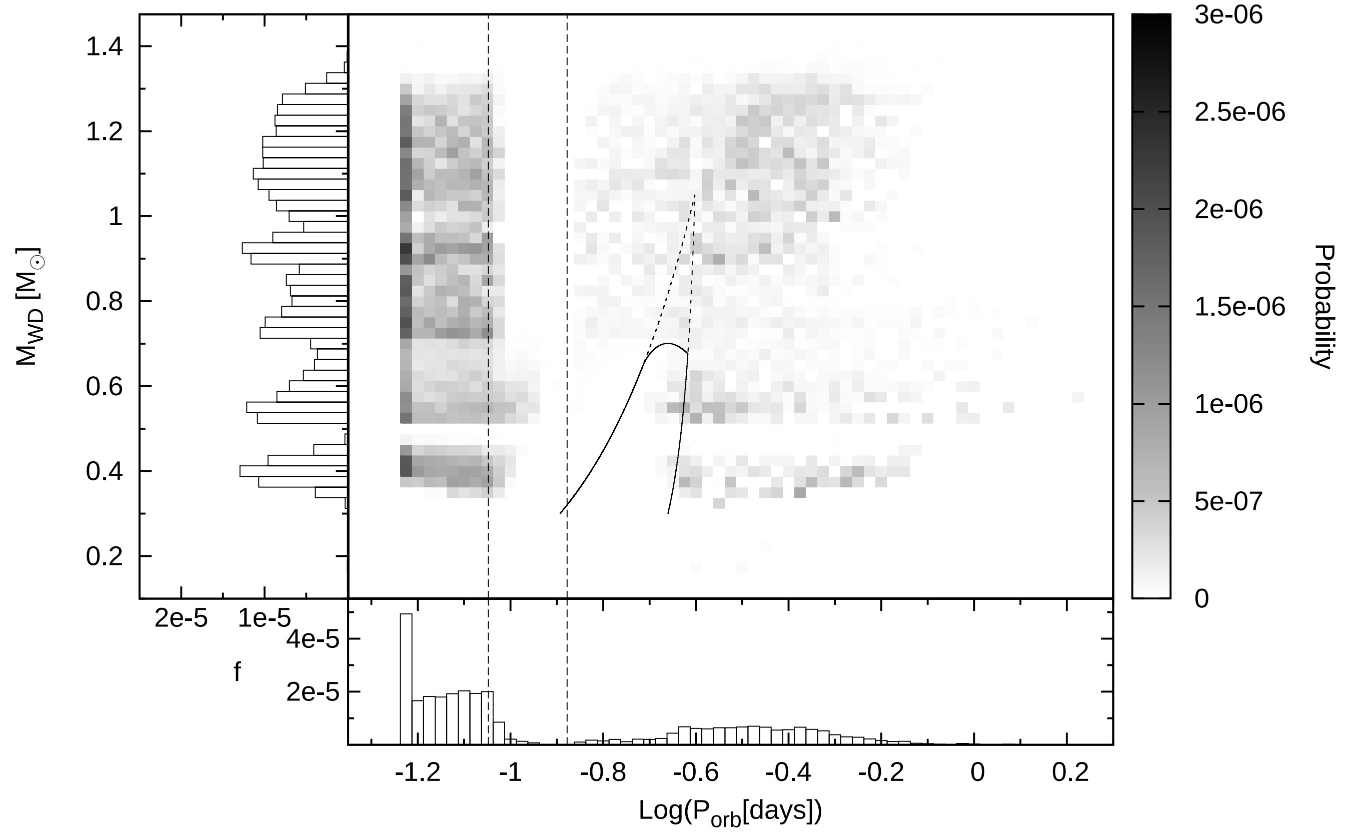

Figure 3. Same as in Fig. 2, but for model 2, in which a wind from the WD is included that stabilizes mass transfer (section 2.2.1). This wind allows more SSSs to evolve into CVs. The prescription for $q_{\rm cr}$ is crucial for the subsequent CV evolution.

massive WDs to evolve towards lower periods and the CVs that descend from TTMT therefore provide a significant contribution to the total number of CVs in general and the number of CVs with a massive WD in particular.

Almost two-thirds of all CVs in the second model, i.e. 65.7 %, have undergone TTMT. The mean WD mass of CVs that descended from a SSS increased significantly during TTMT: from $0.65\,{\rm M}_\odot$ prior to the phase of TTMT, to $1.03\,{\rm M}_\odot$ afterwards. When only the CVs with a WD $\gtrsim 0.7{\rm M}_\odot$ are considered, 94.6 % had a phase of TTMT.

Although $\langle M_{\rm WD}\rangle = 0.86\,{\rm M}_\odot$ in model 2 is in accordance with the mean mass derived from the observed CVs by Zorotovic et al. (2011) i.e. $\langle M_{\rm WD}\rangle = 0.83\pm0.02$, there is still a significant contribution of low mass WDs, in particular HeWDs, to the WD mass distribution, which is not present in the sample of Zorotovic et al. (2011). We would like to emphasize that an initial mass ratio distribution that is flat in q makes the contribution of low mass WDs, with respect to massive WDs, to the mass distribution even larger. We will adjourn the possible reduction of the number of HeWDs to the discussion, because we are primarily interested in accounting for the observed peak at $\sim 0.8\,{\rm M}_\odot$. We therefore investigate how both mass loss and mass growth during the CV phase affect the WD mass distribution, since there is currently no consensus on which of these two scenarios is more plausible. In model 3 we investigate if mass loss creates a clear and distinct peak around $0.8\,{\rm M}_\odot$ and in model 4 we investigate if mass growth shifts the low mass WDs significantly towards higher masses.

3.3. Mass loss during nova eruptions

In model 3, mass loss is implemented as described in section 2.6.1 and the results are shown in Fig. 4. The additional effect of the mass loss in this model is clearly visible with respect to Fig. 3, in particular for CVs with massive WDs below the gap. The majority of these CVs descended from TTMT and evolved from longer orbital periods, ~ 0.8 days, through the gap. Therefore they have experienced mass loss on a longer timescale than CVs above the gap. The characteristics of the distributions are the same as in the second model, with the exception that the massive WDs accumulate around $0.85\,{\rm M}_\odot$. The statistical characteristics are also similar to the second model: 64.3 % of all CVs have undergone TTMT and $\langle M_{\rm WD}\rangle = 0.82\,{\rm M}_\odot$. The distribution of WD masses above the gap shows a larger spread than the distribution of WD masses below the gap. This is in agreement with the sample from Zorotovic et al. (2011), which also shows a concentration of WD mass around 0.8 below the gap while the CVs above the gap are more widely spread. We will adress this in more detail in the discussion section. The number of HeWDs is still considerably large, although the peaks at 0.4 and $0.55\,{\rm M}_\odot$ are less pronounced than in model 2.

3.4. Mass growth during nova eruptions

In model 4 we investigate whether mass growth of the WD, as described in section 2.6.2, shifts the low mass WDs towards higher masses. That is, whether the CO WDs of $\sim 0.55\,{\rm M}_\odot$ can contribute to the observed peak around

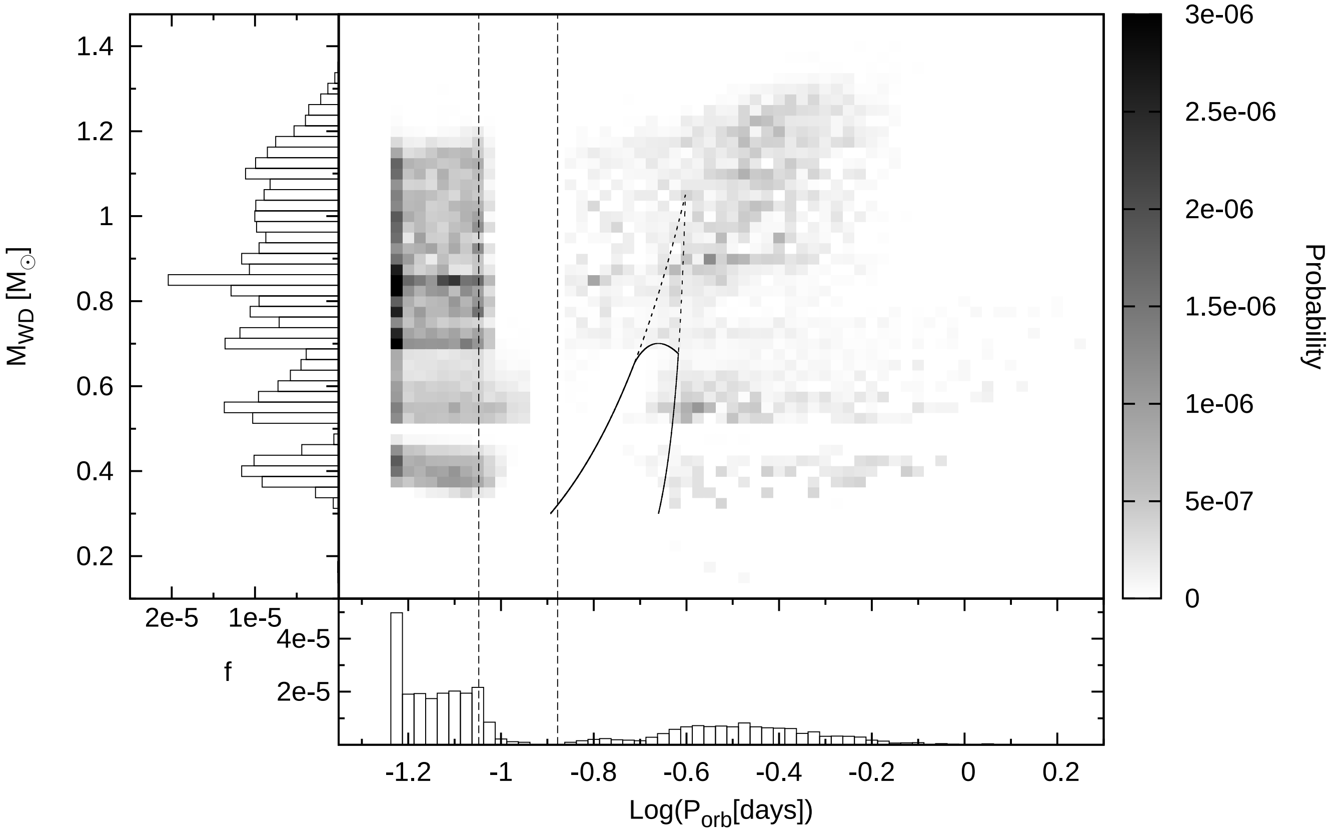

Figure 4. Same as in Fig. 2, but for model 3, in which both the *Hachisu* wind and mass loss during nova outbursts are included.

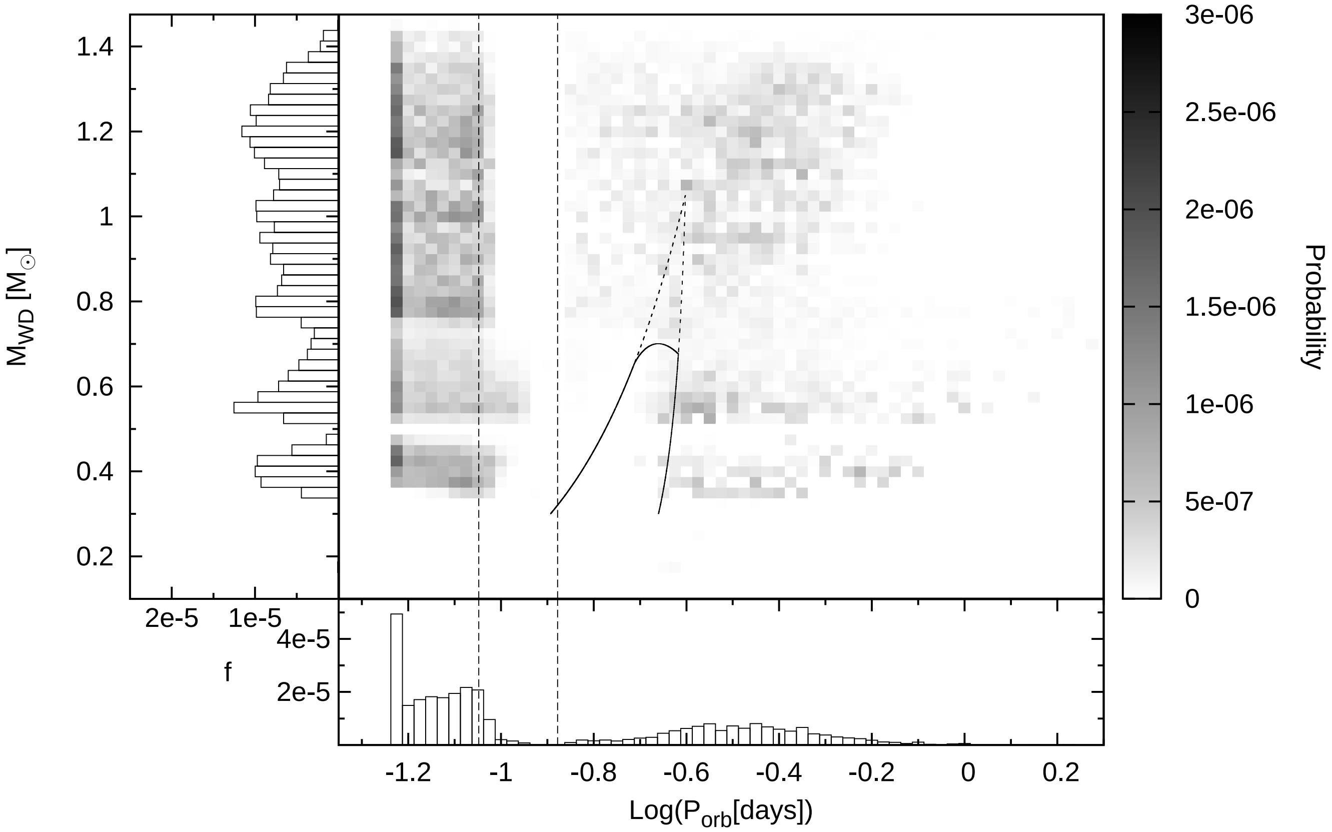

Figure 5. Same as in Fig. 2, but for model 4, in which both the *Hachisu* wind and mass growth during nova outbursts are included.

$0.8\,M_\odot$ and if a significant number of HeWDs can become more massive than $0.5\,M_\odot$, which could explain the small number of observed HeWDs. Fig. 5 shows the result of model 4, which again is very similar to model 2: 66.1 % of the CVs had a preliminary phase of TTMT and $\langle M_{\rm WD}\rangle$ increased slightly to $0.90 M_\odot$. Like in model 3, the CVs that are affected the most are systems that descend from a SSS and are currently below the gap. The peaks at 0.4 and $0.55\,M_\odot$ are less pronounced than in model 2, but the number of low mass WDs is still larger than in the observed distribution. Apart from these low mass WDs, the WD mass distribution of model 4 in general does not match the observed distribution. Allowing the WDs to accrete a larger fraction than 10 % would shift the massive WDs beyond $0.8\,M_\odot$ while the peaks at 0.4 and $0.55\,M_\odot$ would still persist. A larger accretion efficiency would therefore not provide a WD mass distribution that is more similar to the observed one.

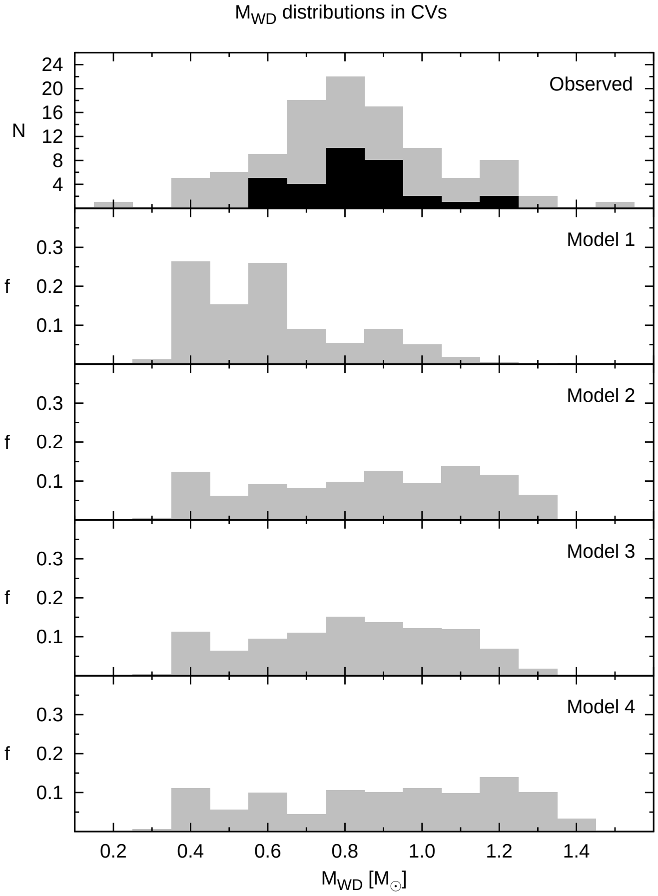

Figure 6. The mass distribution of WDs in CVs. *Top panel*: observed sample used in Zorotovic et al. (2011). The black histogram represents a subsample of which the mass determination is presumably more reliable. *Subsequent to bottom*: distributions derived from our 4 models, given by the relative probability normalized to the total formation probability of all CVs in the corresponding model. These are the same distributions as in the left panel of Figs. 2 through 5, but with a binsize of 0.1 $M_\odot$.

4. Discussion

The results of the 4 different models are summarized in Table 1 and their WD mass distributions are shown in Fig. 6. The Hachisu wind drastically increases the number of massive WDs and doubles the number of predicted CVs. Model 3 produces the WD mass distribution that is most similar to the observed distribution. However, the relative number of low mass WDs is too high in all models. According to each model, CVs with a WD more massive than $\sim 0.8\,M_\odot$ are most likely to descend from a phase of TTMT instead of being born this massive.

The models are very sensitive to several assumptions, e.g. the critical mass ratio and the *Hachisu wind*, which are fits to detailed models and thus subject to uncertainties. We will first adress the implications of these uncertainties and then compare our model predictions with the observations.

4.1. Model uncertainties

4.1.1. Critical mass ratio

We demonstrated that the simulation of CV evolution is extremely sensitive to the analytic fit to $q_{\rm cr}$ from Politano (1996). This analytic fit allows a significant number of CVs with a massive WD to evolve towards lower periods, while they would have been regarded as dynamically unstable if one would have used a constant $q_{\rm cr}$ for all low mass MS stars, i.e. a rough cut-off at $\sim 0.7\,M_\odot$. The critical mass ratio, and the corresponding region in which mass transfer becomes dynamically unstable, functions as a kind of 'road block' that prevents CVs with low mass WDs, i.e. lower than the mass corresponding to the maximum of this region, to evolve towards shorter orbital periods and remain a CV. As can be seen from the dotted regions in Fig. 2 to 5, the value of $q_{\rm cr}$ has the greatest influence on the formation of $\sim 0.8\,M_\odot$ WDs. Even fine-tuning all other parameters towards producing many post TTMT CVs, such as the Hachisu wind and an initial mass ratio distribution $\propto q$, would predict few WDs around $0.8\,M_\odot$ if $q_{\rm cr}$ is small. It is therefore of crucial importance to use an accurate value of $q_{\rm cr}$, instead of a crude approximation.

Since the critical mass ratio depends on the adiabatic mass-radius exponent, it is mainly determined by the stellar structure of the donor star and whether mass transfer is conservative or not. Although MS stars $\lesssim 0.7\,M_\odot$ don't evolve significantly within the Hubble time, we have a large number of donors that experienced TTMT and thus were initially more massive. Furthermore, these donors are forced out of thermal equilibrium due to mass transfer. Analogous to the case of MB, in which the structure of the donor star preserves the dynamo mechanism at masses lower than $0.35\,M_\odot$, the donor star may not be able to adjust fast enough to the reduced mass due to the long thermal timescale on which it readjusts to thermal equilibrium. Therefore, the structure of these donor stars could correspond to that of a more massive star. If this would be the case, both the value of the corresponding $q_{\rm cr}$ and the mass at which the adiabatic mass-radius exponent declines steeply, could change. The value for $q_{\rm cr}$ would increase, as can also be inferred by shifting the adiabatic mass-radius exponent to the left in Fig. 1, which would allow CVs with less massive WDs to evolve towards lower periods without merging. Furthermore, the steep decline in the mass-radius exponent could occur at a smaller mass for the donor star, which corresponds to a smaller period. We have tested that this provides more time for the donor to lose mass and the corresponding WD therefore has to be less massive in order

Model	fraction (%)	$\langle \mathbf{M_{WD}} \rangle$	CVs with TTMT $\langle \mathbf{M_{WD,prior}} \rangle$	$\langle \mathbf{M_{WD,after}} \rangle$	%
1	0.15	$0.61\mathrm{M}_\odot$	$0.59\mathrm{M}_\odot$	$0.92\mathrm{M}_\odot$	14.3
2	0.37	$0.86\mathrm{M}_\odot$	$0.65\mathrm{M}_\odot$	$1.03\mathrm{M}_\odot$	65.7
3	0.38	$0.82\mathrm{M}_\odot$	$0.64\mathrm{M}_\odot$	$0.96\mathrm{M}_\odot$	64.3
4	0.37	$0.90\mathrm{M}_\odot$	$0.66\mathrm{M}_\odot$	$1.08\mathrm{M}_\odot$	66.1

Table 1. Statistics of the 4 models. *From left to right*: the fraction of binaries in the grid that is currently a CV, the average WD mass of the CV population, the average WD mass at the beginning of the TTMT phase[2], the average WD mass at the end of the TTMT phase and the percentage of CVs that had a phase of TTMT.

to prevent dynamically unstable mass transfer. The influence on the WD mass distribution could be even bigger when the mass of the WDs grows during the CV phase, which would allow low mass WDs at long orbital periods to 'circumnavigate' dynamically unstable mass transfer if they accrete a sufficient amount of mass.

Moreover, we assume that mass transfer is conservative during the CV phase. For non-conservative mass transfer the critical mass ratio will be higher for a given value of the mass-radius exponent than it would be in the case of conservative mass transfer, depending on the associated loss of angular momentum.

The above reasoning and the sensitivity of the results to the critical mass ratio imply that the number of massive WDs in CVs can be increased significantly in our models. The adiabatic mass-radius exponent as shown in Fig. 1 is currently being scrutinized (Webbink, private communication). A more accurate value for mass transferring stars based on detailed stellar models would provide a more definitive insight on the possible evolutionary scenarios for CVs.

4.1.2. *Hachisu* wind

Since there is a consensus on the regime in which the mass transfer rate enables stable hydrogen burning (Nomoto et al. 2007), the alternative to the *Hachisu* wind would be that an envelope forms on the WD and the system likely evolves into a CE configuration and merges, as pointed out above. However, the reference model does not produce enough massive WDs to account for the observed distribution, cf. Fig. 6 and it is therefore likely that there is a mechanism that prevents the SSS from evolving into a CE.

The mass accumulation efficiency for hydrogen burning, η_{H}, and in particular the mass accumulation efficiency for helium shell flashes, η_{He}, during the wind determine how much the WD is growing and thus how fast the mass ratio changes as the mass of the secondary decreases. These efficiencies therefore define the evolutionary course along which a CV evolves towards lower secondary masses, i.e. to the left in figure 1. Higher efficiencies would imply a steeper decline of the mass ratio and more CVs with a phase of TTMT could circumnagivate dynamically unstable mass transfer. In contrast, lower efficiencies imply that CVs with a phase of TTMT are more likely to run into dynamically unstable mass transfer. These efficiencies could thus significantly change the WD mass distribution. The actual effect is not only determined by the efficiencies, but also strongly depends on the assumption for the critical mass ratio and the corresponding minimum M_{wd} (for a given secondary mass), to retain mass transfer stable, i.e. the maximum of the solid line in Figs. 2 to 5. If this minimum M_{wd} is $\geq 0.8\,\mathrm{M}_\odot$, then altering the efficiencies does not enhance the formation of CVs with WDs $\sim 0.8\,\mathrm{M}_\odot$.

4.1.3. Fate of the transferred mass

Since model 3 provides the best reproduction of the observed WD mass distribution the results seem to slightly favor mass loss over mass growth during the CV phase. Still, nothing conclusive can be said about which of these two scenarios is most plausible.

The amount of mass lost in a nova is based on, amongst others, the core temperature of the WD. According to Table (2) from Yaron et al. (2005), a low core temperature implies that the WD loses less mass. We have derived the core temperature of the WD from its mass and luminosity, which in *Binary_C* is based on the cooling prescription from Mestel (1952) for single WDs. This cooling prescription does not take into account an (external) energy source for the radiation, such as accretion. The WD might actually cool slower during accretion, which could result in a higher core temperature at later times during the CV evolution. Especially for long-lived CVs, i.e. older than 1 Gigayear, this will influence the amount of mass loss during a nova. A more accurate prescription for the cooling of the WD could therefore shift the most massive WDs in model 3 to lower masses.

The assumed maximum mass of HeWDs is particularly important for model 4. As discussed above, it is uncertain how much mass a HeWD can accrete. If HeWD can be more massive than $0.7\,\mathrm{M}_\odot$, they could provide a serious contribution to the observed peak at $0.8\,\mathrm{M}_\odot$, while simultaneously reducing the contribution of WDs $\lesssim 0.5\,\mathrm{M}_\odot$ to the distribution. We have tested for model 4 that their contribution to the WD masses in the range of $[0.7\text{-}0.9]\,\mathrm{M}_\odot$ could be in the order of 50 %. Observational evidence should confirm or rule out the existence of such a large predicted fraction. Unfortunately, there is (yet) no possibility to observationally distinguish between a HeWD and a CO WD other than based on their mass. Perhaps asteroseismology can offer a solution in the (near) future.

4.2. *Comparison with observations*

We will discuss the predicted and observed evolution above and below the period gap, but first we compare the distribution of WD masses in PCEBs and pre-CVs with observations.

[2] Only CVs that experienced TTMT have been used in the calculation of the average WD mass at the beginning and end of the TTMT phase

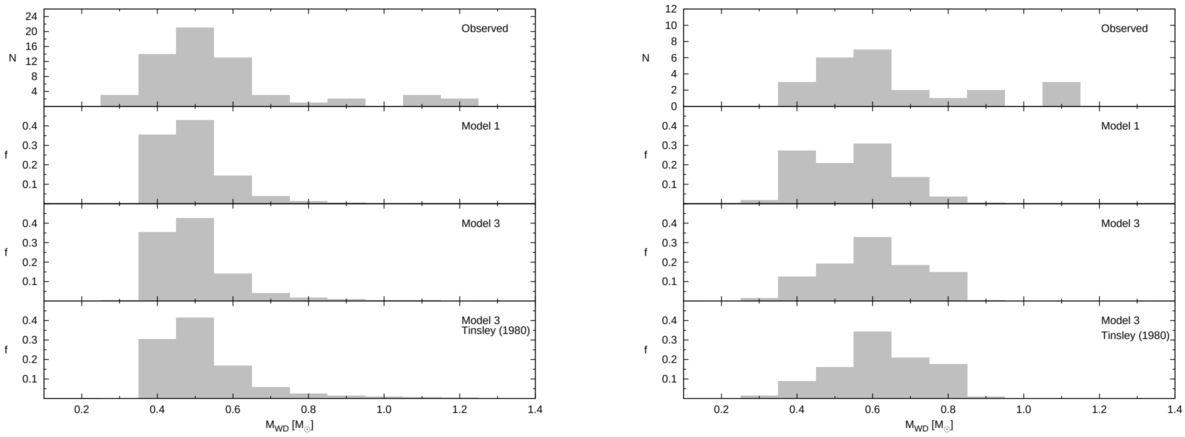

Figure 7. The mass distribution of WDs in PCEBs[3] (left) and pre-CVs[4] (right). *From top to bottom*: observed sample used in Zorotovic et al. (2011), distribution derived from model 1, distribution derived from model 3 and distribution derived from model 3 with the IMF from Tinsley (1980). The modelled distributions are given by the relative probability normalized to the total formation probability of all CVs in the corresponding model.

4.2.1. WD masses in PCEBs and pre-CVs

Zorotovic et al. (2011) extensively discussed the selection effects for their pre-CV sample and showed that the massive WDs are not already present in their pre-CV sample. By comparing the predicted and observed distribution of WD masses in both PCEBs[3] and pre-CVs[4], we can deduce if and to which extent, according to our models, massive WDs are indeed absent in the intrinsic population of PCEBs and possible CV progenitors. We emphasize at this point, that the additional assumptions for each model do not affect the pre-common-envelope evolution, thus the $M_{\rm wd}$ distritutions of PCEBs are identical for all 4 models. We use model 1 and 3 in the comparison, because the former agrees with the predictions of previous works and the latter provides the best agreement with the observed CV distributon.

As shown in the left side of Fig. 7, the simulated WD mass distribution of PCEBs looks similar to the PCEB distribution from Zorotovic et al. (2011), except for the tails. The contribution of high mass WDs in the models is too small to be visible. Both distributions have the same tendency to peak at $0.5\,\mathrm{M}_\odot$ and show similar scatter around their mean value. The right side of Fig. (7) shows that the predicted distribution of pre-CVs is also in rough agreement with the observations, in particular for model 3. The additional assumptions for model 3 clearly affect the binaries that can evolve into a CV. The number of WDs $\gtrsim 0.5\,\mathrm{M}_\odot$ that can evolve into a CV in model 3 has doubled with respect to model 1. Most importantly, Fig. (7) shows that the dominance of high mass WDs observed for CVs is not present in the pre-CV and PCEB population, neither the observed nor the predicted ones. Therefore, it confirms the finding in Zorotovic et al. (2011) that the WD mass distribution in CVs is not imprinted by their progenitors.

If, within the current standard model of CV formation, the WD mass distribution in CVs is imprinted by their progenitors, then an IMF favoring more massive primaries can be considered, e.g. Tinsley (1980); Scalo (1986); Chabrier (2003). Of these 3 IMFs, Tinsley (1980) is the one that favors massive primaries the most. However, the bottom panels in Fig. 7 show that even if we assume the IMF from Tinsley (1980) in the model that has the best agreement with the observed CV distribution, i.e. model 3, the distribution of the CV progenitors is not dominated by massive WDs.

4.2.2. Period gap

The period distributions of all 4 models agree with the period minimum and the gap as observed in the largest homogeneous sample available (Gänsicke et al. 2009). Furthermore, most CVs are predicted to be below the gap, which is in agreement with both observations (Gänsicke et al. 2009) and previous models (de Kool 1992; Kolb 1993; Howell et al. 2001; Davis et al. 2008). Our models also predict a deficit of CVs between $log(\frac{P_{\rm orb}}{\rm days}) = -0.9$ and -0.7 but a significant number of CVs at longer orbital periods, whereas the sample of Gänsicke et al. (2009) only shows some CVs in the former region, i.e. at the upper edge of the period gap, and almost none in the latter. However, the sample from Gänsicke et al. (2009) is biased against the detection of long-period CVs and the predictions about such CVs can thus not be compared to a large and representative sample of observed CVs above the gap. We have tested that the number of CVs at the upper edge of the period gap in our models can be increased if the original strength of MB, i.e. without the factor of 0.19, is assumed. The strength of MB determines the evolutionary timescale above the gap. If MB is stronger, then CVs with massive WDs above the gap would have evolved to shorter periods, therewith increasing the possibility of detecting a CV at the upper edge of the gap.

Zorotovic et al. (2011) showed the WD mass distribution of their CV sample separated in systems above and below the gap, see the left side of Fig. (8). This division shows that the dispersion of WD masses above the gap is larger than of WD masses below the gap, which are strongly peaked around $0.8\,\mathrm{M}_\odot$. Model 3, which provides the best

[3] In the models, A binary is defined as a PCEB if it had a CE, currently does not have RLOF and consists of a WD (He, CO, ONe) and a MS star.

[4] The modelled pre-CV distribution consists of the binaries that are currently a CV in each model, but the WD mass is taken at the moment the primary became a WD.

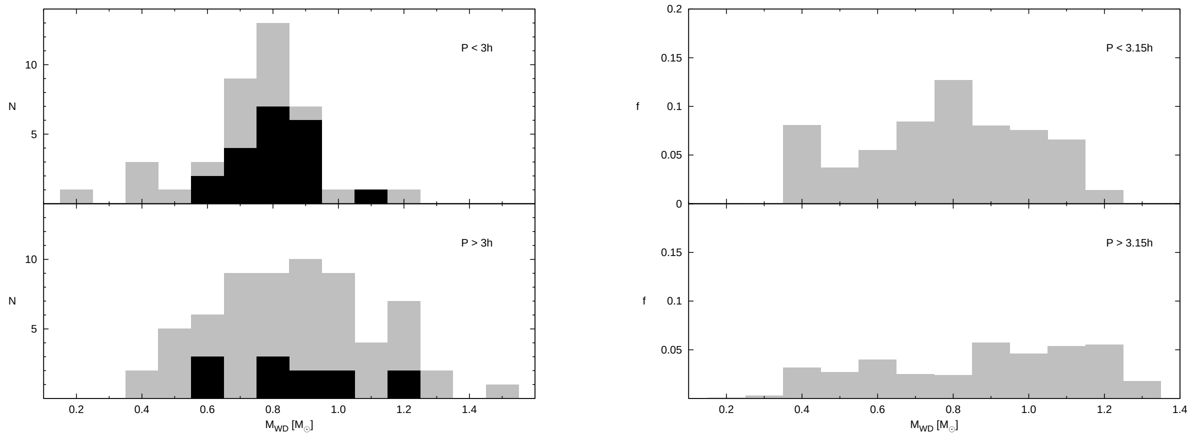

Figure 8. The WD mass distribution used by Zorotovic et al. (2011) (left) and of model 3 (right) separated into the distribution of CVs in or below the gap (*top panel*) and CVs above the gap (*Bottom panel*). The black histograms in the left figure represent a subsample of which the mass determination is presumably more reliable. The fractions in the right panel are normalized to the total formation probability of all CVs in model 3.

reproduction of the observed WD mass distribution, also shows a large spread of WD masses above the gap and a concentration around $0.8\,\mathrm{M}_{\odot}$below the gap, see the right side of Fig. (8). This could indicate that WDs in CVs do indeed lose mass during nova outbursts. We should mention that the difference between the observed WD mass distribution above and below the gap might be affected by observational biases. CVs close to the period minimum might be dominated by emission from the WD, which means a bias towards low-mass WDs (Zorotovic et al. 2011), while CVs above the gap are dominated by the accretion generated luminosity, which is a strong function of the WD mass and therefore means a bias towards high mass WDs (Ritter & Burkert 1986). Although these biases are unlikely to change the entire picture, i.e. model 3 shows the best agreement with the observations, one should keep in mind that these biases do exist. These biases also impy that our models produce too many HeWDs, predominantly below the gap. This number could be reduced by using a smaller common envelope efficiency or letting the HeWDs accrete more than $\sim 0.3\,\mathrm{M}_{\odot}$, as discussed in section 4.1.3.

5. Conclusion

The theoretical models suggest that a phase of TTMT prior to the birth of a CV provides a plausible explanation for the formation of a large number of massive WDs in CVs. The results thus support the possibility that a large fraction of the CV population could have experienced a preliminary phase of TTMT. In particular, CVs with a WD more massive than $0.8\,\mathrm{M}_{\odot}$ are most likely to descend from a phase of TTMT instead of being born this massive.

An initial mass ratio distribution that favors more massive secondaries and a wind that blows from the WD and stabilizes TTMT are necessary assumptions to produce a WD mass distribution that is dominated by massive WDs. Furthermore, the formation of CVs with a WD mass of $\sim 0.8\,\mathrm{M}_{\odot}$, around which the observed distribution is strongly peaked, is primarily influenced by the prescription for the critical mass ratio at which mass transfer in CVs becomes dynamically unstable. If the dependence of the adiabatic mass-radius exponent on the mass of the donor is approximated too roughly, the CVs with a WD mass of $\sim 0.8\,\mathrm{M}_{\odot}$ will experience dynamically unstable mass transfer and merge, leaving a cavity in the WD mass distribution where the observed distribution is peaked.

The model that provides the best reproduction of the observed WD mass distribution, if no selection effects are taken into account, furthermore assumes that mass is lost during nova outbursts. The results of this model show a dispersion of WD masses above the gap, while they are more concentrated below the gap; a characteristic that can also be seen in the observed distribution.

The simulations imply that we can expect traces of CNO processed material (indicating TTMT) in the majority of CVs with massive WDs ($\gtrsim 0.7\mathrm{M}_{\odot}$). A larger sample of CVs with massive WDs that show these features in their spectra (or the absence thereof), would therefore provide a conclusive insight on the formation of massive WDs in CVs.

Acknowledgements. I am very grateful to Matthias Schreiber and Monica Zorotovic for their warm hospitality and excellent, personal guidance during my research. Thanks to them I greatly enjoyed both my research and stay in Valparaíso. My gratitude also goes to the proficient supervision of Onno Pols, which has fortunately been extended with 4 years. Last but not least, I would like to thank Joke Claeys and Rob Izzard for their valuable comments and programming expertise.

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