

## THE FORMATION OF CATAclySMIC VARIABLES: THE INFLUENCE OF NOVA ERUPTIONS

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### ABSTRACT

The theoretical and observed populations of pre-cataclysmic variables (pre-CVs) are dominated by systems with low-mass white dwarfs (WDs), while the WD masses in CVs are typically high. In addition, the space density of CVs is found to be significantly lower than theoretical models. We investigate the influence of nova outbursts on the formation and (initial) evolution of CVs. In particular, we calculate the stability of the mass transfer in case all the material accreted on the WD is lost in classical novae, and part of the energy to eject the material comes from a common-envelope like interaction with the companion. In addition, we study the effect of an asymmetry in the mass ejection, that may lead to small eccentricities in the orbit. We find that a common-envelope like ejection significantly decreases the stability of the mass transfer, in particular for low-mass WD. Similarly, the influence of asymmetric mass loss can be important for short-period systems and even more so for low-mass WD, but likely disappears long before the next nova outburst due to orbital circularization. In both cases the mass-transfer rates increase, which may lead to observable (and perhaps already observed) consequences for systems that do survive to become CVs. However, a more detailed investigation of the interaction between nova ejecta and the companion and the evolution of slightly eccentric CVs is needed before definite conclusions can be drawn.

*Subject headings:* stars: evolution – binaries: cataclysmic variables

### 1. INTRODUCTION

Cataclysmic Variables (CVs, Warner 1995) have long been recognized as interacting binaries in which a white dwarf (WD) accretes material from a companion star via an accretion disk. The systems with non-magnetic WDs are in the standard picture thought to follow an evolution that passes through the following stages (e.g. Rappaport et al. 1983; Knigge et al. 2011): i) Onset of mass transfer at periods of several hours. ii) Evolution to shorter periods with mass transfer driven by magnetic braking leading to mass-transfer rates of order  $10^{-8} M_{\odot} \text{ yr}^{-1}$ . iii) Cessation of the mass transfer at periods of about 3 hours leading to a “period gap”. iv) Re-establishment of mass transfer at periods of around 2 hours, now driven by gravitational wave emission, leading to substantially lower mass-transfer rates of order  $10^{-10} M_{\odot} \text{ yr}^{-1}$ . v) A period minimum around 60-80 min, where the mass-transfer rate drops significantly. A (significant) part of the population may form from systems with low-mass donors that join the evolution at stage iv).

In this picture, the progenitors of CVs are wide binaries in which the intermediate-mass primary evolves to the RGB/AGB stage after which the substantially lower-mass companion experiences a spiral-in in a common-envelope phase to end with a WD and a main-sequence (MS) star in a close binary (e.g. Paczyński 1976).

This standard scenario suffers from a number of problems and shortcomings. One of them is that studies of the potential progenitors of CVs, find that the majority of progenitors

( $\gtrsim 75\%$ ) have low-mass primaries (e.g. Politano & Webbink 1989; de Kool 1992; Kolb 1993; Politano 1996), leading to a predicted mass distribution of WDs in CVs that is dominated by low-mass WDs, contrary to the observed trend that WDs in CVs are massive ( $M_{\text{WD}} > 0.7M_{\odot}$ , see Zorotovic et al. 2011, and references therein). In addition, the theoretical models predict a rather large space density of CVs, compared to observational estimates (see Pretorius 2014, and references therein). There could be a number of different solutions to these problems. On the one hand, it could be that the observational estimates are dominated by selection effects: there exist in fact many CVs and most of them have lower-mass WDs, but we predominantly see the small number of systems that have massive WD. However, recent much more homogeneous samples of CVs, in particular those found in SDSS, make this argument not very convincing (see Zorotovic et al. 2011; Gänsicke et al. 2009). A second solution could be that for some reason the true space density of CVs is lower than in the models and that the WDs in CVs actually grow in mass so that the massive WDs we see now were in fact low-mass WDs when the CVs formed (e.g. Toonen et al. 2014). This option is studied in detail by Wijnen et al. (2015), who conclude that it is unable to explain the observed WD mass distribution. A third solution could be that for some reason the theoretical models are incomplete and, for instance, the common-envelope phase through which the CV progenitors go (Paczynski 1976) preferentially selects massive WDs to become CVs. Yet, this hypothesis is ruled out because the direct progenitors of CVs (WD with MS companions) are observed and do preferentially have relatively low-mass WDs (Zorotovic et al. 2011). In this paper we study the alternative, that in fact the lower-mass WD that exist in the pre-CV population do not make it to become long-lived CVs because they merge due to additional angular momentum loss or induced small eccentricity in the first nova outbursts. Schreiber et al. (2015) independently came to the conclusion that the lower-mass WDs could be removed from the sample if for some reason they suffer extra angular momentum loss. In Sect. 2 we review the factors

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that determine the stability of the mass transfer. In Sect. 3 we derive ways to estimate the effect of classical nova outburst on the mass transfer stability, first for a brief common-envelope phase (Sect. 3.1), then for rapid asymmetric mass loss (Sect. 3.2). In Sect. 4 we show the results of our calculations for different assumptions. In Sect. 5 we discuss how our findings fit in the theoretical and observational knowledge about novae. In Sect. 6 we summarize our conclusions.

## 2. THE STABILITY OF MASS TRANSFER

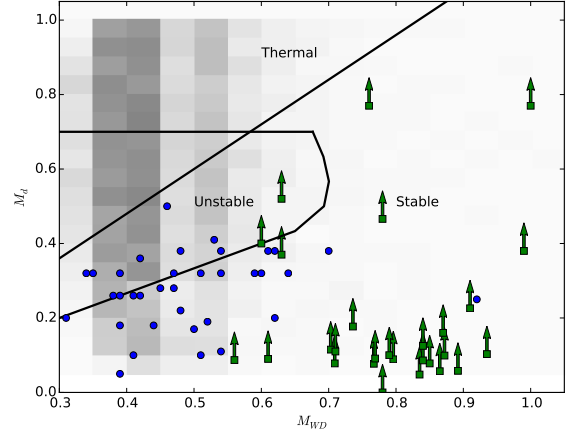
When the MS star in a WD – MS binary first fills its Roche lobe, a complex process starts, in which material is transferred from the MS star to the WD, changing the mass ratio of the system, which in turn changes the orbital separation (and thus the size of the Roche lobe). In addition, (some) of the material may not end up on the WD, but leave the binary, taking away angular momentum. Finally, the MS star will change its radius owing to its loss of mass. The net effect will be a change in the relative size of the MS star radius to its Roche lobe, which drives the mass transfer to either go up, go down or stay the same. Because the radius change of the MS star depends on the speed at which mass is lost, the final result can be

- stabilization of the mass transfer on a time scale such that the MS is roughly in equilibrium. The mass-transfer rate is set by the time scale of the angular momentum loss from the binary, through magnetic braking, gravitational wave radiation and mass loss from the system.
- stabilization of the mass transfer on a shorter time scale. The MS star tries to evolve back to thermal equilibrium on its thermal time scale and this is the time scale that sets the mass-transfer rate (e.g. Schenker & King 2002).
- the mass transfer does not stabilize and the system most likely merges to become a single object, consisting of the WD surrounded by the mass of the MS star.

In Fig. 1 we show the expected stability regions for WD – MS stars when filling their Roche lobe, assuming conservative mass transfer (all material lost from the donor is accreted by the WD). The regions are taken from Politano & Webbink (1989), and are based on two limits: for low-mass MS stars (below  $0.7 M_{\odot}$ , that have a significant convective envelope), the mass transfer is expected to be unstable if the mass ratio ( $M_{\text{donor}}/M_{\text{WD}}$ ) is larger than  $2/3$  (marked “Unstable” in the figure). For MS masses approaching the  $0.7 M_{\odot}$  this limit becomes larger (smoothly curving to a mass ratio around one). For MS stars above  $0.7 M_{\odot}$ , with mainly radiative envelopes, the mass transfer is expected to be stable for large mass ratios, but above 1.2 would proceed on the thermal time scale (marked “Thermal” in the figure, above the diagonal line).

In the same figure we show the known pre-CVs and the CVs with known WD masses (both from Zorotovic et al. 2011), where the arrows indicate that in the CVs the donors could have started mass transfer at higher mass. In grey we plot a theoretical pre-CV population, showing the preference for low-mass WD. It is model  $\alpha\alpha 2$  described in Toonen & Nelemans (2013), which was found to fit best with the observed post common-envelope binary population.

## 3. CLASSICAL NOVAE AND THEIR INFLUENCE ON THE EVOLUTION



**Figure 1.** Accretor versus donor mass at the onset of mass transfer. The lines indicate the theoretical stability limits, below which the mass transfer is expected to be stable. The grey shade shows the distribution of these parameters for the best model of post common-envelope binaries from Toonen & Nelemans (2013). The blue circles show the pre-CV systems, while the green squares with arrows indicate the masses in CVs (both from Zorotovic et al. (2011))

The above theoretical stability limits are based on overly simplified assumptions, in particular that all the transferred mass stays on the WD. Accreting WD accumulate the accreted material in a layer and when the density and temperature at the bottom of the layer are high enough, nuclear fusion in the layer causes a classical nova outburst (Starrfield et al. 1972; Townsley & Bildsten 2004), in which much, if not all, accreted mass is lost from the system. This causes different effects on the binary evolution: the mass loss can widen the binary, lowering the mass-transfer rate. On the other hand, if the expanding envelope interacts strongly with the companion, the ejected mass could take along relatively large amounts of angular momentum, shrinking the orbit (e.g. Livio 1992). Finally, if the mass-loss happens fast and is asymmetric, it may induce a small eccentricity in the orbit that may influence the mass transfer. Shara et al. (1986) have studied the influence of novae on the orbit and concluded that in principle CVs could have long periods of “hibernation”, in which the binary becomes detached and mass transfer ceases. This happens if the nova outburst ejects the mass rapidly without much scope for interaction with the companion. However, recent observations of nova outbursts suggest that the ejecta are in fact strongly influenced by the companion (e.g. Woudt et al. 2009; Ribeiro et al. 2013; Chomiuk et al. 2014). We therefore below study how such interactions could affect the stability of the mass transfer.

### 3.1. Angular momentum loss in a common-envelope

For a given formalism that describes the change in orbital separation due to a common-envelope-like phase we can determine the associated angular momentum loss. This then can be added to the other angular momentum losses to calculate the stability of the mass transfer (e.g. Livio et al. 1991; Shen 2015).

We assume here that the nova eruption leads to expansion of the envelope and that at the time this envelope reaches the companion star (i.e. at a radius equal to the orbital separation) the friction of the common-envelope takes over the energy generation to bring the material to infinity. Of course

the nuclear burning in principle can provide enough energy to eject the envelope (if it is not radiated) so we simply assume the common-envelope’s orbital energy is used to eject a fraction  $f_{\text{CE}}$  of the material, the rest being ejected by the energy from the burning. To calculate the angular momentum loss associated with the common-envelope, we here consider only this fraction of the ejected mass  $M_{\text{ej}} = f_{\text{CE}}M_{\text{accreted}}$  and can write its binding energy as

$$E_{\text{bind}} = \frac{GM_{\text{WD}}M_{\text{ej}}}{a_i}, \quad (1)$$

while the orbital energy is given by

$$E_{\text{orb},i} = \frac{GM_{\text{WD}}M_d}{2a_i}. \quad (2)$$

The final orbital energy then is

$$E_{\text{orb},f} = E_{\text{orb},i} - E_{\text{bind}} = \frac{G(M_{\text{WD}} - M_{\text{ej}})M_d}{2a_f}. \quad (3)$$

Rearranging the terms and writing out the last term of eq. 3 we get

$$\frac{2M_{\text{WD}}M_{\text{ej}} + M_{\text{WD}}M_d}{2a_i} = \frac{M_{\text{WD}}M_d - M_{\text{ej}}M_d}{2a_f} \quad (4)$$

so

$$\frac{a_f}{a_i} = \frac{1 - M_{\text{ej}}/M_{\text{WD}}}{1 + 2M_{\text{ej}}/M_d} \quad (5)$$

which (because  $M_{\text{ej}} \ll M_{\text{WD}}, M_d$ ) is well approximated by

$$\frac{a_f}{a_i} \approx 1 - M_{\text{ej}}/M_{\text{WD}} - 2M_{\text{ej}}/M_d \quad (6)$$

so with  $q = M_d/M_{\text{WD}}$ , the relative change in orbit is

$$\frac{\Delta a}{a} = \frac{a_f - a_i}{a_i} = -\frac{M_{\text{ej}}}{M_d}(2 + q). \quad (7)$$

This result is somewhat different (smaller) than eq. (2) of Shen (2015), who considers as binding energy the energy needed to bring the envelope to infinity from the L1 point.

The change in orbital angular momentum (due to the change in separation and mass) is

$$\frac{\Delta J_{\text{orb}}}{J_{\text{orb}}} = -\frac{M_{\text{ej}}}{M_d} \left( 1 + q + \frac{q^2}{2(1+q)} \right). \quad (8)$$

For values of  $q$  between 0.2 and 1 (relevant for CV systems) the above expression is within ten per cent of the simple and often used angular momentum loss from a ‘‘circumbinary’’ ring with radius of  $a$  (Soberman et al. 1997; Tauris & van den Heuvel 2006).

$$\frac{\Delta J_{\text{orb}}}{J_{\text{orb}}} = -\frac{M_{\text{ej}}}{M_d}(1 + q) \quad (9)$$

We performed MESA (Paxton et al. 2013, 2015, rev. 7184) calculations of the evolution of CVs for several different assumptions for the angular momentum loss due to nova eruptions. For a grid of donor masses and accretor masses we used the standard magnetic braking prescription of MESA (based on Rappaport et al. 1983) to simulate the evolution from an orbital period slightly longer than the one at which Roche-lobe overflow starts. We only simulate the donor star in detail and prescribe the mass and angular momentum loss from the

system as a combination of isotropic re-emission (see Soberman et al. 1997; Tauris & van den Heuvel 2006) and mass and angular momentum loss due to a common-envelope-like process according to eq. 9. We can model the latter as a continuous process, because the recurrence time between the novae is significantly shorter than any of the relevant time scales of the donor star, so the MESA calculations actually use time steps longer than the recurrence time. We classify the mass transfer as unstable, if it reaches above  $\sim 10^{-4} M_{\odot} \text{ yr}^{-1}$  when it is at least a factor of 1000 larger than thermal time scale mass-transfer and the code breaks down.

### 3.2. White dwarf kicks due to asymmetric mass loss

Alternatively, if (part of) the envelope is ejected asymmetrically in a fast nova eruption, the accreting white dwarf will get a small velocity kick to conserve linear momentum. As in the case of an asymmetric supernova explosion that gives a kick to newly formed neutron stars, this kick will introduce an eccentricity in the orbit. We performed a Monte Carlo calculation of the effect of a small, isotropic kick on the orbit using the same method as in Repetto & Nelemans (2015) and found that depending on the direction of the kick, the semi-major axis either increases or decreases, but that in the vast majority of the case the periastron distance in the new orbit is smaller than the pre-nova separation. This could lead to a (strong) increase in the mass transfer rate at periastron. In order to estimate the maximum effect of asymmetric mass loss, we calculate the most extreme case, in which the kick is directed opposite to the orbital velocity of the WD. We assume the mass is leaving the accreting white dwarf with an ejection velocity  $v_{\text{ej}}$ . The resulting kick velocity of the white dwarf  $v_{\text{kick}}$  is given by

$$v_{\text{kick}} = f_{\text{kick}} v_{\text{ej}} \frac{M_{\text{ej}}}{M_{\text{WD}}} \quad (10)$$

where  $f_{\text{kick}}$  is the fraction of the mass that is ejected asymmetrically. With  $v_{\text{ej}} = 500 - 3000 \text{ km/s}$  (Chesneau & Banerjee 2012; Ribeiro et al. 2013, and references therein), and  $M_{\text{ej}}/M_{\text{WD}} \lesssim 10^{-3}$  the kick could be up to a km/s.

For initial orbital separation  $a_0$ , the eccentricity and semi-major axis after the kick can be derived in the relevant small-change limit showing its main effects. For our actual calculations below we use the full equations (e.g. Brandt & Podsiadlowski 1995; Kalogera 1996). Defining

$$M_{\text{tot},f}/M_{\text{tot},i} = 1 - \delta \quad (11)$$

(so  $\delta > 0$  is the fractional change in total mass), and

$$\nu = v_{\text{kick}}/v_{\text{rel}} \quad (12)$$

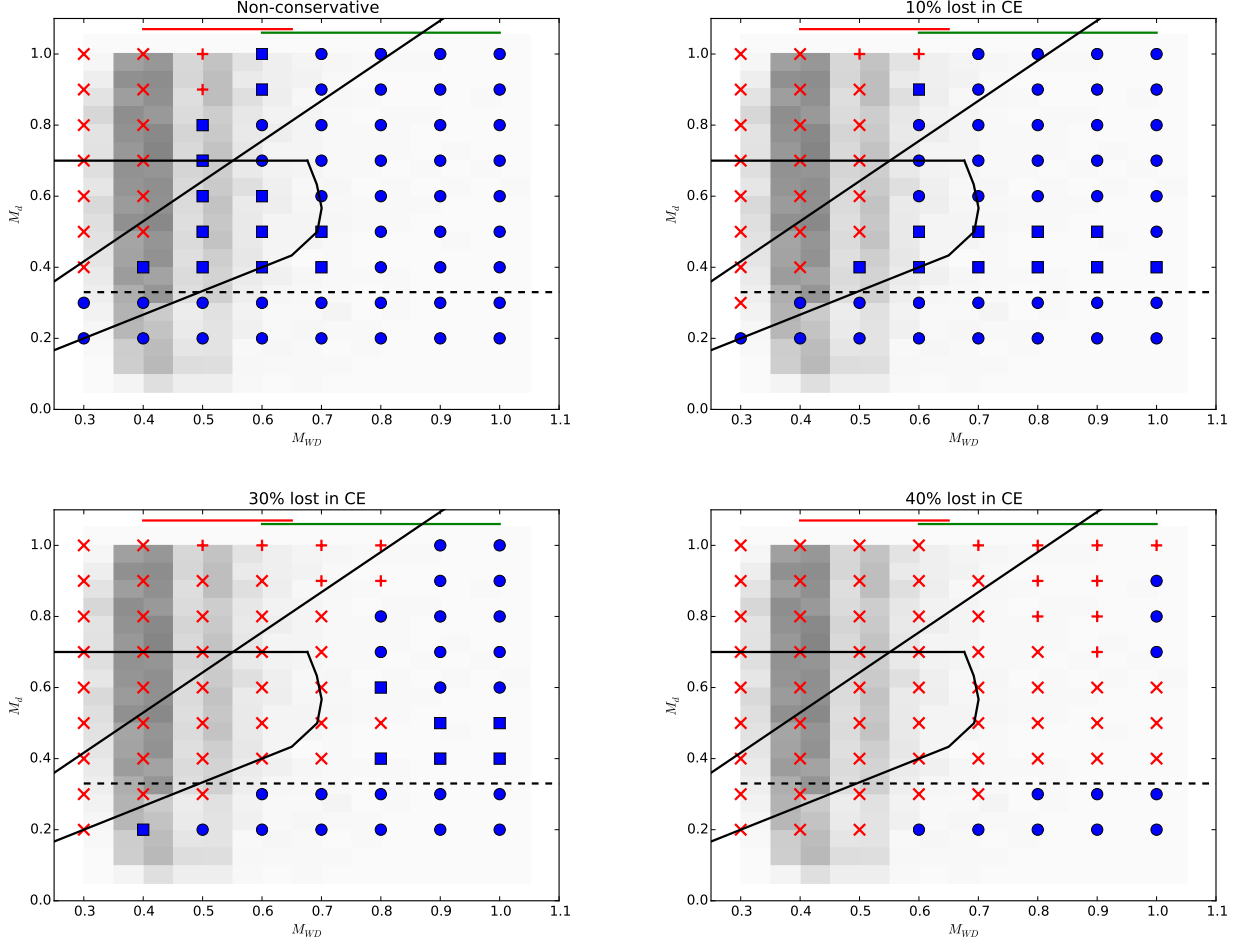
where  $v_{\text{rel}}$  is the relative velocity of the two stars (and taking  $\nu > 0$  when the kick is directly opposed to  $v_{\text{rel}}$ ), one gets<sup>6</sup>

$$\frac{a_f}{a_i} = 1 - 2\nu + \delta \quad (13)$$

and the resulting eccentricity is

$$e_{\text{strong}} = |2\nu - \delta| \quad (14)$$

<sup>6</sup> An interesting point is that the pericenter is then given, to linear order in  $\delta$  and  $\nu$ , by  $r_p = 1 - 2(2\nu - \delta)$  for  $2\nu > \delta$ ;  $r_p = 1$  for  $2\nu < \delta$ , i.e. unless the kick velocity is greater than  $(1/2)\delta v_{\text{rel}}$ , about 10m/s for a typical case, the initial semi major axis is the pericenter, not the apocenter, so no enhanced Roche lobe overflow is possible.



**Figure 2.** Grid of initial accretor versus donor mass for the MESA calculations at the onset of mass transfer. The lines and grey shade denote the stability limits and theoretical population as in Fig. 1. The symbols indicate the outcome of the MESA calculations. (red) cross: directly unstable, (red) plus: unstable after a brief stable phase; (blue) square: thermal time scale stable, (blue) circle: stable. The dashed lines give the separate onset of mass transfer above and below the period gap. The different plots are for for  $f_{\text{CE}} = 0.0$ , i.e. fully non-conservative mass transfer,  $f_{\text{CE}} = 0.1, 0.3$  and  $0.4$ .

To estimate the effect on the mass-transfer rate we calculate the Roche-lobe overfill factor  $\Delta = (R_* - R_L)$  as function of the orbital phase ( $\phi$ ), assuming to first order that the relative change in the Roche lobe follows the relative change in the separation and assuming that before the nova  $\Delta = 0$ . For the relevant case  $2\nu > \delta$ ,

$$\Delta(\phi)/R_* = -(1+q)\delta \frac{\partial \ln R_L}{\partial \ln q} + (2\nu - \delta)(1 + \cos \phi) \quad (15)$$

with  $\frac{\partial \ln R_L}{\partial \ln q}$  derived from the Roche-lobe approximation, e.g. Eggleton (1983). For small values of  $\Delta$  the mass-transfer rate scales as (Ritter 1988)

$$\dot{M} \propto e^{\Delta/H}, \quad (16)$$

with

$$H = \frac{k_B T_{\text{eff}}}{\mu m_H g}, \quad (17)$$

the pressure scale height of the MS atmosphere.

In order to determine the eccentricities that could arise from asymmetric mass loss, we have to calculate the effects of single novae, and therefore have to assume ignition masses and mass transfer rates. We take the ignition masses from Townsley & Bildsten (2004), assuming mass transfer rates of

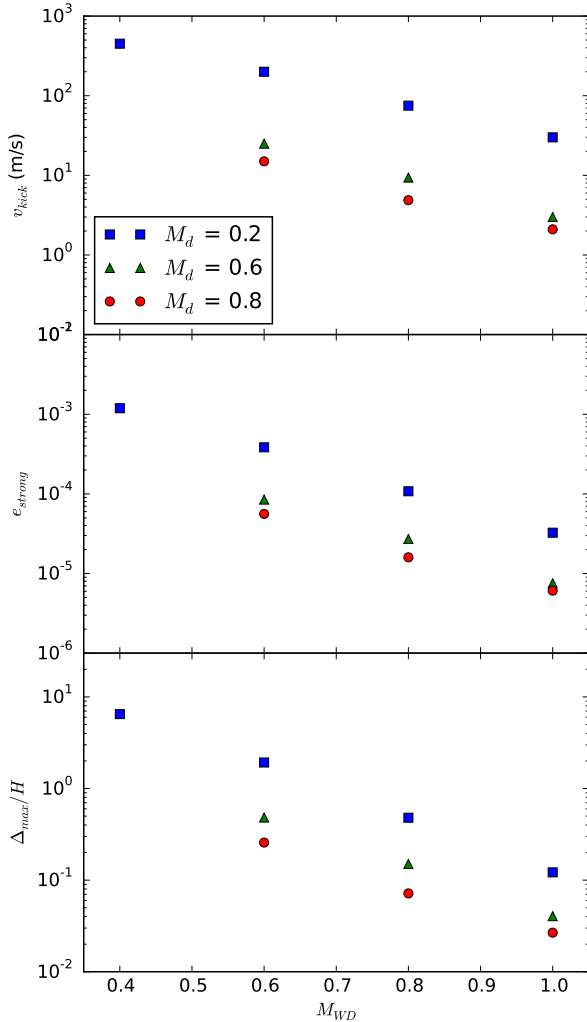
$10^{-8} - 10^{-9} M_{\odot} \text{ yr}^{-1}$  above the period gap and  $10^{-10} M_{\odot} \text{ yr}^{-1}$  below the period gap. We then calculate the effect of kick on the orbit and the mass-transfer rate, find the new ignition mass and calculate the time to the next nova which we compare to the circularization time scale (taken from Verbunt & Phinney 1995).

Furthermore, we use the BINSTAR code described in Siess et al. (2013); Davis et al. (2013), that performs mass transfer calculations in eccentric orbits with a full stellar evolution code, to test the above simplified treatment.

## 4. RESULTS

### 4.1. Angular momentum loss in a common-envelope like phase

We calculated the stability of mass transfer for a grid of initial WD and MS stars for different values of  $f_{\text{CE}}$ , assuming the rest of the material is lost in a fast symmetric ejection. In Fig. 2 we show the results for  $f_{\text{CE}} = 0, 0.1, 0.2, 0.4$ . The fully non-conservative case (top left), with no common-envelope interaction, shows that in that case significantly more systems are stable than for the theoretical conservative limits. A large fraction of the pre-CVs with low-mass WDs would evolve into CVs, dominating the population both above and below the period gap. Increasing the fraction of mass ejected via



**Figure 3.** Kick velocities, eccentricities and maximum change in Roche-lobe overflow factor for novae with  $f_{\text{kick}} = 0.1$

a common-envelope like process strongly reduces the number of stable systems, in particular for low-mass WD. For  $f_{\text{CE}} = 0.1$  the results come close to the theoretical conservative boundaries, while for  $f_{\text{CE}} = 0.3$  they become more constraining. In both cases the additional angular momentum loss causes systems that start Roche-lobe overflow just above the period gap to briefly experience a (very) short phase of thermal-time scale mass transfer before settling down on the magnetic braking time scale. For  $f_{\text{CE}} = 0.4$  also a significant fraction of the pre-CVs with massive WDs become unstable and virtually only systems that start mass transfer below the period gap remain stable.

#### 4.2. Eccentric orbits due to asymmetric mass loss

For a more sparse set of initial binaries we calculate the kick velocity, eccentricity and effect on the mass transfer rate for an assumed ejecta velocity of 1500 km/s and assuming an asymmetric mass fraction of 20 per cent,  $f_{\text{kick}} = 0.2$ . The

**Table 1**

Resulting  $e_{\text{strong}}$ ,  $\Delta$  and global increase in mass-transfer rate ( $f_{\dot{M}}$ ) for the different systems considered. For the systems with low-mass donors, where the effect can be significant, we also calculate the ignition mass for the increased mass-transfer rate, its recurrence time and the tidal circularization time scale.

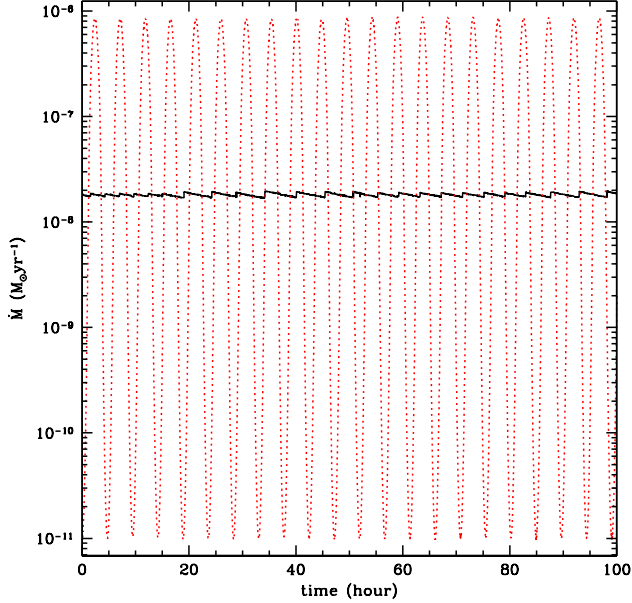
$M_{\text{WD}}$ ( $M_{\odot}$ )	$M_d$ ( $M_{\odot}$ )	$\frac{M'_{\text{ign}}}{10^{-5}}$ ( $M_{\odot}$ )	$e_{\text{strong}}$ ( $10^{-4}$ )	$v_{\text{kick}}$ (m/s)	$\frac{\Delta_{\text{max}}}{H}$	$f_{\dot{M}}$	$\frac{M'_{\text{ign}}}{10^{-5}}$ ( $M_{\odot}$ )	$t_{\text{rec}}$ (yr)	$\tau_{\text{tide}}$ (yr)
1.0	0.2	10	0.3	30	0.12	1.0	10	1.e6	185
0.8	0.2	20	1.1	75	0.5	1.2	20	1.7e6	171
0.6	0.2	40	3.9	200	1.9	2.9	20	6.7e5	157
0.4	0.2	60	12	450	6.5	144	10/S? <sup>a</sup>	6.9e3	146
1.0	0.6	1	0.08	3.0	0.04	1.0			
0.8	0.6	2.5	0.27	9.4	0.215	1.1			
0.6	0.6	5.	0.85	25	0.5	1.3			
1.0	0.8	0.7	0.06	2.1	0.03	1.0			
0.8	0.8	1.3	0.16	4.9	0.07	1.0			
0.6	0.8	3.0	0.56	15	0.26	1.1			

<sup>a</sup>steady burning

masses and ignition masses (taken from fig. 9 of [Townsend & Bildsten 2004](#)) we use are shown in the first three columns of Table 1, the resulting eccentricity ( $e_{\text{strong}}$ ), kick velocity and maximum change in the Roche-lobe overflow factor ( $\Delta$ ) compared to the donor's pressure scale height in the next three columns. The latter three are graphically shown in Fig. 3. We assume  $M_{\text{ej}} = M_{\text{ign}}$ .

For the massive donors, i.e. systems above the period gap, the resulting kicks are typically very small, of order of several m/s, resulting in very small eccentricities. The change in the overflow factor then is only a fraction of the scale height and very little change in the system is expected. For the systems with a  $0.2 M_{\odot}$  donor, the kicks are higher, reaching 500 m/s for the lowest mass WDs. For these systems the eccentricity reaches  $10^{-3}$  and the orbits change so much that the overflow factor changes by several scale heights.

We numerically integrate the average increase of the mass-transfer rate over one orbit compared to the pre-nova circular orbit, using eq. (16) and show the results in the next column in Table 1. As before, for the systems above the period gap there is hardly any change. However, for the short period systems there is a significant change. For the  $0.4 + 0.2 M_{\odot}$  system, the average mass transfer rate is expected to increase by a factor larger than 100. In order to estimate the effect on the system, we look up the appropriate ignition masses for these new mass-transfer rates in [Townsend & Bildsten \(2005\)](#) and calculate the time it would take the system to experience another nova (columns 8 and 9). They are significantly shorter than the millions of years in unperturbed systems, but still much longer than the tidal circularization time scales for the binaries that we calculate using eq. (2) of [Verbunt & Phinney \(1995\)](#), which for these very close binaries are only of order of 100 years. So unless the enhanced mass-transfer rate leads directly to mass loss from the system (e.g. through the L2/L3 points) that could influence the further evolution, the effect of asymmetric mass loss seems short lived, providing only a relatively small increase in the average mass-transfer rate between novae. For the most extreme system, the mass-transfer rates increase so dramatically, that the system may actually get into the regime where the newly accreted material is burnt directly and stably to helium, rather than accumulated (indicated by ‘‘S?’’ in the table, see fig. 1 of [Townsend & Bildsten 2005](#)) and the system might show up (briefly) as a super-soft X-ray source (see [van den Heuvel et al. 1992](#)).



**Figure 4.** Evolution of the mass transfer rate in a  $0.6 + 0.6 M_{\odot}$ , slightly eccentric ( $e = 2 \times 10^{-3}$ ) orbit in red, compared to a circular orbit in black.

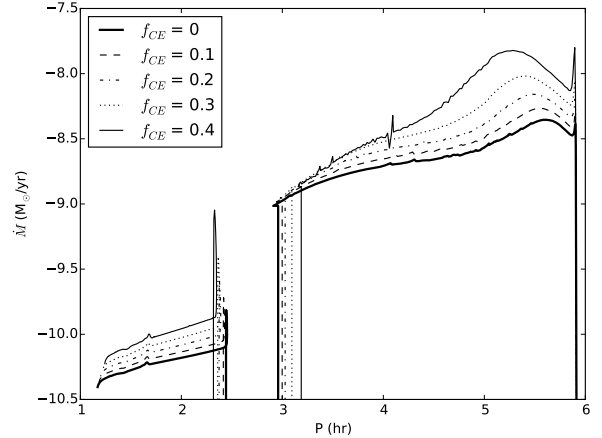
#### 4.3. The influence of eccentricity on the evolution

As a test case we evolved a  $0.6$  white dwarf +  $0.6$  main sequence star with a relatively large eccentricity  $e = 2 \times 10^{-3}$  using the BINSTAR code (Fig. 4). We started the system in such an orbit, that the semi-major axis is equal to the pre-nova orbital separation. The mass-transfer rate thus alternating increases and decreases compared to the pre-nova mass-transfer rate, for which we use  $2 \times 10^{-8} M_{\odot} \text{ yr}^{-1}$ . The mass transfer in the eccentric case indeed varies strongly, with the maximum almost a factor 50 higher than the pre-nova rate. On average the mass-transfer rate is more than a factor 10 higher than in the circular case. For comparison, for these parameters, our simple calculation as in Sect. 3.2 gives a factor 100, i.e. overestimates the effect. It is clear, that in order to fully assess the influence of such small asymmetric mass loss, a systematic study including all the different effect should be undertaken, which is beyond the scope of this paper.

## 5. DISCUSSION

The results show that potentially a common-envelope like phase and asymmetric mass loss can significantly change the evolution of CVs. The two main questions are if these effects actually happen and if so, if they change the stability of the systems in such a way that the discrepancies between the theoretical and observed CV population disappear.

From Fig. 2 it is clear that for the mechanism to work comfortably, the systems with low-mass WD should eject a fairly significant fraction ( $\sim 40$  per cent) of the mass via a common-envelope like mechanism, while more massive WDs should be affected less in order to avoid a deficit of systems above the period gap. There is no a priori reason to assume the fraction would be the same. The ejecta velocities are expected to be lower and envelope masses higher for lower-mass WD, which could lead to more and stronger interaction of the envelope with the companion (see Livio et al. 1991). Indeed, Kato & Hachisu (2009, 2011) find that optically thick winds that drive the mass loss always happen on WD with mass above



**Figure 5.** Mass-transfer rate as function of periods for different values of  $\delta$ . The system initially consists of a  $1.0 M_{\odot}$  WD with a  $0.8 M_{\odot}$  MS companion.

$0.7 M_{\odot}$ , but not below, where instead a static giant-like envelope is found initially. They suggest that for lower-mass WD a common-envelope like interaction may trigger the transition to a (wind) mass losing structure. On the other hand, for asymmetric mass loss to produce a kick, the ejection should happen on a short time scale compared to the orbital period, so would most likely be diminished if the nova was slow.

Schreiber et al. (2015) find that a parametrized angular momentum loss, where the specific angular momentum loss is inversely proportional to the WD mass works well in an analytic model for the stability of the mass transfer. The WD mass distribution of the resulting CV population shows a very good agreement with the observed WD mass distribution. Williams (2013) suggests that the “transient heavy element absorbing” gas seen in many nova spectra is due to significant mass loss from the disks in the system, most likely to a circumbinary disk, which would lead to additional angular momentum loss with the same scaling as our eq. (9).

Observationally, the effect of both the common-envelope like ejection as well as (in most cases) the asymmetric mass loss would be an enhancement of the mass-transfer rate and mass loss from the system. To show this, we plot in Fig. 5 the period – mass-transfer rate evolution of a system that initially consists of a  $1.0 M_{\odot}$  WD and an  $0.8 M_{\odot}$  donor, for different values of  $f_{CE}$ . The mass transfer rate increases significantly, although we have to caution that in these calculations the standard magnetic braking laws are used that likely overestimate the mass-transfer rate (see Knigge et al. 2011, and references therein). For the eccentric system, the strong orbital modulation of the mass-transfer rate is likely severely damped by the accretion disk, which provides a buffer between the instantaneous mass-transfer rate and the brightness of the system. Patterson et al. (2013) make an interesting case for the CV BK Lyn to be a system where, following a nova outburst 2000 years ago, the system has had a long phase of much higher mass-transfer rate, only now coming down into the regime of low-mass transfer dwarf novae. The ER UMa class of CVs in that picture would be slightly older “post-novae”. They also suggest that the finding of Schaefer & Collazzi (2010) that some systems are significantly brighter after a nova outburst, while others not, is due to the same effect and that this occurs only in short-period systems.

A second observational effect would be a change in the

orbital period after a nova outburst (Schaefer & Patterson 1983). In case of the common-envelope like ejection the period would decrease by a factor that follows from eq. (9) and the relative change ( $\Delta P/P$ ) is roughly a factor 10 larger than the relative mass change ( $\Delta M_{\text{ej}}/M_{\text{tot}}$ ), i.e.  $f_{\text{CE}} \times 10^{-3} - 10^{-4}$ . For the asymmetric mass ejection, the period could both increase and decrease, within a factor few from the relative mass change. There are very few measurements of period changes, showing both increases and decreases (Schaefer & Patterson 1983; Schaefer 2011), but future determinations, in particular for different types of systems could be used to measure the relative importance of mass and angular momentum loss from the systems.

Another way to test our hypothesis, is whether there is any observational signature that could be used to find the systems that experience unstable mass transfer and thus merge. The merged product would most likely form some kind of low-mass giant star, where the WD becomes the core and the MS star formed the envelope. They would be vastly outnumbered by ordinary giants. Perhaps if via asteroseismology we could measure the core/envelope mass ratio, some of them would stand out as having a very high ratio compared to ordinary giants evolved from single stars.

Finally, we mention that the higher mass- and angular-momentum loss needed to explain the lack of low-mass WDs in CVs also eases the discrepancy between the theoretical and observed period minimum (see e.g. Knigge et al. 2011; Schreiber et al. 2015), because higher mass-transfer rates lead to a period minimum at longer period, as can be seen in Fig. 5.

## 6. CONCLUSIONS

We study the mass-transfer stability of binary systems in which a MS star starts mass transfer to a WD to become a CV. Motivated by the problem that the WD masses in CVs are higher than in pre-CVs and that their space density seems significantly lower than theoretically predicted, we investigate whether the influence of nova outbursts on the stability of the mass transfer could selectively remove the pre-CVs with low-mass WDs so that only the systems with massive WDs remain. Interaction between the expanding nova envelope and the companion may lead to a common-envelope like phase that could take away angular momentum. Low-mass WDs are more prone to this instability and can be effectively removed from the CV population if some 40 per cent of the ejection energy is provided by the orbital interaction. However, more massive WD would also be affected and for this mechanism to work comfortably, the higher ejecta velocities expected and observed for more massive WD, should lead to less interaction with the companion.

We also investigate the influence of any asymmetry of the mass ejection in the nova and find that for low-mass WD this can significantly influence the orbit. The induced a small eccentricity drives up the average mass-transfer rate, maybe even to a regime where the material burns directly on the WD when it arrives, as a super-soft X-ray source. However, it depends strongly on the magnitude of the asymmetry and we find that the tidal circularization time scale in our simplified models, is always significantly shorter than the time to the next nova outburst, but it may explain the temporary mass-transfer rate increase inferred by Patterson et al. (2013) for BK Lyn and the ER UMa systems. A more detailed and systematic investigation of asymmetric mass loss in CVs is needed to assess its potential influence on the CV population.

We conclude that it seems possible that the pre-CVs with low-mass WDs do not make it to become CVs, because the first (few) nova outburst(s) drive additional angular momentum loss that leads to unstable mass transfer and merger of the system. As also suggested by Schreiber et al. (2015), this would significantly decrease the total space density of CVs and may make the theoretical WD mass distribution in CVs consistent with the observations.

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