



THE FORMATION OF CATAclySMIC VARIABLES: THE INFLUENCE OF NOVA ERUPTIONS

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ABSTRACT

The theoretical and observed populations of pre-cataclysmic variables are dominated by systems with low-mass white dwarfs (WDs), while the WD masses in cataclysmic variables (CVs) are typically high. In addition, the space density of CVs is found to be significantly lower than in the 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 the case where all of 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, particularly for low-mass WDs. Similarly, the influence of asymmetric mass loss can be important for short-period systems and even more so for low-mass WDs; however, this influence 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.

Key words: binaries: close – novae, cataclysmic variables – stars: evolution

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 in the standard picture are thought to follow an evolution that passes through the following stages (e.g., Rappaport et al. 1983; Knigge et al. 2011): (1) the onset of mass transfer at periods of several hours; (2) the evolution to shorter periods with mass transfer driven by magnetic braking that leads to mass-transfer rates of the order of $10^{-8} M_{\odot} \text{ yr}^{-1}$; (3) the cessation of the mass transfer at periods of about three hours that leads to a “period gap”; (4) the reestablishment of mass transfer at periods of about two hours that is driven by gravitational wave emission that leads to substantially lower mass-transfer rates of the order of $10^{-10} M_{\odot} \text{ yr}^{-1}$; and (5) a period minimum around 60–80 minutes in which 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 (5).

In the picture described above, 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 ($\lesssim 75\%$) have low-mass primaries (e.g., Politano & Webbink 1989; de Kool 1992; Kolb 1993; Politano 1996); this leads to a predicted mass distribution of WDs in CVs that is dominated by low-mass WDs, which is contrary to the observed trend that WDs in CVs

are massive ($M_{\text{WD}} > 0.7 M_{\odot}$, see Zorotovic et al. 2011 and references therein). In addition, the theoretical models predict a rather large space density of CVs, compared with 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 WDs. However, recent and much more homogeneous samples of CVs, in particular those found in SDSS, make this argument not very convincing (see Gänsicke et al. 2009; Zorotovic et al. 2011). 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 this solution 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 of the CV progenitors (Paczynski 1976) preferentially selects massive WDs to become CVs. Yet this hypothesis is ruled out because the direct progenitors of CVs (WDs with MS companions) are observed and preferentially have relatively low-mass WDs (Zorotovic et al. 2011). In this paper we study the alternative: the lower-mass WDs that exist in the pre-cataclysmic variable (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. (2016) independently concluded that lower-mass WDs are removed from the sample and were the first to propose extra angular momentum loss due to mass loss as its cause. In

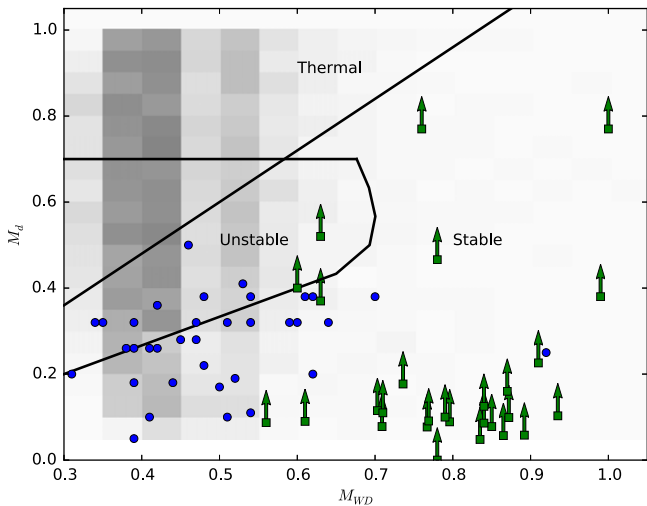


Figure 1. Accretor vs. donor mass at the onset of mass transfer. The lines indicate the theoretical stability limits below which the mass transfer is expected to be stable. The gray shade shows the distribution of these parameters for the best model of post-common-envelope binaries from Toonen & Nelemans (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).

Section 2 we review the factors that determine the stability of the mass transfer. In Section 3 we derive ways to estimate the effect of classical nova outbursts on the mass transfer stability, first for a brief common-envelope phase (Section 3.1) and then for rapid asymmetric mass loss (Section 3.2). In Section 4 we show the results of our calculations for different assumptions. In Section 5 we discuss how our findings fit into the theoretical and observational knowledge about novae. In Section 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 that transfers material from the MS star to the WD and changes 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 and take 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 compared to its Roche lobe. This change drives the mass transfer to 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 one of the following.

1. Stabilization of the mass transfer on a timescale 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.
2. 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. This time scale sets the mass-transfer rate (e.g., Schenker et al. 2002).
3. The mass transfer does not stabilize and the system most likely merges to become a single object that consists of the WD surrounded by the mass of the MS star.

In Figure 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 $0.7 M_{\odot}$, 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. However, for mass ratios above 1.2, the mass transfer proceeds on the thermal time scale (marked “Thermal” in Figure 1 above the diagonal line).

Figure 1 also shows the known pre-CVs and the CVs with known WD masses (both from Zorotovic et al. 2011) where the green arrows indicate that in the CVs the donors could have started mass transfer at a higher mass. In gray, we plot a theoretical pre-CV population, showing the preference for low-mass WD. The model is $\alpha\alpha 2$ described in Toonen & Nelemans (2013) and was found to fit best with the observed post-common-envelope binary population.

3. CLASSICAL NOVAE AND THEIR INFLUENCE ON THE EVOLUTION

The above theoretical stability limits are based on overly simplified assumptions, in particular that all the transferred mass stays on the WD. The accreting WD accumulates the accreted material in a layer. When the density and temperature at the bottom of the layer are high enough, nuclear fusion 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 outburst causes different effects on the binary evolution. The mass loss can widen the binary and lower the mass-transfer rate or if the expanding envelope interacts strongly with the companion, the ejected mass could take along relatively large amounts of angular momentum and shrink the orbit (e.g., Livio 1992). Finally, if the mass loss happens fast and is asymmetric, it can 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 hibernation 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 discuss below 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 which can then 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 an 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 in principle, the nuclear burning 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_{CE} of the material and the rest is 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

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

The final orbital energy then is

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

Rearranging the terms and writing out the last term of Equation (3), we get

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

so

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

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

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

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

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

This result is somewhat different (smaller) than Equation (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

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

For values of q between 0.2 and 1 (relevant for CV systems) the above expression is within 10% of the simple and often used angular momentum loss from a ‘‘circumbinary’’ ring with a radius of a (Soberman et al. 1997; Tauris & van den Heuvel 2006).

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

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 Equation (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 donors 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. WD Kicks Due to Asymmetric Mass Loss

Alternatively, if part of the envelope is ejected asymmetrically in a fast nova eruption, the accreting WD 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 cases 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. 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 WD with an ejection velocity v_{ej} . The resulting kick velocity of the WD v_{kick} is given by

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

where f_{kick} is the fraction of the mass that is ejected asymmetrically. With $v_{\text{ej}} = 500\text{--}3000 \text{ km s}^{-1}$ (Chesneau & Banerjee 2012; Ribeiro et al. 2013 and references therein), and $M_{\text{ej}}/M_{\text{WD}} \leq 10^{-3}$ the kick could be up to a km s^{-1} .

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_{rel} is the relative velocity of the two stars (and taking $\nu > 0$ when the kick is directly opposed to v_{rel}), one gets⁶

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

⁶ An interesting point is that the pericenter is then given to linear order in δ and ν , 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 10 m s^{-1} for a typical case, the initial semi-major axis is the pericenter, not the apocenter, so no enhanced Roche lobe overflow is possible.

and the resulting eccentricity is

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

To estimate the effect on the mass-transfer rate we calculate the Roche-lobe overflow factor $\Delta = (R_* - R_L)$ as a function of the orbital phase (ϕ), 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 Δ 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.

To determine the eccentricities that could arise from asymmetric mass loss, we have to calculate the effects of single novae and therefore assume ignition masses and mass transfer rates. We take the ignition masses from Townsley & Bildsten (2004) and assume 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 that performs mass transfer calculations in eccentric orbits with a full stellar evolution code as described in Siess et al. (2013) and Davis et al. (2013) 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_{CE} , assuming the rest of the material is lost in a fast symmetric ejection. In Figure 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 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 and dominate the population both above and below the period gap. Increasing the fraction of mass ejected via a common-envelope-like process strongly reduces the number of stable systems, particularly for low-mass WDs. 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 $f_{\text{CE}} = 0.4$ a significant fraction of the pre-CVs with massive WDs also 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^{-1} , assuming an asymmetric mass fraction of 20%, $f_{\text{kick}} = 0.2$. The masses and ignition masses (taken from Figure 9 of Townsley & Bildsten 2004) we use are shown in the first three columns of Table 1, the resulting eccentricity (e_{strong}), kick velocity, and maximum change in the Roche-lobe overflow factor (Δ) compared to the donor's pressure scale height in the next three columns which are graphically shown in Figure 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 the order of several m s^{-1} , and result 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^{-1} 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 Equation (16) and show the results in column 7 of 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. To estimate the effect on the system, we look up the appropriate ignition masses for these new mass-transfer rates in Townsley & 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 Equation (2) of Verbunt & Phinney (1995), which for these very close binaries are only of the 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 Figure 1 of Townsley & Bildsten 2005), and the system might show up (briefly) as a super-soft X-ray source (see van den Heuvel et al. 1992).

4.3. The Influence of Eccentricity on the Evolution

As a test case we evolved a $0.6 M_\odot$ WD + $0.6 M_\odot$ MS star with a relatively large eccentricity $e = 2 \times 10^{-3}$ using the BINSTAR code (Figure 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

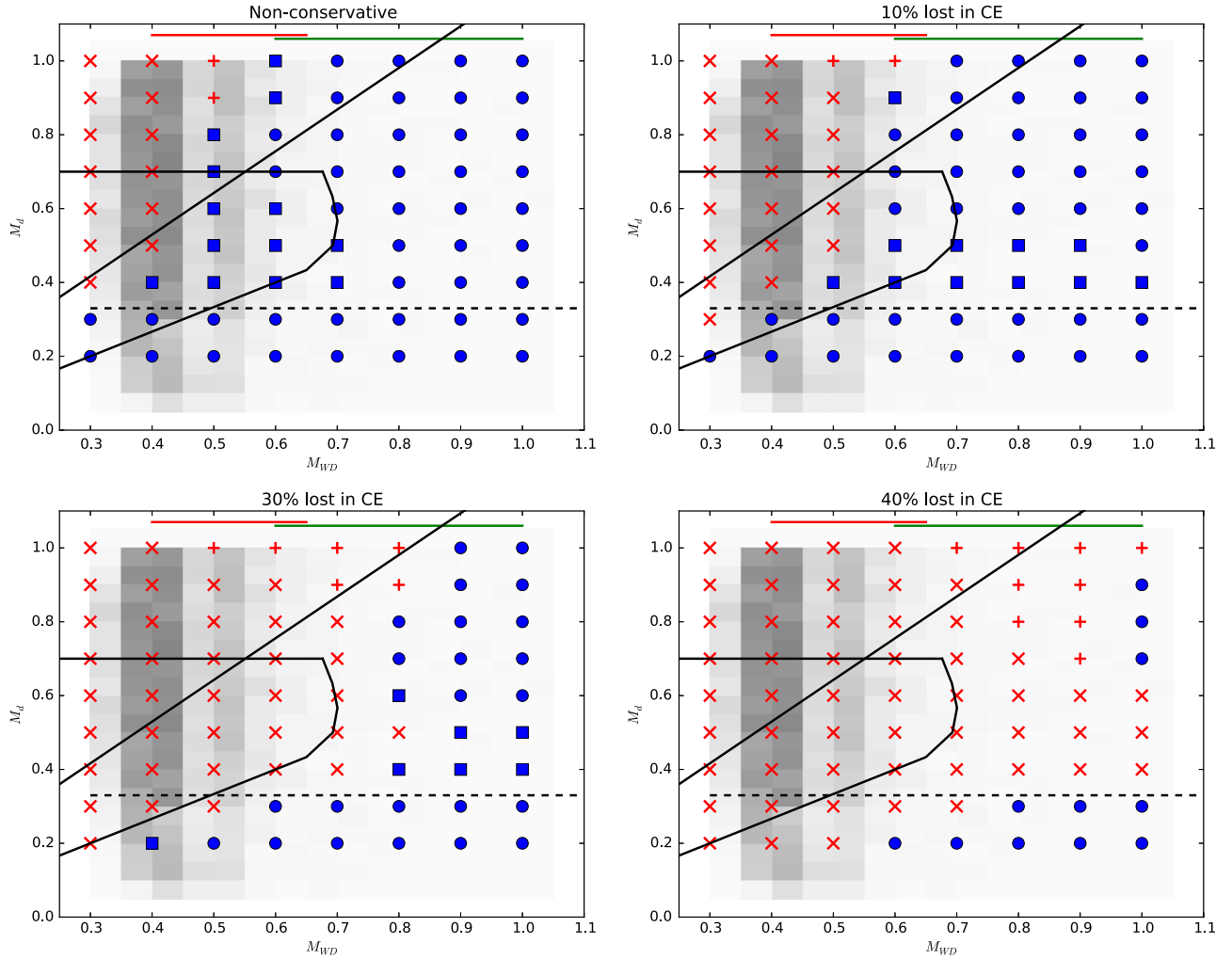


Figure 2. Grid of initial accretor vs. donor mass for the MESA calculations at the onset of mass transfer. The lines and gray shade denote the stability limits and theoretical population as in Figure 1. The symbols indicate the outcome of the MESA calculations. Red cross: directly unstable; red plus: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

Table 1
Resulting e_{strong} , Δ and Global Increase in Mass-transfer Rate ($f_{\dot{M}}$) for the Different Systems Considered

M_{WD} (M_{\odot})	M_{d} (M_{\odot})	$\frac{M_{\text{ign}}}{10^{-5}}$ (M_{\odot})	e_{strong} (10^{-4})	v_{kick} (m s^{-1})	$\frac{\Delta_{\text{max}}}{H}$	$f_{\dot{M}}$	$\frac{M'_{\text{ign}}}{10^{-5}}$ (M_{\odot})	t_{rec} (years)	τ_{tide} (years)
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? ^a	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	...	...	...

Notes. 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.

^a Steady burning.

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. To compare, our simple calculations as in Section 3.2, with the same parameters, gives a factor of 100, i.e., overestimates the effect. It is clear that to fully assess the

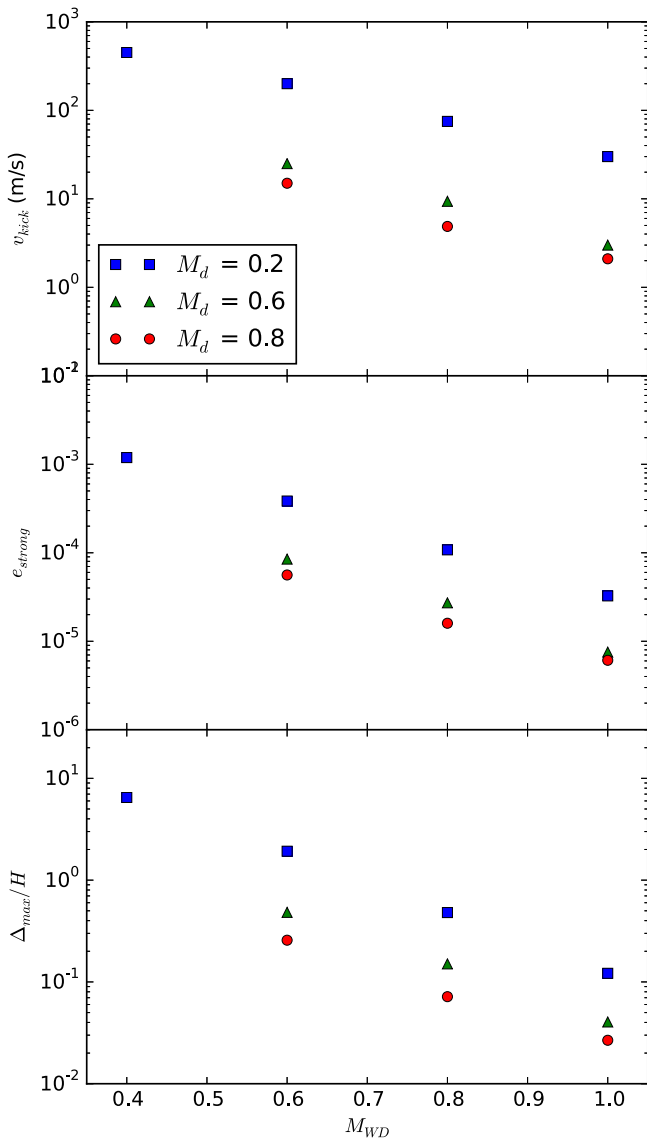


Figure 3. Kick velocities, eccentricities, and maximum change in Roche-lobe overfill factor for novae with $f_{\text{kick}} = 0.1$.

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 whether these effects actually happen and if so, do they change the stability of the systems in such a way that the discrepancies between the theoretical and observed CV population disappear?

From Figure 2 it is clear that for the mechanism to work comfortably, the systems with low-mass WD should eject a fairly significant fraction ($\sim 40\%$) of the mass via a common-envelope-like mechanism, while more massive WDs should be affected less 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

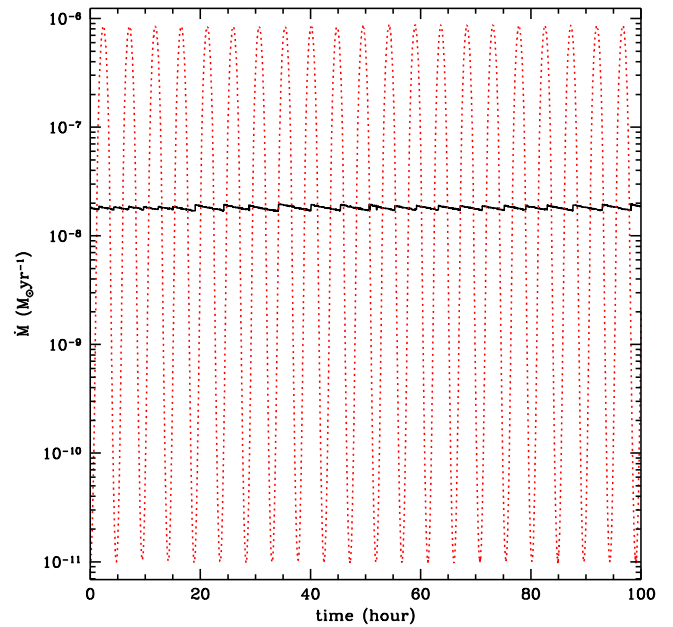


Figure 4. Evolution of the mass-transfer rate in a $0.6 + 0.6 M_{\odot}$ slightly eccentric ($e = 2 \times 10^{-3}$) orbit in red compared with a circular orbit in black.

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 WDs with masses above $0.7 M_{\odot}$ 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 and would most likely be diminished if the nova was slow.

Schreiber et al. (2016) find that a parameterized angular momentum loss in which 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 et al. (2013) suggest 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 Equation (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, in Figure 5 we plot 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 that, following a nova outburst

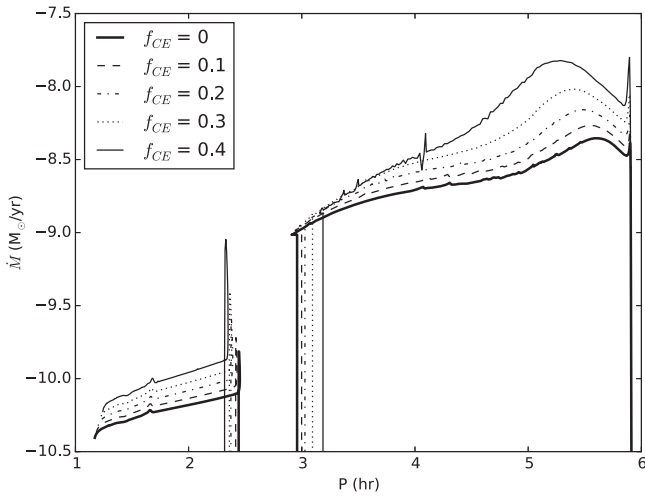


Figure 5. Mass-transfer rate as function of periods for different values of δ . The system initially consists of a $1.0 M_{\odot}$ WD with a $0.8 M_{\odot}$ MS companion.

2000 years ago, has had a long phase of a much higher mass-transfer rate and is 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 by Schaefer & Collazzi (2010) that some systems are significantly brighter after a nova outburst while others are 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 Equation (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 in which the WD becomes the core and the MS star formed the envelope. They would be vastly outnumbered by ordinary giants. Perhaps if we could measure the core/envelope mass ratio via asteroseismology, some of the low-mass giants 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. 2016), because higher mass-transfer rates lead to a period minimum at a longer period as seen in Figure 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% of the ejection energy is provided by the orbital interaction. However, more massive WDs 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 WDs this can significantly influence the orbit. The induced 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. (2016) 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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