

Empirical consequential angular momentum loss can solve long standing problems of CV evolution

Matthias R. Schreiber*

Universidad de Valparaíso, Instituto de Física y Astronomía, Avenida Gran Bretaña 1111, Valparaíso, Chile

Monica Zorotovic

Universidad de Valparaíso, Instituto de Física y Astronomía, Avenida Gran Bretaña 1111, Valparaíso, Chile

Thomas P. G. Wijnen

Department of Astrophysics/IMAPP, Radboud University Nijmegen, PO box 9010, NL-6500 GL Nijmegen, The Netherlands

The observed orbital period distribution of cataclysmic variables (CVs), the space density derived from observations, and the observed orbital period minimum are known to disagree with theoretical predictions since decades. More recently, the white dwarf (WD) masses in CVs have been found to significantly exceed those of single WDs, which is in contrast to theoretical expectations as well. We here claim that all these problems are related and can be solved if CVs with low-mass white dwarfs are driven into dynamically unstable mass transfer due to consequential angular momentum loss (CAML). Indeed, assuming CAML increases as a function of decreasing white dwarf mass can bring into agreement the predictions of binary population models and the observed properties of the CV population. We speculate that a common envelope like evolution of CVs with low-mass WDs following a nova eruption might be the physical process behind our empirical prescription of CAML.

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*Speaker.

1. Introduction

The observed orbital period distribution of CVs shows a lack of systems in the $\sim 2 - 3$ h orbital period range, known as the period gap. In order to explain the gap, Rappaport, Joss & Verbunt (1983) proposed the disrupted magnetic braking (DMB) scenario which today is frequently called the standard scenario for CV evolution. The main assumption of the DMB scenario is that MB turns off when the donor star becomes fully convective at $P_{\text{orb}} \sim 3\text{h}$. Systems above the gap evolve towards shorter orbital periods, due to gravitational radiation (GR) and efficient MB. Due to the strong mass transfer caused by MB the donors are driven out of thermal equilibrium. Once the donor star becomes fully convective, at the upper edge of the gap, MB stops or at least becomes inefficient, causing a drop in the mass-transfer rate, which allows the donor star to relax to a radius which is smaller than its Roche lobe radius. The system detaches, mass transfer stops and the system becomes a detached white dwarf plus main sequence (WD+MS) binary, evolving towards shorter periods only via GR. At orbital periods of $\sim 2\text{h}$ the system is close enough to restart mass transfer and the system appears again as a CV at the lower boundary of the gap. It has been shown frequently that DMB can well explain the orbital period gap (e.g. Howell, Nelson & Rappaport, 2001). Independent evidence for a dramatic change of the strength of MB comes from observations of single stars, as well as WD+MS binaries (Schreiber et al., 2010; Rebassa-Mansergas, Schreiber & Gänsicke, 2013)

However, theoretical binary population synthesis (BPS) models of CVs based on DMB also reveal dramatic disagreements between observations and theoretical predictions: 1. CVs below the period gap should make up ~ 99 per cent of the population (Kolb, 1993), while roughly the same number of systems is observed below and above the gap (Knigge, 2006). 2. The observed orbital period minimum is at 76 min (Knigge, 2006), while the predicted orbital period minimum is 65-70 min (Kolb & Baraffe, 1999). 3. A strong accumulation of systems at the orbital period minimum is predicted, but not observed (Patterson, 1998; Knigge, 2006). 4. The predicted space density (e.g. Ritter & Burkert, 1986; Kolb, 1993) exceeds the observed one by 1-2 orders of magnitude (e.g. Patterson, 1998; Pretorius & Knigge, 2012). 5. BPS models predict an average white dwarf (WD) mass of $\lesssim 0.6M_{\odot}$ (e.g. Politano, 1996) and large numbers of CVs containing helium core (He-core) WDs. Yet, the observed average mass is $\sim 0.83M_{\odot}$ and not a single system with a definite He-core WD primary has been identified so far. The WD mass problem is probably the most severe as observational biases can be clearly excluded to play a significant role (Zorotovic, Schreiber & Gänsicke, 2011).

During the past decade, one of these long standing problems of CV evolution has been solved. The problem of the missing spike at the orbital period minimum disappeared when recent deep surveys identified a previously hidden population of faint CVs (Gänsicke et al., 2009). Furthermore, significant progress has been made with the orbital period minimum problem. If additional angular momentum loss, apart from GR, is assumed to be present in systems with fully convective donor stars, the predicted period minimum is shifted to longer orbital periods as it is observed (e.g. Knigge, Baraffe & Patterson, 2011). However, the cause of the additional braking mechanisms remains unclear.

Here we present BPS models of CVs using the standard model for CV evolution but taking into account additional angular momentum loss generated by the mass transfer in CVs. This con-

sequential angular momentum loss (CAML) can drive CVs with low-mass WDs into dynamically unstable mass transfer which solves the WD mass problem, the space density problem, and also brings into agreement the predicted and observed orbital period distributions. Finally, the proposed CAML might be the same missing angular momentum loss mechanism that is required to shift the theoretically predicted orbital period minimum to longer periods. The idea of CAML potentially solving simultaneously several major problems of CV evolution has been first presented at the CV conference in New York (November 2014) by the lead author of this article and is published in Schreiber, Zorotovic & Wijnen (2016). A nice complementary paper partly inspired by the New York conference is in press (Nelemans et al., 2015).

2. The WD mass problem

The currently most severe problem with CV evolution is the white dwarf mass problem. Four possible solutions for the WD mass problem have been discussed in the literature:

- The observed WD mass distribution is the result of an observational bias. This idea goes back to Ritter & Burkert (1986) who were able to explain the early measurements of large WD masses in the bright CVs discovered decades ago. However, a significant fraction of CVs more recently identified by SDSS are dominated by emission from the WD and the observed sample of such systems should be biased towards low mass WDs while the measured masses still cluster around $0.8M_{\odot}$ (Zorotovic, Schreiber & Gänsicke, 2011).
- The low mass WDs in CVs accrete more mass than is expelled during the subsequent nova eruption. As shown by Wijnen, Zorotovic & Schreiber (2015), mass growth can not solve the problem of the large WD masses in CVs because most of the predicted CVs with low mass WDs have also low mass companions. Even assuming that the total mass of the secondary would be accreted by the WD, which is of course nonsense, does not allow to reproduce the observed distribution with a mean mass of $\sim 0.8M_{\odot}$ (Zorotovic, Schreiber & Gänsicke, 2011).
- Systems that would form CVs with low mass WDs do not survive CE evolution. This idea has been put forward by Ge et al. (2015). However, as shown by Zorotovic, Schreiber & Gänsicke (2011), the existence of detached post common envelope binaries with low mass WDs clearly excludes this option.
- The WDs in CVs grow in mass before they become CVs. This option has been investigated by Wijnen, Zorotovic & Schreiber (2015). Indeed, if a large number of CVs would form from thermal time scale mass transfer, the predicted WD mass distribution would become similar to the observed one. However, this approach would predict even more CVs than the old models with disastrous consequences for the space density problem. In addition, a large number of CVs descending from thermal time scale mass transfer would predict a large number of CVs with evolved secondary stars which contradicts the observations (Gänsicke et al., 2003).

All the above approaches fail to explain the observed WD mass distribution or generate dramatic disagreement with other features of the observed CV sample. Here we show that one frequently

overlooked but crucial and uncertain assumption in binary population models might be responsible for the disagreement between theory and observation. The relatively low mass transfer rates of CVs imply that mass transfer is driven by angular momentum loss. In other words, CVs must be stable against thermal and dynamical time scale mass transfer. The stability limit for mass transfer is therefore a key ingredient of binary population models. It depends crucially on the mass ratio of the system and the mass and angular momentum that is lost as a consequence of the mass transfer. In the following section we show that the WD mass problem and several other problems can be solved if CAML drives CVs with low mass WDs into unstable mass transfer.

3. Binary population models

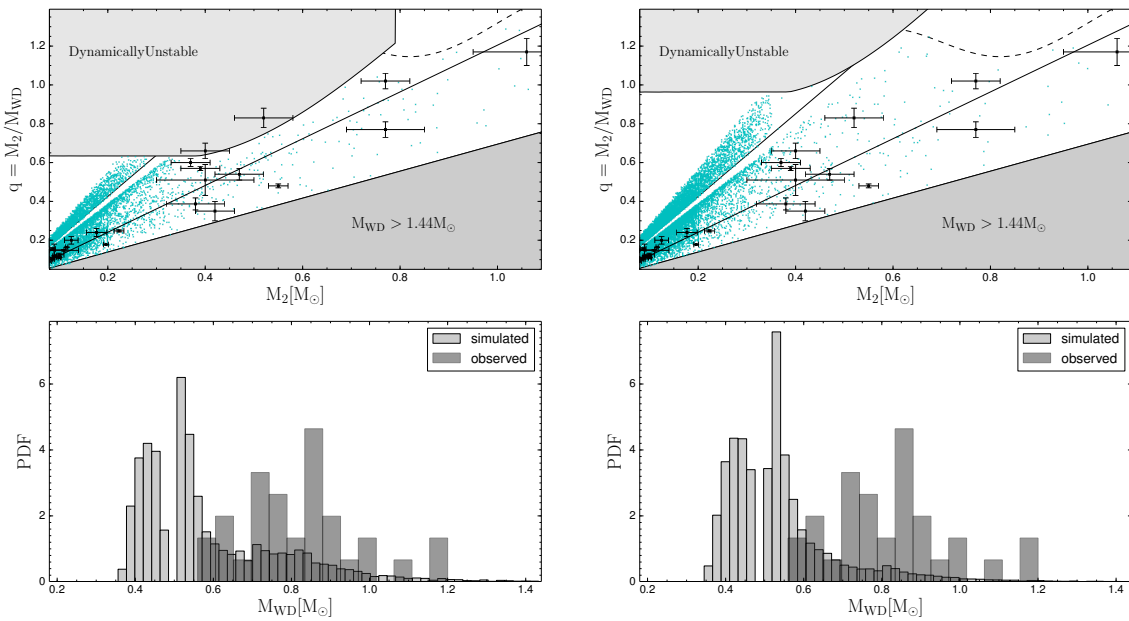


Figure 1: *Top:* Observed (black squares) and predicted (cyan dots) CV populations in the q versus M_2 diagram for the fully conservative case (*left*) and for the classical non-conservative model (*right*). The grey shaded areas represent the forbidden regions either due to dynamically unstable mass transfer or because the WD mass exceeds the Chandrasekhar limit. The black solid lines represent the average of the WD masses measured in CVs ($M_{WD} = 0.83M_\odot$) and the mass limit for He-core WDs ($0.47M_\odot$). The dashed line represents the limit for thermally unstable mass transfer. *Bottom:* Comparison between the observed (dark grey) and simulated (light grey) WD mass distribution. Apparently, both models can not reproduce the observations.

To illustrate the impact of the stability limit we performed BPS calculations with different assumptions for mass and angular momentum loss. Details concerning our model assumptions (concerning e.g. the initial mass ratio distribution, common envelope evolution, and the initial mass function) can be found in Schreiber, Zorotovic & Wijnen (2016).

The stability limit can be calculated by equating the adiabatic mass radius exponent of the secondary star and the mass radius exponent of its Roche-lobe. The first depends only on the structure of the secondary star and has been calculated by Hjellming (1989). The second, however,

depends on the change of the mass ratio and the amount of angular momentum loss generated by mass transfer. In previous binary population models of CVs either the fully conservative case (the total mass and angular momentum of the binary is conserved) or a weak form of CAML was used. In the latter case, it is assumed that during nova eruptions exactly the amount of mass that has been previously accreted by the WD is expelled and carries the specific angular momentum of the WD. We performed binary population models for both these classical assumptions in the framework of the DMB scenario and the results are shown in Fig. 1. Clearly, both models dramatically fail to reproduce the WD mass distribution. However, Fig. 1 also illustrates how strong the stability limit depends on the assumptions concerning mass and angular momentum loss generated by mass transfer. In the fully conservative case less CVs survive because the mass of the white dwarf is assumed to grow which reduces the Roche-volume of the secondary. This effect dominates over the reduced angular momentum loss which makes the secondaries Roche-lobe larger (but to a lesser extent).

Given that the stability limit sensitively depends on the assumptions on CAML and mass loss we investigate if and which form of CAML could change the stability limit in a way that solves the WD mass problem. We assume mass loss during nova eruption keeps the WD mass constant during secular evolution (exactly the same amount of mass that has been previously accreted is expelled in a nova event). However, in contrast to previous works we keep the angular momentum loss associated with mass loss as a free parameter. Given that the disagreement between the observed and predicted WD masses in CVs is mainly caused by the large number of predicted CVs with low-mass WDs with low mass companions (see Fig. 1), we expect significant improvement if consequential angular momentum loss is stronger for low mass WDs.

Indeed, we find good agreement if we assume decreasing CAML for increasing WD masses (for details see Schreiber, Zorotovic & Wijnen, 2016). In the top left panel of Fig. 2 we show the observed and predicted CV populations in the q versus M_2 diagram for a simulated population of CVs assuming this empirical CAML (eCAML from now on) model. Apparently, eCAML can reproduce the observed WD mass distribution in CVs very well. However, before the eCAML model can be considered a viable option for CV evolution, we need to investigate how its predictions compare with other observed properties of CVs and we need to find a physical mechanism that might be responsible for eCAML.

4. Orbital period distribution and space density

As described in the introduction, previous binary population models of CVs failed to reproduce both the predicted space density of CVs and the orbital period distribution. We now show that incorporating eCAML not only solves the WD mass problem but also brings into agreement the predicted and observed space density and orbital period distribution of CVs.

In Fig. 3 we compare the orbital period distribution of SDSS CVs (Gänsicke et al., 2009) with those predicted by the three models discussed in this paper. The two old models do not only dramatically disagree with the WD mass distribution but also predict the existence of too many CVs at short orbital periods and too few above the gap. In contrast, the eCAML model that was designed to solve the WD mass problem agrees very well with the observed period distribution.

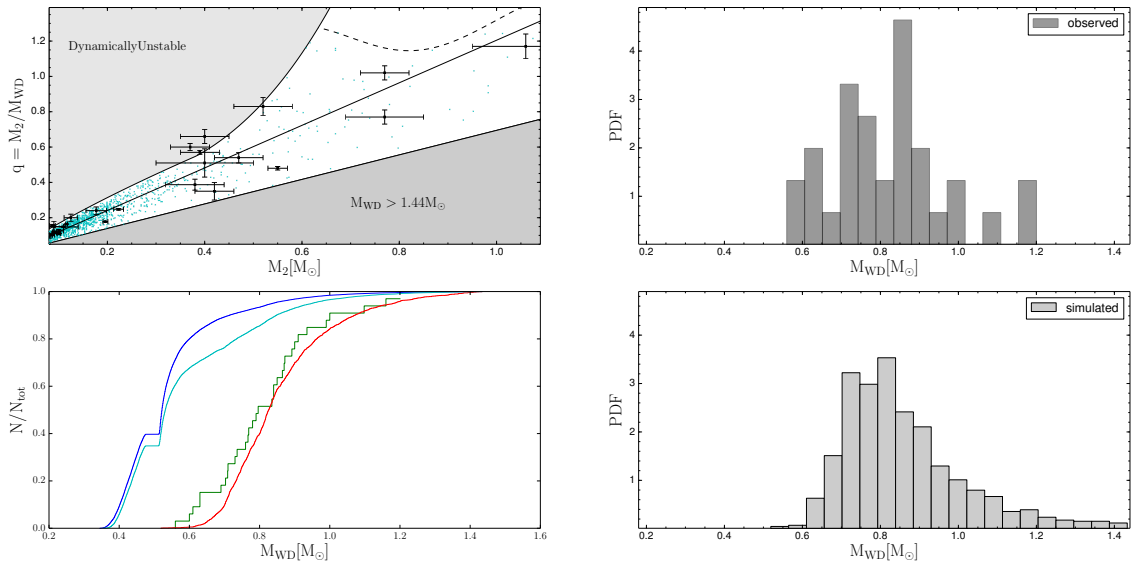


Figure 2: *Top left:* Observed and predicted CV populations in the q versus M_2 diagram for our empirical CAML model. Colours and symbols are the same as in Fig. 1. *Right:* Observed (*top*) and simulated (*bottom*) WD mass distribution for the empirical CAML model. *Bottom left:* Cumulative distribution of WD masses in CVs for the observed systems (green) and for our three models: fully conservative (cyan), classical non-conservative (blue) and empirical CAML (red). Clearly, the latter model can reproduce the observations while the predictions of the other two models dramatically disagree with the observations.

The period distribution problem is not the only long standing issue the eCAML approach solves simultaneously with the WD mass problem. As a large number of systems containing low-mass WDs is supposed to suffer from unstable mass transfer, the total number of CVs predicted by the eCAML is about one order of magnitude smaller than in previous models which brings the predicted CV space density into the range of the values derived from observations.

5. Physical interpretation of eCAML

The eCAML model presented in this paper can simultaneously solve the three biggest problems of CV evolution. However, there must be a physical mechanism behind this parameterised model. The most obvious mechanism that may generate significant CAML in CVs are nova eruptions. In fact, the classical CAML model represents a weak form of CAML caused by novae. This model assumes the expelled material to carry away the specific angular momentum of the WD which represents a reasonable assumption *if* friction between the ejecta and the secondary star is negligible. If, on the other hand, friction contributes significantly, CAML might be much stronger than predicted by the classical CAML model. In other words, when a CV formed from a detached post common envelope binary, the first nova may lead to a common envelope like situation in which a significant amount of orbital energy and angular momentum is used to expel the nova shell which causes the two stars to merge (see also Nelemans et al., 2015).

As shown by Schenker, Kolb & Ritter (1998), frictional angular momentum loss produced by novae only weakly depends on the mass ratio but is very sensitive to the expansion velocity of the

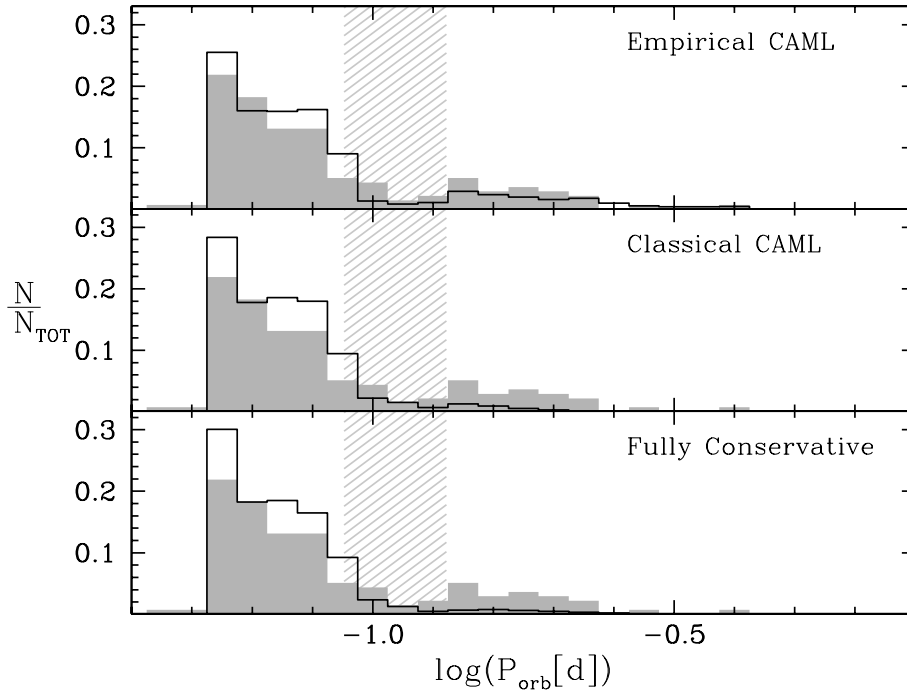


Figure 3: Orbital-period distributions for our three models of CV population: eCAML (*top*), classical CAML (*middle*), and the fully conservative (*bottom*). In grey the observed orbital period as measured by Gänsicke et al. (2009). The eCAML model is not only the first model able to reproduce the observed WD mass distribution but also the first one to be in agreement with the observed orbital period distribution.

ejecta, i.e. assuming slow expansion velocities, the consequential (frictional) angular momentum loss can be significant (see Schenker, Kolb & Ritter, 1998, their Figure 5). Interestingly, nova models predict significantly faster expansion velocities for CVs containing high-mass WDs than for those containing low-mass WDs (see e.g. Yaron et al., 2005, their Fig. 2c). The CAML generated by slow nova eruptions in CVs containing low-mass WDs might therefore be the physical cause behind the eCAML model we used to bring into agreement observations and theory.

6. Conclusion

For decades we used simple assumptions like the full conservation of mass and angular momentum to determine the stability limits of mass transfer in CVs. While these assumptions have been reasonable when no additional information was available, with thousands of CVs known and with accurate stellar and binary parameters measured for many of them, now the time has come to use observational constraints to improve our models of compact binary evolution. We used measurements of the white dwarf masses in CVs to define an empirical description of consequential angular momentum loss that brings into agreement observation and theory. The key prediction of the new scenario is that post common envelope binaries containing low mass white dwarfs merge quickly after the secondary filled its Roche-lobe. This new model for CV evolution, first presented by the lead author of this paper at the CV conference in New York (November, 2014) and described

in detail in Schreiber, Zorotovic & Wijnen (2016), simultaneously solves several major problems of CV evolution. It is the only model presented so far that reproduces the observed white dwarf mass distribution. In addition, the predicted space density and the relative number of systems below the gap are significantly reduced which solves the space density and the orbital period distribution problem. Finally, the additional angular momentum loss may shift the predicted orbital period minimum to longer orbital periods solving the orbital period minimum problem (see also Nelemans et al., 2015).

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