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LETTER TO THE EDITOR

# A modest change in magnetic braking at the fully convective boundary explains the evolution of cataclysmic variables

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## ABSTRACT

**Context.** For decades, reproducing the orbital period distribution of nonmagnetic cataclysmic variables (CVs) seemed to require a drastic decrease, usually termed disruption, in the angular momentum loss through magnetic braking at the fully convective boundary, which argued for a change in the dynamo mechanism operating in fully and partially convective stars. However, recent studies showed that the prescription for magnetic braking that is traditionally used in CV evolution theory is clearly outdated because saturation, that is, a weak period dependence for rapidly rotating stars, is not included.

**Aims.** We test an updated version of a prescription for saturated magnetic braking that has been developed to explain the spin-down of single stars in the context of CV evolution. This prescription contains a boosting and a disruption parameter that represent the change in the strength of magnetic braking at the fully convective boundary.

**Methods.** We performed dedicated MESA simulations for CVs with the revised prescription for saturated magnetic braking.

**Results.** As in previous studies, we found that magnetic braking needs to be stronger in close binaries than in single stars, and that, in contrast to what is observed in single stars, magnetic braking needs to be reduced at the fully convective boundary. However, in contrast to previous studies of CV evolution, only a moderate disruption by a factor of 2–3 is sufficient to explain key features of the CV orbital period distribution and the measured mass-radius relation for CV donors.

**Conclusions.** The relatively small decrease in the efficiency of magnetic braking at the fully convective boundary might have implications for our understanding of dynamo models for fully and partially convective stars.

**Key words.** methods: numerical – binaries: close – stars: evolution – white dwarfs

## 1. Introduction

For decades, a central assumption in the standard evolution model of close white dwarf binaries has been a sharp and drastic reduction in angular momentum loss at the fully convective boundary. This assumption is mostly based on the observational fact that only a few cataclysmic variables (CVs), close binary systems in which a white dwarf accretes from a Roche-lobe filling low-mass companion star, have been found in the period range between  $\sim 2$  and  $\sim 3$  hours, a feature that has been termed the orbital period gap (e.g. Schreiber et al. 2024).

The orbital period gap can be explained by assuming strong angular momentum loss, which drives high mass-transfer rates in systems with donor stars that still possess a radiative core, followed by a drastic reduction in angular momentum loss when the donor becomes fully convective. The initially high mass-transfer rates drive the donor star out of thermal equilibrium, and its radius becomes inflated relative to that of single stars of the same mass. When angular momentum loss decreases sharply, the donor reestablishes thermal equilibrium, contracts, and detaches from its Roche lobe. The resulting detached system

then evolves through the period gap driven by angular momentum loss through gravitational radiation without undergoing further mass transfer until at an orbital period of  $\sim 2$  h the Roche lobe has sufficiently shrunk to again trigger Roche-lobe overflow (e.g. Belloni & Schreiber 2023).

To the best of our knowledge, the only mechanism that can produce strong angular momentum loss for donor stars with a radiative core is magnetic braking. To reproduce the orbital period gap of CVs, it is therefore usually assumed that magnetic braking completely ceases or is at least drastically reduced at the fully convective boundary (e.g. Rappaport et al. 1983).

The assumption that disrupted magnetic braking is responsible for the high mass transfer rates and also the detachment at the fully convective boundary also nicely explains why the period gap is much less pronounced, or might even be absent, in CVs that host a strongly magnetic white dwarf (Schreiber et al. 2021, 2024; Schwope 2025) because the strong magnetic field of the white dwarf can reduce the wind zones of the donor star (Webbink & Wickramasinghe 2002; Belloni et al. 2020). Furthermore, it seems that CVs indeed evolve through the orbital period gap as detached systems (Zorotovic et al. 2016) and that in close detached binaries consisting of a white dwarf with an M dwarf companion, angular momentum loss is indeed much

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lower when the companion is fully convective (Schreiber et al. 2010; Shariat & El-Badry 2026).

However, there is growing evidence that the prescriptions for magnetic braking used in the standard scenario of CV evolution are not adequate. First of all, El-Badry et al. (2022) showed that the period distribution of close main-sequence binary stars is flat, which can only be explained if magnetic braking saturates, that is, if the period dependence of magnetic braking for close binaries is much shallower than assumed in the prescription proposed by Rappaport et al. (1983). Such a saturation has been previously observed in various magnetic activity indicators and across the fully convective boundary (e.g., Reiners et al. 2009; Wright et al. 2011; Magaúda et al. 2020; Medina et al. 2020). Moreover, in contrast to the most fundamental assumption in the standard scenario for CV evolution, in single M dwarfs, angular momentum loss seems to increase by a factor of  $\sim 1.5$  across the fully convective boundary (Lu et al. 2024; Chiti et al. 2024).

Recently, CV evolution theory has started to take saturation into account. In particular, Belloni et al. (2024) showed that a boosted and disrupted but saturated prescription can explain observations of detached white dwarf binaries, and Barraza-Jorquera et al. (2025) showed that the very same prescription works for CVs. While including saturation clearly represents a step forward toward a unified magnetic braking prescription, saturated prescriptions used in close binaries still require a dramatic decrease (by a factor of 30–100) of the efficiency of magnetic braking, the so-called disruption, at the fully convective boundary (Belloni et al. 2024; Blomberg et al. 2024; Barraza-Jorquera et al. 2025).

The saturated magnetic braking prescription used in close binaries so far is based on the early work by Sills et al. (2000). Alternative saturated models discussed for single stars have so far been largely ignored. We present results from implementing an improved version of the saturated magnetic braking model suggested by Matt et al. (2015) for single stars in the context of CVs. While both models consider saturation of magnetic braking, the prescription from Matt et al. (2015) depends more strongly on the mass and radius of the star and does not depend on the convective turnover time in the saturated regime.

## 2. Recalibrating saturated magnetic braking

The most important feature for all saturated magnetic braking prescriptions is the critical rotation period ( $P_{\text{crit}}$ ) for which saturation occurs. Using semi-empirical relations, Wright et al. (2011) demonstrated that  $P_{\text{crit}}$  depends on the convective turnover time as  $P_{\text{crit}} = R_{0,\text{crit}} \times \tau_c$ , and they estimated the critical Rossby number to be  $R_{0,\text{crit}} \approx 0.13$ . This calibration has been widely used in different contexts. However, it was shown recently that this semi-empirical convective turnover time significantly differs from theoretical values obtained from mixing length theory (Landin et al. 2023; Gossage et al. 2025).

We therefore calculated the global convective turnover time directly in MESA at each step of the evolution following the equation defined by Kim & Demarque (1996),

$$\tau_c = \int_{R_b}^{R_*} \frac{dr}{v_c}, \quad (1)$$

where  $R_b$  and  $R_*$  are the radius of the base of the convective envelope and the radius of the surface of the star, respectively, and  $v_c$  is the convective velocity. We calculated  $\tau_c$  for the same set of stars as was used by Wright et al. (2011) to determine the critical Rossby number. For each mass, we used the MESA code

to calculate the age at the zero-age main sequence defined as the moment when  $L_{\text{nuc}}/L_{\text{tot}} > 0.99$  (see Paxton et al. 2011). For simplicity, we excluded stars that would still be on the pre-main sequence according to our calculations, and for field stars, we assumed an age of 1 Gyr (the exact value of the assumed age does not affect our results). The saturation threshold we obtained this way is much lower, that is,  $R_{0,\text{crit}} \approx 0.04$  (see Fig. 1). This result is consistent with the results from Argiroffi et al. (2016).

Saturated magnetic braking models have traditionally been calibrated for a critical rotation period defined as  $P_{\text{crit}} = 0.1 P_{\odot} \tau_c / \tau_{\odot}$ , where the factor 0.1 comes from the value of  $R_{0,\text{crit}}$  estimated by Wright et al. (2011). The values  $P_{\odot}$  and  $\tau_{\odot}$  are included to reproduce the observed rotation period of the Sun. Calibration of magnetic braking to match the solar rotation rate can introduce significant inconsistencies because there is no consensus of the real value of  $\tau_{\odot}$  (Jao et al. 2022). Therefore, we adopted a different equation for the critical rotation period that included the revised value of the critical saturation threshold and does not depend on  $\tau_{\odot}$  and  $P_{\odot}$ , that is,  $P_{\text{crit}} = 0.04 \times \tau_c$ .

This threshold was combined with the prescription for saturated magnetic braking suggested by Matt et al. (2015), which is based on the general equation of the torque derived from models of stellar wind dynamics (Kawaler 1988; Matt et al. 2012), the effects of magnetic field geometry, and the wind acceleration profile (Réville et al. 2015). The resulting magnetic braking law is

$$J_{\text{SAT}} = T_0 \left( \frac{R_*}{R_{\odot}} \right)^{3.1} \left( \frac{M_*}{M_{\odot}} \right)^{0.5} \left( \frac{\tau_c}{d} \right)^2 \begin{cases} P_{\text{rot}}^{-3}, & \text{unsaturated,} \\ P_{\text{rot}}^{-1} P_{\text{crit}}^{-2}, & \text{saturated,} \end{cases} \quad (2)$$

where  $T_0 = -1.135 \times 10^{32}$  erg is a calibrated constant assuming  $P_{\text{crit}}$  as defined above and our estimated value of  $\tau_{\odot} = 34.869$  days.  $M_*$ ,  $R_*$ , and  $P_{\text{rot}}$  are the mass, radius, and rotation period (in days) of the companion main-sequence star, respectively, and  $\tau_c$  is the global convective turnover time of the companion star.

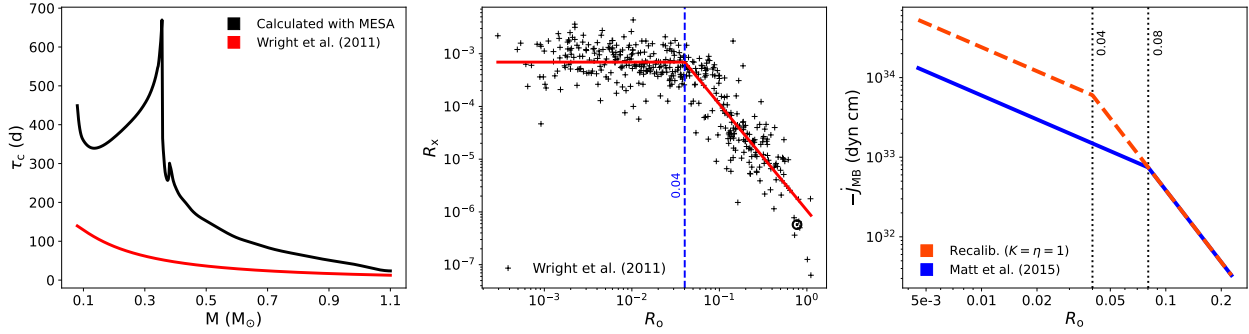
Finally, we added the previously introduced boosting (for stars with a radiative core) and disruption (for fully convective stars) factors  $K$  and  $\eta$  (Belloni et al. 2024; Barraza-Jorquera et al. 2025),

$$J_{\text{SBD}} = \begin{cases} K J_{\text{SAT}}, & \text{(partially convective),} \\ (K J_{\text{SAT}}) / \eta, & \text{(fully convective).} \end{cases} \quad (3)$$

This prescription defines our revised saturated, boosted, and disrupted (hereafter SBD) magnetic braking law.

## 3. CV evolution with the revised SBD model

We used the code called modules for experiments in stellar astrophysics (MESA) (Jermyn et al. 2023, version 24.03.1) to compute the evolution of CVs to test the prescription for magnetic braking suggested by Matt et al. (2015) with the modifications of boosting and disruption (Barraza-Jorquera et al. 2025). We assumed solar metallicity for the donor star ( $Z_{\odot} = 0.02$ ) and standard assumptions for CV evolution. The Roche-lobe radii in binary systems were computed using the fit of Eggleton (1983). The mass-transfer rates through Roche-lobe overflow in binary systems were determined following the prescription of Ritter (1988). Systemic angular momentum loss through the emission of gravitational waves was included as described in Paczyński (1967). We assumed that the white dwarf is a point mass and that its mass remains constant at a typical CV mass of WD



**Fig. 1.** New saturation threshold that appears naturally from fitting observational data using calculated turnover times. The global convective turnover time is very different to frequently used approximations (Wright et al. 2011), especially around and below the fully convective boundary (left panel). A lower threshold (0.04) for the Rossby number separating the saturated from the unsaturated regime is derived from fitting observations using the calculated global convective turnover time (middle panel). This causes magnetic braking to be stronger in the saturated regime as we keep the strength and slope of magnetic braking in the unsaturated regime unchanged (right panel).

$M_{\text{WD}} = 0.83 M_\odot$  (Zorotovic et al. 2011), that is, that the same amount of mass that is accreted during a nova cycle is expelled during the eruption, in rough agreement with model predictions (e.g., Yaron et al. 2005).

Additionally, it has been shown that consequential angular momentum loss (CAML) can cause CVs with low-mass white dwarfs to evolve into dynamically unstable mass transfer, which brings the predicted and observed white dwarf mass distributions of CVs into agreement and leads to a substantially reduced predicted space density (Schreiber et al. 2016; Belloni et al. 2018). We therefore included angular momentum loss according to the empirical relation for CAML proposed by Schreiber et al. (2016). Our MESA inlists are made available at Zenodo<sup>1</sup>.

Equipped with the revised SBD magnetic braking prescription, we ran several MESA simulations, assuming an initial donor star mass of  $M_2 = 0.8 M_\odot$  and an initial orbital period  $P_{\text{orb}} = 1.0$  d, exploring the boosting and disruption parameters in the range  $K = [10, 20, 50, 80, 100]$  and  $\eta = [1, 2, 3, 4, 10, 20]$ . The observables that define these two parameters are the mass-radius relation of CV donor stars (Knigge et al. 2011; McAllister et al. 2019), the boundaries of the period gap (Knigge et al. 2011; Schreiber et al. 2024), and the period minimum (Knigge et al. 2011; McAllister et al. 2019). The boosting parameter  $K$  determines how bloated CV donors are compared to main-sequence stars of the same mass, and it is crucial for the upper and lower edge of the period gap. The disruption parameter  $\eta$  is critical for the lower edge of the period gap and the period minimum. Evolutionary tracks and observational constraints are compared in Fig. 2.

The upper boundary of the period gap is well reproduced assuming  $K \sim 20$ , which is smaller than previously estimated (e.g. Barraza-Jorquera et al. 2025; Belloni et al. 2024). This result is related to the recalibration of magnetic braking we performed, which increases the unboosted angular momentum loss in the saturated regime by a factor of  $\sim 4$  (see Fig. 1). We found even more drastic changes in the disruption parameter. In previous works,  $\eta \gtrsim 30\text{--}100$  was required (Belloni et al. 2024; Barraza-Jorquera et al. 2025; Knigge et al. 2011). For the recalibrated saturated prescription based on Matt et al. (2015), we found that  $\eta$  needs to be just 2–3 to reproduce the boundaries of the period gap and period minimum (see the left panel of Fig. 2).

The observed mass-radius relation is reasonably well reproduced without any disruption at all ( $\eta = 1$ ), but seems to

improve for low values of  $\sim 2\text{--}3$  (right panel of Fig. 2). We computed the reduced  $\chi^2$  values for models with  $K = 20$  and  $\eta = [1, 2, 3, 4, 10, 20]$  and obtained  $\chi_{\text{red}}^2 \approx [60, 18, 32, 43, 67, 77]$ , respectively, which confirms that  $\eta = 2\text{--}3$  indeed provides the best fit. By fitting the observed mass radius relation, our model predicts mass transfer rates exceeding those derived from white dwarf temperatures (Pala et al. 2022).

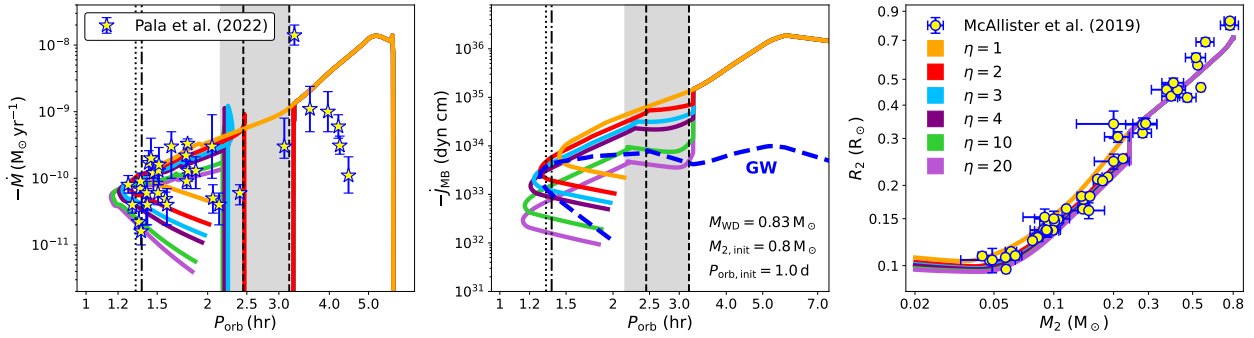
In summary, a moderate disruption ( $\eta = 2\text{--}3$ ) is sufficient to reproduce the period gap and the period minimum and is also indicated by the observed mass radius relation. This result might have far-reaching consequences for our understanding of magnetic braking and dynamo theory. While disruption is still required to reproduce the period gap, a drastic change, which was typically thought to provide clear indications of a change in the dynamo mechanism (Taam & Spruit 1989), is no longer required.

#### 4. Concluding discussion

We recalibrated the magnetic braking prescription proposed by Matt et al. (2015), which led to stronger angular momentum loss through magnetic braking in the saturated regime. Using this prescription and further increasing magnetic braking by a factor of 20, we showed that in contrast to what has been assumed for decades in CV evolution theory, a relatively moderate decrease in the efficiency in angular momentum loss through magnetic braking by a factor of  $\sim 2\text{--}3$  can fully explain the key features of the observed orbital period distribution and the observed mass-radius relation. While this might imply that we approach a prescription for unified magnetic braking, it still remains unclear why the change in angular momentum loss at the fully convective boundary is opposite in single stars (Lu et al. 2024) and why angular momentum loss through magnetic braking is stronger in close binaries in general. We discuss possible explanations below.

The strongest constraints on the secular mass transfer rates in CVs come from the measured radii of the donor stars (Knigge et al. 2011). These measured radii are typically larger than the radii of main-sequence stars as calculated with MESA. This has been interpreted as compelling evidence for efficient magnetic braking in close binaries that drives the mass transfer. However, it has recently been shown that the radii of low-mass stars are larger than predicted by standard models, especially in magnetically active stars (MacDonald & Mullan 2024; Parsons et al. 2018; Brown et al.

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**Fig. 2.** Mass-transfer rates (left) and angular momentum loss rates (middle) as a function of orbital period and the mass-radius relation (right) predicted by our model for a fixed value of the boosting parameter ( $K = 20$ ) and different values for disruption ( $1 \leq \eta \leq 20$ ). The tracks have been calculated assuming typical parameters, i.e., an initial donor mass and period of  $M_2 = 0.8 M_\odot$  and  $P_{\text{orb}} = 1$  day, respectively, and a constant white dwarf mass of  $M_{\text{WD}} = 0.83 M_\odot$ . The mass-radius relation derived from observations (McAllister et al. 2019) is reasonably well reproduced regardless of the value of  $\eta$  (right), but the fit improves for  $\eta = 2-3$  according to a  $\chi^2$  test (see text). This moderate disruption is also required to generate a detached phase as an explanation for the orbital period gap (Knigge et al. 2011; Schreiber et al. 2024, shaded region and dashed vertical lines in the left and middle panels). These values of  $\eta$  also predict a period minimum similar to that derived from observations (Knigge et al. 2011; McAllister et al. 2019, dotted and dashed-dotted vertical lines). This mild disruption is very different to (almost) fully turning magnetic braking off as assumed in the standard scenario of CV evolution. By fitting the mass-radius relation (right panel), we predict mass-transfer rates above the gap that exceed those measured from white dwarf temperatures on average (Pala et al. 2022, left panel).

2022). This radius increase, most likely magnetically induced, is typically around 10%, but may reach more than 20% in particular cases (MacDonald & Mullan 2024). This might imply that assuming all the bloating results from mass transfer driven by angular momentum loss might lead to significantly overestimating magnetic braking. Taking this effect into account might reduce the differences in the strength of magnetic braking in single stars and in binaries, and also the differences between the predicted mass-transfer rates and those measured from white dwarf temperatures (see Fig. 2, left panel).

We note that several processes might play a role in magnetic braking at the fully convective boundary, but we did not consider them in detail in the CV evolution. First, the self-consistently calculated convective turnover time peaks at the fully convective boundary (see Fig. 2), and therefore, a dependence of magnetic braking on this timescale should be considered. Second, if we indeed significantly overestimate magnetic braking as outlined above, the convective kissing instability, previously discussed by (Larsen & MacDonald 2025), might operate in CVs. Finally, the observed stalling in single stars is typically explained by internal angular momentum exchange between the convective envelope and the radiative core (e.g. Curtis et al. 2019, 2020).

In closing, we note that full validation for suggested magnetic braking prescriptions requires performing population synthesis, which we plan to perform in the future. We also intend to consider internal angular momentum redistribution and updated donor star radii in future models and plan to present the result in future publications.

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