Boletim da Sociedade Astronômica Brasileira, **36**, no. 1, 35-39

Evidence for saturated and disrupted magnetic braking from samples of detached close binaries with M and K dwarfs

Diogo Belloni[1], Matthias R. Schreiber[1,2], Maxwell Moe[3], Kareem El-Badry[4], & Ken J. Shen[5]

[1] Departamento de Física, Universidad Técnica Federico Santa María, Av. España 1680, Valparaíso, Chile
e-mail: diogobellonizorzi@gmail.com
[2] Millenium Nucleus for Planet Formation, Valparaíso, Chile
[3] Department of Physics & Astronomy, University of Wyoming, Laramie, USA
[4] Department of Astronomy, California Institute of Technology, 1200 E. California Blvd., Pasadena, USA
[5] Department of Astronomy and Theoretical Astrophysics Center, University of California, Berkeley, USA

Abstract. Recent observations of detached close eclipsing M and K dwarf binaries have provided substantial support for magnetic saturation when stars rotate sufficiently fast, leading to a magnetic braking (MB) torque proportional to the spin of the star. We investigated in this work how strong MB torques need to be to reproduce the observationally inferred relative numbers of white dwarf plus M dwarf post-common-envelope binaries under the assumption of magnetic saturation. We carried out binary population simulations with the BSE code adopting empirically derived inter-correlated main-sequence binary distributions as initial binary populations and compared the simulation outcomes with observations. We found that the dearth of extreme mass ratio binaries in the inter-correlated initial distributions is key to reproduce the large fraction of post-common-envelope binaries hosting low-mass M dwarfs ($\sim 0.1 - 0.2$ $M_\odot$). In addition, orbital angular momentum loss rates due to MB should be high for M dwarfs with radiative cores and orders of magnitude smaller for fully convective stars to explain the observed dramatic change of the fraction of short-period binaries at the fully convective boundary. We conclude that saturated but disrupted, that is, dropping drastically at the fully convective boundary, MB can explain the observations of both close main-sequence binaries containing M and K dwarfs and post-common-envelope binaries.

Resumo. Observações recentes de binárias anãs M e K eclipsantes próximas e separadas forneceram suporte substancial para saturação magnética quando estrelas giram suficientemente rápido, levando a um torque de frenagem magnética proporcional ao spin da estrela. Investigamos aqui quão fortes os torques de frenagem magnética precisam ser para reproduzir os números relativos inferidos observacionalmente de binárias pós-envelope-comum de anã branca mais anã M sob a suposição de saturação magnética. Realizamos simulações de população de binárias com o código BSE adotando distribuições de binárias da sequência principal intercorrelacionadas derivadas empiricamente como população inicial de binárias e comparamos os resultados das simulações com as observações. Descobrimos que as taxas de perda de momento angular orbital devido à frenagem magnética devem ser altas para anãs M com núcleos radiativos e ordens de magnitude menores para estrelas totalmente convectivas para explicar a mudança dramática observada na fração de binárias de curto período na fronteira parcialmente/totalmente convectiva. Concluímos que uma frenagem magnética saturada, mas interrompida, ou seja, que é reduzida drasticamente na fronteira parcialmente/totalmente convectiva, pode explicar as observações de binárias próximas da sequência principal contendo anãs M e K e binárias pós-envelope-comum.

Keywords. binaries: close – methods: numerical – stars: evolution – white dwarfs

1. Introduction

Understanding how a magnetized wind extracts angular momentum from a star, so-called magnetic braking, is a key ingredient to understanding the evolution of close binaries as important as cataclysmic variables, low-mass X-ray binaries, ultra-compact X-ray binaries, or double white dwarfs (see Belloni & Schreiber 2023, for a recent review). Despite this importance, the strength and main dependencies of magnetic braking, particularly on the star's mass and rotation period, remain puzzling.

In early studies, magnetic braking was calibrated using the spin-down rates of solar-type stars (Skumanich 1972) but recently it has become clear that, in particular for lower-mass main-sequence stars, the situation is more complicated (e.g. Barnes 2003; Newton et al. 2016) which most likely hints towards different and mass-dependent magnetic braking laws. One frequently discussed attempt to describe magnetic braking is based on the observation that chromospheric activity, coronal X-ray emission, flare activity, and magnetic field strengths in low-mass main-sequence stars are correlated and increase with rotation up to a mass-dependent critical rotation rate above which the relation between activity and rotation saturates. The assumption that these observables also relate to magnetic braking led to postulating saturated magnetic braking prescriptions in which the dependence of the magnetic braking torque on the spin period becomes shallower above a given rotation rate (e.g. Chaboyer et al. 1995; Sills et al. 2003; Andronov et al. 2003).

In binaries with orbital periods shorter than $\sim 5 - 10$ d (e.g. Fleming et al. 2019), the spin period is synchronized with the orbital period and magnetic braking therefore leads to orbital angular momentum loss. Changes in the orbital period, or distributions of representative samples of close binaries, which are in principle easier to measure than rotation rates of single stars, can therefore be used to constrain the dependencies and strength of magnetic braking.

Instead of using single stars or semi-detached binaries, in this work, we combined observational constraints from the two cleanest and most suitable types of systems towards a better understanding of magnetic braking. The first has been provided by Schreiber et al. (2010). They observed a large number of detached binaries consisting of a white dwarf with an M dwarf companion and found a strong dependence of the relative number of short orbital period systems, which are post-common-envelope binaries (PCEBs), on the mass of the main-sequence star. This measurement is very clean because the orbital period evolution of these systems is not affected by mass transfer, the masses of the stellar components can be estimated relatively easily, and we know that the orbital period distribution of the PCEBs peaks at a few hours and that there are very few systems with orbital periods exceeding one day (Nebot Gómez-Morán et al. 2011). Using these systems to constrain angular momentum loss through magnetic braking has been suggested more than a decade ago (e.g. Politano & Weiler 2006; Zorotovic et al. 2010) but no dedicated simulations have ever been performed.

The second clean observational constraint that we take into account here comes from eclipsing close main-sequence binaries (El-Badry et al. 2022). The observed orbital period distributions of these systems provide evidence for a magnetic braking torque that has a shallower dependence on the star spin than assumed by Rappaport et al. (1983) and can be reasonably well understood assuming saturated magnetic braking laws. While the eclipsing main-sequence binary sample is very useful to constrain the dependence of magnetic braking on the spin period, it is less sensitive to its strength or possible dependencies on the stellar mass.

In this work, we investigated if a prescription of saturated magnetic braking exists that can explain these two critical observational constraints from close detached binaries using binary population synthesis. We carried out binary models with the BSE code and found that the characteristics of both samples can be explained reasonably well with a saturated magnetic braking recipe that is stronger than assumed in standard prescriptions of saturated magnetic braking for M dwarfs with a radiative core and weaker in the case of fully convective main-sequence stars. Here, we present a summary of this work, which was published in Belloni et al. (2024).

2. Binary Population Models

We carried out binary population synthesis using the BSE code (Hurley et al. 2000, 2002; Belloni et al. 2018, 2020) assuming solar metallicity (i.e. $Z = 0.02$) and a constant star formation rate (e.g. Weidner et al. 2004; Kroupa et al. 2013; Recchi & Kroupa 2015; Schulz et al. 2015) over the age of the Galactic disc (≈ 10 Gyr, Kilic et al. 2017). For the initial binary population, we adopted the correlated distributions derived by Moe & Di Stefano (2017), in which the $P_{\rm orb}$ distribution depend critically on M_1 and the binary fraction and e and q distributions depend on both $P_{\rm orb}$ and M_1. Moe & Di Stefano (2017) and Offner et al. (2023) investigated dozens of surveys related to main-sequence binaries and, after combining the samples from such surveys and correcting for their respective selection effects, concluded that the distributions of periods, masses, and mass ratios are not independent at a statistically significant level and fitted joint probability density functions $f(M_1, q, P_{\rm orb}, e) \neq f(M_1)f(q)f(P_{\rm orb})f(e)$ to the corrected distributions, where M_1 is the primary mass, $q = M_2/M_1$ is the mass ratio and M_2 is the secondary mass, $P_{\rm orb}$ is the orbital period and e is the eccentricity. These fitted correlated distributions are the most realistic ones currently available and should be incorporated into binary population models.

For the common-envelope evolution, we adopted an efficiency of 0.25, that is, we assumed that 25% of the change in orbital energy during the spiral-in is used to unbind the common envelope, with no contributions from other energy sources, which is consistent with the increasing evidence that PCEB progenitors experience strong orbital shrinkage during common-envelope evolution (e.g. Zorotovic et al. 2010; Toonen & Nelemans 2013; Camacho et al. 2014; Cojocaru et al. 2017; Belloni et al. 2019; Hernandez et al. 2022; Zorotovic & Schreiber 2022; Scherbak & Fuller 2023). The binding energy parameter was calculated according to the fitting scheme provided by Claeys et al. (2014, their Appendix A), which is based on the detailed numerical stellar evolution calculations by Dewi & Tauris (2000) and takes into account the structure and the evolutionary stage of the red giant donor.

After a PCEB is formed, it evolves towards shorter periods through orbital angular momentum loss. In addition to magnetic braking, we also included emission of gravitational waves as mechanism to remove orbital angular momentum as described in Hurley et al. (2002, section 2.4, equation 48). Regarding magnetic braking, we adopted the following prescription with magnetic saturation, which was first proposed by Chaboyer et al. (1995),

$$\dot{J}_{\rm MB,SAT} = -\beta\left(\frac{R_2}{{\rm R}_\odot}\,\frac{{\rm M}_\odot}{M_2}\right)^{1/2}\begin{cases}\Omega_2^3, & \text{if } \Omega_2 \leq \Omega_{\rm crit},\\ \Omega_2\,\Omega_{\rm crit}^2, & \text{if } \Omega_2 > \Omega_{\rm crit},\end{cases} \quad (1)$$

where $\beta = 2.7\times10^{47}$ erg s^{-1} (Andronov et al. 2003), and M_2, R_2, and Ω_2 are the mass, radius, and spin frequency (in s^{-1}) of the main-sequence star, respectively. The term $\Omega_{\rm crit}$ is the threshold angular velocity beyond which saturation occurs and is assumed to be (El-Badry et al. 2022)

$$\Omega_{\rm crit} = 10\,\Omega_\odot\left(\frac{\tau_\odot}{\tau_2}\right), \quad (2)$$

where $\Omega_\odot = 3\times10^{-6}$ s^{-1} and τ_2 is the convective turnover timescale of the main-sequence star given by Wright et al. (2011) as

$$\log_{10}\left(\frac{\tau_2}{\rm d}\right) = 1.16 - 1.49\log_{10}\left(\frac{M_2}{{\rm M}_\odot}\right) - 0.54\log_{10}^2\left(\frac{M_2}{{\rm M}_\odot}\right). \quad (3)$$

According to Eqs. 3 and 2, the lower the mass of the main-sequence star, the longer the convective turnover time-scale and the longer the critical spin period below which magnetic braking is saturated. In particular, the saturation spin period is as long as ~ 21.6 d, for a 0.1 $\rm M_\odot$ star, and as short as ~ 2.85 d, for a 0.9 $\rm M_\odot$ star.

To test different strength of magnetic braking and different levels of disrupted magnetic braking, we introduced two multiplicative factors. First, we add a factor K with which we can scale the strength of magnetic braking. Second, for fully convective stars, that is, those less massive than $\sim 0.35\ \rm M_\odot$, we added an additional parameter η to the expression such that magnetic braking is reduced by a factor of η for these stars. It then becomes

$$\dot{J}_{\rm MB} = \begin{cases} K\,\dot{J}_{\rm SAT}\,, & \text{if } M_2 > 0.35\,{\rm M}_\odot,\\ \left(K\,\dot{J}_{\rm SAT}\right)/\eta\,, & \text{if } M_2 \leq 0.35\,{\rm M}_\odot \text{ (fully convective).}\end{cases} \quad (4)$$

We here focus on this prescription and test whether it can also explain the fraction of PCEBs amongst the entire population of white dwarf plus M dwarf binaries, and for which combination of K and η. Naturally, Eq. 4 reduces to Eq. 1 when $K = 1$ and $\eta = 1$. In addition, magnetic braking becomes entirely disrupted for fully convective M dwarfs when $\eta \to \infty$ is assumed.

3. Results and Discussion

We show in Fig. 1 the fractions of PCEBs amongst white dwarf plus M dwarf binaries as a function of the M dwarf mass for

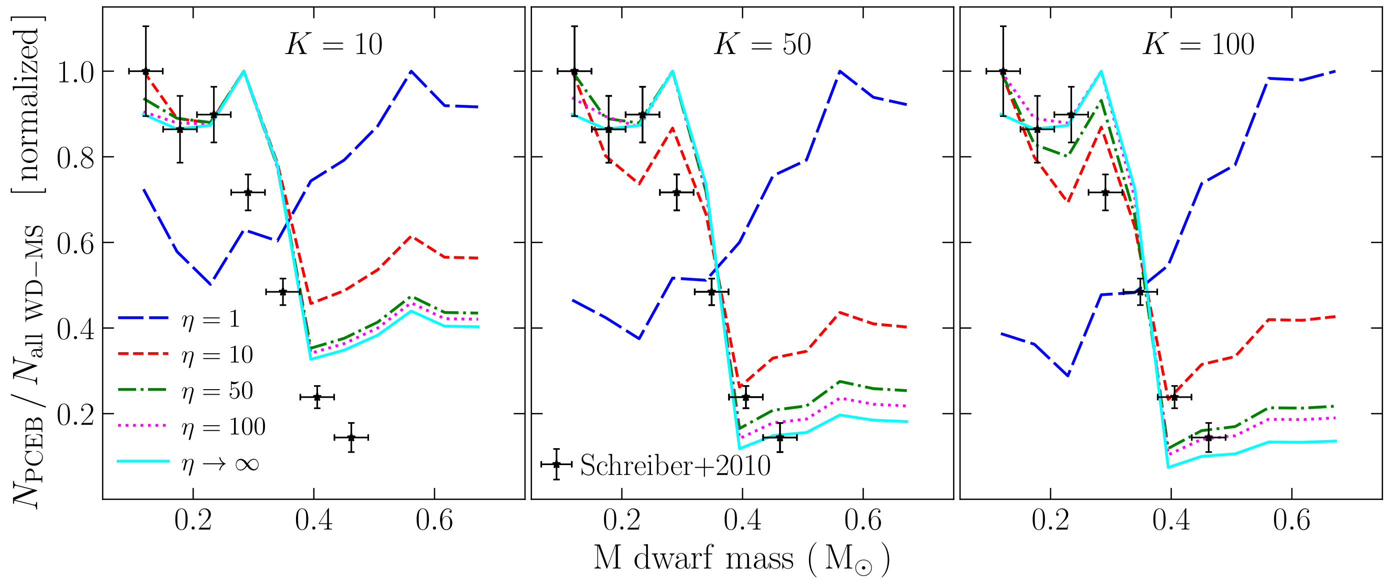

Figure 1. Comparison between the observed fractions of PCEBs amongst white dwarf plus M dwarf binaries across the M dwarf mass (Schreiber et al. 2010) and the predicted with Eq. 4 for several combinations of model parameters. Both predicted and observed fractions were normalized at their highest values. Each panel corresponds to a different choice for K, while the line colour and type indicate the assumed value of η. We can see that any combination of the parameters such that $K \gtrsim 50$ and $\eta \gtrsim 50$ is able to explain the high fraction of systems reasonably well for M dwarf masses $\lesssim 0.3$ M$_\odot$ as well as the huge reduction of systems at ~ 0.5 M$_\odot$. Additionally, we can also reproduce the high fraction of systems for M dwarf masses $\lesssim 0.3$ M$_\odot$.

several combinations of the model parameters K and η and compare with the observationally inferred fractions (Schreiber et al. 2010). The observational and all predicted distributions are normalized at their highest fractions since our goal is to reproduce the qualitative shape of the observed distribution as well as the relative changes in the fractions across the M dwarf mass. From this comparison, we can derive clear constraints on the strengths and mass dependencies of magnetic braking.

3.1. Evidence for Disrupted Magnetic Braking

Towards main-sequence star masses larger than 0.2 M$_\odot$, the observed fraction of PCEBs continuously decreases. At an M dwarf mass of ~ 0.5 M$_\odot$, the observed fraction of PCEBs has dropped by a factor of $5 - 10$ compared to systems with low-mass M dwarfs.

The observed fraction of PCEBs with M dwarfs of masses $\gtrsim 0.3$ M$_\odot$ can be fairly well reproduced, as long as the magnetic braking torque is sufficiently strong, which occurs when $K \gtrsim 50$, and drops at the fully convective boundary by at least a factor of $\eta \sim 50$. Therefore, the drop of the fraction of PCEBs with respect to white dwarf plus main-sequence binaries is consistent with the disrupted magnetic braking scenario, that is, because the orbital angular momentum loss due to magnetic braking drastically decreases at the fully convective boundary. Efficient magnetic braking causes zero-age PCEBs with main-sequence stars that have a radiative core to evolve into semi-detached binaries on a short timescale compared to PCEBs with fully convective main-sequence stars. We discuss in more detail in what follows how K and η shape the distribution of the fraction of PCEBs across the M dwarf mass.

3.2. Evidence for Strong and Weak Magnetic Braking

Comparison with the observations does not only provide evidence for disrupted magnetic braking for fully convective main-sequence stars but also an increased strength of magnetic braking for main-sequence stars with a radiative core. Assuming $K = 1$ or $K = 10$ (top panels of Fig. 1), the high fractions of PCEBs hosting fully convective M dwarfs can be nicely reproduced for all values of η, except $\eta = 1$. However, even no magnetic braking ($\eta \rightarrow \infty$) does not provide evolutionary timescales different enough to reproduce the decrease at of the fraction of PCEBs at the fully convective boundary.

Only if the strength of magnetic braking is increased by a factor of at least $K \sim 50$ and disrupted (i.e. $\eta \gtrsim 50$), the relative numbers of PCEBs with fully convective M dwarfs and the number of those with more massive M dwarfs agree with the observations. In other words, magnetic saturation alone cannot account for the relatively larger number of PCEBs with fully convective M dwarfs in comparison with PCEBs with more massive M dwarfs. Magnetic braking needs to be stronger ($K \gtrsim 50$) for main-sequence stars with radiative cores than provided by the standard saturated magnetic braking prescription (i.e. Eq. 1).

3.3. Main-Sequence Binaries

In the previous subsections, we have provided clear evidence for disrupted magnetic braking from observations of close binaries. At this point, one might be wondering whether the constraints for the detached eclipsing low-mass main-sequence binaries provided by El-Badry et al. (2022) would be violated or not by arbitrarily changing the strength of magnetic braking.

We carried out main-sequence binary population synthesis with the assumptions described in Sect. 2. We picked the primary mass from the canonical Kroupa (2001) initial mass function and the secondary from a uniform mass ratio distribution, assuming a minimum mass of 0.1 M$_\odot$. The orbital period was also picked

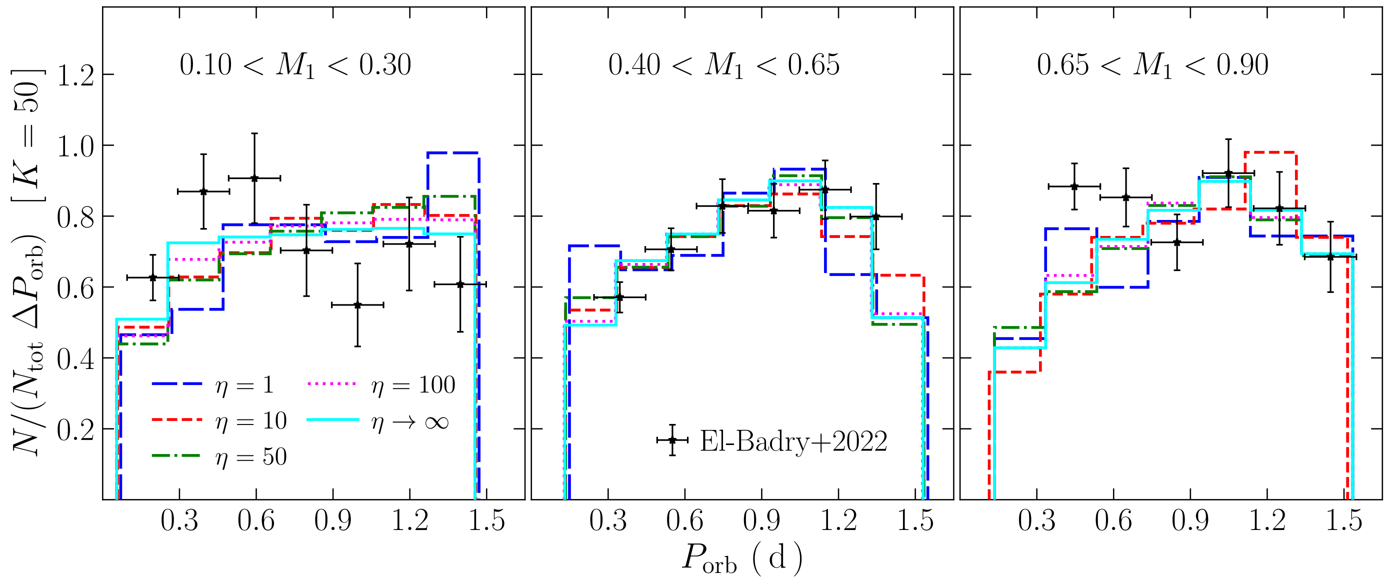

Figure 2. Comparison between the observed orbital period distributions for different mass bins (El-Badry et al. 2022) and the predicted assuming $K = 50$ and several values of η. The line types and colours indicate the assumed value of η, while each panel corresponds to a different primary mass bin, being 0.10 – 0.30 $M_\odot$ (left panel), 0.40 – 0.65 $M_\odot$ (middle panel), and 0.65 – 0.90 $M_\odot$ (right panel). It is clear from the figure, especially when the binaries host only fully convective stars (left panel), that the strength of magnetic braking does not strongly contribute to shaping the distributions. On the other hand, the orbital period distribution of main-sequence binaries is strongly affected by how the magnetic braking torque depends on the star spins as shown by El-Badry et al. (2022).

from a uniform distribution assuming a maximum of 5 d and a minimum corresponding to a separation equal to 1.1 times the sum of the primary and secondary radii. The orbit was assumed to be circular, which is consistent with the strong tidal interaction expected to take place in such close binaries. The age of each binary was chosen from a uniform distribution extending up to 10 Gyr.

We compare in Fig. 2 predicted and observed distributions fixing $K = 50$. Our simulations fit the observations as well as the one based on saturated magnetic braking by El-Badry et al. (2022). This is not surprising because the normalized period distribution of main-sequence binaries only constrains the dependence of magnetic braking on the spin period which is identical in our prescription and any other saturated magnetic braking prescription.

3.4. Do Reasonable Alternative Explanations Exist?

In what follows we briefly discuss to which degree alternative explanations of the observations might exist. If the significant decrease in the fraction of PCEBs among white dwarf plus M dwarf binaries at the fully convective boundary was not caused by a dramatic change in the efficiency of orbital angular momentum loss through magnetic braking, the observations would need to be explained by previous evolutionary effects that make the formation of PCEBs with M dwarfs with a radiative core unlikely. This would imply that for some reason, common-envelope evolution leads to the merger or very short post-common-envelope orbital periods of white dwarf plus early M dwarf companions while fully convective stars are more likely to emerge at longer periods.

This possibility, however, appears to be very unlikely. First, for a given primary mass and orbital period, the available orbital energy is larger for more massive secondary stars which makes it actually easier to survive the common-envelope phase. Second, we do not see evidence for a relation between common-envelope efficiency and main-sequence star mass in the observed samples of PCEBs (Zorotovic et al. 2014; Zorotovic & Schreiber 2022), and last but not least we find a significant number of descendants from PCEBs with early low-mass main-sequence stars in observed samples of cataclysmic variables (Pala et al. 2020, 2022).

Concerning the main-sequence binary orbital period distribution as measured by El-Badry et al. (2022), we do not see any reasonable alternative explanation than a magnetic braking prescription that depends weakly on the spin period. One could in principle think of a flat birth distribution combined with extremely weak magnetic braking but this would not only disagree strongly with the fraction of PCEBs but also with observations of the spin down rates of single stars (e.g. Newton et al. 2016). It therefore appears to us that the two samples we analysed in this work provide solid evidence for a disrupted and saturated magnetic braking prescription for binaries hosting main-sequence stars with masses between ~ 0.1 – 0.9 $M_\odot$.

4. Conclusions

We carried out binary population synthesis with the BSE code and combined two very clean constraints on orbital angular momentum loss through magnetic braking (observations of detached eclipsing main-sequence binaries and detached white dwarf plus M dwarf binaries) and found a purely empirical prescription for magnetic braking that can reproduce both observations. To explain the observed PCEB distribution, the strength of magnetic braking needs to significantly change at the fully convective boundary. Magnetic braking needs to be $\gtrsim 50$ times stronger for stars that still contain a radiative core compared to fully convective stars to explain the dramatically increased fraction of PCEBs among white dwarf plus M dwarf binaries with fully convective main-sequence stars. To also reproduce the observed flat period distributions of main-sequence binaries for all types of main-sequence M dwarf binaries, magnetic braking needs to weakly depend on the orbital period as predicted by the saturated magnetic braking prescriptions. Combining both these constraints leads to a prescription that can simultaneously explain both samples. Our results, published in Belloni et al. (2024), support a saturated and disrupted magnetic braking as an adequate magnetic braking law for $\sim 0.1 - 0.9$ $M_{\odot}$ main-sequence stars that are members of close binaries. However, a physically rather than empirically motivated saturated magnetic braking law is required to eventually understand magnetic braking.

Acknowledgements. DB acknowledges financial support from FONDECYT grant number 3220167. MRS was supported from FONDECYT grant number 1221059 and ANID, – Millennium Science Initiative Program – NCN19_171. KJS was supported by NASA through the Astrophysics Theory Program (80NSSC20K0544).

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