Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **492,** 1523–1529 (2020) doi:10.1093/mnras/stz3601
Advance Access publication 2019 December 28

Are white dwarf magnetic fields in close binaries generated during common-envelope evolution?

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Accepted 2019 December 19. Received 2019 December 18; in original form 2019 October 18

ABSTRACT

Understanding the origin of the magnetic fields in white dwarfs (WDs) has been a puzzle for decades. A scenario that has gained considerable attention in the past years assumes that such magnetic fields are generated through a dynamo process during common-envelope evolution. We performed binary population models using an up-to-date version of the BSE code to confront the predictions of this model with observational results. We found that this hypothesis can explain only the observed distribution of WD magnetic fields in polars and pre-polars and the low-temperature WDs in pre-polars if it is re-scaled to fit the observational data. Furthermore, in its present version, the model fails to explain the absence of young, close detached WD+M-dwarf binaries harbouring hot magnetic WDs and predicts that the overwhelming majority of WDs in close binaries should be strongly magnetic, which is also in serious conflict with the observations. We conclude that either the common-envelope dynamo scenario needs to be substantially revised or a different mechanism is responsible for the generation of strong WD magnetic fields in close binaries.

Key words: methods: numerical – stars: evolution – stars: magnetic field – novae, cataclysmic variables – white dwarfs.

1 INTRODUCTION

White dwarfs (WDs) in cataclysmic variables (CVs) are more frequently magnetic and have, on average, stronger magnetic fields than single WDs (e.g. Ferrario, de Martino & Gänsicke 2015), while the population of observed close detached WD+M-dwarf post-common-envelope binaries (PCEBs) is dominated by systems with negligible WD magnetic fields (Liebert et al. 2015). Understanding these differences may provide insight about magnetic field generation with implications beyond WD research.

In recent years, several hypotheses have been put forward to explain magnetic field generation in WDs. In the fossil field scenario (e.g. Angel, Borra & Landstreet 1981), it is assumed that the magnetic flux is conserved during the WD formation and that strongly magnetic Ap and Bp stars are the progenitors of magnetic WDs. However, Kawka et al. (2007) showed that the magnetic Ap and Bp stars cannot be the only progenitors of magnetic WDs as their birth rate is simply too small. In an alternative scenario, strong magnetic field generation occurs in the corona present in the outer layers of the remnant of coalescing double WDs (García-Berro et al. 2012). This scenario, however, can explain only the large field strength of massive magnetic single WDs but is not applicable to CVs or their detached progenitors. More recently, Isern et al. (2017) argued that when the WD temperature is low enough and its interior crystallizes, a dynamo similar to those operating in main-sequence stars and planets can generate a magnetic field. While this mechanism may work in both single WDs and WDs in close binaries, the field strengths predicted by Isern et al. (2017) are much smaller than those derived from observations of strongly magnetic WDs in CVs and detached PCEBs.

A hypothesis that gained significant attention during the last years and that has recently been claimed to fully explain the magnetic fields observed in WDs has been put forward by Tout et al. (2008). According to this scenario, the high magnetic fields in WDs are generated by a dynamo created during the common-envelope (CE) evolution. Based on this CE dynamo hypothesis, Briggs et al. (2018b) investigated the origin of WD magnetic fields in CVs and claimed that this scenario can explain the observed characteristics of magnetic CVs, which, if true, would provide considerable support for the CE dynamo hypothesis. However, these authors compared only the predicted and observed WD magnetic field distributions of all close WD binaries harbouring main-sequence stars. While this is a first step in confronting the model with observations, a separate comparison of model predictions and observations for detached PCEBs and CVs provides crucial additional constraints on the model. This is particularly true because the fraction of magnetic systems and the underlying WD masses and orbital

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periods are very different for both populations. Therefore, the question whether dynamo processes generated during CE evolution can indeed explain occurrence rates and field strength of magnetic WDs in PCEBs and CVs remains unanswered.

We test here the CE dynamo hypothesis using binary population models of magnetic CVs performed with an updated version of the BSE code, which includes state-of-the-art prescriptions for the CE evolution and mass transfer stability. The new code furthermore takes into account the impact of the WD magnetic field on magnetic braking. We compare the model predictions with the main observed properties of magnetic CVs and their progenitors, i.e. (i) the WD magnetic field distribution of magnetic CVs (Ferrario et al. 2015); (ii) the WD magnetic field, the WD effective temperature, and the orbital period distributions of pre-polars (Schwope et al. 2009; Parsons et al. 2013, and references therein); and (iii) the relative numbers of magnetic WDs among close detached WD+M-dwarf PCEBs (Liebert et al. 2015) and CVs (Pala et al. 2019).

2 BINARY POPULATION MODEL

In order to test the origin of WD magnetic fields during CE evolution, we carried out binary population synthesis with the BSE code (Hurley, Tout & Pols 2002), which has recently been modified and calibrated[1] to carry out population synthesis of non-magnetic (Belloni et al. 2018) and magnetic CVs (Belloni et al. 2020).

2.1 General assumptions

The binary population simulations presented here are similar to those shown in Belloni et al. (2020). In brief, we first generated an initial population of 2×10^7 binaries using the following initial distributions. The primary mass was obtained from the canonical Kroupa (2001) initial mass function (i.e. with two stellar segments) in the range [1, 8] $M_\odot$; the secondary one was generated assuming a uniform mass ratio distribution, where $M_2 \leq M_1$, and requesting that $M_2 \geq 0.07$; the semimajor axis was assumed to follow a log-uniform distribution in the range [$10^{-0.5}$, $10^{4.5}$] $R_\odot$ and the eccentricity to follow a thermal distribution in the range [0, 1].

We then evolved the generated binary star systems and selected those that start dynamically unstable mass transfer when the primary was on the first giant branch or the asymptotic giant branch. The critical mass ratio q_c separating stable and unstable mass transfer adopted here is based on the assumption of conservative mass transfer and the condensed polytropic models by Hjellming & Webbink (1987), i.e. $q_c = 0.362 + [3(1 - M_c/M_g)]^{-1}$, where M_c is the giant core mass and M_g is the giant mass. Dynamically unstable mass transfer gives rise to CE evolution, which we modelled using equations (69)–(77) of Hurley et al. (2002), taking into account the upgrades described in appendix A of Claeys et al. (2014) related to the binding energy parameter. We considered three relatively small values for the CE efficiency α (0.1, 0.25, and 0.4), assumed that no recombination energy contributes to the CE ejection, and computed the binding energy parameter of each system based on the properties of the giant star. These assumptions have been shown to be reasonable in simulations of CVs and PCEBs (e.g. Zorotovic et al. 2010; Toonen & Nelemans 2013; Camacho et al. 2014; Cojocaru et al. 2017; Belloni et al. 2019).

[1] http://www.ifa.uv.cl/bse

For those binaries that survived CE evolution, we assumed standard angular momentum loss prescriptions (Knigge, Baraffe & Patterson 2011). For the second phase of mass transfer, i.e. for the CV stage, we adopted the recently suggested empirical model for consequential angular momentum loss (eCAML; Schreiber, Zorotovic & Wijnen 2016). Observational evidence for this new model for CV evolution is growing. It is a good candidate to solve some long-standing problems related to CV evolution models, like the predicted large fraction of low-mass WDs in CVs, the predicted excess of short-period systems, and the overestimated space density (Schreiber et al. 2016; Belloni et al. 2018; McAllister et al. 2019). The eCAML idea also explains the existence of single low-mass WDs (Zorotovic & Schreiber 2017), the properties of detached CVs crossing the orbital period gap (Zorotovic et al. 2016), and the characteristics of CVs in globular clusters (Belloni et al. 2019).

Additionally, we do not consider CVs originating from a phase of thermal time-scale mass transfer, since the BSE code is unable to properly model this phase and observations show that only ≈5 per cent of all CVs emerge from this channel (Pala et al. 2019). We furthermore assume that in CVs, the WD expels the accreted mass in repeated nova eruptions. Therefore, we treat the WD mass as constant during CV evolution. All other stellar/binary evolution parameters not mentioned here are set as in Hurley et al. (2002).

2.2 Assumptions related to the WD magnetic fields

Concerning the influence of the WD magnetic field on CV evolution, we adopted the reduced magnetic braking model proposed by Li, Wu & Wickramasinghe (1994) and developed further by Webbink & Wickramasinghe (2002). This approach can reasonably well explain the observed properties of polars (Belloni et al. 2020) if the WD magnetic field strength distribution is assumed to be the observed one.

In order to test the scenario of magnetic field generation during CE evolution, we changed our code and, instead of using the observed distribution, we determined the WD magnetic field strength $B_{\rm WD}$ in each PCEB using the formula provided by Briggs et al. (2018a), i.e.

$$B_{\rm WD} = 1.35 \times 10^{10} \left(\frac{\Omega}{\Omega_{\rm crit}} \right) {\rm G}, \quad (1)$$

where Ω is the orbital angular velocity just after the CE evolution given by

$$\Omega = \frac{2\,\pi}{P_{\rm orb}}\ {\rm yr}^{-1}, \quad (2)$$

with $P_{\rm orb}$ being the orbital period just after the CE evolution and $\Omega_{\rm crit}$ is the break-up angular velocity of the WD given by

$$\Omega_{\rm crit} = \sqrt{\frac{G M_{\rm WD}}{R_{\rm WD}^3}} = 2\,\pi \sqrt{\left(\frac{M_{\rm WD}}{{\rm M}_\odot}\right)\left(\frac{R_{\rm WD}}{\rm AU}\right)^{-3}}\ {\rm yr}^{-1}, \quad (3)$$

where $M_{\rm WD}$ and $R_{\rm WD}$ are the WD mass and radius, respectively. We additionally assume that $B_{\rm WD}$ is constant during PCEB and CV evolution.

As in Briggs et al. (2018b), we assumed that magnetic fields are not generated in any CE event. Systems in which either (i) the giant has a non-degenerate core, or (ii) the proto-WD experiences further nuclear burning are assumed to form PCEBs with non-magnetic

WDs. The reasons for these additional conditions are that in a non-degenerate core a magnetic field cannot be maintained in a frozen-in state and that nuclear burning in the proto-WD naturally induces convection that would destroy any frozen-in magnetic field.

The selection of CE events with a degenerate core (point i) is implemented using the critical zero-age main-sequence mass ($M_{\rm HeF}$), which separates low-mass stars that develop a degenerate core on the first giant branch from more massive ones that only develop a degenerate core on the asymptotic giant branch. We adopted here the standard value for $M_{\rm HeF}$ from BSE, i.e. 1.995 $M_{\odot}$, for solar metallicity (Hurley, Pols & Tout 2000, their equation 2). CE events with giants that did not develop a degenerate core then occur either if a giant with initial mass smaller than $M_{\rm HeF}$ fills its Roche lobe during the subgiant phase, or if a giant with initial mass larger than $M_{\rm HeF}$ fills its Roche lobe during either the subgiant or the first giant branch phase. We note that CE events with giants having a non-degenerate core are likely to result in mergers, since, in these cases, the initial orbital separation must be relatively small so that the binary orbital energy is typically not large enough to prevent the binary coalescence.

The second condition for the existence of magnetic fields, i.e. no post-CE nuclear burning (point ii), can be violated if the giant progenitor was relatively close to the tip of the first giant branch at the beginning of the dynamically unstable mass transfer that generated CE evolution. In this case, the degenerate core may ignite following CE evolution, which results in a hot B-type subdwarf. These naked helium-burning stars cannot maintain the magnetic field generated during the CE evolution. As in Zorotovic & Schreiber (2013), we select these systems following Han et al. (2002). These authors performed a comprehensive series of stellar evolution calculations, assuming that mass ejection during a CE event takes place on much shorter time-scales than in single giant star evolution. These models provide the minimum core mass as a function of the initial mass, above which the core will still ignite helium after the CE ejection. These minimum core masses and initial masses are listed in their table 1. We here adopted their value for solar metallicity, with stellar wind and convective overshooting, and linearly interpolated their grid to determine the minimum proto-WD mass needed to trigger helium burning as a function of the initial mass.

While these two additional criteria may have a minor impact on the predicted PCEB population, they clearly have no impact for the predicted CV populations, since they are applicable only for progenitor systems of low-mass WDs ($\lesssim$0.5 $M_{\odot}$). Observed CV WD masses, however, are always $\gtrsim$0.5 $M_{\odot}$ (Zorotovic, Schreiber & Gänsicke 2011; McAllister et al. 2019) and the eCAML model (Schreiber et al. 2016) adopted in our simulations always provides CV WD masses $\gtrsim$0.5 $M_{\odot}$, consistent with observations.

When comparing our model predictions to observed populations, we considered only CVs with donor masses greater than 0.05 $M_{\odot}$ and PCEBs having secondary masses smaller than 0.6 $M_{\odot}$. In other words, we neglect period bouncers and concentrate on systems with M-dwarf companions in PCEBs. The reason for both these limits is potential strong observational bias in the observed samples. Period bouncers are hard to find because of their extremely low mass transfer rates. PCEBs with secondary stars earlier than spectral type M are often overlooked as the optical emission is entirely dominated by the main-sequence companion, which makes it difficult to detect the WD component. Finally, we define a limit of $B_{\rm WD}$ = 1 MG to separate magnetic and non-magnetic systems (either PCEBs or CVs). This strict limit is somewhat arbitrary but roughly reflects the minimum field strengths that have been measured for WDs in PCEBs and CVs.

3 CONFRONTING THE MODEL WITH OBSERVATIONS

If the model proposed by Briggs et al. (2018b) was correct, the resulting predictions for magnetic WDs in all WD binaries should resemble their observed properties. The ideal systems to carry out this comparison between model predictions and observations are the large populations of detached WD+M-dwarf PCEBs and CVs.

3.1 Post-common-envelope binaries

Observations clearly show that the number of magnetic systems among PCEBs is small. The population of observed PCEBs is dominated by systems with negligible $B_{\rm WD}$ (Liebert et al. 2015, and references therein). Only 10 PCEBs with strongly magnetic WDs, so-called *pre-polars*, have been identified so far (Schwope et al. 2009; Parsons et al. 2013, and references therein). Given that the Sloan Digital Sky Survey (SDSS) alone has discovered several hundred PCEBs (Schreiber et al. 2010), we can safely state that the observed fraction of magnetic PCEBs is well below 10 per cent. All the magnetic WDs in PCEBs are relatively cool ($T \lesssim 10^4$ K) and they seem to be rather close to Roche lobe filling as the WDs accrete from the wind of their M-dwarf secondaries via a magnetic siphon. The resulting mass transfer rates are very low ($\sim 10^{-14}$ $M_{\odot}$ yr^{-1}). None of the magnetic WDs in detached systems is a He-core WD (Rebassa-Mansergas et al. 2011).

Our binary population models predict that the overwhelming majority of PCEBs have orbital periods shorter than $\sim$5 d and, in general, small $M_{\rm WD}$ ($\sim$0.45–0.55 $M_{\odot}$). Both these predictions are in good agreement with observations of PCEBs (e.g. Schreiber et al. 2010; Zorotovic et al. 2010; Nebot Gómez-Morán et al. 2011; Zorotovic et al. 2011). However, if combined with equation (1), these otherwise reasonable predictions produce an extremely high fraction of magnetic PCEBs. The post-hot subdwarf binaries that are assumed to be non-magnetic make up a small fraction of the PCEB population ($\lesssim$18 per cent), which is consistent with Zorotovic & Schreiber (2013), who found a fraction of $\sim$16 per cent. This relatively small fraction is a direct consequence of the minimum WD mass needed to trigger further nuclear evolution, which results in WD masses lying in a very narrow range ($\sim$0.38–0.45 $M_{\odot}$). After removing these core-helium burning proto-WDs, equation (1) provides that about 60–90 per cent of all PCEBs are magnetic, depending on the CE efficiency. In addition, using equation (1), the model predicts that most systems with He-core WDs are magnetic, with $B_{\rm WD}$ ranging from $\sim$1 to $\sim$100 MG. The predicted large fraction of magnetic systems and especially the large fraction of magnetic He-core WDs in PCEBs predicted by equation (1) are in strong disagreement with the observations.

The fraction of predicted magnetic WDs and its dependence on $M_{\rm WD}$ are not the only predictions of equation (1) that can be confronted with observations. In Fig. 1, we show $B_{\rm WD}$ as a function of orbital period for the simulated PCEBs (assuming a CE efficiency of 0.25) and the observed pre-polars. Apparently, with the exception of two pre-polars, the predicted $B_{\rm WD}$ are significantly below the observed values, which cluster around 60–70 MG. Thus, despite predicting a far too large fraction of magnetic systems among PCEBs, equation (1) predicts relatively weak WD magnetic fields and cannot explain the field strength of most (8 out of 10) pre-polars.

We continue the comparison with observations by addressing now the low WD effective temperatures of the observed pre-polars. As nine pre-polars have secondaries that are very close to filling their Roche lobes, in order to properly compare with observations,

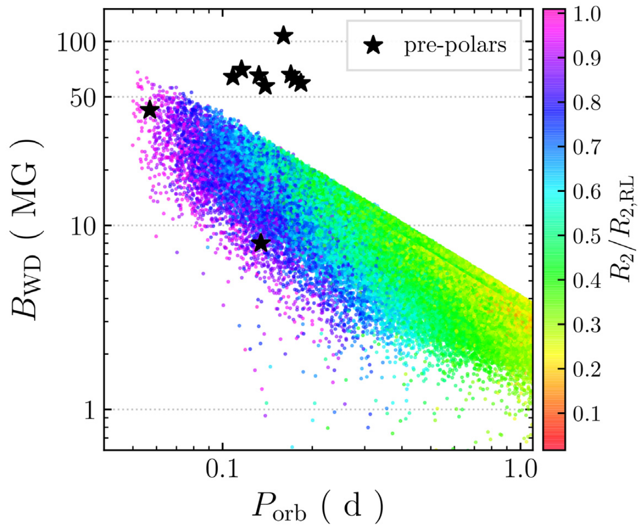

Figure 1. Distribution of predicted PCEBs and observed pre-polars in the plane orbital period ($P_{\rm orb}$) versus WD magnetic field ($B_{\rm WD}$). We show the model for the CE efficiency $\alpha = 0.25$. Colours indicate the secondary Roche lobe overfilling factor for simulated PCEBs. Observed measurements are from Schwope et al. (2009) and references therein, and Parsons et al. (2013). Note that, with the exception of two systems, predicted values for $B_{\rm WD}$ are not strong enough to explain observed values among pre-polars, given their orbital periods.

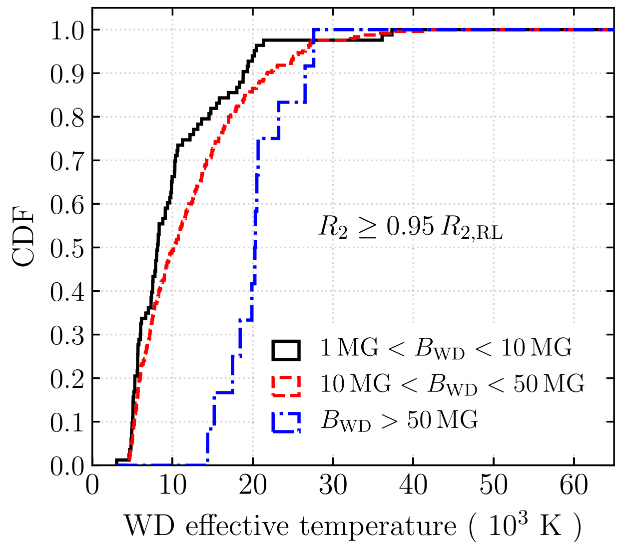

Figure 2. Cumulative distribution function of the WD effective temperature in PCEBs whose secondaries fill at least ~95 per cent of their Roche lobe. We show the case for the CE efficiency $\alpha = 0.25$ and separate the population according to the strength of $B_{\rm WD}$, in units of MG. Notice that ≈50 per cent of systems with 10 MG < $B_{\rm WD}$ < 50 MG have WD effective temperature $\gtrsim$ 10 000 K. In addition, basically all WDs having $B_{\rm WD}$ > 50 MG are hotter than 15 000 K.

we selected simulated PCEBs in which the secondary is filling at least ~95 per cent of its Roche lobe, i.e. $R_2 \geq 0.95\ R_{2,\rm RL}$. For each system, given its $M_{\rm WD}$ and age, we determined its effective temperature by interpolating grids of hydrogen-rich atmosphere WDs. For He-core WDs ($M_{\rm WD} \lesssim 0.5$ M$_\odot$), we used the cooling tracks provided by Panei et al. (2007); for CO-core WDs ($0.5 \lesssim M_{\rm WD} \lesssim 1.05$), we used the cooling sequences of Renedo et al. (2010); and for ONe-core WDs ($M_{\rm WD} \gtrsim 1.05$ M$_\odot$), we used the evolutionary sequences of Althaus et al. (2007).

In Fig. 2, we show the resulting WD effective temperature distributions, separated according to the strength of $B_{\rm WD}$. Virtually all systems with $B_{\rm WD}$ stronger than ~50 MG contain WDs hotter than ~15 000 K. This is in contradiction to the observations, as the WDs in eight pre-polars have fields stronger than 50 MG and are colder than ~10 000 K. On the other hand, the WD temperature in the two pre-polars with fields weaker than ~50 MG can be explained by the model as roughly half of the simulated systems with fields between 10 and 50 MG have WDs cooler than 10 000 K.

The general disagreement between predicted and observed WD temperatures of pre-polars with secondaries close to filling their Roche lobe is again a direct consequence of equation (1). In order to have $B_{\rm WD}$ stronger than ~50 MG, the orbital periods after CE evolution need to be very short. This implies that such systems will be closest to the CV phase after emerging from the CE evolution, and will consequently be the youngest and host the hottest WDs, when the secondary is getting close to filling its Roche lobe.

It furthermore appears difficult to explain the identified discrepancy as an observational bias because current surveys, such as the SDSS, efficiently detect WD+M-dwarf binaries with WD effective temperatures from ~7500 to ~57 000 K (e.g. Zorotovic et al. 2011). If CE evolution was responsible for the magnetic field generation, one would expect large numbers of hot WDs with strong $B_{\rm WD}$. These hot magnetic WDs would clearly be detectable as being magnetic in surveys such as SDSS, via the detection of Zeeman splittings from the surface of WDs with $B_{\rm WD} \gtrsim 1$ MG (Kepler et al. 2013). The M-dwarf companions do not significantly affect the WD spectrum for WD temperatures exceeding ~25 000 K, and magnetic single WDs with such temperatures have been identified (Ferrario et al. 2015). Therefore, the fact that not a single magnetic PCEB with a hot WD is known further suggests that the idea of generating $B_{\rm WD}$ during CE evolution, in its current form, is in disagreement with the observations.

3.2 Cataclysmic variables

One of the easiest and therefore most precise measurement available for CV populations is the fraction of magnetic systems. A recent detailed study of CVs within 150 pc provided a measured value for the fraction of magnetic CVs of $\lesssim$33 per cent (Pala et al. 2019, and references therein). Our binary population model, however, predicts a much large fraction of at least 94 per cent of all CVs being magnetic. This large predicted fraction and the resulting huge discrepancy between theory and observations are simple results of combining equation (1) with realistic binary population models of CVs.

The second observable we can compare with model predictions is the $B_{\rm WD}$ strength. The observed distribution of magnetic CVs contains 77 polars and intermediate polars with measured $B_{\rm WD}$ (Ferrario et al. 2015, their tables 2 and 3), peaks at $\log_{10}(B_{\rm WD}/{\rm MG}) \sim 1.42$, and has a standard deviation of ~0.35. In Fig. 3, we compare this distribution with the model predictions. The predicted distributions, according to equation (1), contain much more low-field systems than in the observed distribution, regardless of the CE efficiency α. In particular, predicted $B_{\rm WD}$ are always weaker than 60 MG, which is below the values measured for high-field polars. Were the observed $B_{\rm WD}$ be as low as predicted by equation (1), intermediate polars would dominate over polars, which is not what observations show. Among the predicted magnetic CVs, only ~25–30 per cent are polars ($B_{\rm WD} \gtrsim 10$ MG) while observations show that

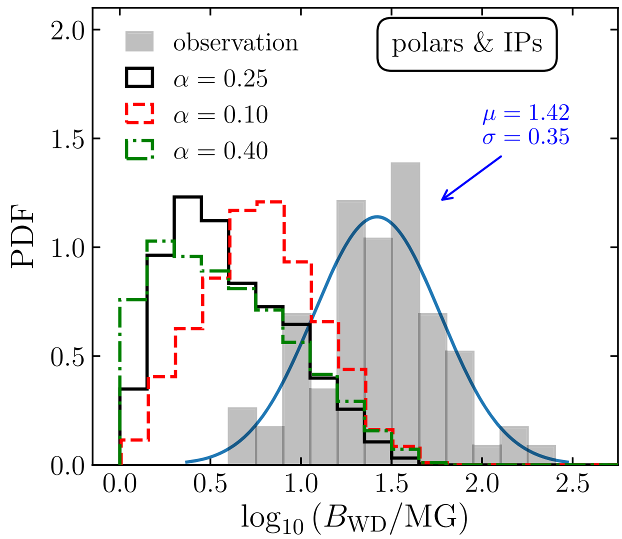

Figure 3. Predicted and observed WD magnetic field strength (B_{WD}) distributions of magnetic CVs. Observed measurements are from Ferrario et al. (2015) and best-fitting Gaussian to the observed distribution is also shown. Note that predicted distributions disagree with the observational, irrespective of the CE efficiency α.

polars are more common than intermediate polars by a factor of ~2–4 (Pretorius, Knigge & Schwope 2013; Pala et al. 2019).

While the observed B_{WD} distribution is likely somewhat biased and not necessarily representative for the intrinsic population in the Galaxy, it is clear from Fig. 3 that equation (1) does not provide B_{WD} strong enough to explain the large fraction of observed systems with $B_{WD} \gtrsim 60$ MG. Therefore, it seems unlikely that the B_{WD} distribution of the intrinsic Galactic population of magnetic CVs, especially polars, can be explained with the hypothesis of magnetic field formation during CE evolution in the way proposed by Briggs et al. (2018a).

4 WHY DO OUR RESULTS DIFFER FROM THOSE OF BRIGGS ET AL.?

While Briggs et al. (2018b) claimed to find agreement between model predictions and observations when generating WD magnetic fields during CE evolution, we found here disagreement. These different conclusions are obtained because of three reasons.

The first reason for the different results obtained by Briggs et al. (2018b) and in this work lies in us addressing the full properties of the few known pre-polars. While Briggs et al. (2018b) speculated that the initial rapid cooling of WDs could explain the low WD effective temperatures in these systems, we compared here the WD effective temperatures, orbital periods, and B_{WD} of the observed pre-polars with our model predictions.

The second reason is connected with the fraction of magnetic systems among the predicted populations. While this fraction was not computed by Briggs et al. (2018b), we found that equation (1) predicts unrealistically high fractions of both magnetic detached WD+M-dwarf PCEBs and CVs.

The third reason is that different binary population codes were used. Unlike Briggs et al. (2018b), we used here a model that includes the evolution of magnetic CVs (Belloni et al. 2020) and recent revisions suggested by Schreiber et al. (2016). The latter is crucial for comparing CV populations as only the revised model brings into agreement the predicted and observed orbital period distributions, WD mass distributions, and space densities.

5 HOW TO PROGRESS WITH THE COMMON-ENVELOPE DYNAMO SCENARIO?

So far, we have shown that the CE dynamo model, as proposed by Briggs et al. (2018a), cannot explain the observations of magnetic WDs in close binaries. The main problems of the current formulation are that the model

(i) predicts WD magnetic fields as too weak to explain those derived from observations of polars and pre-polars;

(ii) predicts that pre-polars close to filling their Roche lobe should mostly contain hot WDs, while observed ones are all cold;

(iii) does not explain the lack of hot strongly magnetized WDs in the observed population of PCEBs;

(iv) predicts that most close WD binaries should harbour WDs with strong magnetic fields, which is inconsistent with measured fractions.

In what follows, we discuss whether plausible revisions of the model exist that might bring into agreement theoretical predictions and observations.

5.1 The field strength problem and the WD temperatures in pre-polars

The problem with the predicted field strength being far lower than the observed ones has a relatively straightforward solution. Given the simplicity of the model, one could just adapt the multiplicative factor ($B_0 = 1.35 \times 10^{10}$ G) in equation (1). Changing the value of this factor does not alter the shape of the distribution but only shifts the predicted field strengths to larger or smaller values. Therefore, increasing B_0 could easily bring into agreement the predicted and observed field strength distributions shown in Figs 1 and 3.

It also appears that the low temperatures of the observed WDs in pre-polars could at least be partly explained by increasing B_0. The fraction of cool WDs in systems close to filling their Roche lobe in Fig. 2 would significantly increase for the field strengths (~50–70 MG) of observed pre-polars.

Changing B_0 can therefore most likely fix the field strength problems in close binaries. As the original value for B_0 has been obtained from fitting the magnetic field strength of single high-field WDs assuming they are the outcome of a merger process during the CE evolution, this would imply that two different values of B_0 would be required. Having different values for B_0 for binaries and single WDs would affect the general validity of equation (1) aimed for by Briggs et al. (2018a,b). However, given how simplistic the proposed model is, it might not be surprising that different values of B_0 are required for different types of objects.

5.2 The missing young magnetic PCEBs

In order to explain the absence of young and hot PCEBs harbouring strongly magnetized WDs in observed samples, an additional mechanism needs to be added to the model. If the WD magnetic fields are generated during CE evolution, their appearance in observed samples of close binaries must be delayed for ~0.5–1.5 Gyr (the typical cooling age of WDs with effective temperatures of ~10 000 K).

One possibility to decrease the magnetic field strength for young PCEBs would be to assume that the fields are buried similarly to those of the weakly magnetized neutron stars in millisecond pulsars (Romani 1990). For such a scenario to work, some material of the CE must remain bound to the system and fall back on to the WD. Indeed, it has been claimed that up to ∼1–10 per cent of the envelope material might remain bound to the binary following CE evolution (Kashi & Soker 2011). Additionally, Zhang, Wickramasinghe & Ferrario (2009) showed that ∼0.1–0.2 $M_{\odot}$ of accreted material is required to bury a strong WD magnetic field in CVs. Thus, to fully bury the generated magnetic field, virtually all the remaining material must be accreted by the WD. Furthermore, the magnetic field would need to be buried for a very long time, i.e. ∼0.5–1.5 Gyr in a detached binary, i.e. without further accretion.

For comparison, in the case of neutron stars, the time-scale needed for magnetic fields buried by a post-supernova episode of hypercritical accretion (e.g. Chevalier 1989; Geppert, Page & Zannias 1999; Bernal, Lee & Page 2010) to diffuse back to the surface is of the order of $\sim 10^3$–10^4 yr (Ho 2011). Thus, a successful model must explain why the WD magnetic fields generated during CE evolution are buried for time-scales several orders of magnitude longer than those in neutron stars.

Detailed and dedicated theoretical investigations of burying fields of magnetic WDs following CE evolution are required to further evaluate this possibility. Based on such detailed investigations, one could hope to confront a quantitative description of the burying mechanism for WDs with observations.

5.3 The fraction of magnetic systems

With respect to the last problem of the CE dynamo model, it is not obvious how the fraction of magnetic systems predicted by the CE dynamo model could be decreased. It is clear that one would need to find a more complex dependency of magnetic field generation on the binary/CE parameters, so far not considered in the model. In order to reproduce the observed fraction of magnetic systems in close WD binaries, such a more complex form of equation (1) should permit strong WD magnetic field generation *only* in a very small subset of CE events.

Typical CE dynamo models for the generation of magnetic fields assume that the dynamo processes are driven by shear due to differential rotation in the envelope (Regős & Tout 1995; Potter & Tout 2010), in an accretion disc (Nordhaus et al. 2011), or in the hot outer layers of the degenerate core (Wickramasinghe, Tout & Ferrario 2014). According to these models, several properties play an important role in amplifying and maintaining the magnetic field. Among them are the differential rotation, the CE mass, radius and density, the total mass of the binary, the total energy generated inside the CE, the orbital energy and angular momentum, the radius of the convective zone, i.e. the interface between the convective and radiative regions, and the thickness of the convective zone, as well as the lifetime of the dynamo activity.

However, which of these parameters are the most important ones involved in CE evolution and the claimed dynamo process is currently unclear. No numerical approach capable of fully addressing the physical mechanisms and time-scales involved in CE evolution has been suggested yet (e.g. Ivanova et al. 2013). It is furthermore not at all clear under which conditions the magnetic fields produced from such dynamos are persistent (e.g. Potter & Tout 2010) and likely to reach (or be generated on) the WD surface with sufficient strength to explain observations of WDs in close binaries (e.g. Ohlmann et al. 2016). Therefore, it remains uncertain whether a more complex version of equation (1) might be able to significantly reduce the predicted fraction of magnetic post-CE systems and, at the same time, provide sufficiently strong magnetic field in some systems to explain the WD magnetic fields observed in pre-polars and CVs.

6 SUMMARY AND CONCLUSIONS

Explaining the origin of magnetic fields in WDs has been a challenge for decades. A handful of mechanisms have been proposed, but none of them is yet considered to be fully convincing. One scenario that has gained some attention in the past years is the model in which the WD magnetic field is generated via a dynamo process during common-envelope evolution. We examined whether such a scenario could explain the observed fraction of magnetic CVs, the observed distribution of WD magnetic fields in polars and pre-polars, the incidence of cool WDs amongst pre-polars, and the paucity of detached WD+M-dwarf PCEBs harbouring magnetic WDs.

By performing binary population synthesis with a state-of-the-art version of the BSE code, we found that this scenario needs to be re-scaled to explain the WD magnetic field distributions of polars and pre-polars as well as the observed low temperatures of the WDs in pre-polars. In order to explain the absence of young detached WD+M-dwarf PCEBs harbouring hot and magnetic WDs, a more severe revision of the model would be required. Somehow, the magnetic fields generated during common-envelope evolution need to be buried for ∼0.5–1.5 Gyr. While this cannot be excluded, there is currently no detailed physical description for a mechanism able to bury the magnetic field for such a long time. Finally, even with these modifications, the common-envelope dynamo scenario would still produce an unrealistically high fraction of systems containing magnetic WDs among CVs, which indicates that the model is currently too simplistic, and a more complex dependency on the binary/common-envelope parameters is needed so that negligible fields are generated in most common-envelope events.

We conclude that the current model is facing serious challenges and needs to be substantially improved to account for the observed properties of magnetic CVs and their detached progenitors. Alternatively, another process might be responsible for the WD magnetic field generation in close WD binaries.

ACKNOWLEDGEMENTS

We would like to thank an anonymous referee for the comments and suggestions that helped to improve this manuscript. We also thank Lilia Ferrario for her feedback on the first version of this paper. We thank MCTIC/FINEP (CT-INFRA grant 0112052700) and the Embrace Space Weather Program for the computing facilities at the National Institute for Space Research, Brazil. DB was supported by the grants #2017/14289-3 and #2018/23562-8, São Paulo Research Foundation (FAPESP). MRS acknowledges financial support from FONDECYT (grant number 1181404).

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