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

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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 only explain 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: novae, cataclysmic variables – methods: numerical – stars: evolution – stars: magnetic field – 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 et al. 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 hypothesis have been put forward to explain magnetic field generation in WDs. In the fossil field scenario (e.g. Angel et al. 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 only explain 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 crystalizes, 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 post-common-envelope binaries (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 WDs which, if true, would provide considerable support for the CE dynamo hypothesis. However, these authors only compared the predicted and observed WD magnetic field distribution 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 pe-
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 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 et al. 2002), which has recently been modified and calibrated to carry out population synthesis of non-magnetic (Belloni et al. 2018) and magnetic CVs (Belloni et al. 2019a).

2.1 General assumptions

The binary population simulations presented here are similar to those shown in Belloni et al. (2019a). In brief, we first generated an initial population of $2 \times 10^7$ 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 was generated assuming a uniform mass ratio distribution, where $M_2 \leq M_1$, and requesting that $M_2 > 0.07$; the semi-major axis was assumed to follow a log-uniform distribution in the range $[10^{-0.5}, 10^{4.5}]$ AU, 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 $M_g$ is the giant core mass and $M_c$ is the giant mass. Dynamically unstable mass transfer gives rise to CE evolution, which we modelled using eqs. 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 $\alpha$ (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. 2019b).

For those binaries that survived CE evolution, we assumed standard angular momentum loss prescriptions (Knigge et al. 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 et al. 2016). Observational evidence for this new model for CE evolution is growing. It is not only a good candidate to solve some longstanding problems related to CE 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. 2019b).

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 $\approx 5$ pcnt 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 and, therefore, treat its 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. 2019a) 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 $B_{WD}$ in each PCEB using the formula provided by Briggs et al. (2018a), i.e.

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

where $\Omega$ is the orbital angular velocity just after the CE evolution given by

$$\Omega = \frac{2\pi}{P_{\text{orb}}} \text{ yr}^{-1},$$

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

$$\Omega_{\text{crit}} = \sqrt{\frac{GM_{WD}}{R_{WD}^3}} = 2\pi \sqrt{\frac{M_{WD}}{M_{\odot}}} \left( \frac{R_{WD}}{\text{AU}} \right)^{-3} \text{ yr}^{-1},$$

where $M_{WD}$ and $R_{WD}$ are the WD mass and radius, respectively. We additionally assume that $B_{WD}$ 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

1 http://www.ifa.uv.cl/bse
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 which 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 \( M_{\text{HeF}} \) which separates low-mass stars that develop a degenerate core on the first giant branch from more massive ones which only develop a degenerate core on the asymptotic giant branch. We adopted here the standard value for \( M_{\text{HeF}} \) from BSE, i.e., \( 1.995 \, M_\odot \), for solar metallicity (Hurley et al. 2000, their eq. 2). CE events with giants that did not develop a degenerate core then occur either if a giant with initial mass smaller than \( M_{\text{HeF}} \) fills its Roche lobe during the sub-giant phase, or if a giant with initial mass larger than \( M_{\text{HeF}} \) fills its Roche lobe during either the sub-giant 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 only applicable for progenitor systems of low-mass WDs \( (\lesssim 0.5 \, M_\odot) \). Observed CV WD masses, however, are always \( \gtrsim 0.5 \, M_\odot \) (McAllister et al. 2019; Zorotovic et al. 2011) 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 are potential strong observational biases 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 \( B_{\text{WD}} = 1 \, \text{MG} \) 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. (2018) 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 \( B_{\text{WD}} \) (Liebert et al., and references therein). Only ten 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 ten per cent. All the magnetic WDs in PCEBs are relatively cool \((T \lesssim 10^4 \, \text{K})\) 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 \((\sim 10^{-14} \, \text{M}_\odot \, \text{yr}^{-1})\). 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 \( \sim 5 \) days and in general small \( M_{\text{WD}} \) \( (\sim 0.45 - 0.55 \, M_\odot) \). Both these predictions are in good agreement with observations of PCEBs (e.g. Schreiber et al. 2010; Zorotovic et al. 2010, 2011; Nebot Gómez-Morán et al. 2011). However, if combined with Eq. 1, these otherwise reasonable predictions produce an extremely high fraction of magnetic PCEBs. The post hot subdwarfs 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, Eq. 1 provides that about \( 60 - 90 \% \) per cent of all PCEBs are magnetic, depending on the CE efficiency. In addition, using Eq. 1, the model predicts that most systems with He-core WDs are magnetic, with \( B_{\text{WD}} \) ranging from \( \sim 1 \) to \( \sim 100 \, \text{MG} \). The predicted large fraction of magnetic systems and especially the large fraction of magnetic He-core WDs in PCEBs predicted by Eq. 1 are in strong disagreement with the observations.

The fraction of predicted magnetic WDs and its dependence on \( M_{\text{WD}} \) are not the only predictions of Eq. 1 that can be confronted with observations. In Fig. 1, we show \( B_{\text{WD}} \) 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 \( B_{\text{WD}} \) are significantly below the observed values, which cluster around \( 60 - 70 \, \text{MG} \). Thus, despite predicting a far too large fraction of magnetic systems among PCEBs, Eq. 1 predicts relatively weak WD magnetic fields and cannot explain the field strength of most (eight out of ten) 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-lobe, in order to properly compare with observations, we selected simulated PCEBs in which the secondary is filling at least $\sim$ 95 per cent of their Roche lobe, i.e. $R_2 \geq 0.95 \cdot R_{2, RL}$. For each system, provided $M_{WD}$ and age, we determined its effective temperature by interpolating grids of hydrogen-rich atmosphere WDs. For He-core WDs ($M_{WD} \lesssim 0.5 \, M_\odot$), we used the cooling tracks provided by Panei et al. (2007); for CO-core WDs ($0.5 \lesssim M_{WD} \lesssim 1.05$), we used the cooling sequences of Renedo et al. (2010); and for ONe-core WDs ($M_{WD} \gtrsim 1.05 \, M_\odot$), 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 $B_{WD}$. Virtually all systems with $B_{WD}$ stronger than $\sim 50$ MG contain WDs hotter than $\sim 15,000$ 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 $\sim 10,000$ K. On the other hand, the WD temperature in the two pre-polars with fields weaker than $\sim 50$ 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 Eq. 1. In order to have $B_{WD}$ stronger than $\sim 50$ 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 $\sim 7,500$ to $\sim 57,000$ 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 $B_{WD}$. 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 $B_{WD} \gtrsim 1$ MG (Kepler et al. 2013). The M-dwarf companions do not significantly affect the WD spectrum for WD temperatures exceeding $\sim 25,000$ 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 $B_{WD}$ 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 is a simple result of combining Eq. 1 with realistic binary population models of CVs.

The second observable we can compare with model predictions is the $B_{WD}$ strength. The observed distribution of magnetic CVs contains 77 polars and intermediate polars with measured $B_{WD}$ (Ferrario et al. 2015, their tables 2 and 3), peaks at $\log_{10}(B_{WD}/\text{MG}) \sim 1.42$, and has a standard deviation of $\sim 0.35$. In Fig. 3, we compare this distribution with the model predictions. The predicted distributions, according to Eq. 1, contain much more low-field systems than in the observed distribution, regardless of the CE efficiency $\alpha$. In particular, predicted $B_{WD}$ are always weaker than 60 MG, which is below the values measured for

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**Figure 1.** Distribution of predicted PCEBs and observed pre-polars in the plane orbital period ($P_{orb}$) versus WD magnetic field ($B_{WD}$). 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). Notice that, with the exception of two systems, predicted values for $B_{WD}$ are not strong enough to explain observed values among pre-polars, provided their orbital periods.

**Figure 2.** Cumulative distribution function of the WD effective temperature in PCEBs whose secondaries fill at least $\sim$ 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 $B_{WD}$, in units of MG. Notice that $\approx 50$ per cent of systems with $10 \, \text{MG} < B_{WD} < 50 \, \text{MG}$ have WD effective temperature $\gtrsim 10,000$ K. In addition, basically all WDs having $B_{WD} > 50 \, \text{MG}$ are hotter than $15,000$ K.
high-field polars. Were the observed $B_{WD}$ be as low as predicted by Eq. 1, intermediate polars would dominate over polars, which is not what observations show. Among the predicted magnetic CVs only $\sim 25 - 30$ per cent are polars ($B_{WD} \gtrsim 10$ MG) while observations show that polars are more common than intermediate polars by a factor of $\sim 2 - 4$ (Pretorious et al. 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 Eq. 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).

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 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 Eq. 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 ($\sim 50 - 70$ 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 Eq. 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 post-common-envelope binaries

In order to explain the absence of young and hot PCEBs harbou- 
ring strongly magnetised WDs in observed samples, an ad-
titional mechanism needs to be added to the model. If the WD  
magnetic fields are generated during CE evolution, their appear-
ance in observed samples of close binaries must be delayed for  
$\sim 0.5 - 1.5$ Gyr (the typical cooling age of WDs with effective  
temperatures of $\sim 10^4$ K).

One possibility to decrease the magnetic field strength for  
young PCEBs would be to assume that the fields are buried simi-
larly to those of the weakly magnetised 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 falls back onto  
the WD. Indeed, it has been claimed that up to $\sim 1 - 10$ per cent of  
the envelope material might remain bound to the binary following CE  
evolution (Kashi & Soker 2011). Additionally, Zhang et al. (2009)  
showed that $\sim 0.1 - 0.2 \, M_\odot$ of accreted material are 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. $\sim 0.5 - 1.5$ 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 et al. 1999;  
Bernal et al. 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 fur-
ther 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 Eq. 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 et al.  
2014). According to these models, several properties play an impor-
tant role for 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 ra-
diative regions, the thickness of the convective zone, as well as the  
life-time of the dynamo activity.

However, which of these parameters are the most important  
one of involved in CE evolution and the claimed dynamo process  
is currently unclear. No numerical approach capable of fully ad-
dressing the physical mechanisms and time-scales involved in CE  
evolution has been suggested yet (e.g. Ivanova et al. 2013). It is  
therefore important 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 bi-
naries (e.g. Ohlmann et al. 2016). Therefore, it remains uncertain  
whether a more complex version of Eq. 1 might be able to sig-
nificantly 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 pro-
posed, 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 cata-
lysmic variables, 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 post-common-
envelope binaries 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 tempera-
tures of the WDs in pre-polars. In order to explain the absence  
of young detached WD+M-dwarf post-common-envelope binaries  
harbouring hot and magnetic WDs, a more severe revision of the  
model would be required. Somehow the magnetic fields gener-
ated during common-envelope evolution need to be buried for  
$\sim 0.5 - 1.5$ 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 mod-
ifications, the common-envelope dynamo scenario would still pro-
duce an unrealistically high fraction of systems containing mag-
netic WDs among cataclysmic variables, which indicates that the  
model is currently too simplistic, and a more complex dependency  
on the binary/common-envelope parameters is needed so that neg-
gligible fields are generated in most common-envelope events.

We conclude that the current model is facing serious chal-
lenge and needs to be substantially improved to account for the  
observed properties of magnetic cataclysmic variables and their de-
tached progenitors. Alternatively, another process might be respon-
sible for the WD magnetic field generation in close WD binaries.

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