The origin and evolution of magnetic white dwarfs in close binary stars

Matthias R. Schreiber, Diogo Belloni, Boris T. Gänsicke, Steven G. Parsons and Monica Zorotovic

The origin of magnetic fields in white dwarfs remains a fundamental unresolved problem in stellar astrophysics. In particular, the very different fractions of strongly (more than about a megagauss) magnetic white dwarfs in evolutionarily linked populations of close white dwarf binary stars cannot be reproduced by any scenario suggested so far. Strongly magnetic white dwarfs are absent among detached white dwarf binary stars that are younger than approximately a billion years. In contrast, of cataclysmic variables (semi-detached binary star systems that contain a white dwarf) in which the white dwarf accretes from a low-mass star companion, more than a third host a strongly magnetic white dwarf. Here we present binary star evolutionary models that include the spin evolution of accreting white dwarfs and crystallization of their cores, as well as magnetic field interactions between the stars. We show that a crystallization- and rotation-driven dynamo similar to those working in planets and low-mass stars can generate strong magnetic fields in the white dwarfs in cataclysmic variables, which explains their large fraction among the observed population. When the magnetic field generated in the white dwarf connects with that of the secondary star in the binary system, synchronization torques and reduced angular momentum loss cause the binary to detach for a relatively short period of time. The few known strongly magnetic white dwarfs in detached binaries, such as AR Scorpii, are in this detached phase.

The vast majority of close binary star systems containing at least one white dwarf form through common envelope evolution. The emerging detached post-common-envelope binary stars evolve towards shorter orbital periods driven by angular momentum loss and eventually become semi-detached cataclysmic variables (CVs). Despite this clear evolutionary link, the fraction of strongly magnetic white dwarfs differs drastically between both types of close white dwarf binaries.

We know of more than 160 CVs with a strongly (larger than 1 MG) magnetic white dwarf. In most of these systems the white dwarf accretes from its Roche-lobe-filling low-mass star companion along the magnetic field lines. If the magnetic fields of both stars interact, the rotation of the white dwarf is synchronized with the orbital motion of the secondary star, and such systems are called polars. In a smaller but still important fraction of CVs, the magnetic field of the white dwarf disrupts the inner parts of the accretion disk but the magnetic fields of both stars do not connect. In these so-called intermediate polars the rotation of the white dwarf and the orbital motion are therefore not synchronized. A recent study of a volume-limited sample has shown that over a third of all CVs contain a magnetic white dwarf, with polars and intermediate polars making up approximately 29% and 7% of the total population, respectively.

The situation is very different among the detached systems that are believed to be the progenitors of CVs. Only 15 strongly magnetic white dwarfs in close detached binaries are currently known and they make up less than 2% of the over one thousand systems known. All but one of these detached magnetic white dwarf binaries have been identified owing to a peculiar emission line, which turned out to be the third harmonic of a cyclotron fundamental emitted by a low-density plasma. This observational finding is convincingly interpreted as resulting from wind accretion onto a strongly magnetic white dwarf in a close but detached binary. Because angular momentum loss will eventually drive them into a semi-detached CV configuration, these systems have been termed pre-polars. The only exception is AR Scorpii (AR Sco), which was discovered because of the optical and radio pulses of its rapidly (period 1.97 min) rotating white dwarf. AR Sco and most pre-polars are located in the orbital period range between 3 h and 5 h, their secondary stars are close to filling their Roche lobes (with the ratio of stellar to Roche radius R/R_L typically exceeding 80%), and the magnetic white dwarfs are cold with effective temperatures typically below 10,000 K, which implies that they formed at least a billion years ago. Among younger close detached white dwarf binaries, not a single strongly magnetic white dwarf has been found.

This puzzling situation of a large fraction (approximately 35%) of strongly magnetic white dwarfs in CVs and the much smaller fraction of magnetic white dwarfs among the detached systems that are believed to be CV progenitors was aptly expressed by Liebert, who asked "Where are the magnetic white dwarfs with detached, non-degenerate companions?". This fundamental question of stellar evolution has remained without an answer for 15 years and the solution must link the evolution of white dwarf binaries and magnetic field generation in white dwarfs.

Several hypotheses have been put forward to explain magnetic field generation in white dwarfs in the past few decades. In their present form, none of the fossil field scenario, a dynamo operating during common-envelope evolution or a double-white-dwarf merger can be the main formation mechanism for close magnetic white dwarf binaries. This is because, in all these cases, the magnetic fields are generated during the formation process of the white dwarf. That is, according to these theories, detached post-common-envelope

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In the only mechanism that depends on the age of the white dwarf, a dynamo similar to those operating in low-mass main-sequence stars and planets has been suggested to operate if the white dwarf is rotating rapidly when the core of the white dwarf is crystallizing. As a white dwarf with a carbon/oxygen core cools, the ions in the core begin to freeze in a lattice structure. During crystallization the chemical potential, temperature and pressure of the liquid and solid phases must remain equal. As a consequence, in crystallizing white dwarfs the solid phase becomes richer in oxygen and sinks, while the carbon excess mixes with the outer liquid envelope, which is redistributed by Rayleigh–Taylor instabilities. This configuration is similar to that found in the core of the Earth, where the light-element release associated with inner-core growth is a primary driver of the dynamo generating the Earth’s magnetic field.

The predicted field strengths generated by this dynamo in white dwarfs depend entirely on the scaling law that is assumed. Applying the same scaling law that is used for planetary magnetic fields leads to field strengths in white dwarfs of up to approximately 1 MG (ref. 20). However, taking into account the probable dependence of the dynamo efficiency on the magnetic Prandtl number and that in white dwarfs this number is orders of magnitudes larger than in planets, one could expect this dynamo to be able to generate fields much stronger than 1 MG (for more details, see Methods).

Assuming that the crystallization- and rotation-driven dynamo can generate strong magnetic fields, we computed evolutionary tracks starting with non-magnetic post-common-envelope binaries. We incorporated several physical mechanisms into the stellar evolution code MESA. The spin-up of the white dwarf due to the accretion of angular momentum was included as well as crystallization of the white dwarf. We furthermore incorporated the reduction in angular momentum loss through magnetic braking when the magnetic fields of both stars connect, which is a condition for synchronization, and a prescription for angular momentum transfer from the spin of the white dwarf to the orbit during synchronization (see Methods for more details).

Figure 1 shows an exemplary evolutionary track resulting from our simulations and a schematic illustration of the different stages the system passes through. In our model the white dwarf is born without a strong magnetic field, which is in agreement with the absence of strongly magnetic white dwarfs in young close detached post-common-envelope binaries (stage 1). The non-magnetic detached binary star then evolves slowly towards shorter orbital periods and the white dwarf cools. When the secondary fills its Roche lobe the binary becomes a CV, accretion spins up the white dwarf and the core may be crystallizing (stage 2). If this happens, both conditions for the crystallization- and rotation-driven dynamo are met and a strong magnetic field is generated (stage 3). If the magnetic field is strong enough to connect with the field of the secondary star the latter provides a synchronizing torque on the white dwarf’s spin. The spin angular momentum transferred to the orbital motion by the synchronizing torque causes the secondary star to detach from its Roche lobe. This effect is supported by the fact that the connection...
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Fig. 2 | Observed white dwarf effective temperatures versus their masses. The data points are for non-magnetic post-common-envelope binaries from the Sloan Digital Sky Survey (light grey)\textsuperscript{10,17}, pre-polars (red)\textsuperscript{10} and the first radio pulsing white dwarf binary AR Sco (blue)\textsuperscript{18,19}. The horizontal and vertical errors on the observations correspond to 1σ and arrows indicate upper limits. The lines represent the mass fraction of crystallized matter in the white dwarf interiors. Solid, dashed, dash-dotted and dotted lines show the temperature for each white dwarf’s mass, corresponding to the onset of crystallization, when 10% of its mass is crystallized, when 50% of its mass is crystallized and when 80% of its mass is crystallized, respectively\textsuperscript{26,27}. As predicted by our scenario, magnetic systems host, on average, much older and more massive white dwarfs than their non-magnetic counterparts.

The trend towards larger masses in magnetic systems is consistent with the observed white dwarf mass distribution in CVs\textsuperscript{10,15}, which fits with the model prediction that these systems have been CVs in the past. In addition, the white dwarfs in AR Sco and all pre-polars are consistent with having crystallizing cores.

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the observed magnetic single white dwarfs within 20 pc (table 1 of ref. 23) rotate with periods ranging from hours to days. Despite rotating orders of magnitudes too slowly for the energy flux scaling law to be applicable (that is, in the saturated regime), the field strengths of these white dwarfs even slightly exceed those predicted by the energy flux scaling law. This implies that, if a convection-driven dynamo works in crystallizing and rotating white dwarfs, the energy flux scaling law underestimates the field strengths of slowly rotating single white dwarfs. The field strengths of rapidly rotating white dwarfs in the saturated regime should therefore also largely exceed those predicted by the energy flux scaling law. A suitably revised scaling law that incorporates the dependence on the magnetic Prandtl number is therefore likely to predict fields much stronger than around 1 MG for white dwarfs that rotate in the saturated regime of the dynamo.

From the above arguments, we here assumed that a rapidly rotating white dwarf (spin period $P_{WD} \approx 20–30$ s) with a fractional crystallized mass between 10% and 80% can drive a dynamo that generates the large magnetic field strengths observed in white dwarfs in CVs (up to several 100 MG). We calculate the evolution of close detached white dwarf binaries and CVs using MESA, taking into account the spin-up due to accretion and crystallization due to cooling of the white dwarf as well as magnetic-field generation if a crystallizing white dwarf rotates rapidly.

**Spin-up of the white dwarf.** If a white dwarf accretes from an accretion disk in a CV its angular momentum and therefore its angular velocity increases, whereas during nova eruptions the white dwarf loses mass and angular momentum. According to King et al., the resulting angular momentum balance for an accreting white dwarf is given by

$$I \frac{d\omega}{dt} = \alpha ( -\dot{M}_2 ) ( GM_{WD} R_{WD} )^{1/2} + ( 1 + \epsilon ) \left( \frac{\dot{M}_2}{\dot{M}_{WD}} \right) R_{WD}^2 \omega,$$

where $\omega$ is the white dwarf spin, $I$ its moment of inertia, $G$ the gravitational constant, $M_2$ the mass transfer rate averaged over nova cycles, and $M_{WD}$ and $R_{WD}$ are the white dwarf’s mass and radius.

The first term in the right-hand part of the equation corresponds to the spin-up due to accretion, while the second term represents the spin-down due to material leaving the white dwarf during nova eruptions. The parameter $0 \leq \alpha \leq 1$ represents the spin-up efficiency, which might be smaller than one due to mass loss processes not considered in equation (1) (such as winds from the inner accretion disk or jets from the boundary layer/white dwarf). The parameter $0 \leq \epsilon = M_{WD}/M_2 \leq 1$ relates the mass loss of the white dwarf to the mass transfer rate. The range of possible values reflects the fact that the white dwarf’s mass might decrease over a nova cycle, that is, more mass might be expelled during a nova eruption than was accreted between two eruptions. The parameter $0 \leq \epsilon \leq 1$ represents the square of the radius of gyration of the ejected envelope and depends on the geometry of nova eruptions.

By solving the non-homogeneous differential equation (1), the white dwarf’s spin as a function of the donor mass is given by

$$\omega(t) = \frac{C_1}{C_2} + C_3 \exp \left( \frac{C_2}{M_2} \right),$$

where $M_2$ is the donor mass in solar masses and the terms $C_1$, $C_2$, and $C_3$ are given by

$$C_1 = \frac{A}{k^2} a_{\text{bd}} \frac{M_{WD}}{R_{WD}},$$

$$C_2 = \frac{\eta}{k^2 R_{WD}} \left( 1 + \epsilon \right) + \beta \epsilon,$$

$$C_3 = \left( a_{\text{bd}} - \frac{C_1}{C_2} \right) \exp \left( -\frac{C_2}{M_2} \right),$$

where $a_{\text{bd}}$ is the white dwarf’s spin at break-up, given by

$$a_{\text{bd}} = \sqrt{\frac{GM_{WD}}{R_{WD}}} \left| \frac{2}{k^2} \left( \frac{M_{WD}}{M_2} \right) \frac{R_{WD}}{a} \right| \text{ yr}^{-1},$$

where $a$ represents an astronomical unit. The moment of inertia $I$ is $k^2 M_{WD} R_{WD}^2$ with $k$ given by $0.452 + 0.0853 \log_{10} \left[ 1 - \left( M_{WD} / 1.44 M_\odot \right) \right]$ if $M_{WD} \leq 1.368 M_\odot$, where $M_\odot$ is the solar mass, and $k=0.275$, if $M_{WD} > 1.368 M_\odot$. The constants $A$ and $B$ are given by

$$A = \left[ 1 - 0.61 \left( M_{WD}/M_\odot \right)^{1/2} \right]^{3/4},$$

$$B = \left[ 3.05 \left( M_{WD}/M_\odot \right)^{1/4} - 1 \right] \left( 1 - 0.61 \left( M_{WD}/M_\odot \right)^{1/2} \right) + \frac{0.051}{\left( 1 - 0.69 \left( M_{WD}/M_\odot \right) \right)}.$$

The sub-index 0 in some quantities indicates their initial values just after the common-envelope evolution.

**Synchronization of the white dwarf.** In accreting high-field magnetic white dwarf binaries, the magnetic field dominates the accretion process. For sufficiently strong white dwarf magnetic moments, the overflowing material is channelled along the white dwarf’s magnetic field lines as soon as the magnetic pressure dominates the gas ram pressure. For such strong white dwarf magnetic fields, the interaction of the magnetospheres of the white dwarf and the donor cause a synchronizing torque on the white dwarf.

We assume here that the onset of synchronization occurs when the synchronizing torque is greater than the accretion torque (assuming that the magnetospheres of the white dwarf and the donor are connected), that is

$$\frac{\mu_{\text{bd}}}{\mu_{\text{wd}}} > 1.11 \left( \frac{M_2}{M_{WD}} \right) \left( \frac{M_{WD}^2}{M_2} \right) \frac{1}{\eta} \left( \frac{a}{R_{WD}} \right)^{-1} \left[ 0.5 - 0.277 \log_{10} \left( \frac{M_{WD}}{M_\odot} \right) \right]^2$$

where $M_2$ is the mass transfer rate (in g s$^{-1}$), $\mu_{\text{bd}}$ is the white dwarf’s magnetic moment (in G cm$^3$), $M_2$ is the donor mass (in M$_\odot$), $M_{WD} = M_{WD1} + M_{WD2}$ is the binary total mass (in M$_\odot$), $P_{cv}$ is the orbital period (in hr), and $R_{WD}$ (in gauss) is the strength of the magnetic field of the secondary star.

Once the condition provided by equation (9) is satisfied, the spin-down process starts. For simplicity, we assume that the white dwarf spin decreases exponentially on a given timescale, that is

$$\omega(t) = \Omega + C e^{-\nu t}$$

where $\nu$ is the synchronization timescale, $\Omega$ the orbital angular velocity, $\omega$ the white dwarf’s spin and $C=\omega_0 - \Omega$ is a constant (because variations in $\Omega$ are negligible during the spin-down phase). This assumption gives

$$\frac{d\omega}{dt} = \frac{(\Omega - \omega)}{\tau},$$

This equation of course represents a very crude approximation of a very complicated process. The torque on the primary as a function of asynchronism has been calculated previously in great detail, but only for rather small asynchronism. Performing such detailed calculations of the magnetic field interaction for the large asynchronism in our systems is beyond the scope of this paper. For the purpose of this paper, we assume that the total angular momentum lost by the white dwarf is transferred to the secondary, incorporated in the orbital motion, and that this occurs on the timescale $\tau$, that is

$$J_{\text{orb}} = -\frac{d}{dt} (\omega(t)) = \frac{(\omega_0 - \Omega)}{\tau} > 0.$$
where $\dot{J}_{\text{nonMag}}$ is the angular momentum loss due to magnetic braking in non-magnetic CVs. Here we used the widely adopted RV prescription\(^7\), with $\gamma = 3$, that is $\dot{J}_{\text{nonMag}} = -3.8 \times 10^{-16} M c^2 R_1^8 \Omega_2^2$.\(^{14}\)

where $R_1$ is the solar radius, $R_2$ is the donor radius (in $R_\odot$), $M$ is the secondary mass (in $M_\odot$) and $Q_2$ is the donor spin (in $s^{-1}$), which is the same as the orbital angular velocity. This reduced magnetic braking model has been incorporated in binary population models of magnetic CVs and has been shown to convincingly reproduce the orbital period distribution of magnetic CVs\(^{20}\) and here we implemented the same prescription in MESA.

Modelling magnetic CV evolution with MESA. The effects described above were incorporated in the stellar evolution code Modules for Experiments in Stellar Astrophysics (MESA) (version r10180)\(^{21,22}\). The MESA equation of state is a blend of the OPAL\(^{49}\), SCVH\(^{50}\), PTEH\(^{51}\), HELM\(^{52}\) and PC\(^{53}\) equations of state. Radiative opacities are primarily from OPAL\(^{54}\), but also cover the low-temperature-dominated\(^{55}\) and high-temperature, Compton-scattering-dominated\(^{56}\) regimes. Electron conduction opacities are also included\(^{57}\). Nuclear reaction rates are a combination of rates from NACRE\(^{58}\), JINA REACLIB\(^{59}\), plus additional tabulated weak reaction rates\(^{60}\). Screening is included\(^{61}\) as well as thermal neutrino loss\(^{62}\). Roche-lobe radii in binary systems are computed using Eggleton\(^{63}\), and mass transfer in Roche-lobe-overflowing binary systems are determined following Ritter’s prescription\(^{64}\). The parameters of our standard model were set as follows. During the whole of the CV evolution we assumed that all material accreted by the white dwarf is lost through nova eruptions. In equation (1), this corresponds to setting $\alpha = 0$. For the geometry of nova shells, we assumed that mass leaves the white dwarf with some asymmetry (that is, neither completely spherical nor radial), which implies values of $q$ in equation (1) between $2/3$ and 1. We set $q = 2.5/3$. Additional mass loss from the system\(^{65}\) was taken into account by using $\alpha = 0.75$ in equation (1). The donor magnetic field was assumed to be $B_1 = 1$ kG, which is consistent with recent measurements of field strengths of low-mass stars\(^{66}\). We fixed the white dwarf mass at $M_2 = 0.5 M_\odot$, which corresponds to the average value found among observed CVs\(^{67}\). For the white dwarf magnetic field, we assume $B_{\text{wd}} = 60$ MG, which is slightly stronger than the average field strength of polars\(^{68}\), but corresponds to the average field strength found in pre-polars\(^69\). We assumed that the dynamo is efficient only if the core of the white dwarf is crystallizing (between 10% and 80% crystallization) and the period of the white dwarf is around 20–30 s. Finally, for the synchronization timescale, we set $tau = 1$ Myr, which is consistent with the expected rapid spin-down in close binaries harbouring a rapidly rotating magnetic white dwarf such as AR Sco\(^70\).

Using this set of parameters, our model can reproduce the observations of magnetic detached and semi-detached close white dwarf binary stars (Supplementary Fig. 1). According to this model, pre-polars and AR Sco used to be CVs and at that time the strong magnetic fields of their white dwarfs were generated. This prediction is in agreement with the cool white dwarf temperatures of these detached systems, with their Roche lobes close to being filled, and with their preferred occurrence in the orbital period range 3–5 h.

We emphasize that no fine-tuning was required to obtain this agreement. The model naturally explains the observations and variations of the key parameters do not affect the general predictions (Supplementary Figs. 2–4). For instance, by changing the spin-up parameters ($\alpha$, $\eta$ and $q$), the only effect is to accelerate or delay the spin-up of the white dwarf and slightly change the minimum spin period that can be reached\(^71\). For all reasonable values of these parameters the white dwarf will manage to spin up to sufficiently large spin rates that the conditions for generating strong magnetic fields can eventually be met. Similarly, varying the synchronization timescale $\tau$ affects the synchronizing torque but does not change the evolutionary sequence (Supplementary Fig. 2). The shorter the $\tau$, the stronger the spin-down torque and therefore the longer the detached phase. Only for $\tau > 100$ Myr can the detached phase be fully prevented, if, in addition, the magnetic field strength of the white dwarf does not exceed about 200 MG. The latter condition does arise, because for very strong fields, reduced magnetic braking alone can cause the system to detach, in full analogy to the mechanism producing the classical orbital period gap.\(^72\)

A stronger co$\phi_0$, or a timescale that is longer than the orbital period at which synchronization can be obtained, is longer for stronger fields (Supplementary Fig. 3). The strength of the white dwarf’s magnetic field also affects the duration of the detached phase. The stronger the white dwarf’s magnetic field, the more orbital angular momentum loss due to magnetic braking is reduced and the longer it takes the system to evolve back into a semi-detached configuration.

The largest and most critical assumptions in our model are the conditions we assume for magnetic field generation, which represent a strong but reasonable simplification. According to the most popular scaling laws\(^73\), the dynamo saturates for fast rotation (in white dwarfs for spin periods below 90 s; cf.\(^77\) and the produced field strength then depends solely on the convective energy flux. However, as outlined above, the efficiency of the dynamo is also expected to be strongly dependent on the magnetic Prandtl number, which is not considered in any currently available scaling law. As long as a reliable scaling law taking into account this dependency is not available, describing the evolution of close magnetic white dwarf binaries needs to be based on simple assumptions such as those made in this paper. As soon as realistic scaling laws for the dynamo operating in crystallizing white dwarfs are available, we plan to incorporate those together with detailed white dwarf models into our simulations.

The aim of this paper is to show how the evolution of close white dwarf binaries is affected if, and that is a reasonable assumption, crystallization and fast rotation can generate a strong magnetic field. We would expect the generated field strength in these models to depend on the rotation rate and the energy flux in the convection zone. Given the large range of orbital periods at the end of common-envelope evolution, and hence the large variety of evolutionary timescales towards the CV phase, we expect that a more detailed model will be able to explain a large range of field observations of those intermediate polars. For the latter, the field is simply not strong enough to synchronize the white dwarf’s spin with its orbital motion and the system does not enter a detached phase, apart from the usual 2–3 h orbital period gap.

In the Supplementary Information we present a detailed discussion of different evolutionary channels predicted by our model and estimate the fraction of magnetic and non-magnetic white dwarfs in CVs, taking into account important parameters for binary star evolution\(^78\) as well as potential accretion heating and chemical impurities in the core of the white dwarf\(^79\). We also elaborate on the implications of our scenario for the generation of magnetic fields in hot single white dwarfs\(^80\) as well as magnetic white dwarfs in wide binaries\(^81\). We find that these magnetic fields are probably generated by alternative mechanisms such as fossil fields resulting from main-sequence star mergers\(^82\), double-white-dwarf mergers\(^83,84\), or common-envelope mergers\(^85,86\).

Data availability

The data presented in this work is available upon request. In addition, the MESA files required to reproduce our simulations will be publicly available at the MESA Zenodo community (https://zenodo.org/communities/mesa/).

Code availability

MESA is publicly available (http://mesa.sourceforge.net/).

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Author contributions

All authors contributed to the discussion and writing of this article. M.R.S. and D.B. developed the idea and carried out the simulations. S.G.P. and B.T.G. provided an observational overview of magnetic white dwarfs and recent observations of pre-polars. M.Z. provided crystallization temperatures for different white dwarf masses based on published white dwarf evolutionary sequences and estimated relative numbers of magnetic and non-magnetic CVs using binary population models.

Competing interests

The authors declare no competing interests.

Additional information

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