Binary star origin of high field magnetic white dwarfs

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ABSTRACT

White dwarfs with surface magnetic fields in excess of 1 MG are found as isolated single stars and relatively more often in magnetic cataclysmic variables (CVs). Some 1253 white dwarfs with a detached low-mass main-sequence companion are identified in the Sloan Digital Sky Survey (SDSS) but none of these is observed to show evidence for Zeeman splitting of hydrogen lines associated with a magnetic field in excess of 1 MG. If such high magnetic fields on white dwarfs result from the isolated evolution of a single star, then there should be the same fraction of high field magnetic white dwarfs among this SDSS binary sample as among single stars. Thus, we deduce that the origin of such high magnetic fields must be intimately tied to the formation of CVs. The formation of a CV must involve orbital shrinkage from giant star to main-sequence star dimensions. It is believed that this shrinkage occurs as the low-mass companion and the white dwarf spiral together inside a common envelope. CVs emerge as very close but detached binary stars that are then brought together by magnetic braking or gravitational radiation. We propose that the smaller the orbital separation at the end of the common envelope phase, the stronger the magnetic field. The magnetic CVs originate from those common envelope systems that almost merge. We propose further that those common envelope systems that do merge are the progenitors of the single high field magnetic white dwarfs. Thus, all highly magnetic white dwarfs, be they single stars or the components of magnetic CVs, have a binary origin. This hypothesis also accounts for the relative dearth of single white dwarfs with fields of $10^4$–$10^6$ G. Such intermediate-field white dwarfs are found preferentially in CVs. In addition, the bias towards higher masses for highly magnetic white dwarfs is expected if a fraction of these form when two degenerate cores merge in a common envelope. Similar scenarios may account for very high field neutron stars. From the space density of single highly magnetic white dwarfs we estimate that about three times as many common envelope events lead to a merged core as to a CV.

Key words: binaries: close – stars: magnetic fields – white dwarfs.

1 INTRODUCTION

White dwarfs (WDs) appear to form with a wide range of surface magnetic fields up to $10^9$ G (Schmidt et al. 2003). Isolated WDs can be separated into two groups, those with high magnetic fields stronger than $10^6$ G (high field magnetic WDs (HFMWDs)) and the rest with lower magnetic fields, typically less than $10^5$ G. About 10 per cent of isolated WDs are HFMWDs (Liebert et al. 2005; Kawka et al. 2007). A WD with a close companion that is overflowing its Roche lobe is a cataclysmic variable (CV) (Warner 1995). Among the CVs about 25 per cent (Wickramasinghe & Ferrario 2000) have WDs that are very magnetic. These fall into two classes. Those with a highly magnetic accreting primary star are called polars or AM Herculis systems. In these systems, the magnetosphere of the primary is able to totally control the accretion flow from the secondary, such that no accretion disc forms and the pair are locked in synchronous rotation at the orbital period. The polars have measured fields in the range $10^7$–$10^8$ G. Of slightly weaker field are the intermediate polars or DQ Her systems in which the magnetic field of the primary does not entirely prevent the formation of an accretion disc. The WD is spun up to a rotation period shorter than the orbital period. The majority are deduced to have primaries with smaller magnetic field strengths than the polars ($5 \times 10^6$–$10^7$ G) but the lower limit is uncertain. There is some overlap at the high field end with the polars.

In the Sloan Digital Sky Survey (SDSS) Data Release Five, some 1253 spectroscopically observed close binary systems comprising a
WD and a non-degenerate, usually M, dwarf (hereinafter WD+M) have been identified and catalogued by Silvestri et al. (2007). Of all these pairs, none has been found in which the WD is observed to have a magnetic field above 2–3 MG, the limit of detectability via the Zeeman splitting of the Balmer lines at the spectral resolutions used. Here, we extend the size of the sample and strengthen greatly the statistics on the apparent absence of magnetic WD pairings with a non-degenerate dwarf star, as first discussed at length by Liebert et al. (2005).

Previously, the best explanation for the apparent absence of magnetic WDs associated with M dwarfs put forth by Liebert et al. (2005) was related to the evidence that at least some strongly magnetic WDs have higher than average masses and smaller radii. As demonstrated by representative simulations of Silvestri et al. (2007), the smaller radius and luminosity of a magnetic primary causes its spectrum to be masked more easily by an M companion. However, recent studies (see Section 2.2) have shown that the HFMWDs are of a range of masses with several of 0.6$M_\odot$ or less. Thus, although the mean mass for the HFMWDs is higher, it is not sufficiently different from non-magnetic WDs to explain the lack of pre-magnetic CVs as an observational selection effect. An alternative explanation is therefore required.

If the origin of magnetic fields in WDs were independent of their binary nature, we would expect the distribution of field strengths amongst isolated WDs, WDs in non-interacting binary stars and WDs in CVs to be similar. This is not the case. There are no HFMWDs in non-interacting binary stars in which the companion is a K or M dwarf. Such systems, if close enough, would be the progenitors of magnetic CVs (MCVs). Ten per cent of isolated, or single star, WDs are highly magnetic and two and a half times this fraction of WDs in interacting CVs are highly magnetic. The fact that there appears to be no HFMWD in a binary system that has not interacted suggests that they were once all binary.1 The fact that HFMWDs are common in CVs but absent in similar but wider non-interacting systems suggests that the generation of the field is entwined with the formation of the CVs themselves.

Here, we revisit the proposal of Tout & Reggós (1995) that the strong magnetic fields are actually generated in the common envelope (CE) evolution that is responsible for shrinking the binary orbit from giant to dwarf dimensions (Paczyński 1976). In this scenario, it is the systems that merge or just avoid merging that are expected to have the strongest fields. These emerge from CE evolution either as single highly magnetic cores of rapidly spinning giants, which go on to lose their envelopes and cool as the isolated HFMWDs, or almost in contact, perhaps already transferring mass, as MCVs.

2 THE OBSERVATIONS

The SDSS sample of 1253 spectroscopically observed WD+M pairs includes only stars with a signal-to-noise ratio of at least 5 per pixel. Any magnetic field over 2–3 MG should be detectable by Zeeman splitting of the Balmer lines. Two candidate magnetic WDs were identified with slightly broad lines indicative of perhaps a 1–2 MG field. However, follow-up spectrophotometry with the Hobby–Eberley Telescope has been obtained for one of these (WD 0828+4217) and did not confirm that it is magnetic (K. Williams, private communication).

The SDSS survey also resulted in a large increase in the number of known isolated magnetic WDs which has now grown to over 170 (Vanlandingham et al. 2005). In the most recent compilation by Kawka et al. (2007), 149 magnetic WDs are listed with $B = 3$ MG or larger. This is a conservative lower limit of the number of stars in which the Zeeman splitting is clear enough for a good spectrum to permit the identification of a HFMWD.

2.1 Assessing the statistics of WD+M pairs

We can estimate how many of the detached magnetic WDs should be expected to have a companion by making the assumption that WD+M pairings occur with the same frequency as for non-magnetic WDs. The sample of WDs within 20 pc (Holberg, Oswalt & Sion 2002) has probably been searched for companions more thoroughly than any sample of more distant objects. Out of the 109 WDs, 21 objects or 19 ± 4.5 per cent have main-sequence companions. This leads us to expect that 14–24 per cent of the 149 strongly magnetic WDs, some 21–35, should have non-degenerate companions. In an unbiased selection of WDs, $N$ of which should be highly magnetic, we expect to find $N \pm \sqrt{N}$ which are. The absence of any main-sequence stars paired with a HFMWD in this sample is therefore significant at a 3σ level.

We can also use larger, more distant samples to improve on these statistics. Many of the several hundred hot WDs found in the Palomar Green Survey (Green, Schmidt & Liebert 1986) show the existence of a companion in the optical spectrum. Holberg & Magargal (2005) used the Two-Micron All-Sky Survey detections at 1.2–2.0 μm JHK bands to look for excesses over the WD Rayleigh–Jeans tail. They found that 23 per cent of the PG sample had definite and 29 per cent had definite or probable cool companions. If we assume that the 149 strongly magnetic WDs should be a sample with a binary frequency similar to the Palomar Green Survey, 34–43 should have companions. We now encroach on a 3σ level of significance.

2.2 Selection effects owing to differences in mass

Decided differences are apparent in the fraction of WDs that are magnetic between the apparent magnitude-limited and the volume-limited samples. In the Palomar Green sample, an example of the former, only 2 per cent are strongly magnetic. In the Holberg et al. (2002) sample, 21 out of the 109 local WDs are magnetic, that is, 19 ± 4 per cent. The latter is arguably close to volume-limited because all lie within 20 pc according to best distance estimates. This distinction has been discussed by Liebert et al. (2005) and by Kawka et al. (2007). Both groups argue that the likely true frequency of strong magnetism in HFMWDs approaches or exceeds 10 per cent. However, given that the SDSS is magnitude limited, we can conservatively estimate that we should expect about 25 pre-magnetic CVs in the sample of the 1253 stars so far observed but none has been found.

A systematic effect that might have gone some way towards explaining this discrepancy is the evidence that magnetic WDs tend to be more massive and hence less luminous than non-magnetic WDs. Liebert (1988) first summarized the evidence that several nearby magnetic WDs with trigonometric parallaxes have relatively small radii and anomalously high masses and lie below the sequence of most WDs in a Hertzsprung–Russell diagram. These objects include the well-known Grw+70° 8247, G227−35, G240−72 and GD 229.
Since then many more magnetic WDs have been shown to be massive. However, there is also evidence that many of them have more ordinary masses near 0.6 M⊙ or less. The presence of a very strong field generally prevents any direct measurement of the mass through log g so that the mass estimates for magnetic WDs have been possible for only a small subset of the known objects.

Three methods have been used to estimate masses for suitable magnetic WDs. First, if the field strength is of the order of 15 MG or less, standard broadening theory applied to each Zeeman component yields an approximate surface gravity (see examples in Bergeron, Leggett & Ruiz 2001). Secondly, the measurement of a good-quality trigonometric parallax is a key way to measure the radius and luminosity of the magnetic star in comparison with the non-magnetic WDs. A third method has been applied to binary systems with a non-magnetic DA white dwarf paired with a magnetic WD. The spectrum of the magnetic component must be subtracted out if the binary is spatially unresolved. The fitting of the Balmer lines of the non-magnetic object to determine log g sets the distance to the system and allows comparison of the radii between the two components. Thus, the mass estimates from these methods are not as accurate as those obtained for non-magnetic objects with log g.

The distribution of measured masses of HFMWDs (Kawka et al. 2007) is shown in Fig. 1 and compared with normal DA WDs in the SDSS sample (Kepler et al. 2007). The mean mass of the HFMWDs is 0.78 M⊙ if we include the rather low-mass helium WDs and 0.82 M⊙ if we exclude these stars. The mean mass is somewhat higher than the mean mass of 0.58 M⊙ of all WDs and the radii are therefore typically smaller than those of non-magnetic WDs. However, the calculations of Silvestri et al. (2007) show that a much larger mass difference is required to explain the absence of any magnetic pre-CVs in terms of such a selection effect. In addition, the distribution of masses of HFMWDs is broad so still includes a substantial fraction of low-mass stars.

![Figure 1](https://example.com/fig1.png)

**Figure 1.** The distribution of measured masses of magnetic WDs compared with normal DA WDs taken from Kawka et al. (2007) compared with normal DA WDs in the SDSS sample (Kepler et al. 2007, without correction for different sampling at different masses). Note that the two distributions peak at roughly the same mass but the distribution for magnetic WDs is much broader than for the non-magnetic WDs. We account for this by claiming that the underlying mass distribution is similar but that the magnetic distribution is augmented at the low end by extra helium WDs and at the high end by merged double degenerate cores. According to our hypothesis, the latter are more abundant and so skew the distribution in such a way that the mean mass is increased.

### 2.3 Low accretion rate polars (LARPs)

There exist a small number of observed high field MCVs that have accretion rates much lower than expected for a semidetached system (Webbink & Wickramasinghe 2005). They are thought to be sufficiently close that the magnetic field of the WD can capture a weak stellar wind from the companion. They have periods ranging from 1.3 to 4.39 h and magnetic fields from 42 to 65 MG or so (Schmidt et al. 2005, 2007). All have low temperatures, 7500 < T eff/K < 13000 and so have not recently emerged from a CE. We propose that these, and systems like them, have emerged from the CE as very close pairs but must still wait for gravitational radiation to bring them close enough for Roche lobe overflow. They are the magnetic analogues of the normal pre-CVs like V471 Tau with a period of 6.9 h (Warner 1995). The narrow field range in which the LARPs have been found is a selection effect related to the use of cyclotron harmonics in their discovery in the SDSS sample. We expect that LARPs with magnetic fields over the entire intermediate polar to AM Her range exist and will be found in the future.

### 2.4 Doubly degenerate systems

In addition to the MCVs, there are seven binary systems in which one star has a high magnetic field listed by Kawka et al. (2007) in their appendix. Four of these have been examined in more detail. EUVE J0317−855 is thought to have evolved from a triple system in which two of the stars merged to form the HFMWD (Ferrario et al. 1997). G62−46 shows evidence that it has emerged from a CE phase (Bergeron, Ruiz & Leggett 1993) as two very close WDs, one of which is highly magnetic and of very low mass, 0.25 M⊙. Similarly, EUVE 1439+75 is a close system that has probably emerged from a CE phase (Vennes, Ferrario & Wickramasinghe 1999) as two close and massive WDs, one of which is highly magnetic. G141−2 (Bergeron, Ruiz & Leggett 1997) has a mass of 0.25 ± 0.12 M⊙ and so could only have formed in binary interaction. Thus, there is no evidence that any of these HFMWDs with degenerate companions must have formed without binary interactions.

### 3 COMMON ENVELOPE EVOLUTION AND MAGNETIC FIELD GENERATION

Because the WDs in CVs must have once been the cores of giants, their binary orbits must have shrunk substantially from at least several hundred solar radii, to accommodate a giant, to only a few, so that the red dwarf companions to the WDs now fill their Roche lobes. The process leading to this is not at all well understood but is encapsulated in the CE evolution described by Paczyński (1976). When a giant star fills its Roche lobe, unstable mass transfer can lead to a state in which the giant envelope surrounds the two dense cores, its own degenerate core and its companion. This companion is most likely an unevolved lower mass main-sequence star but might itself be already a WD. These two cores are then supposed to spiral together inside the CE while energy and angular momentum are transferred from their orbit to the envelope which is gradually ejected.

As the cores get closer together, their orbital period falls and this sets up differential rotation within the CE. By its giant nature the CE is expected to be largely convective. Differential rotation and convection are the key ingredients of a stellar magnetic dynamo (Tout & Pringle 1992). Regős & Tout (1995) go so far as to say that this dynamo actually drives the transfer of energy and angular momentum from the orbit to the envelope as well as the
strong wind that expels the envelope. Irrespective of this, we expect that, at the end of the CE evolution, either when the spiralling cores coalesce or when all the envelope is driven away, there is a very strong magnetic field in the vicinity of the hot degenerate core. This field can penetrate the non-degenerate surface of the core and become frozen in as it later cools and contracts. The closer the cores at the end of CE evolution, the greater the differential rotation in the CE and so the stronger the expected frozen in magnetic field.

We then expect the strongest WD magnetic fields to form in the cores of systems that merge during CE evolution. A main-sequence companion is likely to dissolve into the giant envelope when it has spiralled in deep enough that its density is comparable with its surroundings. The spin angular momentum remaining in the envelope depends on the details of the CE process as well as the initial conditions of the system. If we assume that the remaining envelope has the specific angular momentum of the original orbit, its spin period would have reduced from years to days. The degenerate core therefore finds itself at the centre of a rapidly spinning giant to which its spin is likely to be coupled. Because of the small size of the core, its moment of inertia is negligible compared with that of the remaining envelope. This is consistent with the trend for HFMWDs to be very rapidly spinning by the time they emerge from the giant envelope. This is consistent with the tendency for HFMWDs to be extremely slow rotators, some with spin periods up to 100 yr (Wickramasinghe & Ferrario 2000). From the CE systems that almost merge, we then expect a range of relatively high magnetic field WDs in MCVs which emerge from the CE very close to interacting, the polars and intermediate polars, with a corresponding range of core separations bordering on the systems that merge. Wider core separations and the end of the CE phase end up as the precataclysmic non-magnetic variables and wider systems that will never interact. These coupled with single stars and binary stars that never enter a CE phase make up the low-field WDs in CVs, wider binary stars and single isolated WDs.

The distribution of the masses of the isolated HFMWDs (Fig. 1) appears to be made up of a distribution similar to that of the low-field dwarfs augmented from about 0.6 \( M_\odot \) upwards and especially so at the very high masses. Under our hypothesis, these are simply explained as the result of a CE with two degenerate cores. Typically, this is the second CE phase in a system with two stars that can both evolve to become giants. The first phase leaves a closer MS+WD system. The second star then evolves and unstable mass transfer leads to the second CE phase in which the giant-like envelope surrounds two degenerate cores. If the two cores merge to form a massive WD, it has a high magnetic field in accordance with our hypothesis. If the total mass exceeds the Chandrasekhar limit, the cores may undergo accretion induced collapse to leave a highly magnetic neutron star. In either case, we expect accretion during the merging to be fast enough to burn any material non-degenerate to oxygen and neon (Martin, Tout & Lesaffre 2006). These stars ought to emerge rapidly spinning but should also spin down rapidly by magnetic braking. One star, EUVE 0317–855 (Ferrario et al. 1997), shows both a high spin, \( P = 12 \) min, and a high mass, \( M = 1.35 \) \( M_\odot \).

The magnetic dynamo model for the origin of fields in MCVs should be contrasted with the fossil field model that has been used to explain the properties of the isolated HFMWDs (Wickramasinghe & Ferrario 2005). According to this hypothesis, the magnetic flux in the core of the star that becomes the WD is closely related to the flux of its main-sequence progenitor. The mechanism by which this correspondence occurs has been unclear but recent calculations (Zahn, Brun & Mathis 2007) confirm that a fossil field in radiative regions could act as a seed field to generate a strong magnetic field by a dynamo in the convective core that becomes the WD (cf. Tout, Wickramasinghe & Ferrario 2004). An alternative dynamo origin in single stars was proposed by Levy & Rose (1974) but it still relies on the intrinsic stellar spin of a single star. The major difference in our hypothesis is that, unlike in single star evolution, strong differential rotation is an essential characteristic of CE evolution. Our assumption is that any intrinsic fossil field that is present is destroyed or at most serves as a seed field for the magnetic dynamo in the CE phase.

The space densities and observable lifetimes of CVs and WDs are not well known but we can use current estimates to check consistency with our hypothesis. There are \( 1.1 \pm 2.3 \times 10^{-5} \) CVs per cubic parsec (Pretoius et al. 2007) and about one-quarter of these
have high fields. There are $3 \times 10^{-3}$ WDs per cubic parsec (Liebert et al. 2005) and about one-tenth of these are HFMWDs. If we assume that the observable lifetime of a CV, the time over which its mass-transfer rate is sufficiently high, is about one-tenth that of an isolated WD, the time for it to cool below detectable limits, then the birth rate of HFMWDs is about three times that of CVs. Thus, three times as many systems entering a CE phase should end up merging as emerge separated but close enough to become a CV.

5 CONCLUSIONS

The fact that no WD with a surface magnetic field over 3 MG has been found in a detached binary system suggests that all such highly magnetic WDs have a binary origin. If half of the stars in our neighbourhood have a binary companion and half of these are sufficiently separated not to have interacted, then there should be at least one-quarter as many magnetic WDs in wide detached binary systems as appear as single stars unless their origin depends on binary interaction. This is not the case and so argues very strongly against any single star evolutionary origin of HFMWDs and very much in favour of a mechanism that relies on binary interaction.

Given the conundrum, relating to the MCVs, that there is an absence of evidence for any pre-MCVs in some $1253$ WD+M pairs that have so far been studied, we have provided the solution that the origin of high magnetic fields in WDs relies on a magnetic dynamo during the CE phase of binary evolution. Systems with the strongest magnetic fields emerge from the CE phase either as merged single stars or with their secondary stars more nearly in contact with their Roche lobes thus reducing their chance of being detected as pre-magnetic CVs.

Our hypothesis also predicts the existence of HFMWDs that result from systems that merge during the CE phase. The absence of any MCVs in detached binary stars leads us to conclude that all highly magnetic WDs have formed in this way.

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