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The origin of high magnetic fields in white dwarfs

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Abstract. The lack of evidence for Zeeman splitting of the hydrogen lines in the spectra of the 1,253 close but detached binary systems consisting of a white dwarf and a nondegenerate star, a sample that includes the pre-Cataclysmic Variables, identified in the Sloan Digital Sky Survey indicates that there are no identifiable progenitors for the Magnetic Cataclysmic Variables (MCVs), even though these comprise some 25 per cent of all Cataclysmic Variables (CVs). Indeed, all high-field white dwarfs appear to be either single stars or components of AM Her systems. This suggests that all such white dwarfs have a binary origin. We resolve this dilemma by postulating that the $10^6 - 10^8$ G magnetic fields that are observed in the white dwarfs in the MCVs are generated in the common envelope phase of pre-CV evolution in systems which almost merge. Systems that merge in the common envelope phase yield a population of isolated magnetic white dwarfs with fields of $10^6 - 10^9$ G that make up the entire single magnetic white dwarf population.

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

1. Introduction

White dwarfs form with a wide range of surface magnetic fields up to 10^9 G (Schmidt et al. 2003). Isolated white dwarfs can be separated into two groups, those with high magnetic fields stronger than 10^6 G (HFMWDs) and the rest with lower magnetic fields, typically less than 10^5 G. About ten per cent of isolated WDs are HFMWDs (Liebert et al. 2005; Kawka et al. 2007). A white dwarf with a close companion that is overflowing its Roche lobe is a cataclysmic variable (Warner 1995). Among the cataclysmic variables about twenty-five per cent (Wickramasinghe & Ferrario 2000) of the white dwarfs are highly magnetic. In the polars or AM Herculis 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

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period. They 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 white dwarf 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).

If the origin of magnetic fields in white dwarfs were independent of their binary nature we would expect the distribution of field strengths amongst isolated white dwarfs, white dwarfs in non-interacting binary stars and white dwarfs in cataclysmic variables 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. Ten per cent of isolated single white dwarfs are highly magnetic and two and a half times this fraction in interacting cataclysmic variables are highly magnetic. The fact that there appears to be no HFMWD in a binary system that has not interacted suggests that, like the R stars (McClure 1997), they were once all binary. The fact that HFMWDs are common in cataclysmic variables but absent in similar but wider non-interacting systems suggests that the generation of the field is entwined with the formation of the cataclysmic variables themselves.

2. The observations

In the SDSS sample of spectroscopically-observed WD+M pairs any magnetic field over 2 – 3 MG should be detectable by Zeeman splitting of the Balmer lines. Of the 1,253 such pairs, only two candidate magnetic white dwarfs have been identified but neither of these relatively low fields has been confirmed (K. Williams private communication). The SDSS survey also greatly increased the number of isolated magnetic white dwarfs. The total known has now grown to over 170 (Vanlandingham et al. 2005). In the most recent compilation by Kawka et al. (2007) 149 magnetic white dwarfs are listed with $B =$ 3 MG or larger.

How many of these magnetic white dwarfs should be expected to have a companion if WD+M pairings occur with the same frequency as for non-magnetic white dwarfs? The sample of white dwarfs within 20 pc (Holberg et al. 2002) has probably been searched for companions more thoroughly than any sample of more distant objects. Of the 109 white dwarfs 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 white dwarfs, some 21 – 35, should have nondegenerate companions. For a normal distribution the absence of any pairings has a four sigma level of significance. We can also use larger, more distant samples to improve on these statistics. Many of the several hundred hot white dwarfs found in the Palomar Green Survey (Green et al. 1986) show the existence of a companion in the optical spectrum. Holberg & Magargal (2005) 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 to 43 should have had companions. This is then of six-sigma significance.

Could this be a biased selection? A possible systematic effect is that magnetic white dwarfs tend to be more massive, and hence less luminous, than a nonmagnetic white dwarfs. Liebert (1988) demonstrated that nearby magnetic white dwarfs with trigonometric parallaxes have relatively small radii and anomalously high masses and lie below the sequence of most white dwarfs in an HR Diagram. However there is also evidence that some have more ordinary masses near 0.6 $M_\odot$ or less. The distribution of measured masses of HFMWDs (Kawka et al. 2007) is shown in Fig. 1 and compared with normal DA white dwarfs in the SDSS sample (Kepler et al. 2007). The mean mass of the HFMWDs is 0.78 $M_\odot$ if we include the rather low-mass helium white dwarfs and 0.82 $M_\odot$ if we exclude these stars. The mean mass is somewhat higher than the mean mass of 0.58 $M_\odot$ of all white dwarfs and the radii are therefore typically smaller than those of non-magnetic white dwarfs. However the calcula-

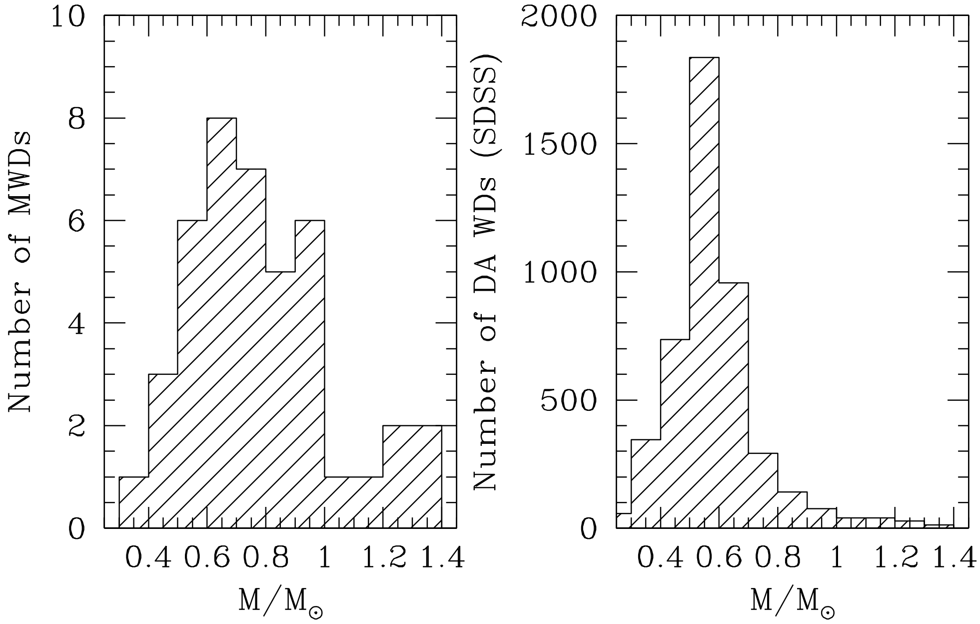

Fig. 1. The distribution of measured masses of magnetic white dwarfs compared with normal DA white dwarfs taken from Kawka et al. (2007) compared with normal DA white dwarfs in the SDSS sample (Kepler et al. 2007, without correction for different sampling at different masses).

tions 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 and so still includes a substantial fraction of low-mass stars. In fact it appears to be similar to that of the non-magnetic white dwarfs augmented with a significant number of higher mass stars.

3. Common envelope evolution and magnetic field generation

Because the white dwarfs in cataclysmic variables 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 white dwarfs now fill their Roche lobes. The process leading to this is not understood at all well but is encapsulated in the common envelope (CE) evolution first 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 which is most likely an unevolved lower-mass main-sequence star but might itself be already a white dwarf. 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 it. Irrespective of this, we expect that, at the end of the common envelope evolution, there is a very strong magnetic field in the vicinity of the hot degenerate core. This field could penetrate the nondegenerate 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 white dwarf magnetic fields to form in the cores that merge during CE evolution. Initially the merged core is expected to form the degenerate core of a rapidly spinning giant. Such a giant would itself generate a strong dynamo and spin down rapidly. Thus, except in the rare case that the envelope is almost completely ejected when the cores merge, we would not expect the HFMWDs to be rapidly spinning by the time they emerge from the giant envelope. We then expect a range of relatively high magnetic fields in MCVs which emerge from the CE very close to interacting, the polars and intermediate polars with a corresponding dearth of such fields amongst the single stars (Koester et al. 2001). Systems which emerge with wider separations should have much lower fields.

4. Magnetic CVs

The absence of evidence of any pre-magnetic CVs in some 1,253 WD+M pairs that have so far been studied suggests that the pre-CV phase of evolution for MCVs must be short lived compared to that of non magnetic CVs. That is, compared to the nonmagnetic CVs, a MCV must be born preferentially in contact or sufficiently close to contact with its Roche lobe to allow it to evolve into contact on a time scale that is significantly shorter than the orbital evolution time scale of these systems. A common envelope magnetic dynamo leads naturally to a scenario in which this may occur. In this model systems that emerge more tightly bound following the CE phase are the systems with the stronger magnetic fields.

5. Isolated HFMWDs

We note that there are some differences in the properties of the isolated HFMWDs and the MCVs which have previously been attributed to their different origins. First the incidence of magnetism in CVs (about 25 per cent) is significantly higher than in the isolated white dwarfs (about 10 per cent). This has also been attributed to possible selection effects (Warner 1995) though no detailed studies have been carried out to test this hypothesis. Secondly the polars are deficient of white dwarfs with fields in excess of 10^8 G compared with the isolated HFMWDs. Our hypothesis accounts for both these differences straightforwardly. The highest fields are expected in the CEs in which the cores are closest together. Thus the isolated HFMWDs can generally have much higher fields than the MCVs because the differential rotation in their progenitor CE can be much greater. It is greatest just before merging. The MCVs then fall in a small range of core separations bordering on the systems that merge. Wider core separations and the end of the CE phase end up as the pre-cataclysmic 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 white dwarfs in cataclysmic variables, wider binary stars and single isolated white dwarfs.

6. Doubly degenerate systems

In addition to the MCVs there are seven double WD 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 et al. 1993) as two very close white dwarfs, one of which is highly magnetic and of very low mass, 0.25 $M_{\odot}$. Similarly EUVE 1439+75 is a close system that has probably emerged from a CE phase (Vennes et al. 1999) as two close and massive white dwarfs, one of which is highly magnetic. G141–2 (Bergeron et al. 1997) has a mass of $0.26 \pm 0.12\,M_{\odot}$ and so could only have formed in a binary interaction. Thus there is no evidence that any of these HFMWDs with degenerate companions must have formed without binary interactions.

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 common envelope with two degenerate cores. Typically this is the second CE phase in a system with two stars that have both evolved to become giants. The first phase leaves a close 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-degenerately to oxygen and neon (Martin et al. 2006). These stars ought to emerge rapidly spinning but should also spin down rapidly by magnetic braking. This is the case for EUVE J 0317-855 (Ferrario et al. 1997), which shows both a high spin, $P = 12\,\mathrm{min}$, and a high mass, $M = 1.35\,M_{\odot}$.

7. Freezing of magnetic fields

It turns out that it is not easy to freeze a magnetic field into a white dwarf. There is however sufficient energy in the shear generated by the spiralling cores to generate a magnetic field of up to $10^{11}\,\mathrm{G}$ in the vicinity of the white dwarf in a typical core merging CE event. Examination of the process (Potter & Tout 2010) reveals that how strong a magnetic field can be frozen in depends strongly on the electrical conductivity of the white dwarf, the lifetime of the convective envelope and the variability of the magnetic dynamo. In the case of a dynamo that leads a randomly oriented magnetic field, the induced field is confined to a thin boundary layer at the surface of the white dwarf. This then decays away rapidly upon dispersal of the common envelope. The residual field is typically less than 10^{-8} times the strength of the external field. Only in the case where there is some preferential direction to the dynamo-generated field can an induced field, which avoids rapid decay, be produced. A surface field of a few per cent of the external field can then be produced after a few Myr and the residual field strength is roughly proportional to the lifetime of the dynamo activity so it would seem that the CE process would need to be slow.

8. Space densities and CE evolution

The space densities and observable lifetimes of CVs and white dwarfs are not well known but we can use current estimates to check consistency with our hypothesis. There are $1.1 \pm 2.3 \times 10^{15}$ CVs per cubic parsec (Pretorius et al. 2007) and about one quarter of these have high fields. There are 3×10^{-3} white dwarfs 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 white dwarf, 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 and emerge separated but close enough to become a CV.

9. Conclusions

The fact that no white dwarf with a surface magnetic field over 3 MG has been found in a detached binary system suggests that all such highly magnetic white dwarfs 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 white dwarfs 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 origin and very much in favour of a mechanism that relies on binary interaction. Systems with the strongest magnetic fields emerge from the CE phase either as merged single stars or with their secondary stars nearly in contact with their Roche lobes thus reducing their chance of being detected as pre-magnetic cataclysmic variables. Single high field magnetic white dwarfs result from systems that merge during the common envelope phase. The absence of any MCVs in detached binary stars leads us to conclude that all highly magnetic white dwarfs have formed in this way.

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