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The properties and origin of magnetic fields in white dwarfs

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Abstract. A significant fraction of white dwarfs harbour a magnetic field with strengths ranging from a few kG up to about 1000 MG. The fraction appears to depend on the specific class of white dwarfs being investigated and may hold some clues to the origin of their magnetic field. The number of white dwarfs with variable fields as a function of their rotation phase have revealed a large field structure diversity, from a simple offset dipole to structures with spots or multipoles. A review of the current challenges in modelling white dwarf atmospheres in the presence of a magnetic field is presented, and the proposed scenarios for the formation of magnetic fields in white dwarfs are examined.

Key words: white dwarfs – stars: magnetic fields – stars: evolution

1. Introduction

White dwarfs represent the final stage of stellar evolution for the majority of stars and a significant fraction of them harbour a magnetic field ranging from a few kG up to several hundred MG. The presence of a magnetic field affects the external appearance of the white dwarf (emerging flux), its temperature structure as well as its evolutionary prospects (cooling age).

In this review I examine the incidence of magnetism in the white dwarf population, and how it differs between different subclasses. The challenges in modelling white dwarf atmospheres in the presence of a magnetic field are discussed in Sect. 3. Finally, eligible scenarios for the origin of magnetic fields in white dwarfs are explored in Sect. 4.

2. Magnetic field incidence

The measured fraction of magnetism in white dwarfs varies between various surveys. Magnetic white dwarfs are identified via polarization measurements (P) or characteristic Zeeman patterns (H). Colourimetric and photometric limited surveys (e.g., Schmidt & Smith, 1995; Kepler et al., 2013) delivered fractions as low as 5% but volume limited surveys (Kawka et al., 2007) resulted in fraction estimates as high as 20%. The number of known magnetic white dwarfs has grown considerably in recent years which helped uncover specific classes of white dwarfs showing a significantly higher incidence of magnetism.

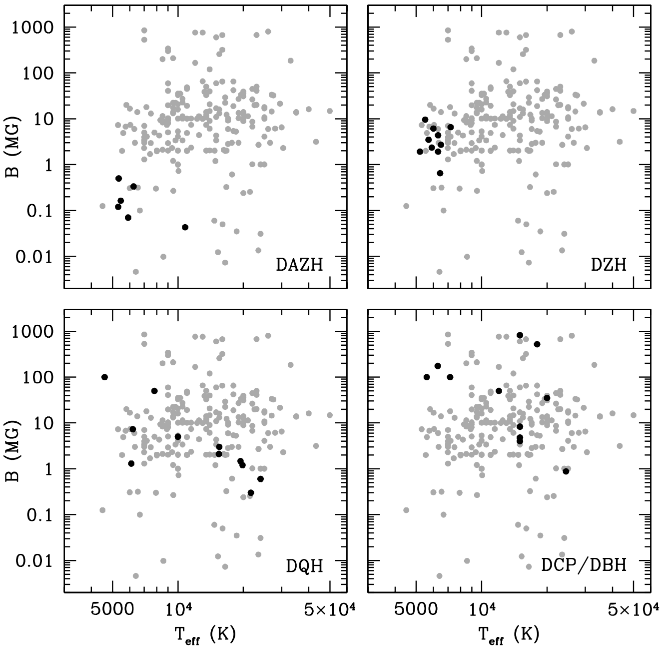

Figure 1. The distribution of known white dwarfs as a function of the magnetic field and effective temperature. The grey points in all panels are magnetic DA white dwarfs. Each panel highlights (in black) the properties of the various spectral type of magnetic white dwarfs (DAZ, DZ, DQ and DC/DB).

Most white dwarfs have a hydrogen-rich atmosphere (DA), with the remainder having an atmosphere dominated by helium, with a visual helium spectrum (DB) or without (DC). A few, rare carbon-dominated objects are known as hot DQ white dwarfs (Dufour et al., 2008) that appear to be high temperature counterparts to the cool helium-dominated but carbon-polluted DQ white dwarfs (Dufour et al., 2005). Approximately 25 to 30% of white dwarfs show traces of heavy elements (Zuckerman et al., 2003, 2010) and for such objects the suffix Z is added to the respective spectral classes, e.g., DAZ, DBZ, DZ (i.e., DC with metal lines).

Fig. 1 shows all currently known magnetic white dwarfs segregated into various spectral types as a function of their field strength and effective temperature. Table 1 lists the number of known magnetic white dwarfs and the incidence of magnetism per spectral class. For hot DQs, 12 are known, but only 6 of these have a published magnetic field measurement. There is no apparent correlation between effective temperature and magnetic field strength for DAH

Table 1. Incidence of magnetism among different classes of white dwarfs

Spectral type	Prototype	Number	Fraction (%)	Reference
DAH	Grw+70°8247	208	4 ± 1.5	Schmidt & Smith (1995)
DAZH	G77-50	6	~ 50	Table 2
DBH	GD229	8	~ 1.5	estimated
DCP	G195-19	3	~ 5	Putney (1997)
DZH	LHS2534	10	13 ± 4	Hollands et al. (2015)
DQH (hot)	SDSS J1337+0026	12 (6)	~ 70	Dufour et al. (2013)
DQH (cool)	G99-37	4	~ 4	Vornanen et al. (2013)

and DCP/DBH white dwarfs. Although only a few are known, polluted magnetic white dwarfs (DAZH, DZH) are clustered at cooler temperatures, with the DAZH at systematically lower field strengths. Featureless DC white dwarfs are difficult to diagnose and only a handful of high-field DCP are known.

2.1. Cool polluted white dwarfs

Studies of cool, polluted white dwarfs have revealed a higher incidence of magnetism than in the general population of white dwarfs. Kawka & Vennes (2014) showed an incidence of 40% in cool, polluted hydrogen-rich (DAZ) white dwarfs. These objects have relatively low fields ($B_S < 1$ MG). Here we revisit this sample and confirm this high incidence. Table 2 lists the known magnetic DAZs. Comparing this sample to all the other known DAZ white dwarfs that have been observed at sufficiently high resolution we find that close to 50% of DAZ white dwarfs with $T_{\rm eff} < 6000$ K are magnetic. The abundance patterns of magnetic DAZs does not appear to differ from those of non-magnetic DAZs and we cannot establish a correlation between magnetic field strengths and abundances. Above a temperature of 6000 K, only 2 magnetic DAZs are known, NLTT 53908 is only slightly warmer at 6250 K and WD2105-820 is hotter with $T_{\rm eff} = 10\,800$ K.

A high incidence of magnetism is also observed in the cool, polluted, helium-rich class (DZ) of white dwarfs. Hollands et al. (2015) reported an incidence of 13% in DZ white dwarfs with $T_{\rm eff} < 8000$ K. The magnetic fields in this case are higher than those in cool DAZs with $1.9 < B_S < 9.6$ MG. Hollands et al. (2015) noted that the incidence of magnetism in DZs hotter than 8000 K is significantly lower in their sample.

2.2. Hot DQ white dwarfs

Hot DQ white dwarfs have temperatures ranging from about 18 000 K up to 24 000 K and an atmosphere dominated by carbon. Half of these stars were found to be photometrically variable with periods ranging from ≈ 5 min up to 2.1 days. Initially, these variations were attributed to pulsations, however, following the discovery of a 2.1 day period in SDSS J0005-1002 (Lawrie et al.,

Table 2. Properties of known magnetic DAZ white dwarfs

Name	T_{eff} (K)	$\log g$	B_S (kG)	V (mag)	Reference
NLTT07547	5460	8.04	163	18.3	1
NLTT10480	5410	8.0	519	17.5	2
NLTT43806	5900	8.0	70	15.9	3,4
NLTT53908	6250	7.87	334	18.0	5
G77-50	5310	8.05	120	16.2	6
WD2105-820	10800	8.19	43	13.6	7,8

References: (1) Kawka et al., in prep; (2) Kawka & Vennes (2011); (3) Kawka & Vennes (2006); (4) Zuckerman et al. (2011); (5) Kawka & Vennes (2014); (6) Farihi et al. (2011); (7) Koester et al. (2009); (8) Landstreet et al. (2012)

2013), the preferred explanation is that they are caused by a rotating field. Recently, Dufour et al. (2013) reported an incidence of 70% in this class of objects, suggesting that all hot DQs may be magnetic at some level. The magnetic fields range from ~ 0.3 up to 2.1 MG. Dufour et al. (2013) also propose that these stars may be more massive than the general white dwarf population. Dunlap & Clemens (2015) also suggests that hot DQs are likely massive, and, since most of them show rapid variability which may be attributed to rotation, they are possibly the product of white dwarf mergers.

3. Modelling magnetic atmospheres

Magnetic fields, particular strong ones, are detected in intensity spectra while weak fields are readily detectable in Stokes V spectra. A combination of intensity and circular polarization spectra are useful for detailed studies of field geometry. Different Zeeman regimes need to be used depending on the field strength. The linear Zeeman regime can be assumed for weak fields, and as the field strength increases, the quadratic effect becomes important. For the strongest magnetic fields the strong field mixing regime needs to be adopted. For more details about these regimes see Wickramasinghe & Ferrario (2000).

In general the magnetic field in white dwarfs is assumed to be a centred or offset dipole. However, rotating magnetic white dwarfs have revealed a diversity in the field topology. Landstreet et al. (2017) showed that the rotating magnetic white dwarf WD 2047+372 which has a weak field of $B_P = 91.8 \pm 0.8$ kG can be modelled by a simple dipole. Their analysis of a second low-field white dwarf WD 2359-434 required the combination of a dipolar and a non-aligned quadrupole to model the spectropolarimetric observations. Some white dwarfs were found to have even more complex structures. For example, the high-field, massive and hot white dwarf EUVE J0317-855 shows a field of 185 MG with a likely 425 MG magnetic spot (Burleigh et al., 1999; Vennes et al., 2003). WD 1953-011 also shows a complex field structure (Maxted et al., 2000; Valyavin et al., 2008) as it rotates with a period of 1.4418 days (Brinkworth et al., 2005).

White dwarfs with hydrogen-rich atmospheres become convective below $T_{\rm eff} \sim 15\,000$ K. Helium-rich atmospheres develop convection zones at much higher temperatures $T_{\rm eff} \lesssim 30\,000$ K. Valyavin et al. (2014) proposed that convection is suppressed in magnetic white dwarfs and slows down the white dwarf cooling rate. Using radiative magnetohydrodynamic simulations Tremblay et al. (2015) confirmed that convection is indeed suppressed, but that the cooling rate is not affected until the convective zone couples with the degenerate core which occurs around 5500 K. Observationally, Gentile Fusillo et al. (2018) fitted far ultraviolet (UV) spectra as well as optical Balmer line spectra of magnetic and non-magnetic white dwarfs with temperatures ranging from 9000 to 10 000 K. They used models with convection and without convection and found that for the magnetic white dwarf WD 2105-820 they could only produce consistent results between the best fitting UV and optical data using radiative models.

4. Origin of magnetic fields in white dwarfs

Magnetic fields in white dwarfs have often been assumed to be fossil fields, and that the progenitors of magnetic white dwarfs are predominantly magnetic Ap and Bp stars. Assuming magnetic flux conservation, the field strengths observed in Ap/Bp stars would correspond to white dwarf fields in excess of 10 MG (Kawka & Vennes, 2004; Wickramasinghe & Ferrario, 2005). Therefore, the progenitors of white dwarfs with weak magnetic fields may be other main-sequence stars that have magnetic fields well below current detection limits.

The fossil field theory implies that magnetic white dwarfs should be found in equal proportion in binary systems with main-sequence stars. However, this does not appear to be the case. Extensive surveys, like those of the Sloan Digital Sky Survey (SDSS), have been unable to find any non-interacting magnetic white dwarf plus main-sequence pairs (Liebert et al., 2015), thus leaving magnetic cataclysmic variables without direct progenitors. Therefore, other mechanisms for producing magnetic fields in white dwarfs have been recently proposed.

Tout et al. (2008) proposed a binary origin where the magnetic field is formed via a dynamo created during a common envelope (CE) phase. In systems that merge during the CE phase, single magnetic white dwarfs are created, but failed mergers would result in binary systems with a secondary nearly filling its Roche lobe. Following up on this theory, Potter & Tout (2010) and Wickramasinghe et al. (2014) showed that a magnetic field can be generated by a dynamo created by differential rotation within the CE, with the strongest fields being created if the merged objects are differentially rotating near break-up. A variation on the merger scenario was proposed by Nordhaus et al. (2011) who proposed that during a CE phase a low-mass star will be tidally disrupted by its proto-white dwarf companion forming an accretion disk. This would generate a dynamo in the disk which is then transferred to the degenerate core via accretion. Magnetic fields can also be produced by the merger of two white dwarfs. García-Berro et al. (2012) have shown that the merger of two white dwarfs can generate a hot, convective and differentially rotating corona producing a dynamo and the resulting magnetic field.

Isern et al. (2017) proposed that magnetic fields with $B \lesssim 0.1$ MG may be produced by phase separation during the onset of crystallization in the white dwarf core. They show that as white dwarfs begin to crystallize at sufficiently low temperatures (~ 8000 K), phase separation of the main elements (in most cases O and C) occurs leading to an unstable, convective liquid mantle on top of a solid core. This produces a dynamo allowing the creation of a magnetic field.

Briggs et al. (2015) conducted a population synthesis of binary systems to investigate which type of system could result in a magnetic white dwarf. They found that the contribution from the double degenerate merger scenario is much smaller than the contribution from the CE merger. Both merger scenarios are able to explain the higher than average mass of magnetic white dwarfs. Once the field is established, the predicted magnetic field strengths should remain throughout the white dwarf life-time since the magnetic flux is not expected to decay significantly once the magnetic field is frozen into the white dwarf.

Evidence for the binary origin of magnetic fields in white dwarfs can be found in a few double degenerate systems. The fast rotating magnetic white dwarf EUVE J0317-855 is in a common proper motion (CPM) binary with LP9802 (Külebi et al., 2010) and has $B \approx 450$ MG magnetic spot with an underlying lower field of $B \approx 185$ MG (Ferrario et al., 1997; Vennes et al., 2003). The cooling age of EUVE J0317-855 which is also the more massive white dwarf in the system is much shorter than that of its CPM companion LP9802 and therefore EUVE J0317-855 is the result of a merger. The CPM binary PG1258+593 plus SDSS J1300+5904 have similar masses, however SDSS J1300+5904 is much cooler (Girven et al., 2010) resulting in an age discrepancy and therefore implying that PG1258+593 is the product of a merger.

Only a few magnetic plus non-magnetic double degenerate systems are known (for a list see Kawka et al., 2017). In some cases, the magnetic white dwarf is hotter and hence younger than its non-magnetic companion, despite being the more massive component. Failed merger may also deliver double degenerate systems with a magnetic component. A magnetic field can be created during the CE without the stars merging. This is the case of the close double degenerate system NLTT 12758 which contains a magnetic white dwarf. The field in the magnetic white dwarf was probably not formed during the merger of two stars, but would have formed in the second CE phase where the differential rotation was greater (Kawka et al., 2017).

5. Summary

The growing sample of known magnetic white dwarfs is revealing a diversity in the properties of magnetic fields. The incidence of magnetism appears to vary between various classes of white dwarfs. This suggests that magnetic fields in white dwarfs are created by several discernible processes.

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