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Magnetic White Dwarfs

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Abstract In this paper we review the current status of research on the observational and theoretical characteristics of isolated and binary magnetic white dwarfs (MWDs).

Magnetic fields of isolated MWDs are observed to lie in the range $10^3 - 10^9$ G. While the upper limit cutoff near 10^9 G appears to be real, the lower limit is more difficult to investigate. The incidence of magnetism below a few 10^3 G still needs to be established by sensitive spectropolarimetric surveys conducted on 8 m class telescopes.

Highly magnetic WDs tend to exhibit a complex and non-dipolar field structure with some objects showing the presence of higher order multipoles. There is no evidence that fields of highly magnetic WDs decay over time, which is consistent with the estimated Ohmic decay times scales of $\sim 10^{11}$ yrs. The slow rotation periods ($\sim$ 100 yrs) inferred for a large number of isolated MWDs in comparison to those of non-magnetic WDs (a few days) suggest that strong magnetic fields augment the braking of the stellar core.

MWDs, as a class, also appear to be more massive ($0.784 \pm 0.047\,\mathrm{M}_\odot$) than their weakly or non-magnetic counterparts ($0.663 \pm 0.136\,\mathrm{M}_\odot$).

MWDs are also found in binary systems where they accrete matter from a low-mass donor star. These binaries, called magnetic Cataclysmic Variables (MCVs) and comprise about 20-25% of all known CVs. Zeeman and cyclotron

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spectroscopy of MCVs have revealed the presence of fields in the range $\sim 7-230\,\mathrm{MG}$. Complex field geometries have been inferred in the high field MCVs (the polars) whilst magnetic field strength and structure in the lower field group (intermediate polars, IPs) are much harder to establish.

The MCVs exhibit an orbital period distribution which is similar to that of non magnetic CVs. Polars dominate the distribution at orbital periods $\lesssim 4\,\mathrm{h}$ and IPs at longer periods. It has been argued that IPs above the $2-3\,\mathrm{hr}$ CV period gap with magnetic moments $\gtrsim 5\times10^{33}\,\mathrm{G\,cm^3}$ may eventually evolve into polars. It is vital to enlarge the still incomplete sample of MCVs to understand not only their accretion processes but also their evolution.

The origin of fields in MWDs is still being debated. While the fossil field hypothesis remains an attractive possibility, field generation within the common envelope of a binary system has been gaining momentum, since it would explain the absence of MWDs paired with non-degenerate companions and also the lack of relatively wide pre-MCVs.

Keywords Magnetic fields · Magnetic white dwarfs · Magnetic Cataclysmic Variables · Binary systems

1 Introduction

The Sloan Digital Sky Survey (SDSS, York et al. 2000) has increased the number of known MWDs with fields B in the range $2-1\,000\,\mathrm{MG}$ from fewer than 70, as listed in Wickramasinghe and Ferrario (2000) to over 600 in 2015 (see Gänsicke et al. 2002; Schmidt et al. 2003; Vanlandingham et al. 2005; Külebi et al. 2009; Kepler et al. 2013, 2015, and this work). However, their space density estimates are still debated. Volume-limited samples suggest that $\sim 10-20\%$ of WDs are magnetic (Kawka et al. 2007; Giammichele et al. 2012; Sion et al. 2014), whereas magnitude-limited samples indicate that only $\sim 2-5\%$ are magnetic (Liebert et al. 2003; Kepler et al. 2013, 2015). This discrepancy may be partly resolved by correcting for the difference in search volume for the MWDs, since, on average, they are more massive than their non-magnetic counterparts (see Sect. 4 and Liebert et al. 2003).

A spectropolarimetric survey of a small sample of cool ($\lesssim$14,000 K) WDs conducted by Landstreet et al. (2012) found that the probability of detecting a kG field in DA[1] WDs is $\sim 10\%$ per decade of field strength but also stress the inability of current precision measures to reveal whether there is a lower cutoff to the field strengths in WDs or there is a field below which all WDs are magnetic.

Furthermore, there seems to be a paucity of young MWDs in the intermediate field range ($0.1-1\,\mathrm{MG}$, see Kawka and Vennes 2012). The reason for this dearth of objects is not clear since they should be easily detected in most spectropolarimetric surveys such as that conducted by Aznar Cuadrado et al. (2004).

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[1] DA type WDs have a hydrogen rich atmosphere.

The ESO SNIa Progenitor Survey (SPY) also pointed to a peculiarly low percentage of MWDs in the field range $0.1-1\,\mathrm{MG}$ (Koester et al. 2001). Therefore, the magnetic field distribution of WDs could be bimodal exhibiting a high field ($1-1,000\,\mathrm{MG}$) population and a low field ($< 0.1\,\mathrm{MG}$) one. Intensive searches for magnetic fields in the direct progenitors of MWDs have so far drawn a blank, both among planetary nebulae (Asensio Ramos et al. 2014; Leone et al. 2014), and hot subdwarfs (Mathys et al. 2012; Savanov et al. 2013).

MWDs can also be found in CVs, which are close binary systems where a WD accretes matter from a late-type main sequence companion through Roche-lobe overflow. Orbital periods are less than a day and orbital separations of the order of the solar radius making these binaries relatively compact. Because of their abundance[2] and proximity, CVs are key objects to understand close binary evolution. In particular, those hosting a strongly magnetic WD ($B \gtrsim 1\,\mathrm{MG}$) allow us to study accretion and emission processes in a strong magnetic field environment as well as improving our understanding of the influence of magnetic fields in close binary evolution.

The number of known MCVs has also increased dramatically over the years from about 60 as listed in Wickramasinghe and Ferrario (2000) to about 170. Magnetic field measures are however available only for about half of them most of which in the range $\sim 7-230\,\mathrm{MG}$.

Here we review the current status of research on MCVs and MWDs and outline key aspects and open problems to be investigated in the future. Previous reviews on the topic can be found in Angel (1978); Angel et al. (1981); Cropper (1990); Chanmugam (1992); Patterson (1994); Wickramasinghe and Ferrario (2000).

2 Historical background

2.1 Isolated Magnetic white dwarfs

Grw+70°8247, discovered by Kuiper (1934), was the first WD to be classified as magnetic when Kemp et al. (1970) demonstrated that its light was strongly circularly polarised. Although the spectrum of Grw+70°8247 appeared to be nearly featureless, close inspection by Minkowski (1938) and Greenstein and Matthews (1957) revealed the presence of unusual shallow broad absorption bands near 3,650Å, 4,135Åand 4,466Å, which became known as “Minkowski bands”. The spectral features of Grw+70°8247 remained unidentified till the mid-80s, when the first computations of the hydrogen transitions in strong magnetic fields became available (see Sect. 3.1). These calculations allowed the spectral features of Grw+70°8247 to be identified as Zeeman shifted hydrogen lines in a magnetic field of $100-320\,\mathrm{MG}$ (Angel et al. 1985; Greenstein et al. 1985; Wickramasinghe and Ferrario 1988a). In partic-

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[2] 1166 CVs are reported in the 7.20 (dec.2013) version of the Ritter and Kolb (2003) catalogue

ular, the famous Minkowski band near 4,135Å was shown to be a Zeeman component of Hβ shifted some 700Å from its zero field position.

Following the discovery of polarisation in Grw+70°8247, Angel and Landstreet (1971a) detected circular polarisation in another object, G195 − 19. Follow-up observations conducted by Angel and Landstreet (1971b) revealed that the circular polarisation in G195 − 19 varies at the spin period of the star under the assumption that the magnetic axis is inclined with respect to the spin axis of the WD (the 'oblique rotator' of Stibbs 1950). In both Grw+70°8247 and G195 − 19, some linear polarisation was also detected, although at a much lower level than circular polarisation. Since the observations showed that the polarisation data in G195 − 19 did not follow a sinusoidal behaviour, Landi Degl'Innocenti (1976) raised the possibility that magnetic spots were responsible for the observed asymmetries.

Landstreet and Angel (1971) soon discovered circular polarisation in a third WD, G99 − 37 and a few years later, polarisation was also detected in GD229 (Swedlund et al. 1974a). The spectral features of GD229 remained a mystery for more than 20 years until the calculations for He I transitions in a strong magnetic field became available (see Sect. 3.1). The absorption structures were thus interpreted as stationary line transitions of helium in a magnetic field of 300 − 700 MG (Jordan et al. 1998; Wickramasinghe et al. 2002).

The sample of known MWDs has rapidly increased since Kemp's first discovery in 1970. Over the past 40 years, thanks to surveys such as the Hamburg/ESO Quasar Survey (HQS Wisotzki et al. 1991), the Edinburgh-Cape survey (Kilkenny et al. 1991), and, as already noted, the SDSS, their number has grown to more than 600 (if we also count objects with uncertain or no field determination) thus providing a large enough sample to allow meaningful statistical studies of their characteristics (see Table 1).

2.2 Magnetic Cataclysmic Variables

Known as a Novalike since 1924, AM Her was the first CV discovered to emit soft X-rays by the *UHURU* and *SAS-3* satellites in 1976 (Hearn et al. 1976). Follow-up optical observations revealed variable linear (up to 7%) and circular (up to 9%) polarisation at the 3.09 h binary orbital period (Tapia 1977). Systems with similar characteristics were named AM Her-type variables. The name "polar" was introduced later for AM Her and other objects identified as X-ray sources that also showed polarised optical light (see Warner 1995).

The binary system DQ Her was discovered in the mid-50s to display a 71 s periodic variability (Walker 1956) and only about two decades later was also found to be weakly polarised (Swedlund et al. 1974b). In 1978, 33 s optical pulsations were detected in AE Aqr, but not in polarised light (Patterson 1979). In the following years, fast optical periodic variations at periods much shorter than the orbital one ($P_{\rm rot} << P_{\rm orb}$) were found in other CVs. These systems were first called DQ Her-type variables and then renamed "intermediate polars" (IPs) (Patterson and Steiner 1983; Patterson 1994; Warner 1995). This led to the division of MCVs into two groups, polars and IPs.

The properties of polarised radiation were first studied by Chanmugam and Dulk (1981) and Meggitt and Wickramasinghe (1982). The magnetic moment of the accreting WD in polars ($\mu \gtrsim 5 \times 10^{33}$ G cm^3) is sufficient to lock the stars into synchronous rotation with the orbital period ($P_{\rm orb} \sim 70 - 480$ mins). On the other hand, the magnetic moment of the WD in IPs is not high enough to phase-lock the stars into synchronous rotation with the orbit, resulting in WD spin periods $P_{\rm s}$ that are shorter than their orbital periods.

Because of their strong soft X-ray emission, the number of polars increased significantly thanks to soft X-ray surveys, and in particular that conducted in the nineties by the *ROSAT* satellite (Beuermann 1999). To date $\sim$110 systems of this class are known hosting WDs with surface field strengths B $\sim$7-230 MG (see Sect.3 and Table 2 for a complete list of known systems as of December 2014). The IPs constituted a minor group of harder X-ray sources and remained elusive objects until the recent hard X-ray surveys conducted by the *INTEGRAL*/IBIS and *Swift*/BAT satellites (Bird et al. 2010; Baumgartner et al. 2013). The flux limits ($\sim 10^{-11}$ erg cm^{-2} s^{-1}) of these surveys can detect sources up to 1 kpc away for X-ray luminosities $L_x \sim 10^{33}$ erg s^{-1}. IPs, being the brightest and hardest X-ray sources among CVs, account for $\sim$ 20% of the Galactic hard X-ray sources discovered (Barlow et al. 2006). Thus, the number of identified IPs has now increased to $\sim$ 55 systems (see Table 3 and reference therein and also Bernardini et al. 2012, 2013), with $\sim$60 candidates still awaiting confirmation through X-ray follow-ups with sensitive facilities such as XMM-Newton and NuSTAR. [3].

3 Magnetic field measures

In this section we shall review the techniques that are routinely adopted to determine the magnetic field strength of isolated MWDs and of accreting MWDs in binary systems.

3.1 Field determination in isolated magnetic white dwarfs

Similarly to their non-magnetic counterparts, most MWDs are hydrogen-rich (DA). They are classified as DAp or DAH, indicating the method used in their discovery. Thus, "p" stands for polarisation measurements and "H" for Zeeman splitting (see Sion et al. 1983, for more information on the WD spectral classification system). An understanding of their properties relies heavily on the theory of the hydrogen atom at strong magnetic fields.

Depending on field strength, different Zeeman regimes become relevant to the understanding of MWD spectra. If (n, l, m_l) are the quantum numbers

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[3] Further details on IP type CVs can be found at http://asd.gsfc.nasa.gov/Koji.Mukai/iphome/iphome.html

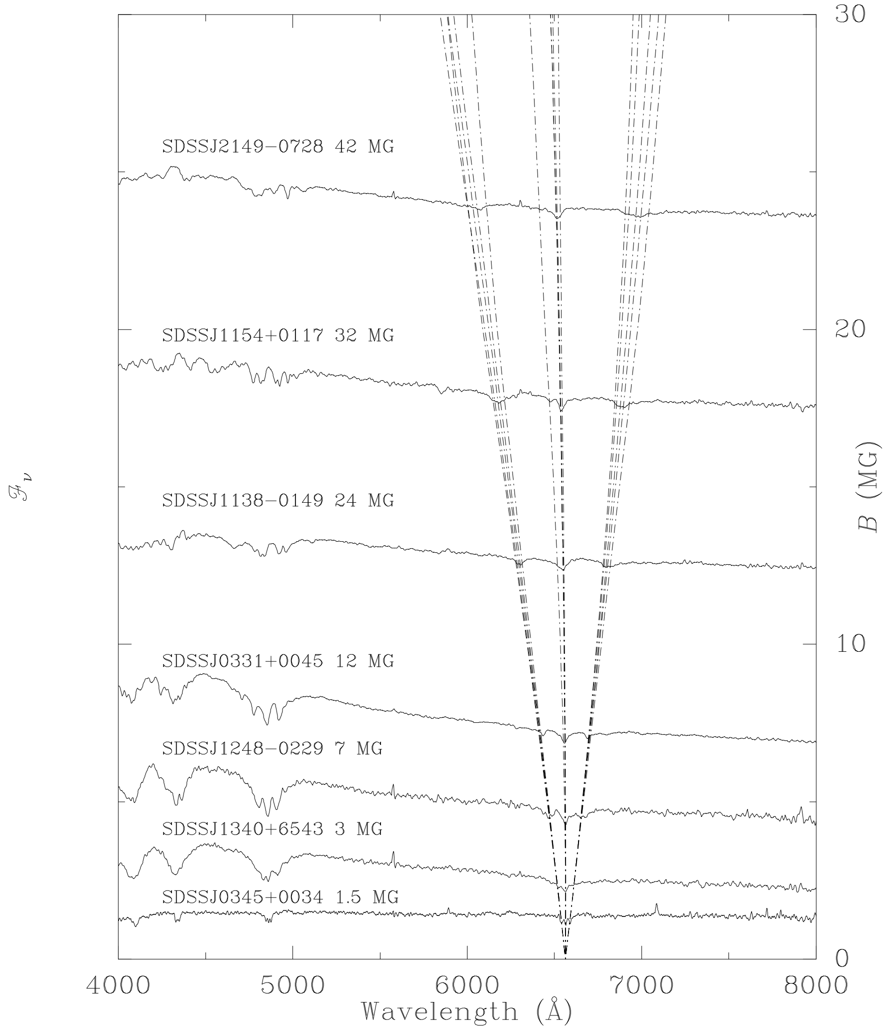


Fig. 1 The Zeeman effect on H_α in the linear and quadratic regimes for fields of $1.5 - 42\,\mathrm{MG}$). The quadratic effect becomes gradually more important in the higher members of the Balmer series and as the field strength increases (Schmidt et al. 2003)

corresponding to zero field, then the removal of the m_l degeneracy will give rise to the linear Zeeman regime ($\sim 1-5\,\mathrm{MG}$ for Balmer lines). Here the energy levels are shifted by $\frac{1}{2} m_l h \omega_C$, where $\omega_C = \dfrac{eB}{m_e c}$ is the cyclotron frequency of a free electron, m_e and e are the mass and charge of the electron respectively and c is the speed of light. A line is split into three components: an unshifted central π component ($\Delta m_l = 0$), a redshifted σ_+ ($\Delta m_l = +1$) component and a blueshifted σ_- ($\Delta m_l = -1$) component. Some Zeeman triplets observed in

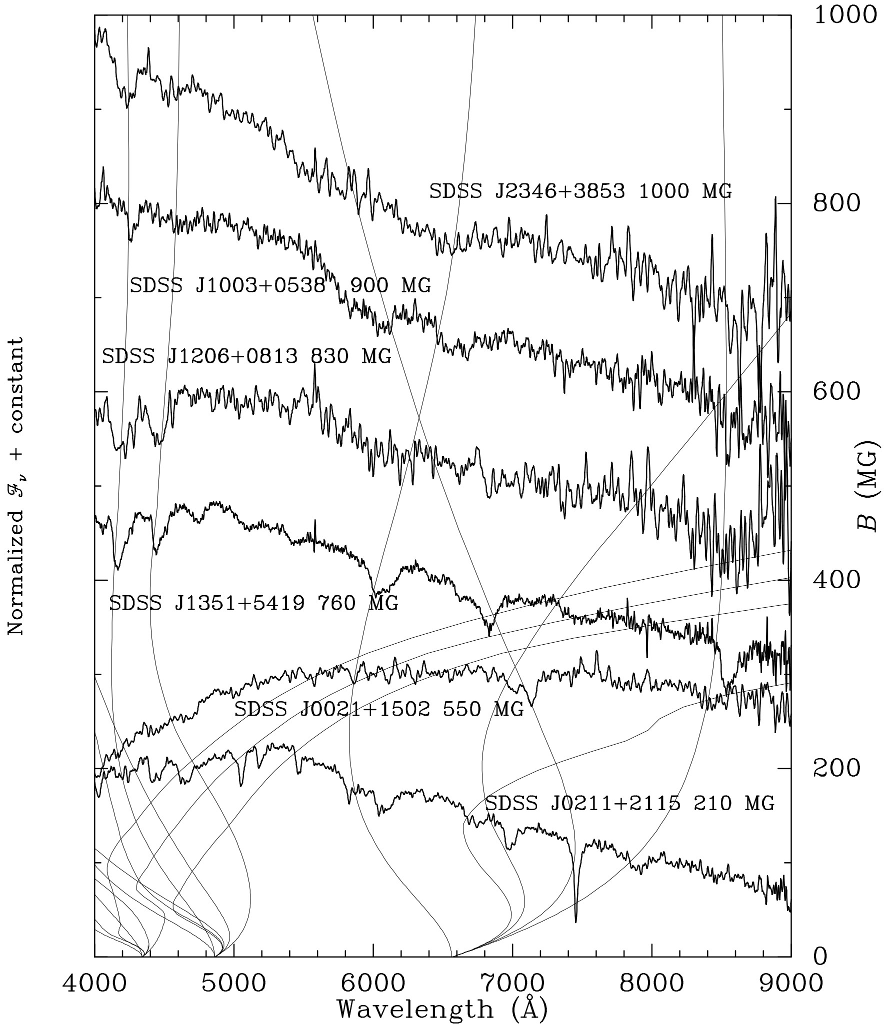


Fig. 2 Stationary Zeeman components of H_α and H_β (from Vanlandingham et al. 2005) in the spectra of strongly magnetic MWDs

MWDs are shown in Fig. 1 (Schmidt et al. 2003). Circular spectropolarimetry across lines can be effectively used to detect low fields ($B \lesssim 1\,\mathrm{MG}$) when Zeeman splits are unresolvable in the flux spectra. When viewed along the magnetic field, the σ_- and the σ_+ components are circularly polarised with opposite signs.

As the field strength increases and/or n increases, the quadratic effect becomes gradually more important and the l degeneracy is also removed (inter-l mixing regime). The energy shifts depend on the excitation of the electron and the π and σ components are shifted by different amounts from their zero field positions. The quadratic shift is comparable to the linear shift for, e.g. H_δ, at $B \sim 4\,\mathrm{MG}$ (see Fig. 1). The first Zeeman calculations in this intermediate field strength regime were conducted in 1974 by Kemic for fields up to $\sim 20\,\mathrm{MG}$.

As the field progressively increases, the Coulomb and magnetic field forces become comparable in strength and neighbouring n manifolds overlap (inter-n mixing regime). In the "strong field mixing regime" the magnetic field dominates (see Wickramasinghe and Ferrario 2000). The first published data of wavelengths and oscillator strengths of hydrogen transitions in the infrared to ultraviolet bands in the presence of very strong magnetic fields (up to $10^6\,\mathrm{MG}$) were published in the mid 80s by Roesner et al. (1984); Forster et al. (1984); Henry and O'Connell (1984, 1985); Wunner et al. (1985), and more recently by Schimeczek and Wunner (2014).

An important characteristic which is clearly visible in the field against wavelength curves diagrams is that the σ^+ components become nearly 'stationary'. That is, appreciable changes in B only yield small changes in wavelength. This is very useful in establishing the field of MWDs, since the features corresponding to these turning points will have the smallest amount of magnetic broadening and will have the largest influence on the observed field averaged spectrum. We display in Fig. 2 some spectra of strongly magnetic WDs showing the presence of stationary components (Vanlandingham et al. 2005).

Another interesting effect in the presence of strong magnetic fields ($\gtrsim 100\,\mathrm{MG}$) and local electric fields in highly ionised plasmas, is an increase of the oscillator strength of the "forbidden" $1s_0 \to 2s_0$ component at the expense of the π $(1s_0 \to 2p_0)$ component. This was first detected in *HST* observations of RE J0317–853 (Burleigh et al. 1999), and later seen in the MCV AR UMa (Gänsicke et al. 2001; Schmidt et al. 1996).

3.1.1 Magnetic field evolution in isolated magnetic white dwarfs

There is no evidence for field evolution along the cooling curve, that is, the mean field strength and the distribution about this mean appear to be independent of effective temperature (see Fig. 3, this work). The Pearson Product Moment Correlation test gives a correlation coefficient $r = 0.03$, which indicates that these variables are not related.

The free Ohmic decay time can be estimated from

$$t_{\mathrm{ohm}} \sim \frac{4\pi\sigma L^2}{c^2}$$

where L is the length scale over which the magnetic field varies and σ is the electrical conductivity. If we set $L \sim R$ (where R is the stellar radius) and σ equal to the value expected in the degenerate cores of WDs then we have $t_{\mathrm{ohm}} \sim 2 - 6 \times 10^{11}\,\mathrm{yr}$ almost independently of mass (Cumming 2002). The lack of evidence for correlation between magnetic field strength and effective temperature is consistent with these long decay time scales.

We note that Kawka and Vennes (2012) find that the distribution of field strengths below 1 MG versus cooling ages may show some selections effects (see

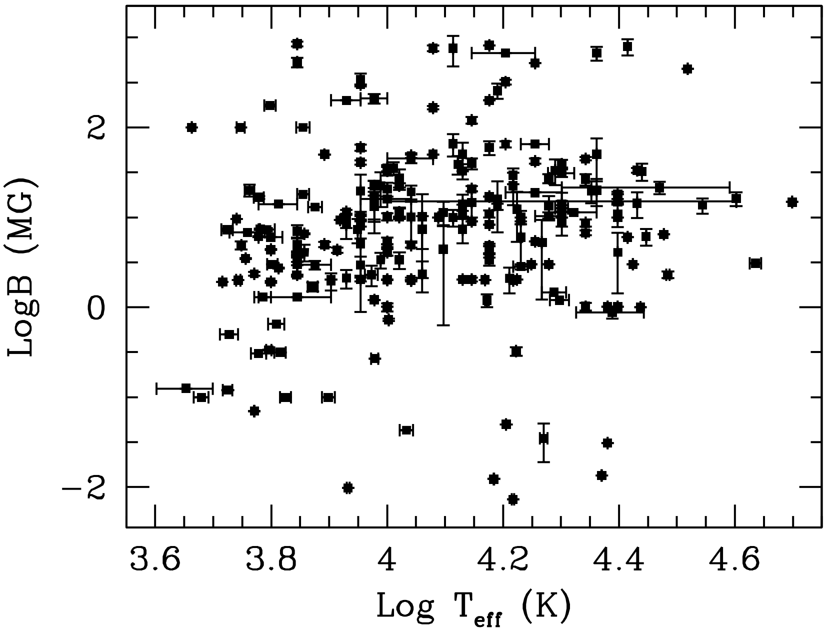


Fig. 3 Magnetic field strength against effective temperature in MWDs showing no indication for field evolution with cooling age (this work)

their Fig. 10). That is, objects with fields $\lesssim 50\,$kG appear to be younger (that is hotter) than those with field $\gtrsim 50\,$kG. We have calculated a correlation coefficient $r = -0.192$ for objects with $B \lesssim 1\,$MG, indicating that this effect does exist also in our sample of weakly magnetic WDs listed in Table 1 (see Fig. 4). This trend could be caused by the fact that cool WDs ($\lesssim$ 7000 K) do not have narrow and deep lines in their spectra that are good magnetic field tracers unless heavy element lines are present (Kawka and Vennes 2012). Another possibility is that the estimation of parameters such as effective temperature and gravity using models for non-magnetic WDs *may* introduce biases even in the presence of very low fields. However, the latter possibility is more difficult to ascertain at the present time. A possible explanation for why this effect is not apparent if we take all MWDs could be because their temperatures are estimated using a wide range of methods so that biases cancel each other out.

Finally, we can state that the claim originally made by Liebert and Sion (1979) and supported by Fabrika and Valyavin (1999) that there is a higher incidence of magnetism among cool WDs than among hot WDs does not appear to be corroborated by the present enlarged sample of MWDs. We show in Fig. 5 the cumulative distribution function of the effective temperatures of the observed sample MWDs (see Table 1). We note that this function is smooth over the entire range of effective temperatures $T_{\rm eff} = 4{,}000 - 45{,}000\,$K thus

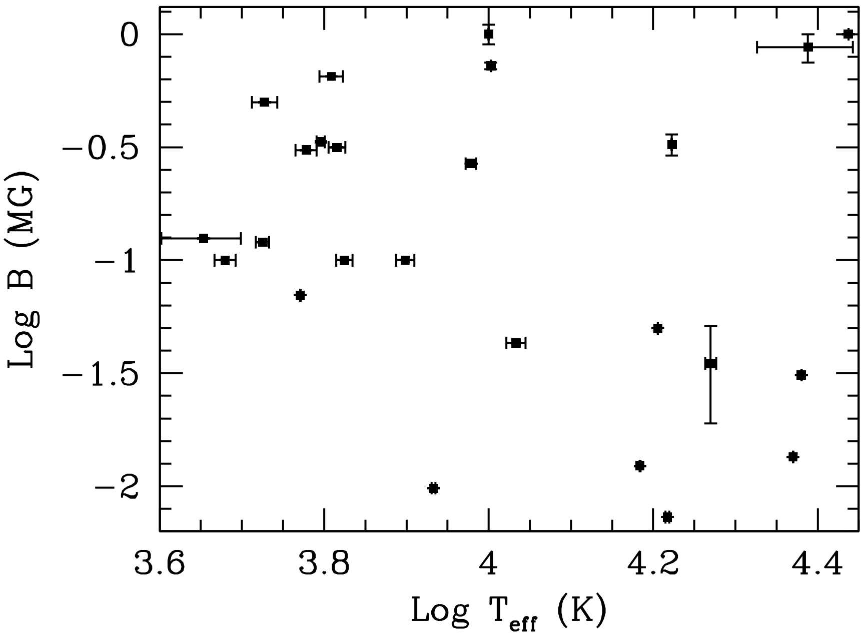


Fig. 4 Magnetic field strength against effective temperature in MWDs with $B \lesssim 1\,\mathrm{MG}$ showing some correlation between field and temperature (this work)

indicating that the birthrate of MWDs has not significantly changed over the age of the Galactic disk.

3.2 Field determination of white dwarfs in binary systems

Direct measurements of the WD magnetic field strength in the high field magnetic CVs, the polars, can be obtained either (i) through Zeeman splitting of the photospheric hydrogen absorptions lines when these systems enter low accretion states (as described in Sect. 3.1) or (ii) through the modelling of cyclotron emission features that characterise the optical to IR spectra during intermediate and high accretion states (see Wickramasinghe and Ferrario 2000) or (iii) via the study of Zeeman features arising from the halo of matter surrounding the accretion shock.

When accreting at low rates, polars reveal the WD photosphere and thus can allow the detection of the Zeeman σ_+, σ_- and π components of Balmer line absorptions. Thus some polars have their field determined through Zeeman spectroscopy of photospheric lines in the optical wavelength range (Wickramasinghe and Martin 1985; Ferrario et al. 1992; Schwope et al. 1995). The highest magnetised polars, AR UMa (230 MG, Schmidt et al. 1996) and AP CrB (144 MG, Gänsicke et al.

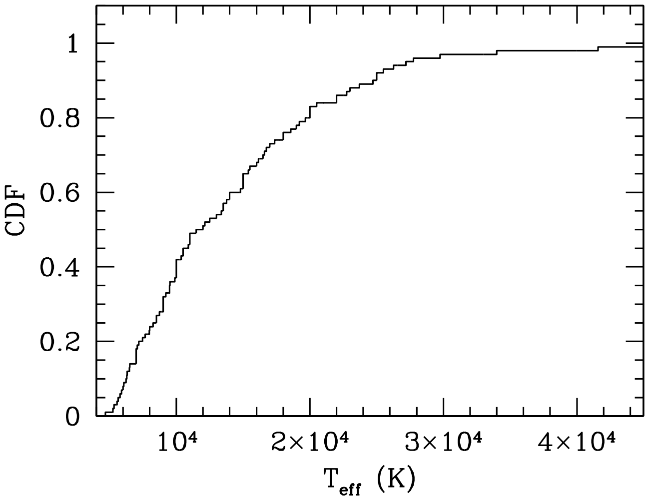


Fig. 5 Cumulative distribution function of MWD effective temperatures. The observed distribution is smooth implying that the birthrate of MWDs has not changed over time (this work)

2004), were instead detected through Zeeman split absorption features in the UV range. We show in Fig. 6 an ultraviolet spectrum of AR UMa covering the range 917–1,182 Å when the system was in its typical low-accretion state. The spectral absorption features are caused by Lyα–Lyγ Zeeman transitions. The modelling indicates a dipolar field strength of about 235 MG offset along its axis by a 0.15 of the stellar radius (Hoard et al. 2004).

The optical to IR spectra of polars may also reveal the typical undulation of cyclotron humps. At low temperatures, the position of the $n^{\rm th}$ harmonic for a magnetic field B and viewing angle near 90° can be estimated using

$$\lambda_{\rm n} = \frac{10\,710}{n}\left(\frac{10^8{\rm G}}{B}\right)\,\text{Å}.$$

Cyclotron lines in polars are only seen when the shocks are viewed at large angles θ to the field direction. The intensity is at its maximum at the fundamental and rapidly decreases as n increases, with the rate of decline depending on temperature.

We show in Fig. 7 a number of theoretical cyclotron emission spectra. These have been obtained using the Wickramasinghe and Meggitt (1985) constant Λ (or "point source") models which assume uniform conditions in the shock but allow for optical depth effects. The parameters of these models have been chosen to yield the characteristic cyclotron undulation in the optical band.

At long wavelengths these spectra display an optically thick Rayleigh-Jeans tail while at shorter wavelengths they are characterised by a power law spectrum modulated by cyclotron lines. The flat-topped profiles of the harmonic

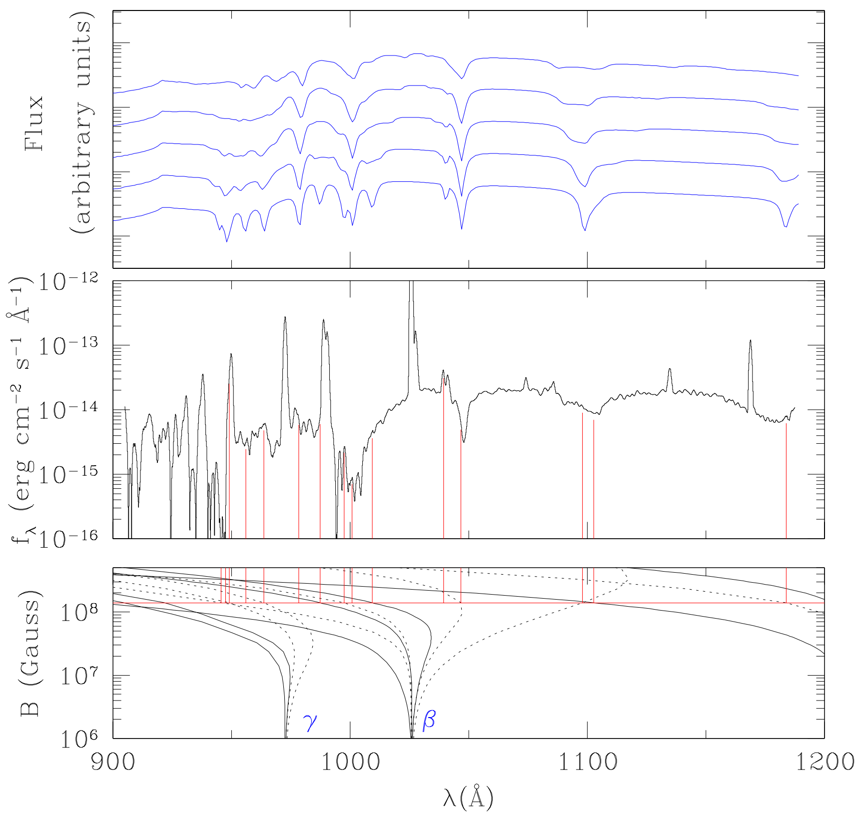


Fig. 6 FUSE spectrum of the high field MCV AR UMa (middle panel) compared with hydrogen Lyman transitions for $1\mathrm{MG} \leq B \leq 500\,\mathrm{MG}$ (bottom panel) and with photospheric model spectra (top panel). The model correspond (from top to bottom) to dipole field strengths and fractional offsets of 200 MG, 0.0; 215 MG, 0.10; 235 MG, 0.15; 260 MG, 0.20; and 280 MG, 0.25. Negative offsets imply that we view the weaker field hemisphere, where the field distribution is more uniform. Dashed lines represent normally forbidden components that are enabled by the strong electric fields present in highly magnetic WDs (Hoard et al. 2004)

peaks at low harmonic numbers implies optically thick emission. As the harmonic number increases the opacity drops and the shock becomes optically thin so that the harmonic structure becomes clearly visible. The switch from optically thin to thick emission is a strong function of the optical depth parameter $\mathit{\Lambda}$

$$\mathit{\Lambda} = 2.01 \times 10^6 \left(\frac{s}{10^6\mathrm{cm}}\right) \left(\frac{N_\mathrm{e}}{10^{16}\mathrm{cm}^{-3}}\right) \left(\frac{3 \times 10^7\mathrm{G}}{B}\right)$$

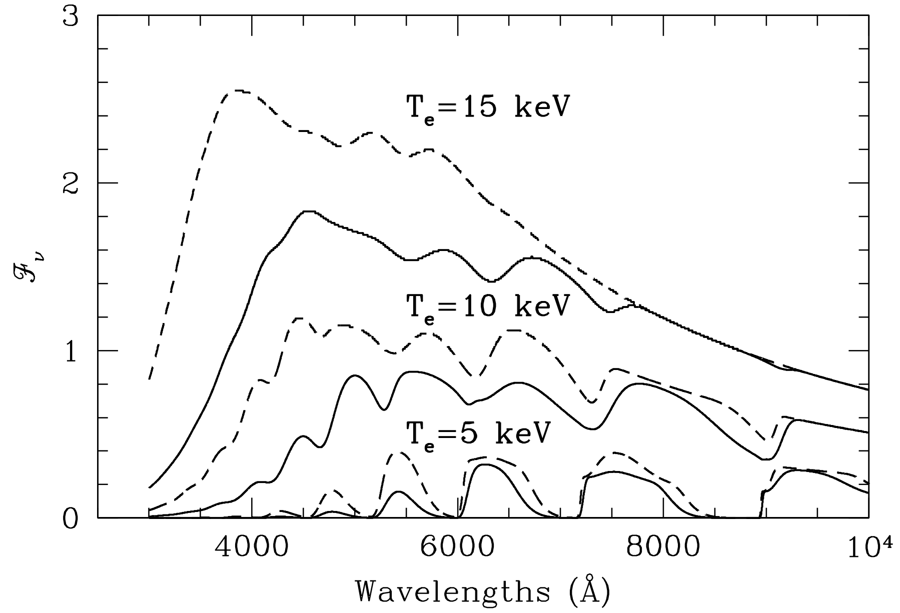


Fig. 7 Theoretical cyclotron spectra for a field $B = 30$ MG as a function of electron temperature T_e for a viewing angle $\theta = 90°$. The solid and dashed curves are for optical depth parameters $\Lambda = 2\times10^5$ and $\Lambda = 10^6$ respectively (from Wickramasinghe and Ferrario 2000)

where s is a characteristic path length through the post-shock region and N_e is the electron density number. The parameter Λ is approximately equal to the optical depth at the cyclotron fundamental at a viewing angle $\theta = 90°$ to the field direction. Cyclotron emission in MCVs has been observed at infrared wavelengths (eg Bailey et al. 1991; Ferrario et al. 1993, 1996; Campbell et al. 2008b,a), optical (eg Visvanathan and Wickramasinghe 1979; Wickramasinghe et al. 1989; Ferrario et al. 1994; Schwope and Beuermann 1990a; Schwope et al. 1995), and in a few systems with the highest field strengths also at ultraviolet wavelengths (eg Rosen et al. 2001; Gänsicke et al. 2001; Ferrario et al. 2003).

The values of Λ inferred from the modelling of cyclotron emission ($\sim 10^5-10^6$) are much lower than those expected for a bremsstrahlung-dominated shock ($\sim 10^8-10^9$, e.g., Lamb and Masters 1979; Chanmugam and Dulk 1981), thus indicating that the cyclotron radiation mainly comes from strongly cyclotron cooled shock regions characterised by low specific accretion rates.

The lack of harmonic features seen in the intensity spectra of most polars also supports the hypothesis that the emission regions of these systems are extended and structured. This flat energy distribution has been attributed to magnetic field spread and to the optical depth parameter varying across a wide region characterised by different specific mass flow rates. More realistic models that take into consideration the effects of extension and temperature and density distribution across the emission region were constructed by, e.g.,

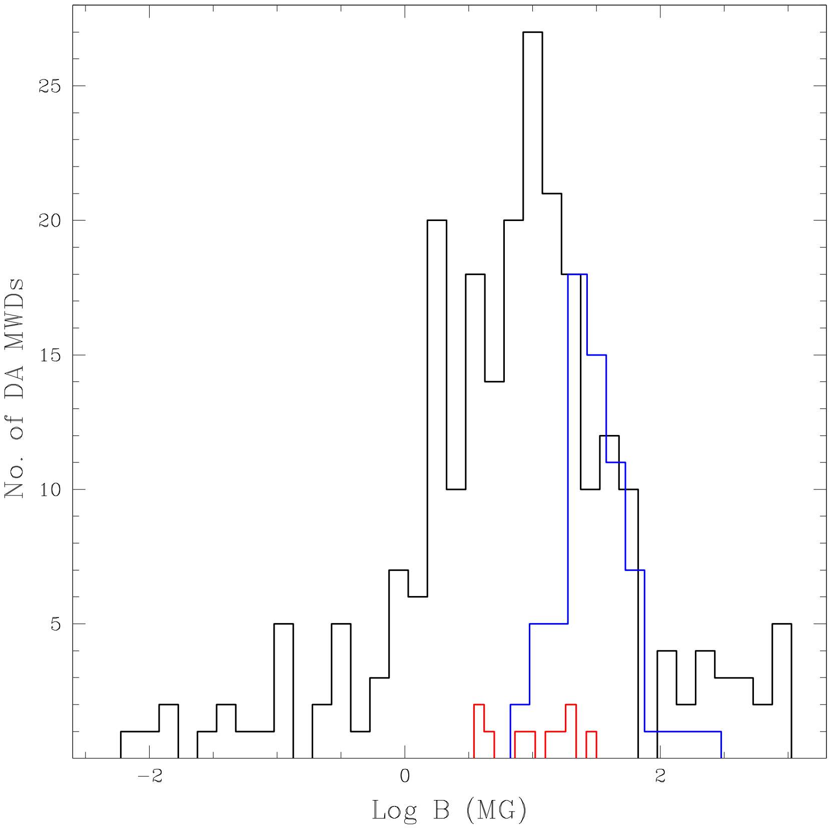


Fig. 8 Distributions of magnetic field strength in polars (Blue line) and IPs (red line) compared to that of single magnetic WDs (black line). This figure has been prepared using the data in Tables 1, 2, and 3 (this work)

Wickramasinghe and Ferrario (1988b); Ferrario and Wickramasinghe (1990); Rousseau et al. (1996).

Through the careful fitting of cyclotron harmonic features it is possible to determine the magnetic field strength and physical parameters of the post-shock region (see Wickramasinghe and Ferrario 2000, and references therein). Many polars have measured field strengths through time-resolved cyclotron spectroscopy. Information on the accretion geometry can also be gained through the study of harmonics that shift with orbital phase due to different parts of the accretion region becoming visible as the WD rotates (e.g. Schwope and Beuermann 1990b; Burwitz et al. 1996b). The cyclotron study of the phase resolved spectra of eclipsing systems such as the bright polar HU Aquarii by Schwope et al. (2003) has proven to be particularly important to establish the accretion geometry of these objects.

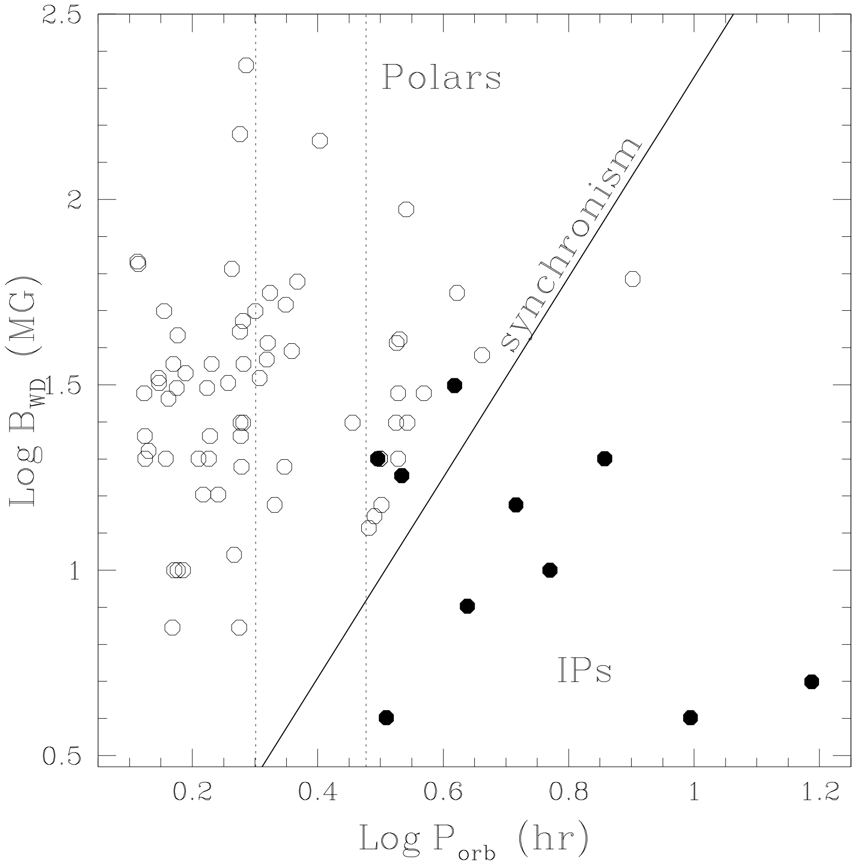


Fig. 9 The magnetic field strength and orbital period diagram for polars (empty circles) and IPs (filled circles). The line at which synchronism is expected for a mean mass accretion rate as a function of $P_{\rm orb}$ is reported as a solid line (adapted from Beuermann 1999). The dotted vertical lines mark the orbital period gap

In many cases two independent sets of cyclotron lines arising from regions with different magnetic field strengths have been found, with the main accreting pole possessing a weaker field (Ferrario et al. 1993; Schwope et al. 1995; Schwope 1996; Ferrario et al. 1996; Campbell et al. 2008b). These studies indicate that the magnetic field distribution is not that of a centred dipole and offsets as high as 10-20% are often inferred (Wickramasinghe and Ferrario 2000). Evidence of non-centred dipole field distribution also comes from Zeeman components which are seen against strong cyclotron emission and are formed in the free fall material surrounding the WD pole, often named "halo" (Achilleos et al. 1992a; Schwope et al. 1995). The study of all these different components have shown that the field strength obtained from the modelling of photospheric Zeeman lines, $B_{\rm Zeem,phot}$, is different from the field strength obtained from the study of halo Zeeman features, $B_{\rm Zeem,halo}$, with the latter comparable to the field strength $B_{\rm cyc}$ obtained through the modelling of cyclotron humps. This is because the field strength measured from photospheric Zeeman split lines is averaged over the entire visible hemisphere of the WD while the fields derived from cyclotron modelling or from the study of halo Zeeman features arise from regions close to the visible accreting pole.

From time–resolved polarimetry (e.g. Potter et al. 2004) and spectropolarimetry (e.g. Beuermann et al. 2007) detailed information on the complexity (quadrupole or even multipoles) of magnetic field topology in these systems can be obtained (see also Sect. 3.3). However, in systems with ages $\gtrsim 1\,$Gyr a substantial decay of multipole components could be expected and thus short period MCVs may not have complex fields (Beuermann et al. 2007). Magnetic field strengths have been measured or estimated for ~ 86 WDs in binaries (see Tables 2 and 3 for a complete list of known systems as of December 2014). Using the main pole magnetic field strength, Fig. 8 depicts the magnetic field distribution of polars compared to that of single MWDs listed in Table 1 with the latter having fields in the range $0.1-1,000\,$MG. The polars clearly populate a more restricted range of field strengths, $7-230\,$MG, with a mean value of 38 MG.

Fields strengths above 230 MG, which are detected in single magnetic WDs, are not found in polars and there is no clear explanation for this yet. High magnetic field polars could be difficult to identify due to selection effects because these systems would be highly intermittent soft X-ray sources such as AR UMa. Hameury et al. (1989) explained the paucity of very high field polars in terms of their very short lifetimes due to efficient loss of angular momentum via magnetic braking mechanism. However, it appears more likely that the strong fields in polars may *decrease* the efficiency of magnetic braking, which would result in a slower evolution of their orbital periods and in lower accretion luminosities (Li and Wickramasinghe 1998; Webbink and Wickramasinghe 2002; Araujo-Betancor et al. 2005a). On the other hand, if the magnetic field is generated during the CE phase, then the highest fields could only be produced when the two stars merge to give rise to an isolated MWD (see Sect. 6 and the chapter on the origin of magnetic fields in this book).

The lowest surface averaged magnetic field strength measured in a polar is 7 MG in V2301 Oph which was modelled by Ferrario et al. (1995) with a dipolar field of 12 MG offset by 20% from the centre of the WD. The lack of lower field synchronous systems could be explained if the asynchronous IPs represent the low field tail of the magnetic field strength distribution in MCVs. However this is difficult to prove, because the absence of low accretion states in IPs prevents the WD photosphere to become visible, thus precluding the detection of photospheric Zeeman split lines. Most of these systems do not show polarised optical/IR emission or cyclotron features, which also prevents the determination of the WD magnetic field. Whether the lack of polarisation in the optical/IR is caused by weaker magnetic fields or is due to efficient depolarisation mechanisms is difficult to ascertain. So far only ten IPs are known to be circularly polarised at a level $\lesssim 1-3\%$ (Penning et al. 1986;

Piirola et al. 1993; Buckley et al. 1995; Potter et al. 1997; Katajainen et al. 2007; Piirola et al. 2008; Butters et al. 2009; Potter et al. 2012). In these IPs, the field strengths are estimated to be in the range $\sim 5-20\,\mathrm{MG}$, with V405 Aur (Piirola et al. 2008) possessing the highest ($\sim$30 MG) field (see Table 3). Seven are also found to show a soft X-ray blackbody component. The fields of these IPs, shown in Fig. 8, are at the low-field end of the distribution and partially overlap with the low field polars. Their orbital periods are all above the CV period gap (see Fig. 9) and, given the large uncertainties in the estimates, they are below or close to the line at which synchronism is expected to occur (see Fig. 9 Beuermann 1999). These systems could in fact be the progenitors of the low-field polars, as suggested by Norton et al. (2004). As the number of polarised IPs has increased by a factor of three in the last few years, further deep polarimetric and spectropolarimetric surveys of all known IPs are crucial to establish their field strengths and accretion properties.

3.3 Field topology

When discussing the magnetic field strength in isolated MWDs, some attention has to be given to the definition of B, as the field strength measured from observations is usually an average value over the visible hemisphere of the WD. In the absence of any other information, it is common practice to assume a dipolar field configuration, in which case the field varies by a factor two between the magnetic pole and the equator. When averaging over the visible hemisphere, the relative weighting of regions with different fields strengths depends on the angle between the observer's line of sight and the magnetic field axis (see. Fig. 2 of Achilleos et al. 1992b).

However, detailed spectroscopy and spectropolarimetry have demonstrated in a number of cases that the field topologies can be very complex (e.g. Putney and Jordan 1995). Several sophisticated tomographic reconstruction methods have been developed to map the field topology (Donati et al. 1994; Euchner et al. 2002). The application of these methods to both single MWDs (Euchner et al. 2005b, 2006) and MWDs in polars (Beuermann et al. 2007) reveals a startling complexity of the field topologies (Fig. 10).

3.4 Beyond hydrogen

The bulk of all WDs have hydrogen-dominated atmospheres, both in magnitude-limited (Kleinman et al. 2013) and volume-limited samples (Giammichele et al. 2012), and the same is true for MWDs.

At temperatures above $\sim 10,000\,\mathrm{K}$, MWDs can also exhibit Zeeman split HeI lines in their spectra (DBp WDs). The two electron problem is much more difficult to treat and calculations for $n \leq 5$ singlet and triplet states for $m = 0, \pm 1, \pm 2, \pm 3$ only became available in the late 90s (Jordan et al. 1998; Jones et al. 1999; Becken et al. 1999; Becken and Schmelcher 2000b,a, 2001;

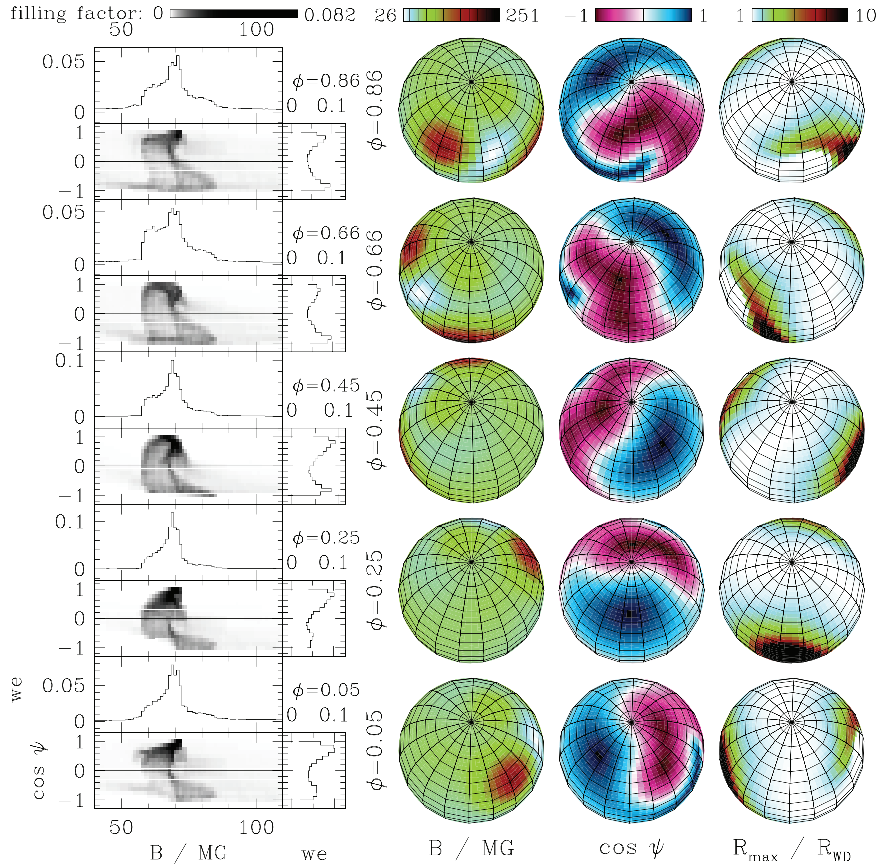


Fig. 10 Field topology of the MWD PG 1015+014, derived from a tomographic analysis of time-resolved spectropolarimetry (Euchner et al. 2005b). Fields in the range 50–80 MG are detected (left panel) with a highly non-dipolar configuration (middle panels: surface field and angle between the line-of-sight and the magnetic field direction). The maximum radial distance reached by field lines in units of the WD radius is shown in the right-most panel

Al-Hujaj and Schmelcher 2003). We show in Fig. 11 a comparison between centred dipole models and observations for three helium-rich MWDs.

Cool helium-dominated atmospheres develop deep convection zones that may dredge-up core material into the photosphere, resulting in atomic or molecular carbon features. The maximum carbon contamination in these DQ WDs is expected around ≃ 12 000 K. A number of very cool DQs show broad absorption troughs reminiscent of C_2 Swan bands, without however matching the laboratory wavelengths of the Swan bands. Spectropolarimetry has revealed magnetism in some of these DQp stars (see Fig. 12; Liebert et al. 1978; Schmidt et al. 1999b), with suggested (but rather uncertain) field strengths of ∼ 100 MG. However, not all DQp WDs show polarisation, and the nature of the

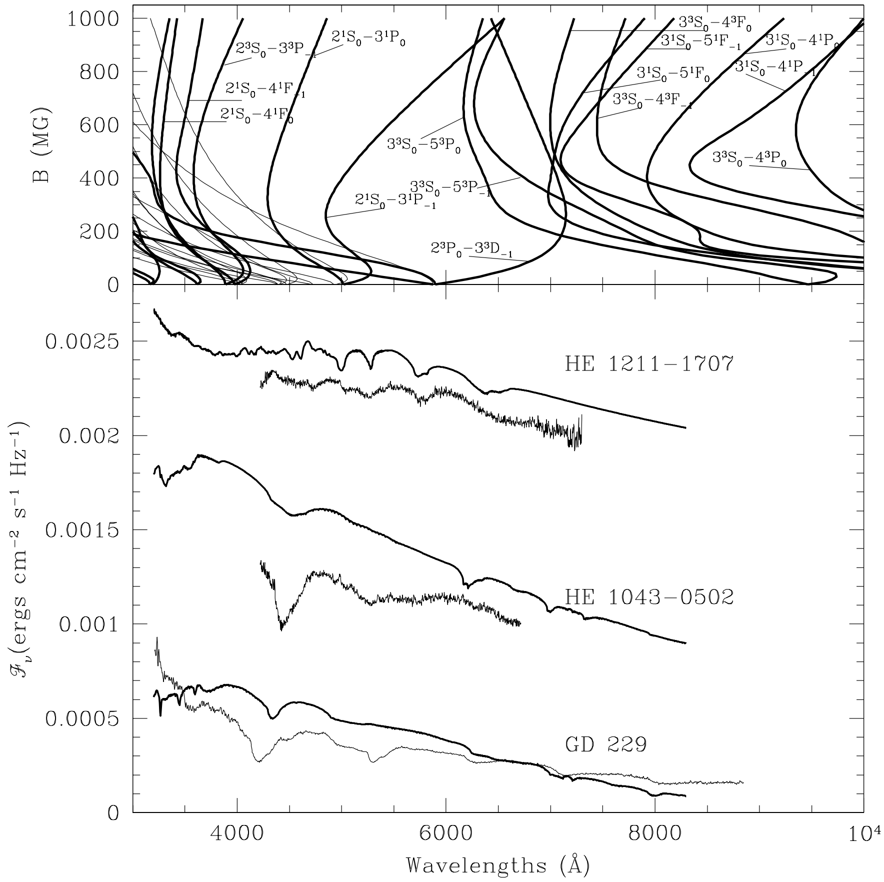


Fig. 11 A comparison of centred dipole models for helium rich WDs with observations of GD229, HE 1043-0502, and HE 1211-1707 (Wickramasinghe et al. 2002). The models have polar fields $B_d = 520$ MG (GD 229), 820 MG (HE 1043-0502) and 50 MG (HE1211 − 1707,). The observation and theory mismatch in GD229 could be due to resonances in the HeI bound-free opacities for which there is at present no adequate theory

peculiar absorption bands is not fully settled – suggestions are absorption by C_2H (Schmidt et al. 1995a) or pressure-shifted Swan bands (Liebert and Dahn 1983; Hall and Maxwell 2008; Kowalski 2010). A number of cool WDs exhibit polarisation in the absorption band of CH (Angel and Landstreet 1974; Vornanen et al. 2010). Berdyugina et al. (2007) applied new calculations of molecular magnetic dichroism to observations of G 99-37, a cool helium-rich MWD showing strongly polarised molecular bands, and estimated a field of 7.5 ± 0.5 MG.

Recently, Dufour et al. (2007) discovered a new class of WDs with carbon-dominated atmospheres, that are substantially hotter than the "classic" cool DQ stars. Short-periodic photometric variability detected in several of the hot

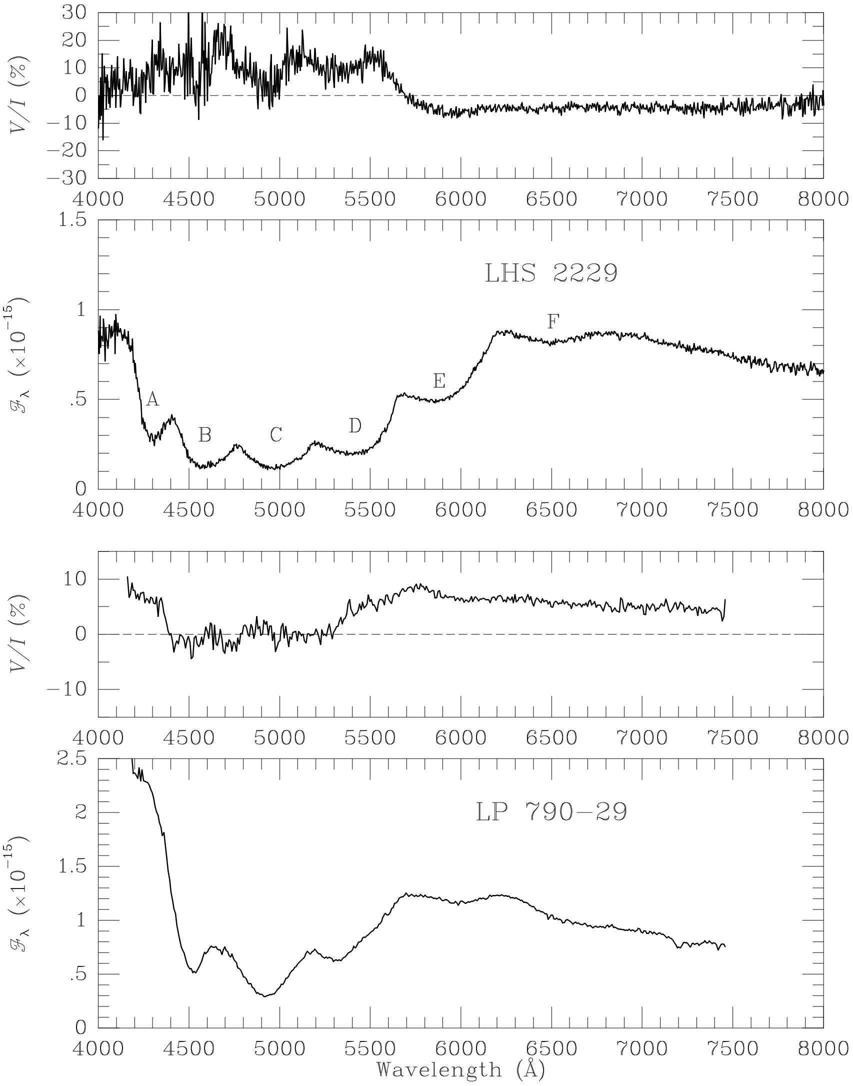


Fig. 12 Flux and polarization spectra of two confirmed magnetic DQp stars, with crude *B*-field estimates of ∼ 100 MG (Schmidt et al. 1999b)

DQs (Montgomery et al. 2008; Dufour et al. 2008b; Dunlap et al. 2010) was initially interpreted as non-radial pulsations, but the discovery of a 2.11 d modulation in SDSS J000555.90-100213.5 (Lawrie et al. 2013) casts some doubt on this hypothesis. The additional discovery of magnetic fields among the hot DQs (Dufour et al. 2008a,b; Williams et al. 2013a) suggests that they may

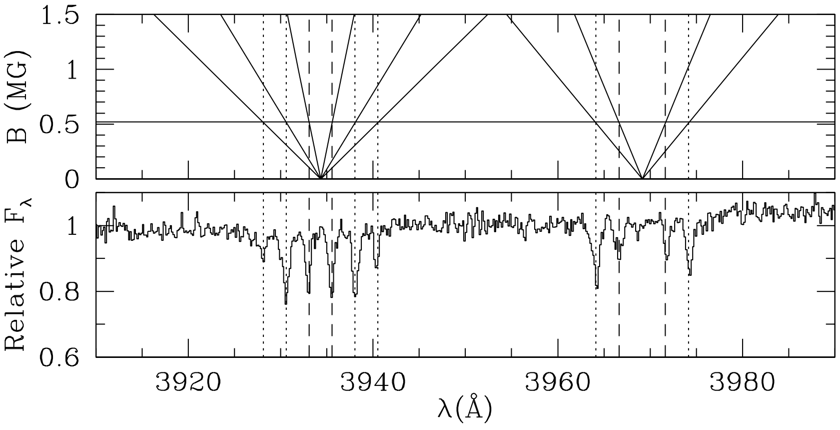


Fig. 13 The Ca H/K absorption lines in the cool ($\simeq 5,000\,$K) hydrogen-dominated atmosphere Zeeman-split in a field of $B = 0.5\,$MG (Kawka and Vennes 2011)

represent a peculiar and rare path in WD evolution. Currently, 5 out of 14 known hot DQs are magnetic (Vornanen et al. 2013).

Because of their high surface gravity, WDs should not have any photospheric elements apart from hydrogen, helium, and dredge-up of carbon or, much more rarely, oxygen (Gänsicke et al. 2010). Yet, ∼ 25% of all WDs show traces of metals – most commonly Ca and Si, but also Mg, Fe, Na and other elements (Zuckerman et al. 2003; Koester et al. 2014). This photospheric pollution requires recent or ongoing accretion and the widely accepted hypothesis for the origin of the material is planetary debris (Jura 2003). This hypothesis is corroborated by the detection of close-in circumstellar dust and gas (Gänsicke et al. 2006a; Farihi et al. 2009). A very small fraction of these debris-polluted WDs show magnetic fields (Reid et al. 2001; Kawka and Vennes 2011; Farihi et al. 2011, see Fig. 13). It is interesting to note that all known metal-polluted MWDs are very cool ($T_{\rm eff} < 7,000\,$K, Kawka and Vennes 2014), including the sample of strongly metal-polluted and highly magnetic DZ WDs recently discovered by Hollands et al. (2015).

4 Mass distribution of isolated magnetic white dwarfs

Mass estimates of isolated MWDs with fields $\gtrsim 1\,$MG are available only for a small number of objects. The mass determination is not straightforward since there is no Stark broadening theory for high field MWDs. Thus, even state-of-the art models fail to fully account for the magnetic effects in MWD atmospheres. As a consequence, the effective temperatures derived often remain inherently uncertain (Fig. 15), and the same is true for the implied MWD masses (e.g. Külebi et al. 2010). The standard procedure of fitting the Balmer lines for $T_{\rm eff}$ and $\log g$ can only be applied to MWDs with fields below a few MG and even in these cases the results have to be treated with some caution

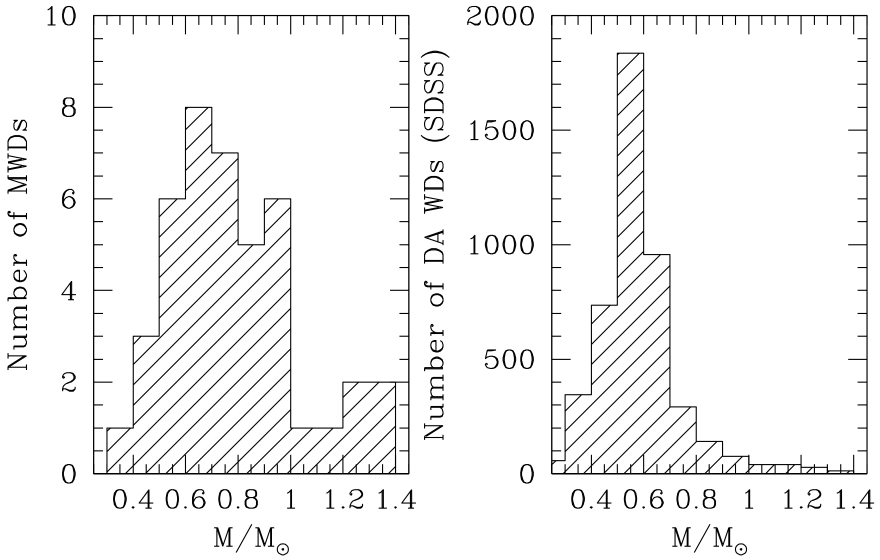


Fig. 14 Left panel: The mass distribution of MWDs (Ferrario and Wickramasinghe 2010). Right panel: The mass distribution of non-magnetic DA WDs from SDSS (Kepler et al. 2007).

(e.g. Ferrario et al. 1998; Dupuis et al. 2003). For higher field strengths, mass estimates are derived from the combination of effective temperatures, parallaxes, and a mass-radius relation. While only a small number of MWDs have accurate parallaxes, an estimate of the distance can be determined for MWDs that have non-degenerate WD companions (Girven et al. 2010; Dobbie et al. 2012, 2013, e.g.), or for MWDs in open clusters (Külebi et al. 2013b). The situation will dramatically improve in the next few years, when parallaxes for practically all known MWDs will become available from the ESA satellite Gaia.

Taking into account the caveats mentioned above, the mean mass of high field isolated MWDs ($B \gtrsim 1\,\mathrm{MG}$) is $0.784 \pm 0.047\,\mathrm{M}_\odot$. High field MWDs also exhibit a strong tail that extends to the Chandrasekhar limit. The most recent estimate for the mean mass of non-magnetic DA WDs is $0.663 \pm 0.136\,\mathrm{M}_\odot$ (Tremblay et al. 2013). That the mean mass of MWDs is higher than that of their non-magnetic counterparts was first noted by Liebert (1988). The mass distribution of all magnetic and non-magnetic WDs is shown in Fig. 14.

5 Spin periods of isolated magnetic white dwarfs

The majority of non-magnetic WDs are slow rotators, with even high-resolution spectroscopy usually only providing lower limits on $v \sin i$ (Karl et al. 2005; Berger et al. 2005). Asteroseismology shows that the spin periods are typically a few days (Fontaine and Brassard 2008; Greiss et al. 2014) and that the angu-

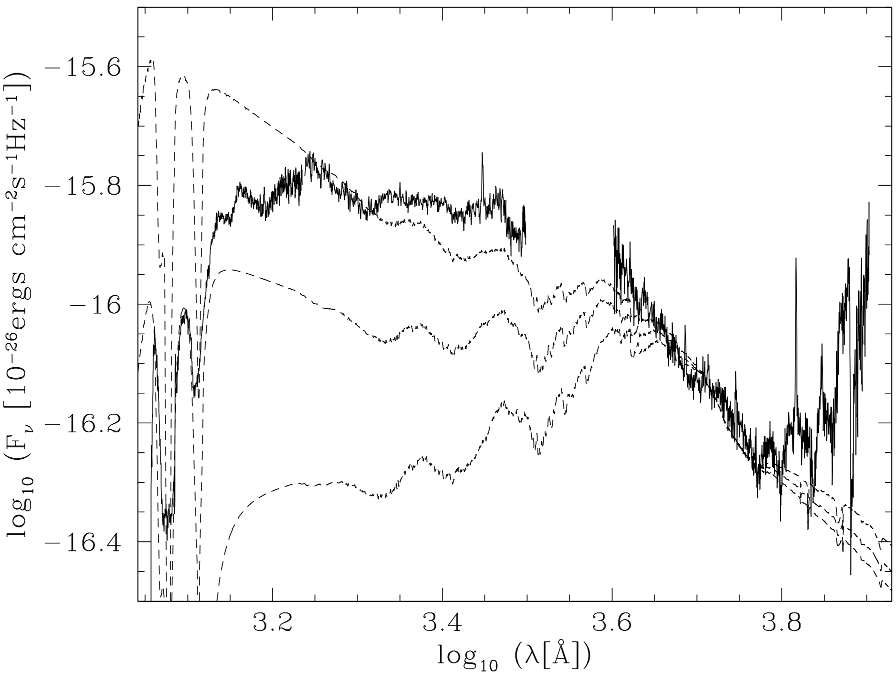


Fig. 15 The combined ultraviolet/optical spectral energy distribution of the high-field (230 MG) MCV AR UMa (solid line), along with model spectra for $T_{\rm eff}$ = $15,000, 20,000, 25,000$ K (dashed lines, top to bottom). Magnetic effects cannot be fully described by current atmosphere models, and consequently the effective temperature of high-field MWDs remains poorly constrained even in the presence of excellent data (Gänsicke et al. 2001)

lar momentum of the stellar core is lost before the WD stage (Charpinet et al. 2009).

In MWDs, the magnetic effects in their atmospheres can give rise to noticeable spectroscopic (Liebert et al. 1977; Latter et al. 1987), photometric Brinkworth et al. (2004, 2005), and polarimetric variability (Schmidt and Norsworthy 1991; Piirola and Reiz 1992).

The observed rotation periods of MWDs span a wide range, from 725 s (RE J0317–853 Barstow et al. 1995; Ferrario et al. 1997a) to lower limits of decades, if not centuries (Berdyugin and Piirola 1999b; Beuermann and Reinsch 2002; Jordan and Friedrich 2002a) (see Table 1).

We show in Fig. 16 (this work) the MWDs with known magnetic fields and rotation (spin) periods, the latter determined from polarimetry and photometry (e.g. Brinkworth et al. 2007, 2013). Inspection of the magnetic field versus spin period distribution may suggest the existence of two groups. One of them characterised by "short" periods of hours to weeks, and the other by rotation periods of decades to centuries as estimated for objects that have

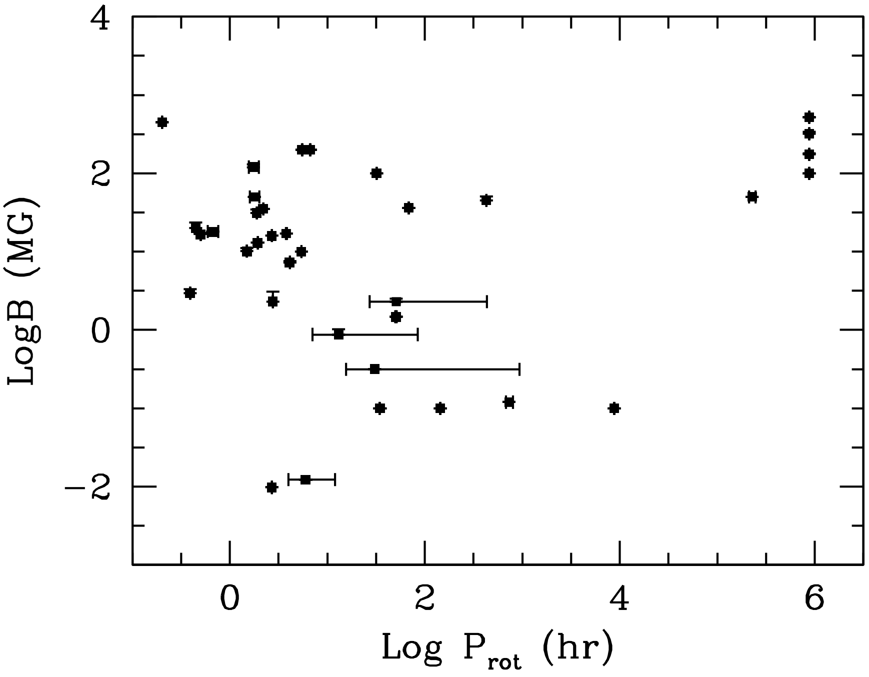


Fig. 16 Rotation periods of isolated MWDs against their magnetic field strength (this work)

been monitored over many decades (e.g., Grw+70°8247, discovered over 80 years ago; Kuiper 1934; Brinkworth et al. 2013). It seems that very long period MWDs tend to possess high fields while short period ones do not show any preferred field strength. Clearly further observations to measure rotation periods of MWDs are needed to ascertain the existence of two groups of MWDs with different rotational properties.

The rotation rate of MWDs holds potentially some crucial clues on their nature and origin. For instance, slow rotators could be the descendants of the magnetic main sequence Ap/Bp stars (and their fields would thus be of fossil origin), whereas fast rotators could be the products of binary interaction, though Külebi et al. (2013a) have argued that in the case of a merger magnetospheric interactions of the MWD with the debris disk may slow down the rotation rather quickly. Unfortunately, the statistics of rotation periods have only slowly improved, however Brinkworth et al. (2013) have demonstrated that the search for photometric variability is relatively cheap in terms of observational requirements, and could extensively be used for future work. An interesting hypothesis is that rapidly rotating MWDs may be detectable as sources of gravitational wave radiation (Heyl 2000).

For the sake of completeness, we recall that the spin period of the MWD in MCVs is dictated by the interaction between the magnetic field of the MWD and that of the secondary and/or by the torque of the accretion flow. That is, for strong fields the rotation of the MWD is locked to the orbital period (polars), and for weaker fields the MWD is rotating faster than the orbital period (IPs).

6 Origin of magnetic fields in white dwarfs and magnetic cataclysmic variables

WDs are often found paired with Main-Sequence (MS) companion stars (generally M dwarfs, but see Ferrario 2012a). A glaring anomaly is that there are no examples of fully detached MWD-MS pairs, as first noted by Liebert et al. (2005) through the study of 501 objects with composite WD+MS spectra from the Sloan Digital Sky Survey (SDSS) DR3. Even the most recent work of Rebassa-Mansergas et al. (2013), which has yielded 3,419 SDSS DR8 WD-MS binary candidates, does not contain objects consisting of a MWD with a non-degenerate companion. Further searches conducted through visual inspection of all SDSS spectra of WDs with a red excess have confirmed the hypothesis that magnetic field and binarity (with M or K dwarfs) are independent at a $9\,\sigma$ level (Liebert et al. 2015). Such a pairing is also absent from catalogues of high field MWDs (Kawka et al. 2007; Kepler et al. 2013, and this work).

Thus, although all magnitude-limited surveys of WDs have lead to the discovery of at least $\sim 2\%$ of strongly magnetised WDs ($B \gtrsim 1\,\mathrm{MG}$), these objects are never found paired with a non-degenerate companion star. Yet, about 20-25% of CVs host a MWD, thus raising some serious questions regarding the progenitors, and thus the origin, of MCVs (see Liebert 2009).

In the late 90s, surveys such as the HQS and the SDSS have revealed the existence of a small number of cool MWDs which accrete matter from the wind of their low-mass MS companions (e.g. Reimers et al. 1999; Reimers and Hagen 2000; Schwope et al. 2002b; Schmidt et al. 2005b, 2007; Vogel et al. 2007; Schwope et al. 2009; Vogel et al. 2011; Parsons et al. 2013). The accretion rate, which is about $10^{-13} - 10^{-14}\mathrm{M}_\odot\ \mathrm{yr}^{-1}$, is a few orders of magnitude larger than that observed in detached non-magnetic Post Common Envelope Binaries (PCEBs, e.g. Parsons et al. 2013, and references therein). Comprehensive studies of these systems have unveiled that the secondary is an active late-type main sequence star underfilling its Roche-lobe (see Schwope et al. 2009, and references therein). Accretion onto the cool MWD primary, constant over years (Schwarz et al. 2001), is consistent with what is expected from the wind emanating from the active companion (Schwope et al. 2002b) and captured by the MWD. The spectra of these systems exhibit strong cyclotron harmonics humps superimposed on the WD+M dwarf stellar continuum. Their very peculiar colour is the reason why the first such systems were uncovered in surveys whose science goal was to identify active galactic nuclei. The suggestion is that these systems could be the progenitors of the high field MCVs. Thus their initial class name "Low-Accretion Rate Polars" ("LARPS", Schwope et al. 2002b) is a misnomer, so they were renamed "Pre-Polars" ("PREPS", Schwope et al. 2009).

There are now ten systems that have been classified as PREPS (see Table 2). The WD magnetic fields determined for these systems cluster in the 60-70 MG range with only one system above (108 MG Schwope et al. 2009) and two below (42 MG and 8 MG Schmidt et al. 2007; Parsons et al. 2013). This field clustering may be due to selection effects. In any case, the field strengths are certainly consistent with the hypothesis that these wind accreting magnetic systems are the progenitors of the high field MCVs. The low magnetic field of 8 MG found in SDSS J030308.35+0054441.1 could instead suggest that this system may evolve into an IP (Parsons et al. 2013).

There are however a few polars that undergo prolonged low-accretion states that cannot be reconciled with wind accretion and therefore these can be rightfully named LARPS (see e.g. Schmidt et al. 2005a; Breedt et al. 2012, and Table 2).

The PREPS hypothesis is consistent with the scenario first proposed by Tout et al. (2008) and further developed by Wickramasinghe et al. (2014) for the origin of fields in MCVs. They have raised the possibility that the strong differential rotation expected in the CE phase may lead to the generation, by the dynamo mechanism, of a magnetic field that becomes frozen into the degenerate core of the pre-WD in MCVs (see also Nordhaus et al. 2011; García-Berro et al. 2012; Kissin and Thompson 2015, about field generation in MWDs). The dynamo mechanism responsible for magnetic field generation during the CE phase proposed by Wickramasinghe et al. (2014) is presented in the chapter of this book on the origin of magnetic fields in stars.

The binary population synthesis calculations of Briggs et al. (2015) are compatible with the hypothesis that MWDs originate from stars merging during common envelope evolution and are also consistent with the observation that MWDs are on average more massive than their non-magnetic counterparts (see Sect. 4).

However, other formation channels for MWDs may be at work and, for instance, the fossil field hypothesis for the origin of high fields MWDs, as proposed by Wickramasinghe and Ferrario (2005), cannot be dismissed. However, the fact that there is no known MWD paired with a non-degenerate companion of M to K spectral type is a serious challenge to the fossil field hypothesis. Of course it is possible that some MWDs could be hidden in the glare of luminous companions (e.g. Ferrario 2012b). Should large enough numbers of these 'Sirius-type systems' hosting a MWD be discovered, this finding could point to different (or additional) formation channels for MWDs. However here we need to stress that Sirius-type systems could not be the progenitors of the MCVs.

According to the stellar merging hypothesis, the absence of relatively wide pre-MCVs can be explained if magnetic systems are born either in an already semi-detached state or with the two stars close enough for the MWD to capture the wind of its companion as it happens in PREPS. Any other alternative would trigger the question "where are the progenitors of the PREPS?"

(Schwope et al. 2009). In the merging star picture, the highest fields are expected to occur when the two stars merge to produce an isolated MWD. The MCVs would then arise when the two stellar cores come close enough to each other to generate a strong field in the WD but fail to merge. Wider core separations after the end of the CE phase would result in non magnetic pre-CVs or in systems where the two stars will never interact. These systems, single stars and binaries that never undergo a CE evolution would account for the populations of low-field WDs in CVs, wide binaries and single isolated WDs. The few known wide binaries consisting of a MWD paired with a non-magnetic WD would result from triple star evolution where two stars merged to produce the MWD and the third one evolved as a single star to become a non-magnetic WD (e.g. LB 11146, RXJ 0317-853, EUVE J1439+750, CBS 229; Glenn et al. 1994a; Barstow et al. 1995; Ferrario et al. 1997a; Vennes et al. 1999; Dobbie et al. 2013).

One would expect that some PREPS should have hotter WDs. However, as Tout et al. (2008) have pointed out, WDs cool down to an effective temperature of $15,000\,$K in only $\sim 10^7$ years and at a period of 2 h, the orbital decay time scale due to gravitational wave radiation is about 3×10^9 years which is sufficient for a WD to cool down considerably and reach the observed effective temperatures of the PREPS before Roche lobe accretion begins. Therefore, although some $20 - 25\%$ of CVs are magnetic, their birthrate may be considerably lower than that of non-magnetic CVs and their presence in large numbers could simply be a reflection of their longer lifespans because of the reduction in magnetic braking (see Sect 7).

Extensive searches for magnetic fields in central stars of planetary nebulae and in hot subdwarfs have until now yielded negative results (Asensio Ramos et al. 2014; Leone et al. 2014; Mathys et al. 2012; Savanov et al. 2013). Should this finding be verified by further spectropolarimetric observations, it would again be consistent with the view that the origin of fields in MWDs is intimately related to their binary nature.

Another possibility that cannot be a priori excluded may involve the screening of the WD magnetic field by an unmagnetised layer of material at the end of the CE phase. Should this be the case, magnetic systems would not distinguish themselves as such in the early post CE phase until their field re-emerges when the stars are in near contact (as in PREPS) or in contact (as in MCVs). Because of the observed low effective temperatures of the WDs in PREPS this phase must last $\gtrsim 10^9$ years. Estimates of the diffusion and advection rates of a dipolar magnetic field would thus suggest the presence of $\sim 0.2\mathrm{M}_\odot$ of hydrogen-rich material screening the field in order to explain the observations (Cumming 2002). However, we need to stress that the calculations of Cumming (2002) are for accreting WDs under the assumption that they retain the accreted mass. The situation in the context of CE evolution is different, in so far as the screening would be caused by a layer of matter which is retained following an incomplete ejection of the envelope.

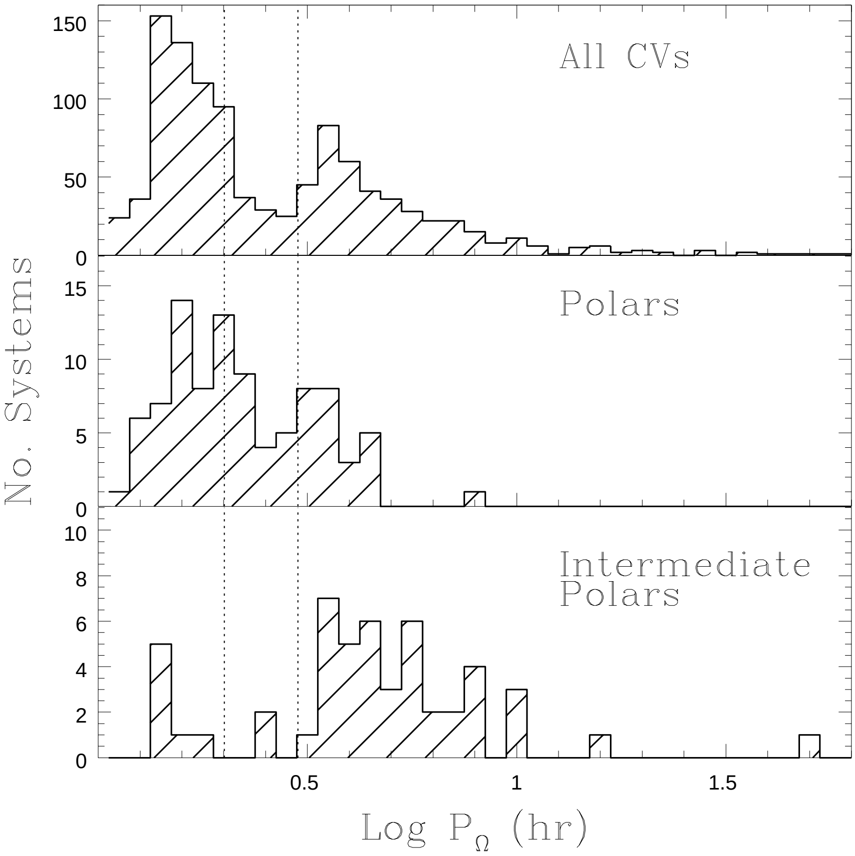


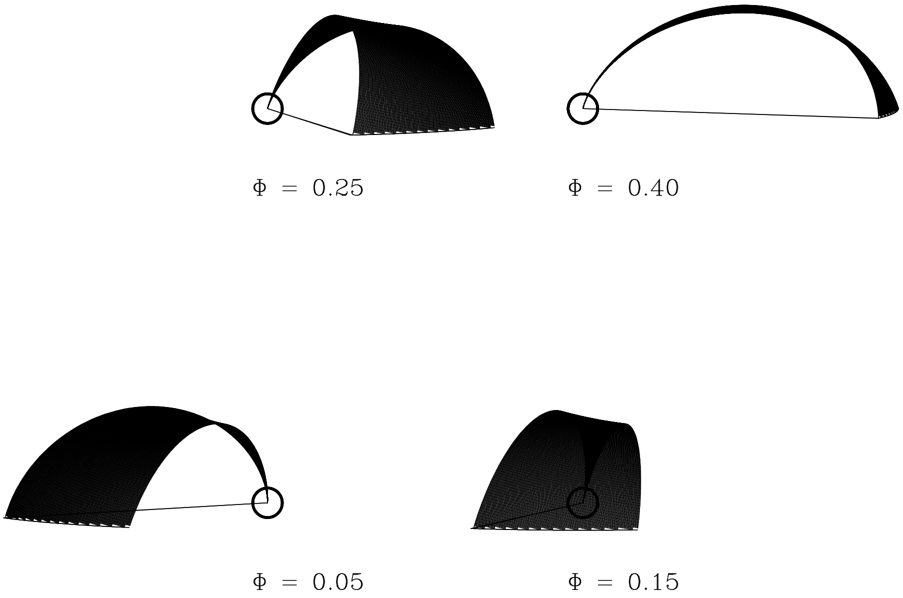
Fig. 17 The orbital period distribution of CVs (top) and of the magnetic types Polars (middle) and IPs (bottom). The latest version (v7.20) of the Ritter and Kolb (2003) CV catalogue is used. A few identifications were corrected. The vertical lines mark the 2-3 h orbital period gap

7 Evolutionary aspects of magnetic white dwarf binaries

Close binary evolution theory predicts compact binary systems with low-mass donors to evolve towards short orbital periods through angular momentum losses (King 1988). At long orbital periods ($\gtrsim$ 3 h) magnetic braking (Verbunt and Zwaan 1981; Rappaport et al. 1983) acts as main mechanism that ceases at ~3 h when secondaries become fully convective and shrink within their Roche lobe. Mass transfer stops until contact is re-established near ~2 h. This gives rise to the so-called 2-3 h CV orbital period gap (Rappaport et al. 1983; Spruit and Ritter 1983; Davis et al. 2008). Below the period gap gravitational radiation drives the systems towards the orbital period minimum, ~70-80 min, as first suggested by Paczynski and Sienkiewicz (1981) (but see also Townsley and Bildsten 2003; Townsley and Gänsicke 2009) until the mass of the donor star becomes too small to sustain nuclear burning and the star becomes degenerate. The present day CV population is expected to densely populate the orbital period distribution close to the period minimum (the "orbital minimum spike"). These systems would then be expected to 'bounce back' and evolve toward longer periods (Kolb and Baraffe 1999). The discrepancy between observations and theory has been a major issue for a long time and only recently mitigated by deep optical surveys, such as the SDSS which has unveiled the long-sought low accretion rate and short orbital period CVs (Gänsicke et al. 2009, see their Fig. 17, top panel). The CV space density also suffers from discrepancies between theoretical predictions (De Kool 1992; Politano 1996) and observations (Schreiber and Gänsicke 2003; Pretorius et al. 2007), although there are recent claims by Reis et al. (2013) that some of these disagreements may now be resolved. The study of Reis et al. (2013) of Swift X-ray spectra of an optically selected sample of nearby CVs has revealed the existence of a population of objects whose X-ray luminosities are an order of magnitude fainter than found in earlier studies indicating that the space density of CVs may be larger than previously forecast and thus in better agreement with population synthesis calculations.

Among the MCVs, the polars dominate the period distribution at short ($\lesssim$4 h) orbital periods while the IPs dominate the distribution at longer periods (see Fig. 17, mid and bottom panels). It is not clear yet whether the IPs, as a class, have generally lower fields than polars or the field strengths of both sub-classes are similar but IPs still need to synchronise (King and Lasota 1991; Norton et al. 2004). Unlike polars, the majority of IPs has not been detected in polarisation searches except for ten systems that may eventually evolve into polars (see Sect.3). Norton et al. (2004, 2008) argued that IPs above the gap with WD surface magnetic moments $\mu_{\rm WD} \gtrsim 5 \times 10^{33}\,{\rm G\,cm^3}$ and $P_{\rm orb} \gtrsim 3\,{\rm h}$ will eventually evolve into polars. IPs below the gap, however, are not expected to evolve into polars. Recently new short period IPs have been discovered both in X-ray (de Martino et al. 2005; Bernardini et al. 2012; Woudt et al. 2012a; Bernardini et al. 2013; Thorstensen and Halpern 2013) and optical bands (Rodríguez-Gil et al. 2004; Araujo-Betancor et al. 2005b; Southworth et al. 2007). From these findings Pretorius and Mukai (2014) have suggested the existence of a low-luminosity (hence low-accretion rate) population of IPs that still need to be unveiled. To enlarge the sample of short period IPs is clearly crucial to understand MCVs and their evolution.

Although the evolution of MCVs was expected to be similar to that of non-magnetic CVs, Wickramasinghe and Wu (1994) predicted a scenario where the strong magnetic field in polars reduces the efficiency of the magnetic braking mechanism (see also Wickramasinghe and Ferrario 2000; Webbink and Wickramasinghe 2002). As a consequence, the mass transfer rates would be lower requiring longer evolutionary timescales than those of non-magnetic systems. The first strong observational evidence in support of this scenario was presented by Sion (1999) on the basis of simple considerations of compressional heating and structure changes in response to accretion in non-magnetic CVs versus



$\Phi = 0.25$ $\Phi = 0.40$

$\Phi = 0.05$ $\Phi = 0.15$

Fig. 18 Accretion funnel in a polar obtained using an orbital inclination, $i = 85°$, and a dipole inclination, $\theta = 15°$. The diagrams for phases $\phi > 0.5$ are mirror images of those shown here (Ferrario et al. 1993)

the known effective temperatures of the WDs in MCVs. This finding was later confirmed by Araujo-Betancor et al. (2005a) for a larger sample of MCVs with exposed MWDs. They showed that polars possess systematically cooler WDs than non-magnetic CVs. Since the WD effective temperature is a good proxy of the secular mass transfer rate (Townsley and Gänsicke 2009) it turns out that CVs with highly magnetised WDs accrete at lower rates and thus evolve on longer timescales. This could explain the higher incidence of magnetism observed among CVs ($\sim 20 - 25\%$) as compared to that of isolated MWDs (Araujo-Betancor et al. 2005a).

The MCVs, being stronger X-ray emitters than non-magnetic CVs, are claimed to be important constituent of the galactic X-ray source population at low luminosities. The deep *Chandra* survey of the galactic centre has revealed a large number of low-luminosity hard X-ray sources attributed to MCVs of the IP type (Muno et al. 2004a; Hong et al. 2012). The hard X-ray surveys of the Galactic Ridge conducted by the *INTEGRAL* (Revnivtsev et al. 2009, 2011), *Rossi-XTE* (Sazonov et al. 2006) and *Suzaku* (Yuasa et al. 2012) satellites have also resolved a large fraction of the diffuse emission into discrete low luminosity hard X-ray sources largely attributed to coronally active stars and MCVs of the IP type. The true contribution of these systems to the X-ray luminosity function of the Galactic X-ray source population at low luminosities is still under investigation (Muno et al. 2004b; Revnivtsev et al. 2006; Yuasa et al. 2012; Reis et al. 2013; Pretorius et al. 2013; Pretorius and Mukai 2014; Warwick 2014).

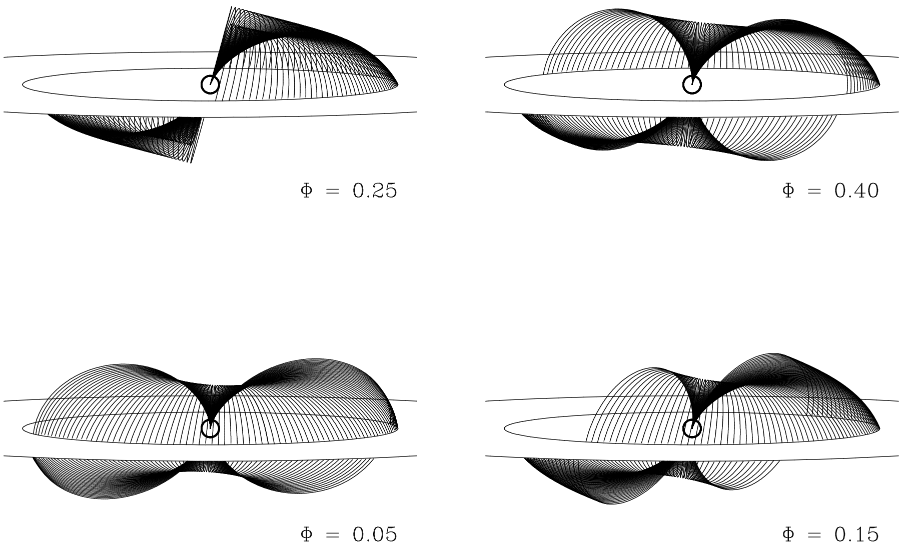


Fig. 19 Visible portions of the two accretion curtains in IPs obtained using a viewing angle $i = 70^\circ$ and a magnetic colatitude of $\theta = 15^\circ$. The diagrams for $\phi > 0.5$ are mirror images of those shown here (Ferrario et al. 1993)

8 Magnetic accretion

The magnetic field of the WD primaries influences the accretion geometry and emission properties of MCVs. It determines the dynamics of accretion when the dynamical timescale is of the order of the timescale of magnetic interaction. This occurs at the magnetospheric boundary where the magnetic pressure balances the ram pressure of the infalling material: $\rho\, v^2 \simeq B^2/8\,\pi$ (Frank et al. 1985). The magnetospheric radius, $R_{\rm mag}$ depends on the magnetic field strength of the WD and the system parameters (see the review by Wickramasinghe 2014). Among polars, the WD magnetic moment is strong enough ($\mu_{\rm WD} \gtrsim 10^{34}\,{\rm G\,cm^3}$) to prevent the formation of an accretion disc, because $R_{\rm mag}$ is of the order of the orbital separation. Thus the accretion stream flowing into the primary Roche lobe along a ballistic trajectory is channelled by the field lines towards the magnetic poles of the WD (Ferrario et al. 1989; Schwope 1996) forming an accretion "funnel". The radiation in the optical and IR bands is characterised by strongly circularly and linearly polarised cyclotron emission from the stand-off shocks located at the base of the accretion funnels. Because of phase locking, radial velocity and light variations are seen only at the orbital period.

There are currently four confirmed polars that show a small degree (several percent) of asynchronism between the spin and orbital periods and two candidate systems (Campbell and Schwope 1999, and see also Table 2). Doppler tomography of the near-synchronous polar BY Cam (Schwarz et al. 2005) has uncovered that most of the matter flowing towards the magnetic WD is ac-

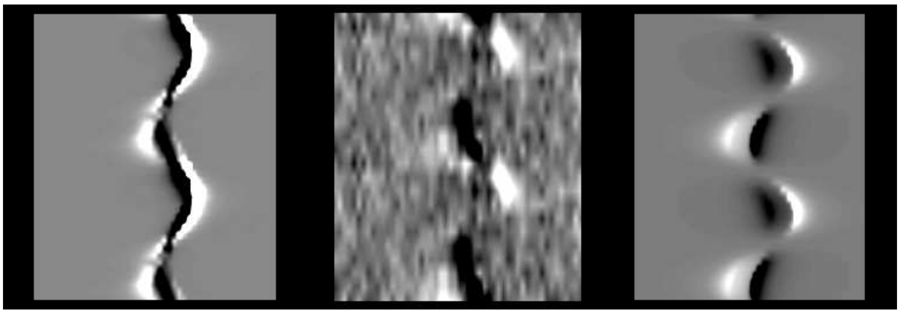


Fig. 20 Middle panel: observed phase-dependence of the circularly polarised flux for the region surrounding H_β. Wavelength runs from 4750 Å to 4950 Å, and orbital phase advances upward, with $\phi = 0.25$ at the bottom and $\phi = 0.25$ at the top of the figure, covering two complete orbital cycles. The polarised flux is white for negative circular polarisation and black for positive circular polarisation. Left panel: “standard” funnel model with $\theta_d = 30^\circ$, $\phi_d = 90^\circ$ and $i = 60^\circ$. Right panel:idealised plane parallel slab model for field aligned flow in the transition region from ballistic stream to funnel flow (Ferrario et al. 2002)

creted via a funnel that extends by $\sim 180^\circ$ in azimuth. This implies that the stream can travel around the WD, making the accretion pattern in this system resemble that of IPs (see below). Thus, asynchronous polars are particularly important for our understanding of magnetic accretion since they display characteristics common to both Polars and IPs.

The reason for this asynchronism is not clear, but it has been proposed that it could be caused by recent nova eruptions (e.g. Nova V1500 Cyg, Schmidt and Stockman 1991; Schmidt et al. 1995b). Furthermore among newly identified MCVs there are a handful of systems with weakly desynchronised MWDs (see Table 3), such as Paloma (Schwarz et al. 2007), IGR J19552+0044 (Bernardini et al. 2013), and V598 Peg (Southworth et al. 2007) indicating that the distinction between polars as synchronous rotators and IPs is not as sharp as formerly believed.

In most IPs, accretion discs or rings usually form (but see Hellier 2014, for a review on accretion in IPs) and $R_{\rm mag} \lesssim R_{\rm cor}$ where $R_{\rm cor} = (G\,M_{\rm WD}/\Omega^2_{\rm rot})^{1/3}$ is the co-rotation radius at which the Keplerian angular velocity equals the spin angular velocity of the primary and $R_{\rm mag} = \phi\,2.7{\times}10^{10}\,\mu_{33}^{4/7}\,\dot{M}_{16}^{-2/7}\,M_{\rm WD,\odot}^{-1/7}$ cm, where $\phi \sim 1$ is a parameter that takes into account the departure from the spherically symmetric case, μ_{33} is the WD magnetic moment in units of 10^{33} G cm^3, M_{16} is the mass accretion rate in units of 10^{16} g s^{-1} and $M_{\rm WD,\odot}$ is the WD mass in solar units (Norton and Watson 1989; Hellier 1995). The details of the threading region depend on the magnetic diffusivity of the disc and the toroidal field produced by the shear between the Keplerian disc and the co-rotating disc (see Wickramasinghe 2014). Close to the WD, the flow in IPs consists of two magnetically confined accretion “curtains” fed by the disk or ring (Ferrario et al. 1993; Hellier 1995).

Since the WD in IPs is not phase-locked into synchronous rotation with the orbit, the emission variations are observed to occur at the spin period of the WD, $P_{\rm s}$, at the beat period $P_{\rm beat} = (P_{\rm s}^{-1} - P_{\rm orb}^{-1})^{-1}$ and often at both. The multi-component model of Ferrario and Wickramasinghe (1999) to calculate the optical and X-ray power spectra of disced and discless MCVs has revealed that as the magnetic field strength of the WD increases, the cyclotron emission from the shocks becomes comparable to the optical radiation from the magnetically confined flow and the dominant power shifts from the beat frequency to the WD spin frequency. Thus those MWDs in IPs with sufficiently large magnetic moments, such as V 2400 Oph (Buckley et al. 1997), do not accrete via a disc while in many other IPs, such as FO Aqr, the stream from the companion star can flow over the disc (Norton et al. 1992; Beardmore et al. 1998; Hellier 2014).

One of the most significant characteristic that distinguishes disc-fed accretion from stream-fed accretion is the amplitude of the radial velocity variations. Disc-fed accretion is characterised by low radial velocity amplitudes ($\sim 50 - 100\,\mathrm{km\,s^{-1}}$), while stream-fed accretion by high radial velocity amplitudes ($\sim 500 - 1,000\,\mathrm{km\,s^{-1}}$).

Here we need to stress that although curtains are generally associated with asynchronous systems, under certain accretion conditions even polars may exhibit extended coupling regions and a curtain-type structure for the magnetically confined infalling matter. Similarly, some IPs may sometime show funnel-like flows typical of polars. In this context we note that Schwope et al. (2004) have shown how tomographic techniques can be effectively used to infer the accretion geometry of MCVs.

We show schematic diagrams of magnetically channelled accretion flows in typical polars and IPs in Fig. 18 and Fig. 19 respectively. As shown in these figures, the observed modulation arises from projection area effects and viewing aspect. Depending on the orbital phase ϕ, parts of the accretion curtains are either self-occulted or are hidden by the disc or the body of the WD (Ferrario et al. 1993; Ferrario and Wickramasinghe 1993).

The discovery of Zeeman-split emission lines in the circular polarisation spectra of AR UMa (Schmidt et al. 1999a) and V884 Her (Schmidt et al. 2001b) have enabled the investigation of the magnetic, thermal and dynamical structure of accretion funnels. The modelling of Ferrario et al. (2002) of these two very high field polars using the funnel structures developed by Ferrario and Wehrse (1999) has revealed that the polarisation spectrum is very sensitive to velocity and field gradients, as shown in Fig. 20. They find that the bulk of the observed emission arises from two components, (i) the material in the magnetically channelled funnel flow and (ii) the threading region at the base of the funnel where the stream changes from ballistic to co-rotational. The latter makes the main contribution in the high field system AR UMa which is viewed at large inclination angles while the former dominates at the low orbital inclinations of V884 Her (Ferrario et al. 2002). Thus, the study of polarised line emission, which is only possible for systems which possess very strong fields, allows one to unravel the contributions from the stream, funnel, and transition region.

Close to the WD surface the densest parts of the supersonic infalling matter produce a strong shock where the gas is heated up to temperatures of $\sim$ 10-

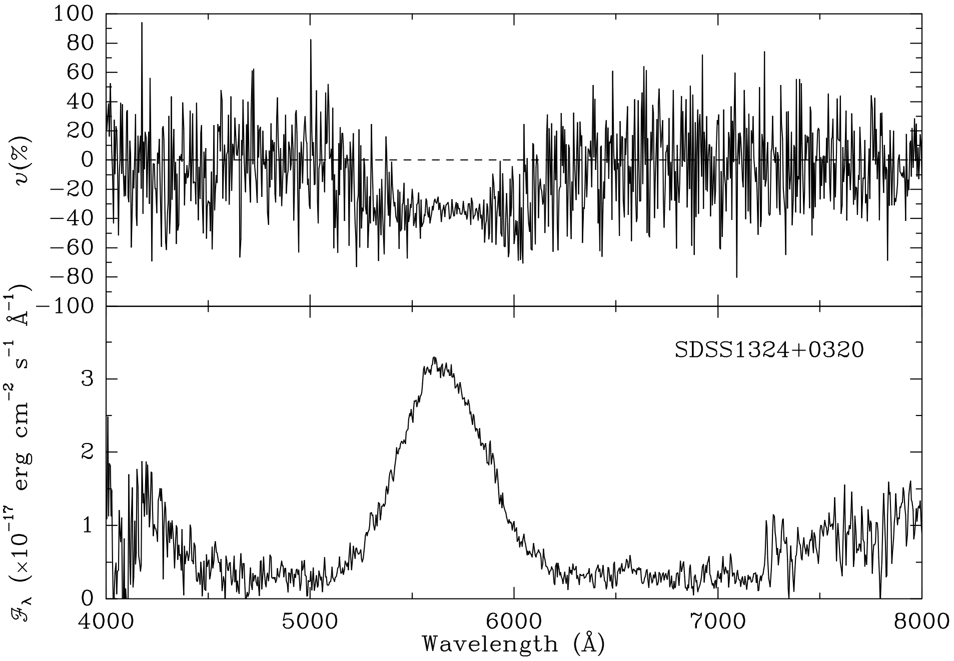


Fig. 21 Bottom panel: Phase-averaged flux spectrum of the PREP PZ Vir (=SDSS J1324+0320). Top panel: phase-averaged circular polarisation spectrum (Szkody et al. 2003)

40 keV. The shock temperature is $T_{\rm s} = 3.7 \times 10^8\, M_{\rm WD,\odot}/R_9$ K, where R_9 is the WD radius in units of 10^9 cm. The post-shock flow becomes subsonic and cools via thermal bremsstrahlung (hard X-rays) and cyclotron radiation (optical/IR) (Aizu 1973; King and Lasota 1979; Lamb and Masters 1979). The relative proportion of cyclotron to bremsstrahlung radiations depends on the WD field strength and specific mass accretion rate. Cyclotron dominates at high field strengths and/or low local mass accretion rates, thus, if $L_{\rm cyc}$ and $L_{\rm brem}$ are the cyclotron and bremsstrahlung luminosities respectively, then $L_{\rm cyc} > L_{\rm hard}$. The temperatures of ions and electrons are different in this case (two-temperature fluid). Bremsstrahlung instead dominates at low field and/or high local mass accretion rates and the ion and electron temperatures are about the same (one-temperature fluid). The WD surface also intercepts these primary emissions, which are partially reflected and thermalised. The poles of the WD are then heated at temperatures $\sim 20-40$ eV and emit a blackbody-like spectrum. However, the prediction that the black body luminosity, $L_{\rm BB}$, should be $\sim L_{\rm brem} + L_{\rm cyc}$ was not confirmed in AM Her and other polars which showed a prominent soft X-ray component. This was referred to as the "soft X-

ray puzzle" (see also Beuermann 1999). Kuijpers and Pringle (1982) suggested that at high local mass accretion rates ($\dot{m} \sim 100 \ \mathrm{g\,cm^{-2}\,s^{-1}}$) the pressure of material is so high that the shock can be buried in the WD atmosphere and that the heating of the WD from below produces an intense blackbody-like emission. This component does not enter in the energy balance, thus solving the soft X-ray puzzle. In AM Her most of the reprocessed radiation was found to emerge in the FUV/UV range (Gänsicke et al. 1995). In this context, we note that the recent modelling of the accretion heated spot of the WD using a temperature distribution across the region can well reproduce the soft X-ray spectrum in AM Her (Beuermann et al. 2012).

The structure of the post-shock region has been the subject of several studies. Detailed one-dimensional two-fluid hydrodynamic calculations coupled with radiative transfer equations for cyclotron and bremsstrahlung were performed for different regimes by Woelk and Beuermann (1992, 1996); Thompson and Cawthorne (1987); Kuijpers and Pringle (1982) and Fischer and Beuermann (2001). They also include the so-called bombardment regime, which is associated with very low specific mass accretion rates and high field strengths. These very low accretion rates do not allow the formation of a hydrodynamic shock, and the photosphere is heated directly by particle bombardment. This is the typical accretion regime of PREPS, as indicated by the observations of systems such as PZ Vir (=SDSS J1324+0320, Fig. 21). The very low electron temperatures and specific accretion rates derived by the modelling of these systems (see Fig. 22 and Ferrario et al. 2005) are found to be consistent with the bombardment regime. The absence of Zeeman features from the photosphere of the WD further strengthens the hypothesis that these systems are not polars in a low state of accretion but pre-MCV with very cool, old, WDs.

When fitting the X-ray spectra, early computations of the structure of the post-shock flow using one-temperature calculations (Cropper et al. 1999) were later demonstrated to provide higher WD masses than those obtained using hydrodynamical models that included two-temperature effects (Saxton et al. 2005) and dipolar field geometry (Saxton et al. 2007).

In the IPs, accretion generally occurs via magnetically confined curtains (see Fig. 19) forming arc-shaped shock regions around the WD magnetic poles (Ferrario et al. 1993; Ferrario and Wickramasinghe 1993; Hellier 1995). Since these systems are strong hard X-ray emitters, the post-shock region mainly cools via thermal bremsstrahlung. Because of the large arc-shaped footprints, the reprocessed radiation was initially expected to emerge in the EUV range. However, the *ROSAT* survey revealed the existence of a few IPs with a soft X-ray component similar to that observed in polars. Observations with the *XMM-Newton* satellite have increased the number of IPs that exhibit a soft blackbody component to ∼ 18, although these cover a wider range of temperatures than those in polars (Anzolin et al. 2008, 2009; Bernardini et al. 2012, and reference therein). Since the soft X-ray component is only a small fraction of the hard X-ray luminosity, it is consistent with reprocessing.

Interestingly, recent X-ray observations with *XMM-Newton* of polars in high states of accretion have revealed an increasing number of systems that

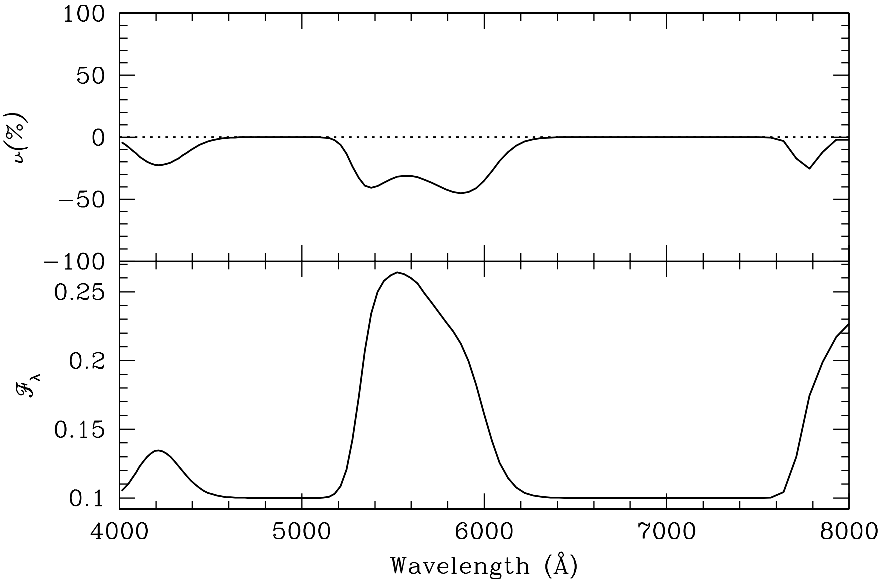


Fig. 22 Phase-averaged cyclotron model for the PREP PZ Vir (=SDSS J1324+0320) corresponding to a magnetic field strength $B = 64$ MG. Lower panel panel: flux. Upper panel: circular polarisation

do not exhibit a distinct soft X-ray component but rather a more 'IP-like' X-ray spectrum (Ramsay and Cropper 2004; Vogel et al. 2008; Ramsay et al. 2009; Bernardini et al. 2014). However, the magnetic fields and orbital periods of these polars do not appear to be very dissimilar from all other polars with a more classic type of behaviour. Hence, the distinction between the two subclasses now appears less marked than ever before, requiring further investigations.

9 Conclusions

To date there are about ~ 250 MWDs with well determined fields (see Table 1) and over ~ 600 if we also count objects with no or uncertain field determination (see Kepler et al. 2013, 2015). These MWDs have been discovered following surveys such as the SDSS, HQS and the Cape Survey. The enlarged sample has shown that the field distribution of MWDs is in the range $10^3 - 10^9$ G. While the high field cut-off appears to be real, the low field one is currently determined solely by the sensitivity of current spectropolarimetric surveys. Observations also indicate that MWDs may be divided into two groups: a high field group ($1 - 1\,000$ MG), where most objects are found, and a low field group (< 0.1 MG), whose importance still needs to be determined by much more sensitive spectropolarimetric surveys conducted on 8 m class telescopes.

The high field group of MWDs differs from the low field group in terms of average mass (see also Kepler et al. 2013). That is, high field MWDs exhibit a higher average mass ($\sim 0.85\,\mathrm{M}_\odot$) than weakly magnetic or non-magnetic WDs ($\sim 0.66\,\mathrm{M}_\odot$). High field MWDs also have a relatively strong tail that extends to the Chandrasekhar limit.

The significant increase in the number of MWDs has also led to new insights on the nature of magnetism. However, we still need to construct (i) more realistic model atmospheres that allow for the presence of magnetic fields and (ii) stellar evolution tracks of intermediate mass stars that take into consideration both fossil and dynamo generated fields. Such calculations may be able to tell us whether all WDs are magnetic at some level.

The origin of fields in highly magnetic WDs is currently being debated. Although the newly proposed scenario that all high field MWDs (single and in binaries) are the result of close binary evolution and mergers is gaining momentum, the fossil field hypothesis cannot be totally dismissed. The attractiveness of the merger hypothesis lies mostly in its ability to explain why there are no wide binaries consisting of a MWD with a non-degenerate companion star and why MWDs are on average more massive than their non-magnetic or weakly magnetic counterparts.

Observations of magnetic WDs in interacting binaries obtained in the last decade have also opened interesting questions on their evolution, accretion and emission properties. Forthcoming surveys such as SDSS-IV and VPHAS+ (Drew et al. 2014) in the optical and in the X-rays, such as the one expected to be conducted by *eROSITA* (e.g., Schwope 2012) will allow the discovery of new systems providing new exciting challenges.

The study of isolated and binary MWDs is likely to remain at the forefront of research for many years to come.

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APPENDIX: Tables of Magnetic White Dwarfs and Magnetic Cataclysmic Variables

Table 1: Magnetic White Dwarfs

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
0003-103	SDSS J000555.91-100213.4	DQ	1.47*	19420±920	$\log g = (8.0)$	2.110±0.045 d	1,2,3
0005-148	NLTT 347, SDSS J010319.70032501.0	DA	-0.0046±0.0019	6400±180	0.59:	···	4
0009+501	LHS 1038, G 217-37, NLTT 574	DA	0.316*	6540±150	0.74±0.04	hrs–2.5 d	5,6,4
0011-134	LHS 1044, G 158-045	DA	16.7±0.6	6010±120	0.71±0.07	30 min-days	7,8,9
0015+004	SDSS J001742.44+004137.4	DB	8.3	15000	···	···	10
0018+147	SDSS J002129.00+150223.7	DA	530.69±63.56	7000	···	···	11,12
0038-084	NLTT 2219	DA	0.307*	6000±180	0.59:	···	4
0040+000	SDSS J004248.19+001955.3	DA	2	11000	···	···	DD, 10,12
0041-102	Feige 7,L 795-7	DBA	35	20000	$\log g = (8.0)$	131.606 min	13,14,15
0051+115	HS 0051+1145, PHL 886	DA	0.240±0.010	···	···	···	16
0058-044	GD 9, GR 407, PHL 940	DA	0.325±0.035	16700	$\log g = 8.07$	···	17,16
0104+149	SDSS J010647.92+151327.8	DQ	not confirmed	23430±1680	$\log g = (8.0)$	···	2
0140+130	SDSS J014245.37+131546.4	DB	4	15000	···	···	10
0155+003	SDSS J015748.15+003315.1	DZ	3.49±0.05*	5700	···	···	10,18
0159-032	1H 0201-029	DA	6	26000	$\log g = (8.0)$	···	19
0208+002	SDSS J021116.34+003128.5	DA	341.31±54.34	9000	···	···	10,12
0209+210	SDSS J021148.22+211548.2	DA	166.16±7.41	12000	···	···	11,12
0231+263	SDSS J023420.63+264801.7	DA	32.82±6.26	13500	···	···	12
0233-083	SDSS J023609.40-080823.9	DQA	5	10000	···	···	11
0236-269	HE 0236-2656	DB	···	6000-7000	···	···	20
0239+109	G 4-34, LTT 10886	DA	0.725±0.025	10060	$\log g = 8.73$	···	DD, 17,16,21
0253+508	KPD 0253+508	DA	17	15000	$\log g = (8.0)$	3.79±0.05 hr	22,23,24
0257+080	LHS 5064, G 76-48	DA	0.1*	6680±150	0.57±0.09	6 d:	25,16,4,9
0301-006	SDSS J030407.40-002541.7	DA	10.95±0.98	15000	···	···	26,12
0307-428	1H0307-426	DA	10	25000	$\log g = (8.0)$	···	19
0315-293	NLTT 10480, LHS 5070, LP 887-66	DAZ	0.5*	5340±190	0.58:	···	27,4,28
0315+422	SDSS J031824.19+422651.0	DA	10.12±0.10	10500	···	···	12
0321-026	KUV 03217-0240	DA	< 1 :	27370	$\log g = 8.45$	···	21
0322-019	G 77-50, NLTT 10871, LHS 1547	DAZ	0.120*	5310±100	0.60±0.01	28-33 d:	29,4

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
0323+051	SDSS J032628.17+052136.3	DA	16.87±2.41	25000	···	···	12
0325-857	RE J0317-853, EUVE J0317-855	DA	185-450	33000	1.34±0.03	725 s	DD, 30,31,32,33
0329+005	KUV 0329+0035, SDSS J033145.69+004517.0	DA	13.13±1.00	15500	···	···	26,10,12
0330-000	HE 0330-0002,	DB	···	6000-7000	···	···	20,26,10
···	SDSS J033320.36+000720.6	DA	849.30±51.75	7000:	···	···	12
0340-068	SDSS J034308.18-064127.3	DA	9.96±2.06	13000:	···	···	10,12
0342+004	SDSS J034511.11+003444.3	DA	1.96±0.42	8000	···	···	26,10,12
0350+098	1RXS J035315.5+095700	···	···	···	···	···	21
0410-114	G 160-51, NLTT 12758	DA	1.7±0.2	7440±150	0.83	···	DD, 34,4
0413-077	40 Eri B	DA	0.0073*	16490±84	0.497±0.005	···	35,4
0416-096	NLTT 13015, LP 714-52	DA	6-7.5	5745±405	0.59:	Variable:	4
0446-789	BPM 3523	DA	0.0135*	23450±20	0.49±0.01	···	36,16
0503-174	LHS 1734, LP 777-001	DA	7.3±0.2	5300±120	0.37±0.07	···	37,7
0548-001	G 99-37	DQB	7.3±0.3	6200±200	0.69±0.02	4.117 hr	38,13,39,40,41,42
0553+053	G 99-47,LTT 17891	DA	20±3	5790±110	0.71±0.03	26.8 ± 0.7 min	13,43,44,39,37,9
0616-649	EUVE J0616-649	DA	14.8	50000	$\log g = (8.0)$	···	45
0637+477	GD 77	DA	1.2±0.2	14870±120	0.69	···	1,46
0728+642	G 234-4	DA	0.125*	4500±500	···	···	8
···	SDSS J073549.19+205720.9	DZ	6.12±0.06	6000	···	···	18
0745+302	SDSS J074850.48+301944.8	DA	6.75±0.41	22000:	···	···	11,12
0745+303	SDSS J074853.07+302543.5	DA	11.4	21000±2000	0.81±0.09	···	47
0746+172	SDSS J074924.91+171355.4	DA	13.99±1.30	20000	···	···	12
0749+173	SDSS J075234.96+172525.0	DA	10.30±1.23	9000	···	···	12
0755+358	SDSS J075819.57+354443.7	DA	26.40±3.94	22000	···	···	10,12
0756+437	G 111-49	DA	180-220	8500±500	···	6.68 hr	44,8,9
0801+124	SDSS J080359.93+122944.0	DA	40.70±2.13	9000	···	···	12
0801+186	SDSS J080440.35+182731.0	DA	48.47±2.93	11000	···	···	11,12
0802+220	SDSS J080502.29+215320.5	DA	6.11±1.29	28000:	···	···	11,12
0804+397	SDSS J080743.33+393829.2	DA	65.75±18.52	13000	···	···	10,12
0806+376	SDSS J080938.10+373053.8	DA	39.74±5.41	14000	···	···	11,12

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
0814+043	SDSS J081648.71+041223.5	DA	10.13±8.03	11500	···	···	11,12
0814+201	SDSS J081716.39+200834.8	DA	3.37±0.44	7000	···	···	12
0816+376	GD 90	DA	9	14000	log $g = (8.0)$	···	48,13,43,49,8
0821-252	EUVE J0823-254	DA	2.8-3.5	43200±1000	1.20±0.04	···	50
0825+297	SDSS J082835.82+293448.7	DA	33.40±10.53	19500	···	···	11,12
···	SDSS J083200.38+410937.9	DZ	2.35±0.11*	5900	···	···	18
0825+822	SDSS J083448.63+821059.1	DA	14.44±4.57	27000	···	···	12
0836+201	EG 59 (Mislabeled as EG 61)	DA	2.83±0.19	17000±500	0.82±0.05	···	51,52
0837+273	SDSS J084008.50+271242.7	DA	10	12250	···	···	11
···	SDSS J083945.56+200015.7	DA	3.38±0.49	15000:	···	···	12
0839+026	SDSS J084155.74+022350.6	DA	5.00±0.99	7000	···	···	10,12
0843+488	SDSS J084716.21+484220.4	DA	∼ 3	19000	···	···	10
0848+121	SDSS J085106.12+120157.8	DA	2.03±0.10	11000		···	12
0853+163	PG 0853+164,LB 8915	DBA	0.75-1.0	21200-27700	log $g = (8.0)$	2-24 hr	8,53,9,4
0853+169	SDSS J085523.87+164059.0	DA	12.6±1.0	20000±500	1.12±0.11	···	12,52
···	SDSS J085550.67+824905.3	DA	10.82±2.99	25000		···	12
0855+416	SDSS J085830.85+412635.1	DA	3.38±0.19	7000	···	···	10,12
···	SDSS J090222.98+362539.6	DZ	1.92±0.05*	6300	···	···	18
0903+083	SDSS J090632.66+080716.0	DA	5.98±3.02	17000	···	···	11,12
0904+358	SDSS J090746.84+353821.5	DA	22.40±8.80	16500	···	···	11,12
0907+083	SDSS J091005.44+081512.2	DA	1.01	25000	···	···	12
0908+422	SDSS J091124.68+420255.9	DA	35.20±5.83	10250	···	···	11,12
0911+059	SDSS J091437.40+054453.3	DA	9.16±0.77	17000	···	···	11,12
0912+536	G195-19	DB	∼ 100	7160±190	0.75±0.02	1.3301 d	37,13,54
0915+211	SDSS J091833.32+205536.9	DA	2.04±0.10	14000	···	···	12
0922+014	SDSS J092527.47+011328.7	DA	2.04	10000	···	···	10,12
···	SDSS J092646.88+132134.5	DA	210±25.1	9500±500	0.62±0.10	···	DD, 55
0930+010	SDSS J093313.14+005135.4	DQB:	···	···	···	···	Like LHS 2229, 10
0931+105	SDSS J093356.40+102215.7	DA	2.11±0.49	8500	···	···	11,12
0931+394	SDSS J093409.90+392759.3	DA	1.01	10000	···	···	12
0931+507	SDSS J093447.90+503312.2	DA	7.35±2.21	8900	···	···	11,12

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
0939+211	SDSS J094235.02+205208.3	DA	39.21±4.55	20000	···	···	12
0941+458	SDSS J094458.92+453901.2	DA	15.91±9.10	15500:	···	···	11,12
0945+246	LB 11146a	DA	670	16000±2000	$0.90^{+}_{-0.14}$	···	DD, 56,57
0952+094	SDSS J095442.91+091354.4	DQ	···	···	···	···	11
0957+022	SDSS J100005.67+015859.2	DA	19.74±10.26	9000	···	···	10,12
···	SDSS J100346.66003123.1	DZ	4.37±0.05	6300	···	···	18
1001+058	SDSS J100356.32+053825.6	DA	672.07±118.63	23000	···	···	11,12
1004+304	SDSS J100657.51+303338.1	DA	1.0±0.1	10000	···	···	12
1004+128	SDSS J100715.55+123709.5	DA	5.41:	18000	···	···	Complex B, 11,12
1005+163	SDSS J100759.80+162349.6	DA	19.18±3.36	11000	···	···	12
1011+371	SDSS J101428.09+365724.3	DA	11.09±1.50	10500	···	···	12
1008+290	LHS 2229	DQB	∼ 100	4600	···	···	58,59
1012+093	SDSS J101529.62+090703.8	DA	4.09±0.86	7200	···	···	11,12
1013+044	SDSS J101618.37+040920.6	DA	2.01	10000	···	···	10,12
1015+014	PG 1015+014, SDSS J101805.04+011123.5	DA	120±10	14000	$\log\ g = (8.0)$	105^{+12}_{-8} min	60,23,61,9
1019+200	SDSS J102239.06+194904.3	DA	2.94±0.71	9000	···	···	12
1019+274	SDSS J102220.69+272539.8	DA	4.91±0.31	11000	···	···	12
1017+367	GD 116, Ton 1206	DA	65±5	16000	···	···	62
1018-103	EC 10188-1019	DA	3:	17720	$\log g = 8.52$	···	21
1026+117	LHS 2273	DA	18	7160±170	0.59:	35-45 min	25,9
···	HS 1031+0343	DA	6.1±0.3	···	···	···	16
1031+234	PG 1031+234, Ton 527	DA	∼ 200-1000	∼ 15000	···	5.53 ± 0.05 hr	63,9
1032+214	LP 372-41,NLTT 24770 SDSS J103532.53+212603.5	DA	2.96±0.33	$7000-8000$:	···	···	34,12
1033+656	SDSS J103655.38+652252.0	DQ	4:*	···	···	···	64,10
1036-204	LP 790-29	DQB?	50	7800	$\log\ g = (8.0)$	24-28 yrs	58,65,66,59
1043-050	HE 1043-0502	DB	∼ 820	∼ 15000	···	···	20,67
1045-091	HE 1045-0908	DA	16	10000±1000	$\log\ g = (8.0)$	2.7 hr	68
1050+598	SDSS J105404.38+593333.3	DA	17.41±7.90	9500	···	···	10,12

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
1053+656	SDSS J105628.49+652313.5	DA	29.27±5.78	16500	···	···	10,12
1054+042	SDSS J105709.81+041130.3	DA	2.03	8000	···	···	12
1105-048	LTT 4099	DA	0.0123*	15280±20	0.52±0.01	>3	36,69,16,4
1107+602	SDSS J111010.50+600141.4	DA	6.5	30000	···	···	10,12
1111+020	LSPM J1113+0146, SDSS J111341.33+014641.7	DQB?	···	···	···	···	Like LP 790-29, 10,59
1115+101	SDSS J111812.67+095241.4	DA	3.38±0.72	10500	···	···	11,12
1117-113	SDSS J112030.34-115051.1	DA	8.90±1.02	20000	···	···	12
1120+324	SDSS J112257.10+322327.8	DA	11.38±3.42	12500	···	···	12
···	SDSS J232538.93+044813.1	DZ	6.56±0.09*	7200	···	···	18
1120+101	SDSS J112328.49+095619.3	DA	1.21	9500	···	···	12
1126-008	SDSS J112852.88-010540.8	DA	2	11000	···	···	10,12
1126+499	SDSS J112924.74+493931.9	DA	5.31±0.64	10000	···	···	11,12
1129+284	SDSS J113215.38+280934.3	DA	3.01±0.82	7000:	···	···	12
1131+521	SDSS J113357.66+515204.8	DA	8.64±0.78	22000	···	···	10,12
1135+579	SDSS J113756.50+574022.4	DA	5.00±0.34	7800	···	···	11,12
1136-015	LBQS 1136-0132 SDSS J113839.51-014903.0	DA	22.71±1.26	10500	···	···	70,10,12
1137+614	SDSS J114006.37+611008.2	DA	50.19±17.78	13500	···	···	10,12
1145+487	SDSS J114829.00+482731.2	DA	32.47±7.11	27500	···	···	11,12
···	SDSS J115224.51+160546.7	DZ	2.72±0.04*	6500	···	···	18
1151+015	SDSS J115418.14+011711.4	DA	33.47±2.07	27000:	···	···	10,12
1156+619	SDSS J115917.39+613914.3	DA	20.10±6.70	23000	···	···	10,12
1159+619	SDSS J120150.10+614257.0	DA	11.35±1.53	10500	···	···	11,12
1203+085	SDSS J120609.80+081323.7	DA	760.63±281.66	13000	···	···	11,12
1204+444	SDSS J120728.96+440731.6	DA	2.03	16750	···	···	11,12
1209+018	SDSS J121209.31+013627.7	DA	10.12±0.93	10000	···	90 min	L5-L8 comp. 71,12
1211-171	HE 1211-1707	DB	50	∼ 12000	···	···	20,9
1212-022	LHS 2534, SDSS 121456.39023402.7	DZ	1.92*	5200	···	···	72,10,18
1214-001	SDSS J121635.37-002656.2	DA	59.70±10.23	15000	···	···	26,10,12

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M (M$_\odot$)	$P_{\rm rot}$	References Notes
1219+005	SDSS J122209.44+001534.0	DA	14.70±4.70	14000	···	···	26,10,12
1220+234	PG 1220+234	DA	3:	26540	0.81	···	73,21
1220+484	SDSS J122249.14+481133.1	DA	8.05±2.24	9000	···	···	11,12
1221+422	SDSS J122401.48+415551.9	DA	22.36±3.02	9500	···	···	11,12
1231+130	SDSS J123414.11+124829.6	DA	4.32±0.27	8200	···	···	11,12
1233-052	HE 1233-0519	DA	0.61±0.01	···	···	···	17,16
1235+422	LHS 5222, NLTT 31347	DQ	···	···	···	···	112
1245+413	SDSS J124806.38+410427.2	DA	7.03±1.19	7000	···	···	11,12
1246+296	SDSS J124836.31+294231.2	DA	3.95±0.25	7000:	···	···	12
1246-022	SDSS J124851.31-022924.7	DA	7.36±2.19	13500	···	···	10,12
1248+161	SDSS J125044.42+154957.4	DA	20.71±3.66	10000	···	···	11,12
1252+564	SDSS J125416.01+561204.7	DA	38.86±9.03	13250	···	···	11,12
···	SDSS J125434.65+371000.1	DA	4.10±0.35	10000	···	···	12
1254+345	HS 1254+3440, SDSS J125715.54+341439.3	DA	11.45±0.71	8500	···	···	74,12
1300+590	SDSS J130033.48+590407.0	DA	$\sim$6	6300±300	0.54±0.06	···	DD, 75
1309+853	G256-7	DA	4.9±0.5	$\sim$ 5600	0.5	···	44,8,73
1312+098	PG 1312+098	DA	10	$\sim$ 20000	···	5.42839 hr	23,8
1317+135	SDSS J132002.48+131901.6	DA	2.02	14750	···	···	11,12
1327+594	SDSS J132858.20+590851.0	DA	18	25000	···	···	11
1328+307	G165-7, SDSS J133059.26+302953.2	DZ	0.65*	6440±210	0.57±0.17	···	76,18
1330+015	G62-46	DA	7.36±0.11	6040	0.25	···	DD, 77
1331+005	SDSS J133359.86+001654.8	DQB?	···	···	···	···	Like LHS 2229 10,59
1332+643	SDSS J133340.34+640627.4	DA	10.71±1.03	13500	···	···	10,12
1334+486	GD 359, SDSS J170751.91+353239.97	DA	2.7	···	···	···	78
1339+659	SDSS J134043.10+654349.2	DA	4.32±0.76	15000	···	···	10,12
1346+383	SDSS J134820.79+381017.2	DA	13.65±2.66	35000	···	···	12
1349+545	SBS 1349+5434, SDSS J135141.13+541947.4	DA	761.00±56.42	12000	···	···	79,11,12

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
1350-090	LP 907-037	DA	0.268*	9520±140	0.83±0.03	· · ·	5,80
1405+501	SDSS J140716.66+495613.7	DA	12.49±6.20	20000	· · ·	· · ·	12
1416+256	SDSS J141906.19+254356.5	DA	2.03±0.10	9000	· · ·	· · ·	12
· · ·	SDSS J142625.71+575218.3	DQB	~ 1.2	19830±750	$\log g = 9.0$	· · ·	Pulsating DQ, 81
1425+375	SDSS J142703.40+372110.5	DA	27.04±3.20	19000	· · ·	· · ·	11,12
1428+282	SDSS J143019.05+281100.8	DA	9.34±1.44	9000	· · ·	· · ·	12
1430+432	SDSS J143218.26+430126.7	DA	1.01	24000	· · ·	· · ·	11,12
1430+460	SDSS J143235.46+454852.5	DA	12.29±6.98	16750	· · ·	· · ·	11,12
1440+753	EUVE J1439+750	DA	14-16	20000-50000	0.88-1.19	· · ·	DD, 45
1444+592	SDSS J144614.00+590216.7	DA	4.42±3.79	12500	· · ·	· · ·	10,12
1452+435	SDSS J145415.01+432149.5	DA	2.35±0.88	11500	· · ·	· · ·	11,12
· · ·	LSPM J1459+0851	DA	~ 2	5535±45	$\log g = (8.0)$	· · ·	T4.5±0.5 companion 82
1503-070	GD 175	DA	2.3	6990	0.70±0.13	· · ·	DD, 37
· · ·	SDSS J150746.80+520958.0	DA	65.2±0.3	18000±1000	0.99±0.05	· · ·	DD, 55
1506+399	CBS 229, SDSS J150813.24+394504.9	DA	18.9	18000±2000	0.81±0.09	· · ·	DD, 11,12,47
1509+425	SDSS J151130.20+422023.0	DA	22.40±9.41	9750	· · ·	· · ·	11,12
1511+076	SDSS J151415.65+074446.5	DA	35.34±2.80	10000	· · ·	· · ·	12
1516+612	SDSS J151745.19+610543.6	DA	13.98±7.36	9500	· · ·	· · ·	10,12
1521+191	SDSS J152401.60+185659.2	DA	11.96±1.85	13500	· · ·	· · ·	12
1531-022	GD 185	DA	0.035±0.016*	18620±285	0.88±0.03	· · ·	Uncertain, 83,80
1533+423	SDSS J153532.25+421305.6	DA	5.27±4.05	18500	· · ·	· · ·	10,12
· · ·	SDSS J153642.53+420519.2	DZ	9.59±0.04*	5500	· · ·	· · ·	18
1533-057	PG 1533-057	DA	31±3	20000±1040	0.94±0.18	1.89 ± 0.001 hr	84,80,22,9
1537+532	SDSS J153829.29+530604.6	DA	13.99±3.82	13500	· · ·	· · ·	10,12
1536+085	SDSS J153843.10+084238.2	DA	13.20±4.34	9500	· · ·	· · ·	12
1539+039	SDSS J154213.48+034800.4	DA	8.35±2.60	8500	· · ·	· · ·	10,12
1541+344	SDSS J154305.67+343223.6	DA	4.09±2.67	25000	· · ·	· · ·	12
· · ·	SDSS J155708.04+041156.52	DA	41	· · ·	· · ·	· · ·	78
1603+492	SDSS J160437.36+490809.2	DA	59.51±4.64	9000	· · ·	· · ·	10,12
1610+330	CBS 418	· · ·	· · ·	· · ·	· · ·	· · ·	21

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
1639+537	GD 356	DA	13	7510±210	0.67±0.07	0.0803 d	H in emission, 85,86,87,88
1641+241	SDSS J164357.02+240201.3	DA	2	16500	···	···	11,12
1645+372	SDSS J164703.24+370910.3	DA	2.10±0.67	16250	···	···	11,12
1647+591	G 226-29, V* DN Dra, NLTT 43637	DA	<0.005:	···	···	···	Pulsating DA, 89,69
1648+342	SDSS J165029.91+341125.5	DA	3.38±0.67	9750	···	···	11,12
1650+355	SDSS J165203.68+352815.8	DA	7.37±2.92	11500	···	···	10,12
1650+334	SDSS J165249.09+333444.9	DA	5.07±4.18	9000	···	···	12
1653+385	NLTT 43806, SDSS J165445.69+382936.5	DAZ	0.07*	5900	···	···	90
1658+440	PG 1658+440	DA	2.3±0.2	30510±200	1.31±0.02	6 hr4 d	91,50,9
1702+322	SDSS J170400.01+321328.7	DA	50.11±25.08	23000	···	···	11,12
1713+393	NLTT 44447	DA	1.3	7000±1000	0.59:	···	92
1715+601	SDSS J171556.29+600643.9	DA	2.03	13500	···	···	11,12
1719+562	SDSS J172045.37+561214.9	DA	19.79±5.42	22500	···	···	26,10,12
1722+541	SDSS J172329.14+540755.8	DA	32.85±3.56	10000	···	···	26,10,12
1728+565	SDSS J172932.48+563204.1	DA	27.26±7.04	10500	···	···	10,12
1743-520	BPM 25114	DA	36	$\sim$ 20000	$\log g = (8.0)$	2.84 d	93,43,94
1748+708	G 240-72	DB	$\gtrsim$ 100	5590±90	0.81±0.01	$\gtrsim$ 100 yr	95,96,97,37
1814+248	G 183-35	DA	$\sim$ 14	6500±500	$\log g = (8.0)$	$\sim$ 50 min-yr	44,8
1818+126	G 141-2	DA	$\sim$ 3	6340±130	0.26±0.12	···	DD, 98,25
1820+609	LP 103-294, G 227-28	DBA	$\leq$ 0.1	4780±140	0.48±0.05	months-years	37,8,9
1829+547	G 227-35	DBA	170-180	6280±140	0.90±0.07	$\gtrsim$ 100 yr	99,100,44,37
1900+705	Grw +70° 8247	DA	320±20	16000	0.95±0.02	$\gtrsim$ 100 yr	101,85,102,103,37
1939+401	NGC 6819-8	DA	10.3±1.1	19000±1000	0.50±0.05	···	104,52
1953-011	NLTT 48454, G 92-40	DA	0.1-0.5	7920±200	0.74±0.03	1.44176 d	Magnetic spot, 37,105,106
2010+310	GD 229	DB	520	18000	$\gtrsim$ 1	$\gtrsim$ 100 yr	101,107,97,67
2022+130	SDSS J202501.10+131025.6	DA	10.10±1.76	17000	···	···	12
2039-682	GJ 2149, LTT 8190	DA	0.05*	16050	···	···	83,4
2043-073	SDSS J204626.15-071037.0	DA	2.03	8000	···	···	10,12
2049-004	SDSS J205233.52-001610.7	DA	13.42±3.73	19000	···	···	10,12
2051-208	HK 22880134	DA	0.22-0.29	···	···	Variable	16

Table 1: continued.

WD	Other names	Comp	B_p (MG)	$T_{\rm eff}$ (K)	M ($M_\odot$)	$P_{\rm rot}$	References Notes
2105-820	L 24-52, LTT 8381, G J820.1	DAZ	0.043*	10800±290	0.75±0.03	···	37,83,16,108
2146+005	SDSS J214900.87+004842.8	DA	10.09±4.71	11000	···	···	11,12
2146-077	SDSS J214930.74-072812.0	DA	44.71±1.92	22000	···	···	10,12
2149+002	SDSS J215135.00+003140.5	DA	∼ 300	9000	···	···	10
2149+126	SDSS J215148.31+125525.5	DA	20.76±1.39	14000	···	···	10,12
2153-512	GJ 841B, BPM 27606	DQ	1.3	6100±200	···	···	109,58,42
···	SDSS J220029.09-074121.5	DQ	Very weak?	21240±180	$\log g = (8.0)$	···	2
2202-000	SDSS J220435.05+001242.9	DA	1.02±0.10	22000	···	···	12
2215-002	SDSS J221828.59-000012.2	DA	257.54±48.71	15500	···	···	10,12
2225+176	NLTT 53908	DAZ	0.334±0.003	6250±70	$\log g = (7.87 \pm 0.12)$	···	28
2245+146	SDSS J224741.46+145638.8	DA	42.11±2.83	18000	···	···	10,12
2254+076	SDSS J225726.05+075541.7	DA	16.17±2.81	40000	···	···	12
2329-291	···	DA	0.031	24000	···	···	83,4
2316+123	KUV 813-14, KUV 23162+1220	DA	45±5	11000±1000	$\log g = (8.0)$	17.856 d	23,44
2317+008	SDSS J231951.73+010909.3	DA	9.35:	8300	···	···	11,12
2320+003	SDSS J232248.22+003900.9	DA	21.40±3.36	20000-39000	···	···	26,10,12
2321-010	SDSS J232337.55-004628.2	DB	4.8	15000	···	···	10
2329+267	PG 2329+267	DA	2.31±0.59	9400±240	0.61±0.16	2.767 hr	110,37,9
2343+386	SDSS J234605.44+385337.7	DA	798.1±163.6	26000	···	···	11,12
2343-106	SDSS J234623.69-102357.0	DA	9.17±1.58	8500	···	···	11,12
2359-434	LP 988-088, LTT 9857, LHS 1005	DA	0.0098*	8570±50	0.98±0.04	2.69479	Different B detected, 83,36,111,16,108,4,112

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(1) Schmidt et al. (1992); (2) Dufour et al. (2008a); (3) Lawrie et al. (2013); (4) Kawka and Vennes (2012); (5) Schmidt and Smith (1994);
(6) Valyavin et al. (2005); (7) Bergeron et al. (1992); (8) Putney (1997); (9) Brinkworth et al. (2013); (10) Schmidt et al. (2003);
(11) Vanlandingham et al. (2005); (12) Külebi et al. (2009); (13) Angel (1977); (14) Achilleos et al. (1992b); (15) Liebert et al. (1977);
(16) Koester et al. (2009); (17) Koester et al. (2001); (18) Hollands et al. (2015); (19) Achilleos et al. (1991); (20) Schmidt et al. (2001a);
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(25) Bergeron et al. (1997); (26) Gänsicke et al. (2002); (27) Kawka and Vennes (2011); (28) Kawka and Vennes (2014); (29) Farihi et al. (2011);

(30) Barstow et al. (1995); (31) Ferrario et al. (1997a); (32) Vennes et al. (2003); (33) Burleigh et al. (1999); (34) Arazimova et al. (2009); (35) Fabrika et al. (2000); (36) Aznar Cuadrado et al. (2004); (37) Bergeron et al. (2001); (38) Angel and Landstreet (1974); (39) Bues and Pragal (1989); (40) Dufour et al. (2005); (41) Berdyugina et al. (2007); (42) Vornanen et al. (2010); (43) Wickramasinghe and Martin (1979); (44) Putney and Jordan (1995); (45) Vennes et al. (1999); (46) Giovannini et al. (1998); (47) Dobbie et al. (2013); (48) Angel et al. (1974a); (49) Martin and Wickramasinghe (1984); (50) Ferrario et al. (1998); (51) Claver et al. (2001); (52) Külebi et al. (2013c); (53) Wesemael et al. (2001); (54) Angel et al. (1972); (55) Dobbie et al. (2012); (56) Liebert et al. (1993); (57) Glenn et al. (1994a); (58) Schmidt et al. (1999b); (59) Hall and Maxwell (2008); (60) Wickramasinghe and Cropper (1988); (61) Euchner et al. (2005b); (62) Saffer et al. (1989); (63) Schmidt et al. (1986); (64) Liebert et al. (2003); (65) Bues (1999); (66) Jordan and Friedrich (2002b); (67) Wickramasinghe et al. (2002); (68) Euchner et al. (2005a); (69) Valyavin et al. (2006); (70) Foltz et al. (1989); (71) Schmidt et al. (2005a); (72) Reid et al. (2001); (73) Liebert et al. (2003); (74) Hagen et al. (1987); (75) Girven et al. (2010); (76) Dufour et al. (2006) (77) Bergeron et al. (1993); (78) Kepler et al. (2015); (79) Liebert et al. (1994); (80) Liebert et al. (2005); (81) Dufour et al. (2008b); (82) Day-Jones et al. (2011); (83) Koester et al. (1998); (84) Liebert et al. (1985); (85) Greenstein et al. (1985); (86) Ferrario et al. (1997b); (87) Brinkworth et al. (2004); (88) Wickramasinghe et al. (2010); (89) Schmidt and Grauer (1997); (90) Zuckerman et al. (2011); (91) Schmidt et al. (1992); (92) Kawka and Vennes (2006); (93) Martin and Wickramasinghe (1978); (94) Wegner (1977); (95) Angel et al. (1974b); (96) Angel (1978); (97) Berdyugin and Piirola (1999a); (98) Greenstein and Saha (1986); (99) Angel et al. (1975); (100) Cohen et al. (1993); (101) Angel et al. (1985); (102) Wickramasinghe and Ferrario (1988a); (103) Jordan (1992); (104) Kalirai et al. (2008); (105) Maxted et al. (2000); (106) Brinkworth et al. (2005); (108) Landstreet et al. (2012); (109) Wickramasinghe and Bessell (1979); (110) Moran et al. (1998); (111) Kawka et al. (2007); (112) Gary (2014); (112) Vornanen et al. (2013)

Table 2: Magnetic white dwarfs in synchronous cataclysmic variables

Name	$B_{\mathrm{cyc},1}$ (MG)	$B_{\mathrm{cyc},2}$ (MG)	$B_{\mathrm{Zeem,phot}}$ (MG)	$B_{\mathrm{Zeem,halo}}$ (MG)	T_{eff} (K)	P_{rot} (min)	Mass ($M_\odot$)	References Notes
Polars								
EQ Cet(= RX J0128.8-2339)	34	45	···	···	···	92.8	···	1,2
CV Hyi(= RX J0132.7-6554)	68	···	···	···	···	77.8	···	3
BL Hyi(= H 0139-68)	23	···	21	12	13300	113.6	0.71	4,5,6
RX J0154.0-5947	···	···	···	···	···	80:	···	7
FL Cet(=SDSS J0155+0028)	29	···	···	···	···	87.1	···	8
AI Tri(=RX J0203.8+2959)	38	···	···	···	···	275.5	···	9
BS Tri(=RX J0209.4+2832)	···	···	···	···	···	96.3	···	10
CW Hyi(=RBS0324)	13	···	···	···	···	181.8	···	11
WW Hor(=EXO 023432-5232)	25	···	···	···	···	114.6	1.1	12
EF Eri(=2A0311-227)	21	17	···	15	9500	81	0.9	13,14,15
CSS091109: J035759+102943	···	···	···	···	114.0	···	16	
SDSS J032855.00+052254.2	33	···	···	···	···	122.0	···	17
VY For(=EXO 0329.9-2606)	···	···	···	···	···	228.0	···	18
UZ For(=EXO 0333.3-2554)	56	75:	···	···	···	126.5	0.7	19,20
RX J0425.6-5714	>50	···	···	···	···	85.8	···	21
IW Eri(=RBS0541)	···	···	···	···	···	87.1	···	11
RS Cae(=RX J0453.4-4213)	36	···	···	···	···	102.1	···	22,23
HY Eri(=RX J0501.7-0359)	25:	···	···	···	···	171.3	0.4	24
V1309 Ori(=RX J0515.6+0105)	61:	···	···	···	<20000	479.0	0.6-0.7	25,26,27
IPHAS J052832.69+283837.6	···	···	···	···	···	···	···	28
UW Pic(=RX J0531.5-4624)	19	···	···	···	···	133.4	···	29,30
BY Cam(=H 0538+608)	41	···	···	···	···	199.3	1.04	31,32,33
								P_{orb}=201.3
RX J0649.8-0737	···	···	···	···	···	265:	···	34
LW Cam(=RX J0704.2+6203)	20	···	···	···	···	97.3	···	35
CSS081231: J071126+440405	···	···	···	···	···	117.2	···	36
HS Cam(=RX J0719.2+6557)	···	···	···	···	···	98.2	0.75	37
V654 Aur(=SDSS J072910.2+365838)	···	···	···	···	···	150	···	38

Table 2: continued.

Name	$B_{cyc,1}$ (MG)	$B_{cyc,2}$ (MG)	$B_{Zeem,phot}$ (MG)	$B_{Zeem,halo}$ (MG)	T_{eff} (K)	P_{rot} (min)	Mass ($M_\odot$)	References Notes
RX J0749.1-0549	···	···	···	···	···	215:	···	34
EU Lyn(=SDSS J075240.45+362823.2)	···	···	···	···	···	164	···	38
V516 Pup(=RX J0803.4-4748)	39	···	···	···	···	136.8	···	39
CSS100108: J081031+002429	···	···	···	···	···	116.2	···	40
VV Pup(=2E 0812.8-1853)	31	56	···	···	12100	100.4	0.73	6,41
EG Lyn(=RBS0696)	···	···	···	···	···	99.4	···	11
EU Cnc(=G 186)	41	···	···	···	···	125.4	$\geq$0.68	42,43
FR Lyn(=SDSS J085414.02+390537.2)	44	···	···	···	···	113.3	···	44,45
SDSS J085909.18+053654.5	···	···	···	···	···	143.8	···	45
SDSS J092122.84+203857.1	32	···	···	···	···	84.2	···	46,47
HU Leo(=SDSSJ 092444.48+080150.9)	···	···	···	···	···	131.24	···	48
MN Hya(=RX J0929.1-2404)	42	···	···	···	···	203.4	···	49,50
SDSSJ 093839.25+534403.8	···	···	···	···	···	$\lesssim$ 120	51	
RX J0953.1+1458	···	···	···	···	···	102	···	7
1RXS J100211.4-192534	···	···	···	···	···	107	$\sim$0.5	52
1RXS J100734.4-201731	94	···	···	···	···	208.6	0.8	52,53
GG Leo(=RBS0842)	23	···	···	···	···	79.9	$\sim$1.0	54,55
V381 Vel(=RX J1016.9-4103)	52	···	···	···	···	134	···	56
FH UMa(=RBS0904)	>20	···	···	···	···	80	···	57
EK UMa(=1E 1048.5+5421)	47	···	···	···	···	114.5	···	58,59
AN UMa(=PG 1101+453)	36	···	···	···	···	114.8	···	60,61
ST LMi(=CW 1103+254)	12	21	19	···	10800	113.9	0.45	6,62,63,64
AR UMa(=1ES 1113+432)	$\gtrsim$160	240	230	···	$\sim$20000	115.9	···	65,66
DP Leo(=1E 1114+18.2)	31	76	···	···	13500	89.8	···	11,67,68
V1033 Cen(=RX J1141.3-6410)	20	···	···	···	···	189.4	···	69,70
EU UMa(=RX J1149.9+2844)	43	···	···	···	···	90.1	···	71,72
SDSSJ 120724.69+223529.8	···	···	···	···	···	···	···	73
V379 Vir(=SDSS J121209.31+013627.7)	7	···	···	···	$\sim$10000	88.4	···	74,75,76 LARP
WD 1248+161(=SDSS J125044.42+154957.4)	20	···	···	···	10000	86.3	···	77 LARP

Table 2: continued.

Name	$B_{cyc,1}$ (MG)	$B_{cyc,2}$ (MG)	$B_{Zeem,phot}$ (MG)	$B_{Zeem,halo}$ (MG)	T_{eff} (K)	P_{rot} (min)	Mass ($M_{\odot}$)	References Notes
EV UMa(=RX J1307.8+5351)	30:	···	···	···	···	79.7	···	78
2XMM J131223.4+173659	$\leq$10	···	···	···	···	91.9	···	79
V1043 Cen(=RX J1313.2-3259)	56	···	···	···	15000	251.4	···	80,81
SDSS J133309.19+143706.9	···	···	···	···	···	132	···	46,47
SDSS J134441.83+204408.4	65:	···	···	···	···	110:	···	82
V834 Cen(=1E 1405-45.1)	23	···	22	23	14300	101.5	0.66	6,83,84,85,86
SDSS J142256.31-022108.0	···	···	···	···	···	202:	···	87
V895 Cen(=EUVE J1429-38.0)	···	···	···	···	13800	285.9	···	6,88
IGR J14536-5522	20	···	···	···	···	189.4	···	89
CSS100216: J150354-220711	···	···	···	···	···	133.4	···	40
SDSS J151415.65+074446.5	36	···	···	···	10000	88.7	···	77
								LARP
SDSS J153023.64+220646.4	···	···	···	···	···	···	90	
BM CrB(=SDSS J154104.66+360252.9)	33	···	···	···	···	84	···	44,45
2XMM J154305.5-522709	···	···	···	···	···	143:	···	91
MR Ser(=PG 1550+191)	25	···	28	25	14000	113.5	0.5	6,64,92
AP CrB(=RX J1554.2+2721)	110	···	144	···	~20000	151.9	···	93,94,95
V519 Ser(=1RXS J161008.0+035222)	15:	···	···	···	···	190.5	···	96,97
V1189 Her(=SDSS J162936.53+263519.5)	···	···	···	···	···	134	···	44
1RXS J170053.7+400354	···	···	···	···	···	116.4	···	38
V1007 Her(=RBS1646)	50	···	···	···	···	119.9	···	98
V2301 Oph(=1H 1752+081)	···	···	···	7	10000	113.0	0.8	99,100,101
V884 Her(=RX J1802.1+1804)	150	···	···	150	···	113.3	···	102,103
AM Her(=3U1809+50)	14	···	13	···	19800	185.6	0.78	104,105,106
XGPS-I J183251-100106	···	···	···	···	···	89.0	···	107
V347 Pav(=RX J1844.7-7418)	10:	20	···	···	12300	90.1	···	6,108,109
1RXS J184542.4+483134	···	···	···	···	···	79.1	···	110
MT Dra(=RX J1846.9+5538)	15:	···	···	···	···	128.7	···	111
EP Dra(=1H 1903+689)	···	···	···	16	···	104.6	0.43	112
CTCV J1928-5001	20:	···	···	···	···	101.0	···	113,114
QS Tel(=RX J1938.6-4613)	47	75:	60	···	17500	139.9	···	115

Table 2: continued.

Name	$B_{\rm cyc,1}$ (MG)	$B_{\rm cyc,2}$ (MG)	$B_{\rm Zeem,phot}$ (MG)	$B_{\rm Zeem,halo}$ (MG)	$T_{\rm eff}$ (K)	$P_{\rm rot}$ (min)	Mass ($M_\odot$)	References Notes
V1432 Aql(=RX J1940.2-1025)	30:	···	···	···	∼35000	202.5	1.2	116,117,118 $P_{\rm orb}$=201.9
CSS100805:J194428-420209	···	···	···	···	···	91.9	···	119
V393 Pav(=RX J1957.1-5738)	···	···	···	16	···	98.8	···	120
QQ Vul(=1E 2003+22.5)	30:	···	···	···	···	222.5	0.58	64, 121, 122
V349 Pav(=Drissen V211b)	···	···	···	···	···	159.7	···	123
V4738 Sgr(=RX J2022.6-3954)	67	···	···	···	···	78.0	···	3
SDSS J205017.83-053626.7	···	···	···	···	···	94.2	···	124
HU Aqr(=RX J2107.9-0517)	37	···	20:	···	14000	125.0	0.9	6,125,126,127
V1500 Cyg(=Nova Cyg 1975)	$\gtrsim$25	···	···	···	70000	197.5	0.9	128,129 $P_{\rm orb}$=201.0
CD Ind(=RX J2115.7-5840)	11	···	···	···	···	109.6	0.79	130,131,132 $P_{\rm orb}$=110.9
CE Gru(=Grus V1)	32	···	···	···	···	108.5	∼1.0	133,134,135
SDSS J215427.19+155713.0	···	···	···	···	···	96.9	···	82
V388 Peg(=RX J2157.5+0855)	20:	···	···	···	···	202.5	···	136
SWIFT J2218.4+1925	···	···	···	···	···	129.5	0.97	137,138
2XMM J225036.9+573154	···	···	···	···	···	174.2	···	139
CP Tuc(=AX J2315-592)	···	···	10	···	···	89.0	0.68	33, 140, 141
1RXS J231603.9-052713	25	···	···	···	···	209.5	1.0	96
SWIFT J2319.4+2619	···	···	···	···	···	180.6	···	142
Pre-polars								
SDSS J030308.35+005444.1	···	···	8	···	9150	193.6	0.84	143
SDSS J083751.0+383012.5	···	···	···	···	···	178.8	···	87
HS 0922+1333	66	81	···	···	≤8000	242.4	···	144,145,146
WX LMi(=HS 1023+3900)	61	70	···	···	···	166.9	···	147,148,149
IL Leo(=SDSS J103100.55+202832.2)	42	···	···	···	9500	83.2	···	150
SDSS J105905.06+272755.4	57	···	···	···	≤ 8500	150:	···	150
SDSS J120615.73+510047.0	108	···	···	···	9000	197:	···	151
PZ Vir(=J132411.57+032050.4)	63:	···	···	···	$\lesssim$ 7500	158.7	···	152,153,154

Table 2: continued.

Name	$B_{\rm cyc,1}$ (MG)	$B_{\rm cyc,2}$ (MG)	$B_{\rm Zeem,phot}$ (MG)	$B_{\rm Zeem,halo}$ (MG)	$T_{\rm eff}$ (K)	$P_{\rm rot}$ (min)	Mass ($M_\odot$)	References Notes
MQ Dra(=SDSS J155331.11+551614.4)	58	···	···	···	$\lesssim$10000	263.5	···	152,154
SDSS J204827.91+005008.9	62:	···	···	···	7500	252	···	154

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(2000); (133) Tuohy et al. (1988); (134) Wickramasinghe et al. (1991); (135) Ramsay and Cropper (2002); (136) Tovmassian et al. (2000); (137) Thorstensen and Halpern (2013); (138) Bernardini et al. (2014); (139) Ramsay et al. (2009); (140) Beuermann et al. (2007); (141) Ramsay et al. (1999b); (142) Shafter et al. (2008); (143) Parsons et al. (2013); (144) Reimers and Hagen (2000); (145) Tovmassian and Zharikov (2007); (146) Vogel et al. (2011); (147) Reimers et al. (1999); (148) Schwarz et al. (2001); (149) Vogel et al. (2007); (150) Schmidt et al. (2007); (151) Schwope et al. (2009); (152) Szkody et al. (2003); (153) Southworth et al. (2015); (154) Schmidt et al. (2005b);

Table 3: Magnetic white dwarfs in asynchronous cataclysmic variables

Name	B (MG)	P_{rot} (min)	P_{orb} (min)	Mass ($M_\odot$)	References Notes
V1033 Cas(=IGR J00234+6141)	···	563.5	242.0	0.9	1,2
V709 Cas(=RX J0028.8+5917)	···	312.8	320.0	0.96	3,4,2
V515 And(=XSS J00564+4548)	···	465.5	163.9	0.79	5,6,7
XY Ari(=H 0253+193)	···	206.3	363.9	1.0	8,9,2
GK Per(=Nova Persei 1901)	···	351.3	2875.4	0.9	10,11,2
V1062 Tau(=H 0459+246)	···	3704	598.9	0.7	2,4,12
UU Col(=RX J0512.2-3241)	10-30:	863.5	207.0	0.6	13,14,15
Paloma(=1RXS J052430.2+424449)	···	8175.4:	157.2	···	16
TV Col(=2A 0526-328)	···	1909.7	329.2	0.78	17,18,2
TX Col(=1 H0542-407)	···	1911	343.2	0.7	19,2
V405 Aur(=RX J0558.0+5353)	32	545.4	249.6	0.89	20,21,22,2
MU Cam(=1RXS J062518.2+733433)	···	1187.2	283.1	0.74	23,2
V902 Mon(=IPHAS J062746.41+014811.3)	···	2210	489.6	···	23b
V647 Aur(=1RXS J063631.9+353537)	···	932.9	207.9	0.74	24,7
V418 Gem(=1RXS J070407.9+262501)	···	480.7	262.8	$\lesssim$0.5	25,26
BG CMi(=3 A0729+103)	$\sim$4	913.5	194.1	0.7	27,28,2
V667 Pup(=Swift J0732.5-1331)	···	512.4	336.2	···	4
PQ Gem(=RX J0751.2+1444)	9-21:	833.4	311.6	0.65	29,30,31,2
HT Cam(=RX J0757.0+6306)	···	515.1	86.0	0.6	32,33
DW Cnc(=HS 0756+1624)	···	2314.7	86.1	···	34
WX Pyx(=1E 0830.9-2238)	···	1559.2	318:	···	35
EI UMa(=1H0832+488)	···	741.6	386.1	···	36,37
IGR J08390-4833	···	1480.8	480:	0.95	7
VZ Sex(=1RXS J094432.1+035738)	···	2450	214.1	···	38,4
YY Dra(=DO Dra)	···	529.3	238.1	0.8	39
V1025 Cen(=RX J1238.2-3842)	···	2146.6	84.6	0.5	40,2
EX Hya(=4U 1249-28)	···	4021.6	98.3	0.79	41,42
IGR J15094-6649	$\gtrsim$ 10	809.4	353.4	0.89	43,44,7
NY Lup(=1RXS J154814.5-452845)	>4	693.0	591.8	1.09	44,45,2

Table 3: continued.

Name	$B_{\rm cyc}$ (MG)	$P_{\rm rot}$ (s)	$P_{\rm orb}$ (min)	Mass ($M_\odot$)	References Notes
IGR J16500-3307	···	571.9	217.0	0.92	7
1RXS J165443.5-191620	···	546.7	222.9	···	46
V2400 Oph(=RX J1712.6-2414)	9-27	927.7	205.8	0.8	47,48,2
IGR J17195-4100	···	1053.7	240.3	0.86	49,50,7
V2731 Oph(=1RXS J173021.5-055933)	5:	128.0	925.3	0.96	51,52,53
AX J1740.1-2847	···	730	125:	···	54,55
AX J1740.2-2903	···	628.6	343.3	···	56
V1323 Her(=1RXS J180340.0+401214)	···	1520.5	264.1	0.69	51,26
1RXS J180431.1-273932	···	494	···	0.8	57
DQ Her(=Nova Her 1934)	···	70.8	278.8	0.60	58,59,
IGR J18173-2509	···	1663.4	91.9	0.96	7,56
IGR J18308-1232	···	1820	322.4	0.85	7,56
AX J1832.3-0840	···	1552.3	···	···	54
AX J1853.3-0128	···	477.6	87.2	···	56
V1223 Sgr(=4 U1851-31)	···	745.5	201.9	0.65	60,61,2
IGR J19267+1325	···	935.1	206.9	···	56
V2306 Cyg(=WGA J1958.2+3232)	8:	1466.7	261.0	0.8	62,63,64,2
IGR J19552+0044	···	4960	101.7	0.77	56,65
AE Aqr(=1E 2037.5-0102)	···	33.1	592.8	0.63	66,67,68
V2069 Cyg(=RX J2123.7+4217)	···	743.1	448.8	0.82	7,69
1RXS J213344.1+510725	$\gtrsim$20	570.8	431.6	0.93	70,71,72
FO Aqr(=H 2215-086)	···	1254.5	290.9	0.61	73,2
AO Psc(=H 2252-035)	···	805.2	215.5	0.55	74,75,2
CC Scl(=1RXS J231532.3-304855)	···	389.5	840.9	···	76
V598 Peg(=SDSS J233325.92+152222.1)	···	2500	83.12	···	77,78
V455 And(=HS 2331+390)	···	67.6	81.1	···	79

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(15) Katajainen et al. (2010); (16) Schwarz et al. (2007); (17) Augusteijn et al. (1994); (18) Rana et al. (2004); (19) Buckley and Tuohy (1989); (20) Harlaftis and Horne (1999); (21) Skillman (1996); (22) Piirola et al. (2008); (23) Staude et al. (2003); (24) Kozhevnikov (2014); (25) Patterson et al. (2011); (26) Anzolin et al. (2008); (27) Kim et al. (2005); (28) Chanmugam et al. (1990); (29) Hellier (1997a); (30) Evans et al. (2006); (31) Potter et al. (1997); (32) Kemp et al. (2002); (33) de Martino et al. (2005); (34) Patterson et al. (2004); (35) Joshi et al. (2011); (36) Baskill et al. (2005); (37) Thorstensen (1986); (38) de Martino (2007); (39) Haswell et al. (1997); (40) Buckley et al. (1998b); (41) Mauche et al. (2009); (42) Beuermann and Reinsch (2008); (43) Pretorius (2009); (44) Potter et al. (2012); (45) de Martino et al. (2006a), (46) Scaringi et al. (2011); (47) Buckley et al. (1995); (48) Vaeth (1997); (49) Girish and Singh (2012); (50) Pretorius (2009); (51) Gänsicke et al. (2005); (52) de Martino et al. (2008); (53) Butters et al. (2009); (54) Kaur et al. (2010); (55) Britt et al. (2013); (56) Thorstensen and Halpern (2013); (57) Masetti et al. (2012); (58) Zhang et al. (1995); (59) Bloemen et al. (2010); (60) Osborne et al. (1985); (61) Jablonski and Steiner (1987); (62) Norton et al. (2002); (63) Zharikov et al. (2002); (64) Uslenghi et al. (2001); (65) Bernardini et al. (2013); (66) Welsh et al. (1993); (67) de Jager et al. (1994); (68) Echevarría et al. (2008); (69) Thorstensen and Taylor (2001); (70) Katajainen et al. (2007); (71) Bonnet-Bidaud et al. (2006); (72) Anzolin et al. (2009); (73) Patterson et al. (1998); (74) Kaluzny and Semeniuk (1988); (75) Hellier et al. (1991); (76) Woudt et al. (2012a); (77) Southworth et al. (2007); (78) Hilton et al. (2009); (79) Araujo-Betancor et al. (2005b)