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The Isolated Magnetic White Dwarfs

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About one star in four will end its life as a magnetic white dwarf. Although magnetism is a very common feature in degenerate stars, we still do not know much about its origin and evolution. Our volume-limited spectropolarimetric survey of white dwarfs reveals statistical characteristics that may help to understand it.

Introduction

White dwarfs (WDs) are the last stage of more than 90% of stars, and more than 20% of those stars possess strong magnetic fields. The field strengths encountered range over four dex, from tens of kG up to about 1000 MG, and are roughly dipolar. On the timescale of a few decades of observations, they show no evidence of secular changes. The origin of these fields is a subject of active debate. The old fossil-field theory of retention and compression amplification of main sequence star fields was rejected by Kawka & Vennes (2004) because this process cannot produce nearly enough magnetic WDs (MWDs). Among the more recent proposals the most plausible seem to be dynamo models, such as a dynamo operating in a convective main sequence stellar core with the flux retained until final collapse (for example, Stello et al., 2016), or a dynamo created during the common-envelope phase leading to the merger of a close binary into a single WD (for example, Tout et al., 2008). A contemporary dynamo acting in the degenerate stellar core after its crystallisation has started has recently been proposed to explain at least the weakest fields of MWDs (Isern et al., 2017).

Observations may help to discriminate amongst different scenarios but may also lead to conflicting conclusions. As with many physical phenomena, our understanding of stellar magnetism depends on the constraints that we are able to obtain from observations. We have just finished carrying out a nearly complete volume-limited survey of magnetic fields in nearby WDs, providing the first data set from which a clear overview of the occurrence and evolution of the fields in MWDs can be obtained. In this article we describe the new data and discuss some of the ways in which they may be used.

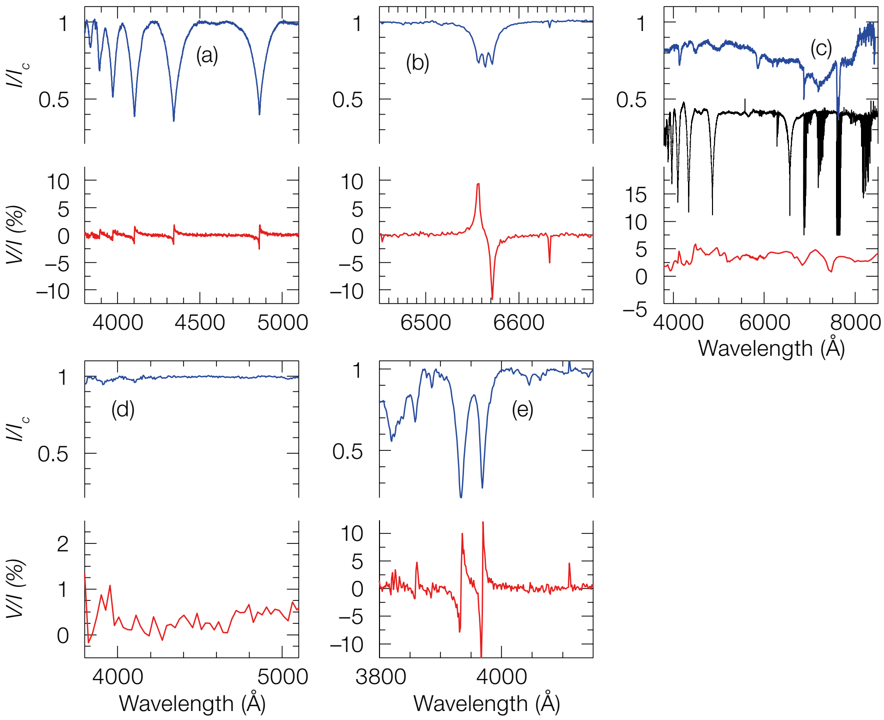

Figure 1. Panel (a) shows the intensity and the circular polarisation spectrum of the weakly magnetic star WD 1105-340 (which has an estimated field modulus of about 150 kG). The H lines do not split when observed with a normal spectrograph, but they may be broadened and polarised, and fields can be easily detected via spectropolarimetric techniques. For fields stronger than a few hundred kG, H Balmer lines split in intensity, as shown in panel (b) for the case of star WD 0011-721 (which exhibits a ~ 350 kG field modulus). The lines are both split and circularly polarised, so the magnetic field may be detected both via normal spectroscopy and via spectropolarimetry. The blue solid line of panel (c) shows the intensity spectrum of the H-rich white dwarf Grw+70°8247, with a field that has a strength of several hundred MG. At that field strength, the components of the spectral lines wander in the spectrum. A blue component of H-α appears at 5900 Å and a red component of H-β at 4200 Å. Without a magnetic field, the spectrum of this star would appear like the spectrum of 40 Eri B, shown with black solid lines. The red solid line is the spectrum of circular polarisation. In the case of featureless white dwarfs, such as WD 0708-670 of panel (d), a star that is so cool that no lines are formed, the magnetic field may be detected only in polarimetric mode, if the field is strong enough to polarise the continuum (we are talking about fields strength > 1MG). However, if the otherwise featureless spectrum has metal lines (DZ stars), the presence of a weak magnetic field may be revealed by their polarisation, as in the case of WD 1009-184 shown in panel (e), where deep Ca lines appear strongly polarised. All data in the Figure were obtained with FORS2, except for those of Grw+70°8247, obtained with ISIS, and of 40 Eri B, obtained with ESPaDOnS.

Detection techniques for magnetic fields in white dwarfs

It is helpful to start by discussing the ways in which the field of a WD may be detected and measured, and several situations are illustrated in Figure 1.

The spectral types of WDs are designated by two or more letters, starting with the letter D, which means “degenerate”, followed by a capital letter, A, B, C, Q or Z, that reflects the presence of specific spectral features. “A” means that hydrogen lines are present, and “B” that only helium lines are visible in the spectrum. A DC star exhibits a featureless spectrum, while DQ stars have spectra dominated by atomic and/or molecular carbon lines. The letter Z means that the spectrum of the star shows metal lines.

A spectral line formed in a stellar atmosphere in the presence of a magnetic field may be broadened or split into various components, and is polarised. For fields of less than about 1 MG (1 MG = 100 Tesla), Zeeman splitting of a spectral line observed in intensity is linearly proportional to the field modulus, and circular polarisation of line components is sensitive to the longitudinal component of the magnetic field averaged over the stellar disc. Broadening effects, such as pressure broadening and the low resolving power commonly used for WD spectroscopy, can wash out the Zeeman effect in intensity. In circular polarisation, the Zeeman polarisation signature is more easily detectable than Zeeman splitting, especially for fields weaker than a few hundred kG. The signal of linear polarisation is smaller than that of circular polarisation and is not often used for WD field detection.

The interpretation of the spectra of magnetic degenerate stars is more complicated than for most of other kinds of stars, because the field may be so strong that it departs from the linear Zeeman regime. We need to consider situations in which the fields are so strong (around 10^9 G) that the magnetic and Coulomb forces are of comparable strength, and both spectral and polarisation structure may be totally different from the familiar Zeeman effect.

The take-away message is that spectroscopy of WDs with strong lines is sensitive to fields with a strength between roughly several hundred kG and perhaps 100 MG, while spectropolarimetry makes possible detection limits of order 1 kG. In addition, some WDs are cool enough to have no spectral lines at all. Magnetic fields in these featureless DC WDs cannot be detected with spectroscopy, but may still be revealed by polarimetry if they are strong enough to polarise the continuum (at least of order 1 MG).

Earliest studies of stellar magnetic fields

The most natural reason that comes to mind to explain the occurrence of a magnetic field in a stellar atmosphere is the presence of a dynamo acting at the time of the observations, as in the Sun. Dynamo action is a very complex phenomenon, but the essential idea is that shear in a very good conductor (a stellar interior, for example) can amplify a tiny seed field to an easily detectable strength. One might suspect that shear, and thus field strength, is also related to the stellar rotation velocity, and may be higher in more rapidly rotating stars than in more slowly rotating stars. We now understand that this link between stellar rotation and dynamo action is actually not so direct, but at the time of the earliest observational efforts a driving idea was that magnetic fields may be closely connected with stellar rotation. A connection between stellar rotation and dynamo action was the idea that Babcock wanted to test when he started his spectropolarimetric observations just after WWII (Babcock, 1947). At the same time, Blackett (1947) predicted that WDs would spin rapidly because of the conservation of angular momentum as they collapse, and that consequently they should host extremely strong fields.

WDs were too faint for Babcock's instruments, but various kinds of main sequence stars were systematically investigated, and it soon became clear that, contrary to earlier expectations, magnetic fields were present mainly in the slowly rotating, chemically peculiar stars of the upper main sequence, the so-called Ap and Bp stars (Babcock, 1958). The presence of a magnetic field could not be ascribed to an active dynamo, not only because these stars rotate particularly slowly, but also because they lack a convective envelope, which is the typical environment in which a dynamo could act. The proposed explanation was that the magnetic field of an Ap or Bp star could be the fossil remnant of a magnetic field that was present in a previous stage of the star's life, maybe even the interstellar field frozen into the matter during star formation.

The motivation for the search for magnetic fields in WDs in the late 1960s was the idea (originally proposed by former ESO Director General Lodewijck Woltjer to one of us more than 50 years ago) that, because of flux conservation, WDs that were descendants of Ap and Bp stars could host fields as strong as 100 MG. These attempts led eventually to the discovery of the first MWD (Kemp et al., 1970). But the fact that MWDs were discovered by searching for the descendants of Ap/Bp stars does not mean that MWDs are in fact the descendants of Ap/Bp stars, and indeed this explanation has been called into question now that it is clear that MWDs are much more common in stellar samples than magnetic Ap/Bp stars are.

Motivation of a spectropolarimetric volume-limited survey

A key strategy for understanding the magnetic fields that were gradually discovered, over 50 years, in a small fraction of WDs has been to search for statistical characteristics of the observed magnetic fields, and correlations with other stellar parameters. These correlations may help us to find an explanation for the origin of the magnetic fields.

It has been suspected for decades that magnetic fields are found more frequently in cooler than in hotter WDs (remember that WDs simply cool down with time, so that usually cooler means older and hotter means younger). However, it has been proposed that this result could be an artefact due to an observational bias. Liebert (1988) noted that magnetic field are more frequent in more massive than in less massive WDs. Because of the nature of degenerate matter, higher-mass WDs are smaller, hence fainter than lower mass stars, therefore a magnitude-limited survey would tend to focus on low-mass WDs (the unconscious bias of most surveys). Liebert, Bergeron & Holberg (2003) suggested that this bias is more effective in hotter massive stars than in cooler massive stars, creating thereby the false impression that magnetic fields are more common in cooler than in hotter stars. Another important finding, again by Liebert et al. (2005), was that when we observe a system composed of a WD and a main sequence star in a non-interacting but very close binary system, we never detect a MWD.

These two findings led to the hypothesis that a magnetic field could be the byproduct of the merging of two stars in a close binary system, creating a single

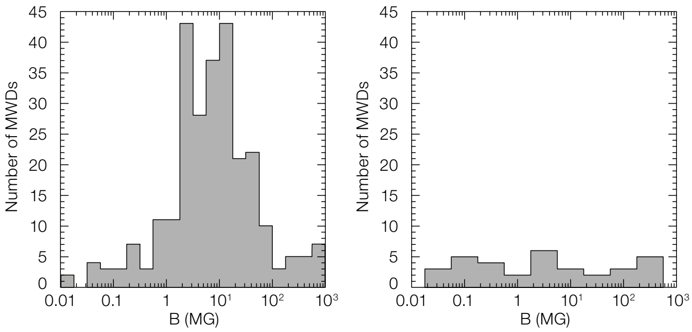

Figure 2. Left panel: the distribution of the field strength for the MWDs obtained using literature data, mainly low-resolution intensity spectra (from Ferrario, Wickramasinghe & Kawka, 2020). Right panel: the distribution of field strength in MWDs obtained from our volume-limited spectropolarimetric survey.

isolated MWD (Tout et al., 2008). Numerical simulations by Briggs et al. (2015) predicted that the distribution of the field strength produced by merging is very similar to the distribution observed among all known MWDs. A variation of this mechanism was proposed to explain another observed characteristic, that WDs which exhibit metal lines in their atmospheres are more frequently magnetic than normal WDs. The presence of metal lines in the atmospheres of some WDs is due to the accretion of a debris disc around the star, probably the remnant of a planetary system. It has been proposed that, similarly to what happens in the merging scenario, the angular momentum lost by the material accreting onto the WD is transformed into shear and then into magnetic energy (Schreiber et al., 2021).

The reality is that some of the observational statistics presented in recent years can easily be called into question. Firstly, it can be reasonably argued that the fact that the observed field strength distribution peaks around 1 to 100 MG is actually the result of an observational bias. Most of the discoveries of MWDs come from the observations of Zeeman-split lines observed in low-resolution spectroscopy by the Sloan Digital Sky Survey, which is effectively sensitive to the range 1 to 100 MG. In contrast, it has been suggested that there may exist a population of WDs with field strengths as weak as a few kG, and that this population could actually be quite large (Aznar Cuadrado et al., 2004). It is also suspected that the spectra of WDs with fields of more than 100 MG may frequently appear in the SDSS spectra as simply noisy, and the fields may be missed. Secondly, the evidence is that DZ stars appear more frequently magnetic than non-DZ stars.

However, we cannot really say whether WDs with metal lines are more frequently magnetic than WDs without metal lines, or whether metal lines allow the observer to detect weak magnetic fields that would be undetected if metal lines were not present in the stellar atmosphere (we recall that only very strong magnetic fields may be detected in featureless stars, or in stars with very weak H lines).

New insights from a volume-limited spectropolarimetric survey of isolated white dwarfs

To obtain the clearest possible view of the occurrence of detectable magnetic fields in WDs, we decided to look at the sample of all WDs within 20 pc of the Sun (about 150 WDs) using spectropolarimetric techniques. These targets represent a fairly unbiased sample of the end points of more than 90% of completed stellar evolution in our part of the Milky Way, and thus provide evidence about the production rate and evolution of both WDs and of their magnetic fields as a function of time over the past 10 Gyr. This sample is small enough to enable us to carry out a careful analysis of each individual member, but large enough to provide some meaningful statistical results. Target selection was possible thanks to Gaia Data Release 2 data (Hollands et al., 2018). The use of spectropolarimetry allowed us to greatly expand the range of strengths within which fields could be detected.

Our survey was carried out with the FOcal Reducer and low dispersion Spectrograph 2 (FORS2) at ESO's Very Large Telescope, the Echelle SpectroPolarimetric Device for the Observation of Stars (ESPaDOnS) at the Canada-France-Hawai'i Telescope, and the Intermediate-dispersion Spectrograph and Imaging System (ISIS) at the William Herschel Telescope. In the course of our survey we observed about 100 WDs, typically at least a couple of times each (Bagnulo & Landstreet, 2021). Most of our targets had been previously observed only in low-dispersion spectroscopic classification surveys. Our new

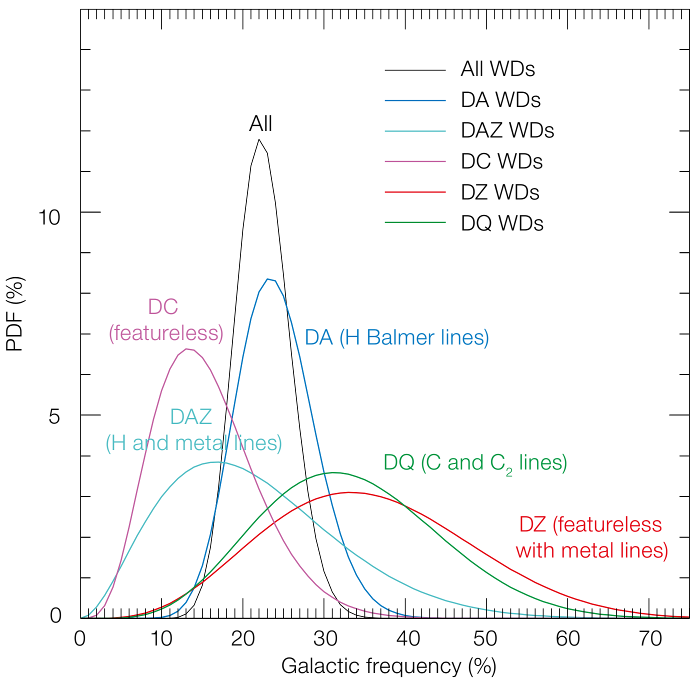

Figure 3. The probability density functions (PDFs) of the Galactic frequency of MWDs of various spectral classes.

observations are characterised by a magnetic field detection precision typically 1 dex better than previous spectropolarimetric surveys, and two dex better than what is obtainable with spectroscopy. We discovered 13 new MWDs, which is about 40% of all MWDs now known in the local 20-parsec volume. In addition to the observational effort, we also had to associate to each star its own stellar parameters, which was possible thanks to a rich literature.

Results

Figure 2 shows the histogram of the distribution of the magnetic field strength of all known WDs before our survey, compared with what we have found in the local 20-parsec volume. Our results suggest a picture quite different from that proposed in the recent literature, with a field strength distribution that is almost constant per decade of field strength from about 40 kG to 1000 MG.

We have correlated the frequency of occurrence of magnetic fields by stellar type, as a function of age, and as a function of mass. Having found that 33 out of 152 WDs are magnetic, Bayesian statistics enables us to calculate the probability density function for the Galactic WDs, as shown in Figure 3. We infer that the frequency of magnetism in all WDs has a peak around 22% and likely ranges between 20% and 25%. This is such a large number that we must now regard magnetism not as a fringe interest, but as an important contributor to WD physics.

The sample of WDs in the local 20-parsec volume is dominated by DA WDs, which represent more than 50% of the total (see blue solid line in Figure 3). The frequency of magnetic fields in DZ stars indeed seems higher than that in normal DA WDs (brown solid line), while featureless DC stars seem to be outliers, in that the field frequency peaks around only 13%. But in DC stars we cannot detect fields weaker than a few MG; therefore, if the field strength distribution is flat, the percentage of magnetic DC stars is probably at least twice as high as measured, and comparable with that of DA WDs. The real outliers of this plot are the DQ stars, because in this kind of star, as for DC

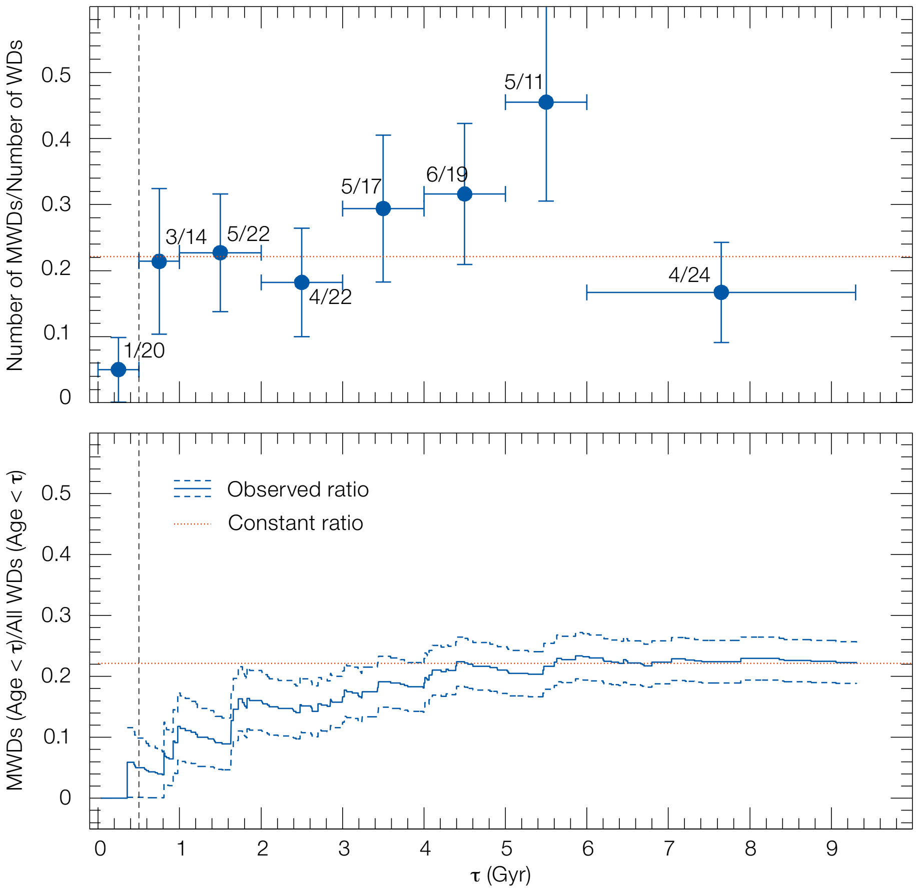

Figure 4. The top panel shows the ratio between the number of MWDs and the number of all WDs that are produced during the interval of time represented by the horizontal error bars, as a function of cooling age τ. The fraction *M/N* printed close to the symbols represents the number of MWDs (*M*) and all WDs (*N*) in the interval of time. The vertical error bars represent the uncertainties associated with the frequency of the occurrence of MWDs extrapolated to the Galactic WD population. In the bottom panel, the blue solid line represents the ratio between the observed MWDs younger than the abscissa value τ and all WDs younger than τ; the blue dashed lines show the $\pm$ 1-σ uncertainties of that frequency. The red dotted line refers to a constant ratio between MWDs and all WDs. The region shaded in red highlights the interval of time with a marked deficiency of MWDs.

stars, only fields stronger than a few MG can be detected. However, the magnetic frequency in the local DQ WDs is already higher than in DA WDs. This means that either DQs have a magnetic field much stronger than average, or that a magnetic field is more frequent in DQs than in any other kind of WD.

Perhaps the most interesting result of our survey is the fact that while MWDs are quite common, our data show that there is a marked deficiency of young MWDs: only one out of 20 stars younger than 500 million years is magnetic (see Figure 4). This result confirms what has long been suspected, that magnetic fields are more common in older than in younger WDs. We fully confirm the well-known result that the average mass of MWDs is higher than the average mass of the non-MWDs, but there is also some marginal evidence that higher mass is a feature primarily of the youngest MWDs. This result seems to be supported by data outside the local 20-parsec volume, and this is the object of an ongoing survey.

Finally, Figure 5 shows an age-mass diagram, where the solid lines show the age at which a WD of a certain mass starts the process of core crystallisation (blue lines refer to H-rich atmospheres, and red lines refer to He-rich atmospheres). The empty symbols show the non magnetic WDs, and the solid symbols show the magnetic white dwarfs in the 20-parsec volume. This plot suggests that magnetic fields occur about twice as frequently after the core crystallisation phase starts than before.

Interpretation

Let's see now how the mechanisms proposed to explain the magnetic field stand up against the observational constraints.

The original idea that MWDs are the descendants of the magnetic chemically peculiar stars of the upper main sequence may be still correct, but it is certainly not the entire story, since Ap/Bp stars account for less than 10% of all A and B type stars, and we know that at least 20% of WDs are magnetic. Of course the magnetic field could be still the remnant of a field that originated inside any star at any previous evolutionary stage, for example in the asymptotic giant branch phase. We do not see evidence of ohmic decay, and we may need to hypothesise that the fossil field is emerging from the interior of the star with time.

Another idea that we have mentioned above is that the available orbital energy and angular momentum of a close binary system could lead to the creation of a strong magnetic field via dynamo action during the common-envelope phase. If merging occurs, the result would be a single, high-mass, high-field MWD. The calculations by Briggs et al. (2015) predict a distribution of magnetic field strength between 1 and 100 MG, which is not what we observe. Therefore the merging scenario is a candidate explanation for a fraction of the observed magnetic fields (maybe the rare young, high-mass MWDs?), but not for all, and there is no evidence of close binary systems' being frequent enough to explain the observed high frequency of MWDs.

The high frequency of magnetic fields observed in stars with metal lines suggests that such WDs are unusually likely to host fields. However we have found that once we remove from the statistics all DAs younger than 500 million years, DZs are not more frequently magnetic than normal DAs.

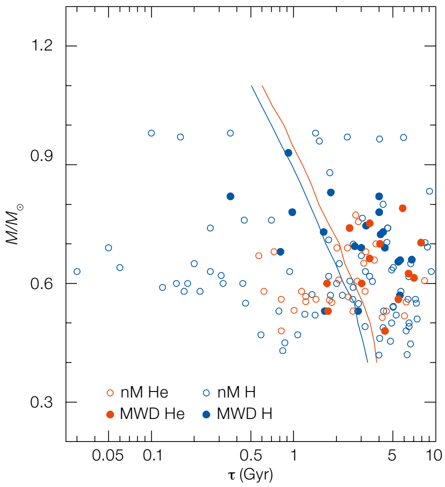

Figure 5. Cooling-age – mass diagram for magnetic (solid symbols) and non-magnetic (empty symbols) WDs, showing the boundary at which crystallisation convection begins as a WD cools with age, for stars with "thick" (blue solid lines) and "thin" (red solid lines) hydrogen layers.

It has been suggested that during crystallisation in the C-O core of a typical WD, separation and sinking of the solidifying O component lead to strong convection in the core. Provided that the WD is rotating rapidly, a dynamo of the same type that produces the magnetic fields of Earth, Jupiter, and M dwarfs can operate (Isern et al., 2017). This theory may well be consistent with the evidence that fields are more frequent after the crystallisation phase. However, this dynamo requires rapid rotation to function in a saturated state and thus produce detectable fields. This is not generally observed in WDs. Also, even in rapidly rotating stars, it remains to be demonstrated how this mechanism may produce fields stronger than 1 MG.

In conclusion, there is no single mechanism amongst those that have been proposed that is capable of explaining all the observations, so perhaps several of those discussed are acting.

To continue to provide constraints it will be necessary not only to expand the survey but also to model the magnetic fields, and try to understand whether different classes of morphologies exist.

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