Contrib. Astron. Obs. Skalnaté Pleso **48**, 236 – 244, (2018)

A high-precision survey of magnetic white dwarfs

S. Bagnulo[1], J. D. Landstreet[1,2], A. J. Martin[3] and G. Valyavin[4]

[1] *Armagh Observatory & Planetarium, College Hill, Armagh BT61 9DG, UK*
[2] *Dept. of Physics & Astronomy, University of Western Ontario, London, Ontario N6A 3K7, Canada*
[3] *LESIA, 5 place Jules Janssen, F-92195 Meudon, France*
[4] *Special Astrophysical Observatory, RAS, Nizhnij Arkhiz, Zelenchukskij Region, 369167 Karachai-Cherkessian Republic, Russia*

Received: Dezember 22, 2017; Accepted: Dezember 27, 2017

Abstract. We have carried out a survey of magnetic fields in 60 bright white dwarfs. Our observations have a mean uncertainty of about 0.5 kG. The large sample and high accuracy of our measurements allows us to obtain a clearer picture of the frequency of magnetic fields in degenerate stars, and shows that even relatively weak fields are in fact quite rare in white dwarfs.
Key words: polarization – stars: white dwarfs – stars: magnetic field

1. Introduction

There are many important questions to be explored concerning magnetic fields in white dwarfs (WDs). Primarily: is there a lower limit for field strength in WDs below which all, or none, have magnetic fields? We know that the strength of the fossil field of Ap stars is always above a threshold of about 300 G (Aurière et al., 2007). Does the field of WDs exhibit a similar behaviour? Finding this limit, if it exists, will help to define similarities between the fields of Ap stars and those of WDs, which will in turn guide the development of new theories and models for how WD magnetic fields form and evolve. Motivated by this and other important questions about stellar magnetism we have started a high-precision magnetic survey of WDs. Here we present our preliminary results. This workshop, which is dedicated to the general theme of stellar magnetic fields, is in fact a direct descendant of a series of conferences that were dedicated to Ap/Bp stars. Accordingly we have decided to present our work making references to our experience in detection and modelling of magnetic fields of Ap/Bp stars.

2. Detection techniques for the magnetic field of WDs

Together with Ap/Bp stars, WDs are the kinds of star to which we most commonly associate the idea that a magnetic field may be present and possibly be a predominant feature of the stellar atmosphere. Like Ap/Bp stars, there exist different varieties of WDs. The classification (developed by Sion et al., 1983) includes a first letter D which means "Degenerate", followed by a capital letter that reflects the spectral features. For instance, we have DA WDs, with spectra that show only H lines, DB WDs, that show only He lines, DC WDs, with featureless spectra, etc. To these two letters, a number from 0 to 9 is usually added to report about the stellar temperature, 9 being the coolest end, and 0 the hottest end. Most WDs show only a single atom in their spectra because gravitational diffusion leads to the lightest surviving element floating on everything else.

Prior to the presentation of our survey we need to discuss the observing techniques for WDs, which may be quite different from those commonly used for other kinds of stars.

The top left panel of Fig. 1 shows the intensity spectrum of an Ap star observed at medium-low resolution ($R \sim 8\,000$). This spectrum exhibits Balmer lines from Hβ down to the Balmer jump. What we see between Balmer lines is not noise, but the superposition of hundreds of metal lines. Balmer lines are sensitive to the magnetic field, but for various reasons, the magnetic field of Ap/Bp stars is usually measured from metal lines observed with high-resolution spectropolarimetry.

The top right panel of Fig. 1 shows the spectrum of the DA star WD 1647+591 observed with the same instrument setting as the Ap star. The two spectra are not very dissimilar, except that the continuum of the spectrum of the WD is actually featureless (any wrinkle is actually due to noise). Compared to Ap/Bp stars, WDs are generally much fainter objects (there exist only about 60 WDs known to be brighter than $V = 13$). We note that the intensity spectrum of this DA WD represents a best-case situation. Some spectra appear like the one of WD 0426+588 (mid left panel of Fig. 1), or like WD 1900+705 (mid right panel).

Regarding polarisation, in Ap/Bp stars we are used to Stokes V/I profiles spectra like the one in the left bottom panel of Fig. 1, i.e., with the continuum oscillating around zero, and with large amplitude in proximity of spectral lines. This polarisation spectrum was obtained at low resolution and only Balmer lines show a prominent signal of polarisation. However, this example is qualitatively also representative of the polarised spectrum of metal lines when observed in high-resolution. The polarisation spectrum of WDs may be totally different, like the one of WD 1900+705 shown in the bottom right panel of Fig. 1, where also the continuum is polarised.

Compared to field measurements in Ap stars, two new characteristics appear for WDs: 1) Some WDs have featureless spectra, which simply makes it impossible to detect the magnetic field from the analysis of Zeeman effect on the Stokes profiles of spectral lines. 2) Magnetic fields of WDs may be very strong, so strong that Hydrogen Balmer lines wander around in wavelength, and that even the continuum becomes polarised. For instance, the spectral feature around 4100 Å observed in the intensity spectrum of WD 1900+705 is one

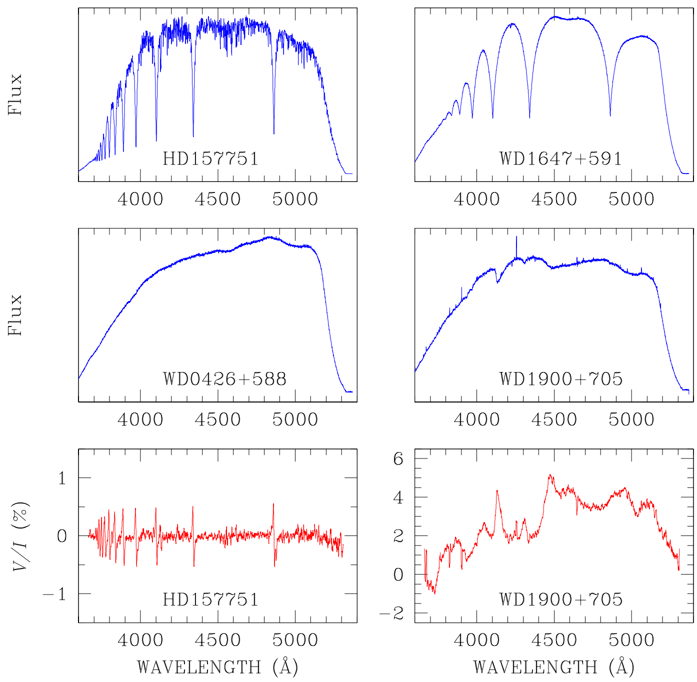

Figure 1. Low-resolution intensity and circularly polarised spectra of the Ap star HD 157751 and of three WDs observed with the blue arm of the ISIS instrument of the WTH.

of the component of Hβ shifted by 700 Å by the presence of a magnetic field. Both stars (WD 1900+705 and WD 1647+591) have a H-rich atmosphere with a similar temperature!

A simple introduction to the effects of strong magnetic fields in stellar atmospheres was presented by Putney (1997) as follows.

1) For field strength $|B| > 50$ MG the magnetic force acting on the electrons is comparable to the Coulomb force due to the atom nucleus; the continuum is polarised and spectral lines may be shifted; e.g., in presence of a 10^9 G magnetic field, some of the Balmer and Paschen transitions of H are in the ultraviolet. Many of line transitions have extrema, or stationary points where a transition occurs at a particular wavelength, or over a very small wavelength range (e.g., 50 Å), for a large range of magnetic fields (e.g., 100 MG). A spectral feature may develop at the wavelength of a stationary point if a large enough fraction of the star is characterised by a magnetic field in the corresponding range of magnetic field strength. Calculations have been made by Wunner et al. (1985).

2) For 1 MG< $|B|$ < 50 MG we are in the Zeeman quadratic regime. We still need numerical computation to interpret line polarisation and splitting in terms of field strength (e.g. Kemic, 1974).
3) In the linear Zeeman regime we can adopt formulas that are similar to those used for Ap/Bp stars, e.g. the relationship between Zeeman splitting and field modulus is linear.
4) Zeeman splitting is not detectable for field strength less than 50 kG, a regime that may be probed only by means of spectropolarimetric techniques.

It is important to note that there is no instrument that suits perfectly well all these regimes, which as we will discuss later may introduce a bias in the survey.

3. S, M, L, XL, XXL WD surveys

Kemp et al. (1970) obtained the first field detection in a WD using broadband circular polarisation (BBCP) measurements. This work was followed by various BBCP surveys, e.g., by Angel et al. (1981). Over the last few five decades, several surveys of WDs have been performed to search for magnetic fields. In the following we shall mention some of those, highlighting the technique used, their sample size, mean uncertainty of the field measurements and the field detection rate.
– Schmidt & Smith (1995) carried out a large spectropolarimetric survey of 170 DA WDs characterised by a mean uncertainty of 8.6 kG, with a 4 % detection rate.
– Putney (1997) carried out a medium-size spectropolarimetric survey of 46 WDs, with typical uncertainty > 10 kG and a claimed (but overestimated) detection rate of 15 − 20 %.
– Koester et al. (1998) carried out a medium-size high-resolution spectroscopic survey of 30 stars with a 16 % detection rate.
– Aznar Cuadrado et al. (2004) and Jordan et al. (2007) obtained FORS circular spectropolarimetry of 12 and 10 stars, respectively, with an uncertainty < 1 kG and a detection rate of 25 % and 10 % respectively. These two small surveys introduced the concept that it could be very interesting to investigate WDs with high-precision spectropolarimetry.
– Valyavin et al. (2006) used the 6 m Russian telescope (BTA) for a small spectropolarimetric survey of six WDs, with typical uncertainties of 1 to 3 kG, and a formal detection rate of 17 %.
– Koester et al. (2009) used the extremely large SPY UVES high-resolution spectroscopic survey of 1 000 isolated WDs and WD+dM systems for a detection rate of 1.6 % for fields small enough (less than about 1 MG) or sufficiently non-obvious to have been missed in low-resolution spectroscopic surveys.
– Landstreet et al. (2012) presented a small FORS specpolarimetric survey of 8 WDs field measurements with an uncertainty of 1 kG, for a 12 % detection rate.

Landstreet et al. (2012) also presented a reassessment of the results obtained in previous surveys.
– Kawka & Vennes (2012) presented a medium-size FORS spectropolarimetric survey of 58 cool WDs with uncertainty $> 2 - 5$ kG, and resulting in a 3.5 % detection rate.
– Külebi et al. (2009), Kleinman et al. (2013) and Kepler et al. (2013) analysed 20 000 spectra of WD from the SDSS spectroscopic survey, and scored a 5 % detection rate.

Without going into details, one can see that different surveys had a different success in detecting new magnetic stars. It is not easy to get a comprehensive view of the incidence of magnetic fields in WDs from individual surveys, because different surveys have a target list with different size and compiled with different criteria, and because observations were carried out with different techniques and with different typical S/N (resulting in different sensitivity). Note also that magnetic fields in WDs with featureless spectra (DC) can be detected only if the magnetic field is strong enough to polarise the continuum ($|B| > 50$ MG). Most of surveys include stars that were already known as magnetic or suspected magnetic stars. Finally we note that some surveys report results with an ambiguous to misleading language. For instance, sentences like "The WD has a field strength less than N kG" (where N kG is the detection threshold) or "Field was detected at $2\,\sigma$ level" mean both that no field was detected, but may give the impression that the stars are indeed magnetic.

4. This survey

We have surveyed about 60 WDs in low and/or medium and/or high-resolution spectropolarimetric mode using three different instruments: the FORS instrument of the ESO VLT, the ISIS instrument of the WHT, and the ESPaDOnS instrument of the CHFT. Most of the targets of our survey were never observed before with high precision polarimetric techniques (or never observed at all in polarimetric mode). With FORS and ISIS we adopted the slope technique described by Bagnulo et al. (2002) and with ESPaDOnS we used the technique introduced by Landstreet et al. (2015).

FORS and ISIS are somehow very similar instruments, but they have some important differences that are interesting to emphasise. First of all, ISIS reaches a higher spectral resolution than FORS, up to 8 000 (compared to 2-3 000 with FORS). ISIS has two arms and covers double the spectral range of FORS. At the highest spectral resolution ISIS may cover the ranges 3700–5200 and 6100–6800 Å, while FORS covers only one of these spectral regions at a time. For our survey we decided to observe with FORS in the blue spectral region.

With ISIS, grisms cannot be exchanged quickly during the night, and grism insertion must be generally followed by some fine tuning and calibration procedures, whereas with FORS, changing a grism is as fast and simple as exchanging a filter. Practically speaking, the instrument mode with ISIS is fixed for the entire observing night, while FORS gives much more flexibility. Once the instrument mode is set, ISIS has much shorter overheads than FORS, e.g., CCD readout and rotation of the wave plate require 15 secs at most, against at least 1 minute with FORS. Since polarimetry requires multiple exposure, this difference in overheads is really felt by the observer. On the other hand, ISIS operations are less automatised than with FORS, therefore it is easier to make errors and waste telescope time at the console.

Both ISIS and FORS are Cassegrain-mounted instruments, which means they are prone to flexures when the telescope is pointed. Also, because of the alt-az mounting of the telescope, the instrument is continuously rotating to keep the field of view fixed in the camera. If flexures happen during an exposure or an exposure series, it means that that the image or the spectrum on the CCD may be slightly blurred or move from one exposure to the next. The implication for spectropolarimetric measurements has been thoroughly discussed by Bagnulo et al. (2013), and we will not come back to this point here, but we shall just remember that *flexures are much more likely to produce spurious detections than to hide a magnetic field*.

The third instrument that we have used, ESPaDOnS, does not have problems with flexures as it sits on a bench and it is fibre fed from a polarimetric module attached at the Cassegrain focus. Since the telescope has an equatorial mounting, the instrument does not have to rotate. The caveat is that a high-resolution spectropolarimeter may not be the ideal instrument for the measurement of the magnetic field in stars with very broad spectral lines, for the following reason. As the retarders rotate, or simply as time passes and fibres are moved, the way in which fibres are fed and transmit the signal may change, in particular the ratio between the signal in the two beams of the Wollaston prism or any other beam splitter device may change. This produces a nearly unavoidable and spurious polarisation signal in the continuum which is usually removed by a normalisation procedure that assumes that the continuum is not polarised. The Balmer lines are very broad and may even extend beyond an individual order of the echelle spectrograph, making it very difficult to disentangle in the line wings the polarisation due to a magnetic field from that due to instrument polarisation. However, Landstreet et al. (2015) showed that the core of Hα behaves somehow like a metal line, so that Stokes profile may be analysed with the usual technique that measures the first order moment of Stokes V about the line centre and converts this quantity into an estimate of the mean longitudinal magnetic field $\langle B_z \rangle$. Landstreet et al. (2015) introduced and validated the use of this technique and at the same time failed to confirm the magnetic nature of the WD 40 Eri B (this conclusion was based also on ISIS data).

An obvious advantage of ESPaDOnS is that it allows us also to measure the mean magnetic field modulus $\langle |B| \rangle$ even in relatively weak-field stars: we estimate that ESPaDOnS can measure $\langle |B| \rangle \geq 20\,\mathrm{kG}$, and detect clear Zeeman splitting in stars with $\langle |B| \rangle$ as weak as 40 kG, while the detection limit with

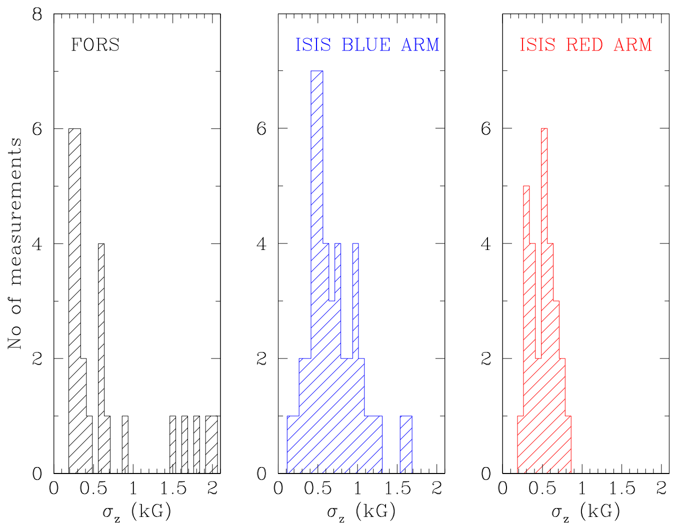

Figure 2. Histograms showing the distribution of the error bars obtained with FORS and with the two ISIS arms.

ISIS would be twice as much, and FORS can detect Zeeman splitting in the intensity spectrum only in stars that have at least a 2-300 kG field.

At the moment of writing we are in the process of revising the technique used to measure the mean longitudinal magnetic field with ESPaDOnS, therefore in these proceedings we will discuss only FORS and ISIS measurements.

The precision of the $\langle B_z \rangle$ field measurements of our survey is shown in Fig. 2 with the histograms of the error bars. We have considered separately the observations obtained with the blue arm and with the red arm of ISIS. This allows us to see that observing Hα alone leads to measurements that have the same precision as those obtained observing several Balmer lines from Hβ down. The explanation is that Zeeman effect is proportional to λ^2, therefore the higher number of spectral lines in the blue region is balanced by the higher sensitivity of Hα. In fact, about 2/3 of the ISIS observations used the blue and red arm to observe (simultaneously) the same star. These observations may be combined, leading to even higher precisions for individual stars. Our survey led to very few field detections, mostly in stars that were already known to be magnetic from previous investigations. The full results of our surveys will be presented in two forthcoming papers by Bagnulo et al. (in prep.) and Landstreet et al. (in prep.).

We finally would like to mention that we also used telescope time to monitor individual WDs that show variability to measure their rotation period and eventually to model their magnetic field. The special case of stars WD 2047+372 and WD 2359-434 is presented by Landstreet et al. (2017, and these proceedings).

References

Angel, J. R. P., Borra, E. F., & Landstreet, J. D. 1981, *Astrophys. J., Suppl.*, **45**, 457

Aurière, M., Wade, G. A., Silvester, J., et al. 2007, *Astron. Astrophys.*, **475**, 1053

Aznar Cuadrado, R., Jordan, S., Napiwotzki, R., et al. 2004, *Astron. Astrophys.*, **423**, 1081

Bagnulo, S., Fossati, L., Kochukhov, O., & Landstreet, J. D. 2013, *Astron. Astrophys.*, **559**, A103

Bagnulo, S., Szeifert, T., Wade, G. A., Landstreet, J. D., & Mathys, G. 2002, *Astron. Astrophys.*, **389**, 191

Jordan, S., Aznar Cuadrado, R., Napiwotzki, R., Schmid, H. M., & Solanki, S. K. 2007, *Astron. Astrophys.*, **462**, 1097

Kawka, A. & Vennes, S. 2012, *Mon. Not. R. Astron. Soc.*, **425**, 1394

Kemic, S. B. 1974, *Astrophys. J.*, **193**, 213

Kemp, J. C., Swedlund, J. B., Landstreet, J. D., & Angel, J. R. P. 1970, *Astrophys. J., Lett.*, **161**, L77

Kepler, S. O., Pelisoli, I., Jordan, S., et al. 2013, *Mon. Not. R. Astron. Soc.*, **429**, 2934

Kleinman, S. J., Kepler, S. O., Koester, D., et al. 2013, *Astrophys. J., Suppl.*, **204**, 5

Koester, D., Dreizler, S., Weidemann, V., & Allard, N. F. 1998, *Astron. Astrophys.*, **338**, 612

Koester, D., Voss, B., Napiwotzki, R., et al. 2009, *Astron. Astrophys.*, **505**, 441

Külebi, B., Jordan, S., Euchner, F., Gänsicke, B. T., & Hirsch, H. 2009, *Astron. Astrophys.*, **506**, 1341

Landstreet, J. D., Bagnulo, S., Fossati, L., Jordan, S., & O'Toole, S. J. 2012, *Astron. Astrophys.*, **541**, A100

Landstreet, J. D., Bagnulo, S., Valyavin, G., & Valeev, A. F. 2017, *Astron. Astrophys.* **607**, A92

Landstreet, J. D., Bagnulo, S., Valyavin, G. G., et al. 2015, *Astron. Astrophys.*, **580**, A120

Putney, A. 1997, *Astrophys. J., Suppl.*, **112**, 527

Schmidt, G. D. & Smith, P. S. 1995, *Astrophys. J.*, **448**, 305

Sion, E. M., Greenstein, J. L., Landstreet, J. D., et al. 1983, *Astrophys. J.*, **269**, 253

Valyavin, G., Bagnulo, S., Fabrika, S., et al. 2006, *Astrophys. J.*, **648**, 559

Wunner, G., Roesner, W., Herold, H., & Ruder, H. 1985, *Astron. Astrophys.*, **149**, 102

Stefano Bagnulo, Lilia Ferrario, Adela Kawka and Stéphane Vennes

Gregg Wade