

# Discovery of magnetic fields in five DC white dwarfs

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## ABSTRACT

About half of white dwarfs (WDs) evolve to the DC state as they cool; the others become DQ or (temporarily?) DZ WDs. The recent magnetic survey of the local 20 pc volume has established a high frequency of magnetic fields among WDs older than 2–3 Gyr, demonstrating that in low- and average-mass WDs, the effects of magnetism become more common as they age, and the fields on average become stronger. However, the available statistics of WDs older than about 5 Gyr do not clearly establish how fields evolve beyond this age. We are carrying out a survey to clarify the occurrence of magnetism in DC-type WDs in order to better understand this late evolution. We use broadband filter polarimetry, arguably the most efficient way to detect magnetic fields in featureless WDs via continuum circular polarization. Here we report the discovery of a magnetic field in five DC WDs (of 23 observed), almost doubling the total sample of known magnetic WDs belonging to the DC spectral class.

**Key words.** magnetic fields – white dwarfs – polarization

## 1. Introduction

Single stars of  $M \lesssim 8 M_{\odot}$  evolve to become white dwarfs (WDs). The descendants of these single stars of intermediate mass provide most of the population of WDs, concentrated around the mean mass of  $0.6 M_{\odot}$ . A smaller fraction of current WDs were also formed from close binary systems. Some of these systems eventually merged to form a single collapsed remnant, frequently of a significantly larger mass; others ended their nuclear lifetimes as double WD binaries.

Once formed, the evolution of a WD is normally to cool slowly over several gigayears. Cooling is a fairly complex process even for single-star evolution, both to observe and to understand. Observationally, young hot WDs usually show strong spectra of H (DA WDs), He (DB WDs), or sometimes C (DQs). As they cool, spectral lines of the dominant elements H or He become weaker: He lines vanish at about 11 000 K, H lines around 5000 K. In parallel with this general evolution, WDs may (temporarily) show lines of metals such as Mg, Si, Ca, and/or Fe (DZ, DAZ, and DZA stars), and some have spectra dominated by C. Below about 5000 K, about one-quarter of WDs have very weak  $H\alpha$ , another quarter show spectral lines of metals (especially Ca II) or of  $C_2$ , and the remaining half show essentially featureless spectra (DC WDs; Bagnulo & Landstreet 2021, Table 1). It appears that the dominant element(s) in the atmosphere can change as cooling occurs, for example due to gravitational diffusion, development of convection, and accretion of circumstellar planetary debris.

One of the physical effects adding complexity to our efforts to understand WD evolution is that a significant fraction, about 20–25%, of WDs in the local volume near the Sun

(Bagnulo & Landstreet 2021) possess detectable surface magnetic fields (this high frequency was already suggested on the basis of literature reports of fields in nine WDs in the 13 pc volume by Kawka et al. 2007). The fields observed at the surface range in strength, measured by the mean surface field  $\langle |B| \rangle$ , from tens of kG to hundreds of MG. Such fields can significantly affect WD evolution by altering or suppressing surface convection and internal shear, and by transferring angular momentum between internal layers or during accretion or mass loss (see for example Tremblay et al. 2015). The fields may also introduce additional forces into envelope and atmosphere layers, altering their hydrostatic structure from that expected when magnetic effects are absent (Landstreet 1987).

For WDs formed by single-star evolution, which generates most of the large populations of WDs with masses around  $0.6 M_{\odot}$ , it has become clear that recently formed WDs (with cooling ages of less than, say, 1 Gyr) are very rarely detectably magnetic, and when they are magnetic, the fields are usually very weak (Bagnulo & Landstreet 2022). As WDs cool, fields begin to appear more frequently and usually become stronger. In WDs older than 3 or 4 Gyr, megagauss-scale fields are not uncommon (Bagnulo & Landstreet 2021).

The observed evolution in magnetic field frequency and strength of normal-mass WDs for the first few gigayears of cooling may be understood as a slow emergence – as a result of field relaxation to the stellar surface – of the internal fields present in the degenerate cores of the WD precursors. An additional contribution to observed surface fields may be due to magnetic fields generated during cooling by a dynamo that acts during the period when the core of the WD is crystallising (Isern et al. 2017; Gentile Fusillo et al. 2018). Beyond the end of crystallisation,

the only identified evolution mechanisms are continued field relaxation and Ohmic decay.

Observationally, however, after about 5 Gyr of WD cooling, we have very limited information with which to guide and confront theory. Only small survey samples constrain observed field evolution on cool WDs, such as DQ WDs, where  $C_2$  bands show no polarization in strong fields (Berdyugina et al. 2007). Particularly little is known about the magnetic fields of DC WDs, in which no spectral features are seen at all, leading to the questions of whether field strength begins to decay Ohmically and whether the frequency of surface fields continues to increase. Data that could help us answer these questions are very limited. For WDs within 20 pc of the Sun (the 20 pc volume sample), Bagnulo & Landstreet (2021) showed that of 31 DC WDs, only 4 are magnetic white dwarfs (MWDs), and that only 4 of 24 WDs of any spectral class older than  $\sim 6$  Gyr are magnetic. These data are obviously too limited to clearly describe the evolution of fields in these old WDs.

Previous surveys have provided almost no information about magnetic fields in DC WDs. Fields in such stars cannot be detected through the magnetic splitting of spectral lines. They can only be detected via the observation of continuum circular polarisation (CCP; Kemp 1970), a method of observation hardly employed since the 1970s (Angel et al. 1981). Remarkably, most CCP observations have led to the discovery of magnetic fields in stars that are not featureless but in which the magnetic field is strong enough to shift and broaden spectral lines in a such a way as to make their intensity spectra unrecognisable. Only seven featureless DC WDs are presently known to be magnetic. Five of them were discovered only in the last couple of years (Bagnulo & Landstreet 2020; Berdyugin et al. 2022). Before these results, the only known magnetic DC stars were G195-19 and G111-49, discovered respectively by Angel & Landstreet (1971) and Putney (1995).

To improve our knowledge of the magnetic fields in the latest stages of stellar evolution, we have started a volume-limited survey of DC stars in the local 33 pc volume, which is about 4.5 times larger than the previously explored 20 pc volume and should have a correspondingly larger sample of DCs and DC MWDs. With this sample we expect to find enough DC MWDs to delineate the evolution of their magnetic fields, both in the WDs with He-rich atmospheres that become DCs as soon as their effective temperatures reach about 11 000 K ('young' DCs), and in DC WDs with  $T_{\text{eff}}$  below about 5000 K, with cooling ages of around 4 Gyr or more ('old' DCs).

## 2. Observations

Almost all known MWDs have been discovered via the magnetic (Zeeman) splitting of spectral lines, observed in stellar flux spectra, or via the Zeeman polarisation of spectral features (Ferrario et al. 2015). Using these methods, fields of a few kG up to 1 GG can be reliably detected. However, these techniques cannot be used to measure fields in WDs that lack spectral lines. For such stars, it is necessary to rely on continuum polarisation, which Kemp (1970) showed should occur in radiation from a magnetized emitter. The value of this effect was confirmed by the discovery of a very strong field in the bright WD Grw+70 8247 = WD 1900+705 through the detection of broadband circular polarisation (BBCP) by Kemp et al. (1970).

Broadband circular polarisation is a relatively weak effect. Bagnulo & Landstreet (2020) have estimated that a field of  $\langle B_z \rangle \sim 15$  MG is required to produce BBCP of order 1% in optical radiation from a cool WD. However, with a sensi-

tive polarimeter, especially one with a very stable and well-established zero point, it is possible in principle to detect polarisation of  $10^{-4}$  or less, corresponding to  $\sim 100$  kG fields in 'sufficiently bright' WDs.

To detect and measure broadband continuum polarisation, one uses either spectropolarimetry or filter polarimetry with broad, photometry-like filters. It is very difficult to establish the zero point with sufficient accuracy below polarisation levels of the order of  $10^{-3}$  in spectropolarimetric measurements of the continuum (Fossati et al. 2007; Siebenmorgen et al. 2014); therefore, in DC WDs, only megagauss-scale fields can be detected in this way (Bagnulo & Landstreet 2020). In contrast, broadband filter polarimeters can be very stable, and instrumental polarisation can be calibrated at the  $10^{-5}$  level, so detections with such instruments of fields of hundreds of kilogauss are in practice limited by the telescope aperture and WD brightness (Berdyugin et al. 2022).

The search for magnetic fields of a fraction of 1 MG or stronger in DC WDs that is reported here was carried out with the DIPol-UF broadband filter polarimeter (Pirola et al. 2020) mounted on the 2.5 m Nordic Optical Telescope (NOT) at the Observatorio del Roque de los Muchachos on the island of La Palma, in the Canaries. This instrument obtains simultaneous circular polarisation (normalized Stokes  $V/I$ ) measurements in three filter bands isolated by dichroic mirrors. The passbands are centred at about 4450 Å (the  $B'$  band), 5400 Å (the  $V'$  band), and 6400 Å (the  $R'$  band) with full widths at half maximum (FWHMs) of 1140, 750, and 960 Å, respectively. With this instrument on the NOT, we can detect a polarisation degree at the  $3\sigma$  level of  $\sim 10^{-4}$  for the *Gaia*  $G$ -band magnitude  $G \sim 12$ , down to a degree of  $\sim 10^{-3}$  at  $G \sim 17$ . This instrument and the filter system are discussed in more detail in our previous paper, which reports the results of the first part of our search for magnetic fields in DC WDs (Berdyugin et al. 2022).

Here we report observations of 23 DC WDs and discovery of 5 new DC MWDs. We note that our survey includes nine young DCs of He-rich atmospheres with  $11\,000 \lesssim T_{\text{eff}} \lesssim 5000$  K and 14 old WDs with  $T_{\text{eff}} \lesssim 5000$  K and ages  $\tau \gtrsim 4$  Gyr. The stars are selected from available classifications and with help from Gentile Fusillo et al. (2021). Our new observations were obtained between June 27 and July 5, 2022.

### 2.1. Instrumental polarisation and alignment of the polarimetric optics

During our observing run we obtained seven observations of seven different bright nearby stars, which are believed to have zero circular polarisation, to check for instrumental polarisation. These observations are reported in Table 1.

As in our previous run in July 2021, the high S/N measurements of non-polarised stars yield the instrumental polarisation to a precision better than  $10^{-5}$ . In the  $B'V'R'$  bands, the values of Stokes  $V/I$  are  $0.0121 \pm 0.0004\%$ ,  $0.0109 \pm 0.0005\%$ , and  $0.0084 \pm 0.0004\%$ , respectively. These are very close to the values obtained in 2021. The instrumental polarisation was subtracted from the observed polarisation of all targets, including the measurements of the standard stars reported in Table 1.

In addition, we obtained one measurement of the well-known MWD WD 1900+705, which appears to show a signal of circular polarisation that is nearly constant with time (see e.g., Bagnulo & Landstreet 2019). Our new measurement is compared in Table 1 to one of the same star that we made during the July 2021 run. The agreement is very satisfactory and demonstrates that we can obtain measurements that are precise at the

**Table 1.** Observing log of bright non-polarised standard stars and the highly polarised MWD WD 1900+705.

Star	$G$	Date yyyy-mm-dd	UT hh:mm	JD – 2400000	Exp. (s)	$V/I$ (%)		
						$B'$	$V'$	$R'$
HD 107146	6.9	2022-06-27	21:23	59758.391	1680	$0.0005 \pm 0.0007$	$-0.0006 \pm 0.0007$	$-0.0001 \pm 0.0006$
HD 115043	6.7	2022-06-28	21:21	59759.390	1520	$0.0005 \pm 0.0008$	$-0.0001 \pm 0.0012$	$-0.0004 \pm 0.0004$
HD 122652	7.0	2022-06-29	21:18	59760.387	1520	$-0.0012 \pm 0.0009$	$-0.0015 \pm 0.0015$	$-0.0019 \pm 0.0014$
HD 122676	7.1	2022-06-30	21:17	59761.387	1520	$0.0000 \pm 0.0011$	$0.0003 \pm 0.0010$	$0.0018 \pm 0.0008$
HD 124694	7.0	2022-07-01	21:16	59762.386	1520	$-0.0012 \pm 0.0008$	$0.0014 \pm 0.0011$	$0.0002 \pm 0.0007$
HD 135891	6.9	2022-07-02	21:18	59763.387	1520	$0.0014 \pm 0.0008$	$0.0006 \pm 0.0010$	$-0.0004 \pm 0.0007$
HD 117860	7.2	2022-07-03	21:16	59764.386	1520	$-0.0004 \pm 0.0010$	$-0.0002 \pm 0.0012$	$0.0005 \pm 0.0006$
WD 1900+705	13.2	2021-07-02	22:22	59398.432	640	$3.756 \pm 0.016$	$3.604 \pm 0.016$	$3.827 \pm 0.019$
		2022-07-02	00:25	59762.518		$3.789 \pm 0.016$	$3.602 \pm 0.019$	$3.838 \pm 0.018$

**Notes.** Polarisation values are given assuming as instrumental polarisation the values of  $0.0121 \pm 0.0004\%$ ,  $0.0109 \pm 0.0005\%$ , and  $0.0084 \pm 0.0004\%$  in the  $B'$ ,  $V'$ , and  $R'$  filters, respectively. For comparison, we report the polarisation values of WD 1900+705 measured in our 2021 and 2022 runs.

**Table 2.** Programme stars and their main physical features.

Star		$G$	$d$ (pc)	$T_{\text{eff}}$ (K)	$\log g$ c.g.s.	$M$ ( $M_{\odot}$ )	Age (Gyr)	Atmosphere and ref.
WD 0005+395	LP 240-30	16.6	34.4	4680	6.77	0.08	1.40	DC, H Prob <sub>WD</sub> = 0.70 (1,3)
WD 0010+543	LSR J0013+5437	18.0	32.3	4123	7.77	0.46	7.08	DC, (2, H assumed)
WD 0028+035	PB 6002	16.1	27.8	6548	8.14	0.68	2.40	DC, (2, H assumed)
WD 1251+366	LP 267-311	17.2	28.5	4445	7.62	0.37	3.78	DC, He (1)
<b>WD 1315+222</b>	<b>LP 378-956</b>	16.7	31.8	6235	8.21	0.71	3.61	DCH, He (1)
<b>WD 1346+121</b>	<b>LP 498-66</b>	17.8	28.3	4150	7.88	0.50	6.58	DCH, He (1)
WD 1425+495	CSO 649	16.7	33.9	6895	8.41	0.85	3.77	DC, (2, H assumed)
WD 1427–238	LP 857-45	17.4	32.6	4866	7.90	0.52	5.40	DC, (2, H assumed)
WD 1434+437	LP 221-217	17.2	27.2	4685	7.93	0.54	6.30	DC, H–He (1)
WD 1533+469	LP 176-60	17.8	30.8	4310	7.83	0.48	6.45	DC?, H (1)
<b>WD 1601-073</b>	<b>LP 684-16</b>	17.9	26.9	4920	8.55	0.94	9.83	DCH, (2, H assumed)
WD 1612+092	LSPM J1614+0906	17.2	27.9	4775	7.90	0.52	5.57	DC, H (1)
WD 1702–016	LP 626-29	17.3	28.3	4700	7.94	0.54	6.50	DC, (2, H assumed)
WD 1737+798	LP 24-66	16.9	26.8	5535	8.28	0.75	5.72	DC, He (1)
WD 1746+450	GD 366	15.5	29.9	9331	8.47	0.90	1.72	DC, (2, H assumed)
WD 1800+508	LP 139-38	17.4	31.0	4635	7.85	0.48	5.12	DC, He–H (1)
<b>WD 1853+775</b>	<b>LP 25-7</b>	17.0	30.5	4850	7.74	0.43	3.63	DCH, He (1)
WD 2058+550	LSR J2059+5517	17.1	22.7	4415	7.93	0.53	7.15	DC, H–He (1)
WD 2109–295	EC 21096-2934	15.1	32.8	9260	7.98	0.57	0.78	DC, He–H (3)
WD 2152–280	LP930-61	16.3	23.5	5220	7.85	0.48	3.68	DC, He (1)
<b>WD 2211+372</b>	<b>LP 287-35</b>	16.8	29.2	6345	8.47	0.88	4.56	DC?H, He (1)
WD 2215+368	LP 287-39	16.8	20.3	4485	7.92	0.53	6.80	DC, H (1)
WD 2311–068	G 157-34	15.3	25.9	7360	7.97	0.56	1.31	DC, He (1)

**Notes.** Star names in boldface identify WDs in which fields were discovered during the observations reported in this paper (see Table 3). **References.** 1: Blouin et al. (2019); 2: Gentile Fusillo et al. (2021); 3: Bergeron et al. (2021). Where not found in these references, ages have been interpolated using the tables from Bédard et al. (2020).

0.02% level for a  $G = 13.2$  star with about 10 min of exposure time. This shows that the alignment of our polarimetric optics is stable over a few years.

## 2.2. Results

The WDs observed during our 2022 June–July run are listed in Table 2, with their  $G$  magnitudes, distances, physical parameters, cooling ages, and some comments. Physical parameters were obtained from various studies, cited in the table’s notes; cooling ages are interpolated from the online cooling data provided by the Montreal group (Bédard et al. 2020).

The observations are described in the log in Table 3, which gives dates, integration times, and the polarisation data in the three filter bands for each WD observation. We list measured BBCP values in boldface if non-zero polarisation is detected at above the  $3\sigma$  level. We consider that real polarisation has been detected if a consistent picture of detection is found across the bands, and we highlight star names of WDs in which polarisation is convincingly detected in boldface in Tables 2 and 3. Of the 23 stars observed, BBCP has been definitely detected in 5 WDs. The data for these stars are plotted in Fig. 1.

We observed three of the five WDs in which fields were detected in order to fully confirm the weak field detections

**Table 3.** Observing log of WDs.

Star	Date yyyy-mm-dd	UT hh:mm	JD – 2400000	Exp. (s)	$B'$	$V/I$ (%) $V'$	$R'$
WD 0005+395	2022-07-06	04:38	59766.693	3900	$-0.017 \pm 0.063$	$-0.082 \pm 0.056$	$0.028 \pm 0.044$
WD 0010+543	2022-07-05	04:12	59765.675	7100	$-0.028 \pm 0.140$	$-0.011 \pm 0.129$	$0.094 \pm 0.067$
WD 0028+035	2002-07-06	03:39	59766.652	3300	$-0.084 \pm 0.045$	$-0.051 \pm 0.050$	$-0.010 \pm 0.058$
WD 1251+366	2022-06-27	22:41	59758.445	5200	$-0.155 \pm 0.065$	$0.006 \pm 0.063$	$0.039 \pm 0.038$
<b>WD 1315+222</b>	2022-06-28	22:25	59759.435	4200	$0.104 \pm 0.045$	<b><math>0.182 \pm 0.052</math></b>	<b><math>0.215 \pm 0.064</math></b>
	2022-07-01	22:24	59762.434	4200	$0.084 \pm 0.040$	<b><math>0.253 \pm 0.061</math></b>	<b><math>0.199 \pm 0.044</math></b>
<b>WD 1346+121</b>	2022-07-02	22:43	59763.446	6500	<b><math>-0.508 \pm 0.093</math></b>	$0.044 \pm 0.091$	<b><math>-1.074 \pm 0.054</math></b>
	2022-07-04	22:34	59765.44	6500	<b><math>-0.691 \pm 0.109</math></b>	$0.222 \pm 0.098$	<b><math>-1.256 \pm 0.062</math></b>
WD 1425+495	2022-06-29	22:22	59760.432	4200	$0.012 \pm 0.045$	$-0.002 \pm 0.058$	$0.018 \pm 0.038$
WD 1427–238	2022-06-30	23:11	59761.466	5600	$-0.038 \pm 0.114$	$0.102 \pm 0.078$	$-0.044 \pm 0.061$
WD 1434+437	2022-06-30	00:04	59760.503	5200	<b><math>0.231 \pm 0.077</math></b>	$-0.019 \pm 0.067$	$-0.019 \pm 0.059$
WD 1533+469	2022-07-01	01:02	59761.543	6600	$-0.065 \pm 0.127$	$-0.273 \pm 0.110$	<b><math>-0.195 \pm 0.052</math></b>
	2022-07-03	00:42	59763.529	6600	$0.139 \pm 0.098$	<b><math>-0.300 \pm 0.090</math></b>	$-0.019 \pm 0.042$
<b>WD 1601–073</b>	2022-07-05	22:52	59766.453	6800	<b><math>-0.484 \pm 0.111</math></b>	<b><math>-0.386 \pm 0.106</math></b>	<b><math>1.597 \pm 0.054</math></b>
WD 1612+092	2022-06-28	00:59	59758.541	5100	$0.087 \pm 0.069$	$0.033 \pm 0.052$	$0.097 \pm 0.046$
WD 1702–016	2022-06-30	01:59	59760.582	5300	$0.215 \pm 0.091$	$0.087 \pm 0.086$	$-0.104 \pm 0.053$
WD 1737+798	2022-06-29	01:34	59759.566	4500	$-0.014 \pm 0.082$	$-0.085 \pm 0.093$	$-0.071 \pm 0.056$
WD 1746+450	2022-06-28	02:12	59758.592	2600	$0.012 \pm 0.035$	$-0.049 \pm 0.032$	$-0.074 \pm 0.035$
WD 1800+508	2022-07-05	00:59	59765.541	5600	$-0.157 \pm 0.073$	$-0.047 \pm 0.061$	$0.051 \pm 0.053$
<b>WD 1853+775</b>	2002-07-06	01:15	59766.552	4800	$-0.098 \pm 0.066$	<b><math>-0.680 \pm 0.068</math></b>	<b><math>-0.492 \pm 0.039</math></b>
WD 2058+550	2022-07-02	04:15	59762.677	5000	$0.068 \pm 0.075$	$-0.052 \pm 0.070$	$0.064 \pm 0.045$
WD 2109–295	2022-07-01	03:51	59761.660	2200	$0.011 \pm 0.020$	$0.036 \pm 0.034$	$-0.039 \pm 0.037$
WD 2152–280	2022-06-28	03:59	59758.666	3600	$0.007 \pm 0.040$	$-0.055 \pm 0.041$	$-0.043 \pm 0.022$
<b>WD 2211+372</b>	2022-07-02	02:10	59762.590	4400	<b><math>1.254 \pm 0.041</math></b>	<b><math>0.703 \pm 0.054</math></b>	<b><math>0.446 \pm 0.044</math></b>
	2022-07-03	04:24	59763.683	4400	<b><math>1.333 \pm 0.038</math></b>	<b><math>0.623 \pm 0.044</math></b>	<b><math>0.285 \pm 0.040</math></b>
WD 2215+368	2022-06-30	04:12	59760.675	4400	$0.187 \pm 0.083$	$0.133 \pm 0.068$	$0.101 \pm 0.044$
WD 2311–068	2022-06-29	04:38	59759.693	2400	$-0.011 \pm 0.028$	$0.011 \pm 0.039$	$0.032 \pm 0.032$

**Notes.** Detections are marked in boldface.

and to check for possible variability. No variability is detected with confidence. There are in addition two further WDs, WD 1434+437 and WD 1533+469, in which marginal polarisation detections have been obtained; these WDs await further observation to confirm (or not) the fields that may have been detected. However, a single pair of measurements does not probe all the possible timescales of variation; in particular, our measurements require integration of the order of one hour and so cannot probe all the rotation periods that might result from the formation of a MWD from a close binary.

With these new discoveries, we almost double the number of DC WDs in which magnetic fields have been detected. One of the new MWDs discovered, LP 684-16 = WD 1601–073, is quite massive compared to most of the rest of the DC WDs observed. Therefore, because of its relatively small radius, it has cooled quite slowly, reaching only  $T_{\text{eff}} = 4920$  K, but has a computed cooling time of 9.8 Gyr. It is probably the oldest magnetic WD of any spectral type discovered so far. For comparison, according to the parameters listed by Bagnulo & Landstreet (2021), the oldest MWD in the 20 pc volume, in which such old MWDs are most likely to be discovered, is WD 1008+290 = LHS 2229. It is a DQpec star with an age of about 7.9 Gyr, almost 2 Gyr younger than LP 684-16.

We note that no really large polarisation signals, such as that exhibited by WD 1900+705 (see Table 1), are found. However, the observed level of polarisation in three of the five definite detections reaches the range 1.2–1.6%, so some of the fields detected are probably quite strong.

### 3. Discussion and conclusions

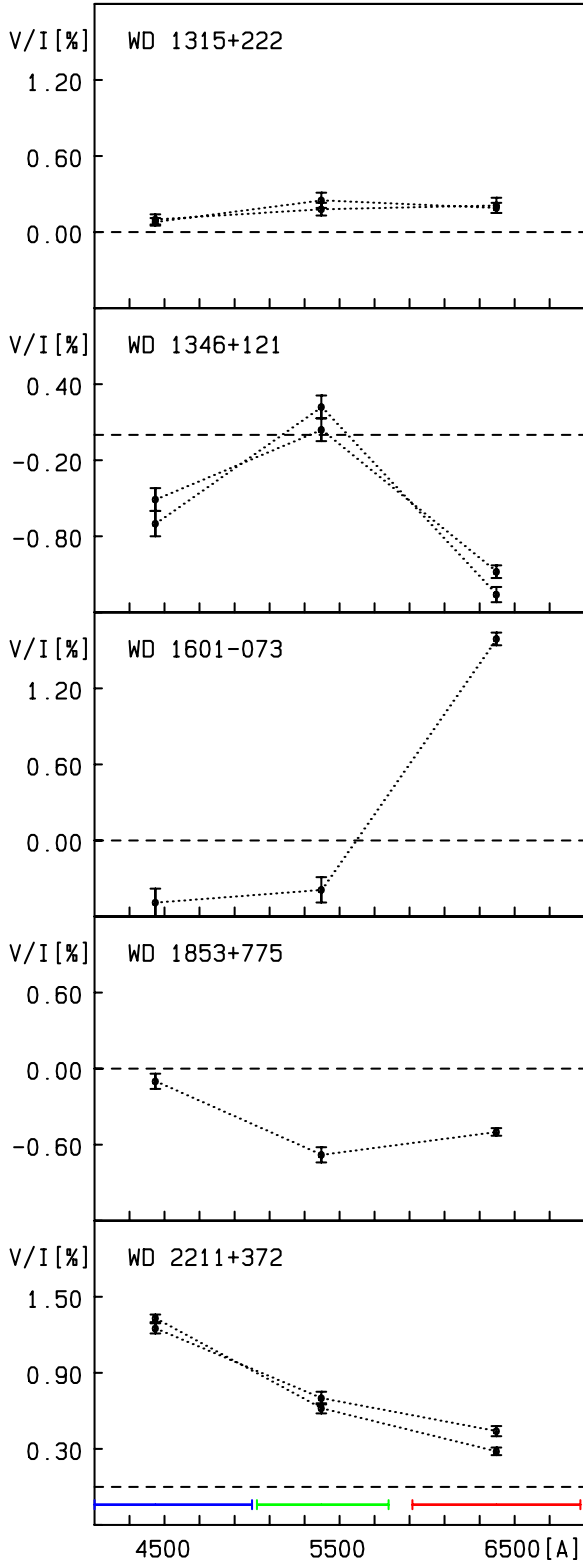
We continue to detect MWDs in roughly one-fifth of the DC sample observed. Considering that only relatively strong fields can be detected in featureless stars, our results suggest that the frequency of the occurrence of magnetic fields in older WDs may be as high as 25 or even 30%, consistent with the frequency suggested by Bagnulo & Landstreet (2021).

Polarisation levels in the seven DC MWDs discovered by Berdyugin et al. (2022) and in this paper range from about 0.1 to 1.6%. Using the order-of-magnitude estimator of Bagnulo & Landstreet (2020) of a longitudinal field of 15 MG, which leads to BBCP of the order of 1%, inferred fields  $\langle B_z \rangle$  are thus estimated to lie between perhaps 1 and 30 MG. From this result, the fields  $\langle |B| \rangle$  that we detect likely lie in the range of roughly 3–200 MG.

Some of the fields produce a polarisation with the same sign in the three filter bands, while in other stars we detect a polarisation that reverses sign between one filter band and another (Fig. 1). Similar behaviour was found in our earlier survey data (Berdyugin et al. 2022) as well as in other strongly magnetic old WDs (Angel & Landstreet 1971; Angel et al. 1974, 1975; Putney 1995).

We carried out a second observation for three of our five new discoveries and for one suspected candidate. The confirming observations were obtained between one and three days after the discovery observations. For each of these four stars, the repeated observation confirms the presence of the magnetic field first detected, except for one  $R'$  observation of WD 1533+469. In no





**Fig. 1.** Wavelength dependence of circular polarisation detected for five targets ( $>3\sigma$  confidence level). A wide variety of polarisation behaviour is observed. Horizontal bars in the bottom panel show the FWHM of the  $B'V'R'$  filter passbands.

case do we detect clearly significant variability; we note, however, that our repeated measurements probe only a very limited range of timescales.

We find that, in practice, a magnetic field can be reliably detected from BBCP at the polarization levels of approximately 0.2% with our broadband filter polarimeter on a 2.5 m telescope in a DC WD of  $G \sim 17$ . We would gain about a factor of 3 in precision, or a 2.5 mag increase in limiting magnitude, by going to an 8 m telescope.

To summarise the current statistical situation, we combine the results from the 20 pc volume magnetic field survey (Bagnulo & Landstreet 2021), our exploratory observing run (Berdyugin et al. 2022), and this work. We have collected literature data on and surveyed 30 young DC stars, of which 7 have been found to host magnetic fields, and 43 old DCs, of which 6 are magnetic.

As more detections of DC MWDs are made, especially in the context of volume-limited surveys such as ours, comparisons with magnetic data for other types of WDs will at first be hampered by our current inability to assign precise field strength values to magnetic DC WDs. However, a first comparison can be made between the overall level of polarisation observed in young and old DC MWDs, which may be taken as an indicator of the evolution of the overall field strength with cooling age between these two populations. In the currently small sample, it appears that larger polarisation levels (say, above Stokes  $V/I \geq 1\%$ ) appear to be at least as common in the old DC MWD population as in the young group. There is no clear signal of Ohmic field strength decay. However, the available sample is still very small, and as our sample increases we can hope to obtain a statistically more significant constraint and carry out modelling to provide more accurate field strength estimates corresponding to observed polarisation. Such surveys need to be carried on until a clearer statistical view of the magnetism in DC WDs is obtained.

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## References

- Angel, J. R. P., & Landstreet, J. D. 1971, *ApJ*, **164**, L15  
Angel, J. R. P., Hintzen, P., Strittmatter, P. A., & Martin, P. G. 1974, *ApJ*, **190**, L71  
Angel, J. R. P., Hintzen, P., & Landstreet, J. D. 1975, *ApJ*, **196**, L27  
Angel, J. R. P., Borra, E. F., & Landstreet, J. D. 1981, *ApJS*, **45**, 457  
Bagnulo, S., & Landstreet, J. D. 2019, *MNRAS*, **486**, 4655  
Bagnulo, S., & Landstreet, J. D. 2020, *A&A*, **643**, A134  
Bagnulo, S., & Landstreet, J. D. 2021, *MNRAS*, **507**, 5902  
Bagnulo, S., & Landstreet, J. D. 2022, *ApJ*, **935**, L12  
Bédard, A., Bergeron, P., Brassard, P., & Fontaine, G. 2020, *ApJ*, **901**, 93  
Berdyugin, A. V., Pirola, V., Bagnulo, S., Landstreet, J. D., & Berdyugina, S. V. 2022, *A&A*, **657**, A105  
Berdyugina, S. V., Berdyugin, A. V., & Pirola, V. 2007, *Phys. Rev. Lett.*, **99**, 091101  
Bergeron, P., Wesemael, F., Fontaine, G., et al. 2021, *AJ*, **162**, 188  
Blouin, S., Dufour, P., Thibault, C., & Allard, N. F. 2019, *ApJ*, **878**, 63  
Ferrario, L., de Martino, D., & Gänsicke, B. T. 2015, *Space Sci. Rev.*, **191**, 111  
Fossati, L., Bagnulo, S., Mason, E., & Landi Degl'innocenti, I. E. 2007, in *The Future of Photometric, Spectrophotometric and Polarimetric Standardization*, ed. C. Sterken, *ASP Conf. Ser.*, **364**, 503

- Gentile Fusillo, N. P., Tremblay, P. E., Jordan, S., et al. 2018, [MNRAS](#), **473**, 3693
- Gentile Fusillo, N. P., Tremblay, P. E., Cukanovaite, E., et al. 2021, [MNRAS](#), **508**, 3877
- Isern, J., García-Berro, E., Külebi, B., & Lorén-Aguilar, P. 2017, [ApJ](#), **836**, L28
- Kawka, A., Vennes, S., Schmidt, G. D., Wickramasinghe, D. T., & Koch, R. 2007, [ApJ](#), **654**, 499
- Kemp, J. C. 1970, [ApJ](#), **162**, 169
- Kemp, J. C., Swedlund, J. B., Landstreet, J. D., & Angel, J. R. P. 1970, [ApJ](#), **161**, L77
- Landstreet, J. D. 1987, [MNRAS](#), **225**, 437
- Piirola, V., Kosenkov, I. A., Berdyugin, A. V., Berdyugina, S. V., & Poutanen, J. 2020, [AJ](#), **161**, 20
- Putney, A. 1995, [ApJ](#), **451**, L67
- Siebenmorgen, R., Voshchinnikov, N. V., & Bagnulo, S. 2014, [A&A](#), **561**, A82
- Tremblay, P. E., Fontaine, G., Freytag, B., et al. 2015, [ApJ](#), **812**, 19