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The nearby magnetic cool DZ white dwarf PM J08186–3110

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ABSTRACT

We present an analysis of photometric, spectroscopic, and spectropolarimetric data of the nearby, cool, magnetic DZ white dwarf PM J08186–3110. High-dispersion spectra show the presence of Zeeman splitted spectral lines due to the presence of a surface average magnetic field of 92 kG. The strong magnesium and calcium lines show extended wings shaped by interactions with neutral helium in a dense, cool helium-rich atmosphere. We found that the abundance of heavy elements varied between spectra taken 10 years apart but we could not establish a time-scale for these variations; such variations may be linked to surface abundance variations in the magnetized atmosphere. Finally, we show that volume-limited samples reveal that about 40 per cent of DZ white dwarfs with effective temperatures below 7000 K are magnetic.

Key words: stars: atmospheres – stars: individual: PM J08186–3110 – stars: magnetic field – white dwarfs.

1 INTRODUCTION

Magnetic fields are detected among all spectral classes of white dwarfs. The incidence of magnetism was reported to be significantly higher in white dwarfs polluted with heavy elements compared to the incidence of magnetism in the general white dwarf population (Kawka & Vennes 2014; Hollands, Gänsicke & Koester 2015; Kawka et al. 2019). In polluted hydrogen-rich (DAZ) white dwarfs, the incidence of magnetism is ≈ 50 per cent for white dwarfs with effective temperatures $T_{\text{eff}} < 6000$ K and all of these have magnetic field strengths below 1 MG (Kawka & Vennes 2014; Kawka et al. 2019). Only two magnetic DAZ white dwarfs are known with $T_{\text{eff}} > 6000$ K, NLTT 53908 ($T_{\text{eff}} = 6250$ K; Kawka & Vennes 2014) and WD 2105–820 ($T_{\text{eff}} = 9890$ K; Landstreet et al. 2012; Gentile Fusillo et al. 2018). The incidence of magnetism in pure-hydrogen DA white dwarfs, i.e. those apparently devoid of heavy elements, may also be age dependent with a higher prevalence at cooler temperatures, $T_{\text{eff}} \sim 5000$ K (Rolland & Bergeron 2015). A study of the local sample (Giammichele, Bergeron & Dufour 2012) does indicate a peak incidence of 20 per cent among cool DA white dwarfs (Kawka et al. 2019). However, the polluted, magnetic DA white dwarfs (DAZH) show a much narrower field spread ($B < 1$ MG) than their unpolluted counterparts (DAH) and they appear to form a distinct population. It is not known whether the magnetic fields in these two populations have a common origin.

In the case of polluted helium-rich white dwarfs (DZ),¹ the incidence of magnetism is about 22 per cent for white dwarfs with

$T_{\text{eff}} < 8000$ K and magnetic field strengths ranging from a few hundred kG up to about 30 MG (Hollands et al. 2015; Hollands 2017). SDSS J1242+0829 is the only known magnetic DZ with $T_{\text{eff}} > 8000$ K (Coutu et al. 2019). Continuum polarization measurements may reveal the presence of a strong magnetic field in unpolluted DC white dwarfs. The detection of continuum polarization in three DC white dwarfs that lie within 20 pc of the Sun (Bagnulo & Landstreet 2020) suggests that the incidence of magnetism in DC white dwarfs is also high, but with much stronger magnetic fields (≈ 100 MG) than in their polluted (DZ) counterparts.

Two scenarios have been proposed to explain the higher incidence of magnetism in cool, polluted white dwarfs. In the first scenario, an old white dwarf encounters and collides with a gaseous planet giving rise to differential rotation in the white dwarf envelope. This differential rotation would then generate a relatively weak magnetic field (Farihi et al. 2011; Kawka et al. 2019). The chance of such a collision increases with time and Farihi et al. (2011) estimated that such a stellar encounter has a 50 per cent probability of occurring every 0.5 Gyr. In the second scenario, the magnetic field in DAZ and DZ white dwarfs is generated in the core of the parent giant stars (Kissin & Thompson 2015; Hollands 2017). Here, a planet or a low-mass stellar companion could generate a dynamo between the radiative and convective envelopes during the shell burning phases. This dynamo would create the magnetic field that would remain hidden below the non-magnetic envelope for about 1–2 Gyr. In either scenario, this magnetic field was created by the engulfment of a planet, it is likely that other planets or asteroids may have survived and over time they would move towards the white dwarf and become the source of pollution in the white dwarf atmosphere.

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¹In this paper, the spectroscopic label ‘DZ’ simply refers to polluted, helium-rich white dwarfs, and the label ‘DAZ’ refers to polluted, hydrogen-rich white dwarfs. However, we note that ultra cool (< 5000 K), polluted, hydrogen-rich white dwarfs with vanishing Balmer lines (not encountered in this study)

may be assimilated to the DZ white dwarfs in the same fashion that ultra cool DA white dwarfs may be assimilated to the featureless DC white dwarfs.

The carbon-rich, hot DQ white dwarfs ($T_{\text{eff}} \gtrsim 18\,000$ K) form another class of objects showing a significantly higher incidence of magnetism. These stars have an incidence of at least 70 per cent (Dunlap et al. 2013) and they are also fast rotators, with periods ranging from a few minutes to a couple of days (Dunlap & Clemens 2015; Williams et al. 2016). These rare objects also have an average mass that is higher than that of the general white dwarf population. The combined properties suggest that these stars have formed in double degenerate mergers (Dunlap & Clemens 2015; Kawka, Vennes & Ferrario 2020) rather than following the engulfment of a planet as suggested in the case of DZ white dwarfs. Coutu et al. (2019) have extended this class of massive DQs to lower temperatures ($10\,000 \lesssim T_{\text{eff}} \lesssim 16\,000$ K) and showed that these stars have a higher carbon abundance than DQ white dwarfs with normal masses ($M \approx 0.6 M_{\odot}$).

PM J08186–3110 was identified as a white dwarf candidate by Lépine (2005) and Subasavage et al. (2005) due to its colour and large proper motion. Follow-up spectroscopy revealed it to be a cool DZ white dwarf (Subasavage et al. 2008) and Bagnulo & Landstreet (2019) reported PM J08186–3110 to have a weak magnetic field based on spectropolarimetric measurements. Finally, a parallax measurement of 52.30 ± 0.71 mas obtained by Subasavage et al. (2017) places PM J08186–3110 within 20 pc of the Sun.

In this paper, we present a photometric, spectroscopic, and spectropolarimetric analysis of PM J08186–3110. Observations of PM J08186–3110 are presented in Section 2. Our analysis of the atmosphere and magnetic field strength is presented in Section 3 and in Section 4 we revisit the incidence of magnetism in DZ white dwarfs. Finally, we present our conclusions in Section 5.

2 OBSERVATIONS

We first observed PM J08186–3110 with the FORS1 spectrograph attached to the Very Large Telescope (VLT) of the European Southern Observatory (ESO) at Paranal on UT 2007 October 22. We used the 600 lines mm^{-1} grism centred at 4650 Å. The slit width was set to 1 arcsec providing a resolution of ~ 6 Å. The observations were conducted in the spectropolarimetric mode where we obtained an exposure of 480 s with the retarder plate rotated to -45° , immediately followed by another exposure of 480 s with the retarder plate rotated to $+45^\circ$.

These FORS1 spectra revealed PM J08186–3110 to be a cool DZ with a weak magnetic field. We also obtained two 1200 s observations of PM J08186–3110 with the R-C spectrograph attached to the 4 m telescope at Cerro Tololo Inter-American Observatory (CTIO) on UT 2008 February 23. We used the KPGL2 (316 lines per mm) grating with the WG360 order blocking filter. We set the slit width to 1.5 arcsec providing a resolution of ~ 8 Å. This spectrum showed the asymmetric Mg I optical line triplet characteristic of cool DZ white dwarfs and appeared as a lower quality replica of the FORS1 spectrum.

Consequently, we obtained a higher resolution spectrum with the X-shooter spectrograph (Vernet et al. 2011) attached to the VLT at ESO. The spectrum was obtained on UT 2017 October 23 with the slit width set to 0.5, 0.9, and 0.6 arcsec with total exposure times of 2975, 3040, and 3060 s for the UVB, VIS, NIR arms, respectively. This set-up provided a resolving power of 9700, 8900, and 5600 for the UVB, VIS, and NIR arms, respectively. We removed telluric absorption bands using MOLECFIT recipes (Kausch et al. 2015).

We collected photometric optical measurements from the SkyMapper survey (Onken et al. 2019) and infrared (IR) photometric measurements from the Two degree All Sky Survey (2MASS; Skrutskie et al. 2006) and the Wide-field Infrared Survey Explorer (WISE; Cutri et al. 2014). We also obtained astrometric and photometric

Table 1. Astrometry and photometry of PM J08186–3110.

Parameter	Measurement		Ref.		
RA (J2000)	08 ^h 18 ^m 40 ^s .26		1		
Dec (J2000)	−31°10′20″.3		1		
$\mu_{\sigma} \cos \delta$ (arcsec yr ^{−1})	0.23772 ± 0.00004		1		
μ_{δ} (arcsec yr ^{−1})	−0.78598 ± 0.00005		1		
π (mas)	51.65 ± 0.03		1		
Photometry					
Band	Measurement	Ref.	Band	Measurement	Ref.
<i>G</i>	15.408 ± 0.001	1	<i>i</i>	15.432 ± 0.005	2
<i>b_p</i>	15.639 ± 0.003	1	<i>z</i>	15.515 ± 0.006	2
<i>r_p</i>	15.072 ± 0.003	1	<i>J</i>	14.916 ± 0.036	3
<i>u</i>	16.659 ± 0.034	2	<i>H</i>	14.728 ± 0.073	3
<i>v</i>	16.827 ± 0.016	2	<i>K</i>	14.829 ± 0.122	3
<i>g</i>	15.531 ± 0.006	2	W1	14.680 ± 0.036	4
<i>r</i>	15.376 ± 0.017	2	W2	15.014 ± 0.070	4

Note. References: (1) Gaia Collaboration (2018); (2) Onken et al. (2019); (3) Skrutskie et al. (2006); (4) Cutri et al. (2014).

measurements from *Gaia* (Gaia Collaboration 2018). Table 1 lists available astrometric and photometric data.

PM J08186–3110 was observed with the *Transiting Exoplanet Survey Satellite* (*TESS*; Ricker et al. 2015) in Sector 7 from 2019 January 1 to February 2. The spectral range of the *TESS* bandpass is from 6000 to 10 000 Å. Since PM J08186–3110 (TIC 147018085) was a target of interest, 2 min cadence images were available. We used the pre-search data conditioning simple aperture photometry.

3 ANALYSIS

New model atmospheres appropriate for the analysis of low-dispersion (FORS1, R.-C. spec.) and high-dispersion X-shooter spectra have been computed with a mixed H/He composition including a selection of trace elements (C, N, O, Na, Mg, Al, Si, Ca, Cr, Mn, Fe, Ni). The models are in a joint radiative and convective equilibrium adopting the mixing length convection theory. Although the presence of a magnetic field may inhibit convective motion (Tremblay et al. 2015), Bédard, Bergeron & Fontaine (2017) and Kawka et al. (2019) found that deep convection zones cannot be suppressed in cool white dwarfs such as PM J08186–3110.

3.1 Models

The model atmospheres are converged to a tolerance of 0.1 per cent in the depth-dependant integrated flux. The input parameters are the effective temperature (T_{eff}), surface gravity ($\log g$), and the chemical composition expressed as the number density relative to helium. The total radiative opacity includes dominant contributions displayed in Fig. 1 (top panel) for a representative model. Line profiles of most spectral lines are described by Voigt functions with the width of the Lorentzian component dominated by neutral helium collisions. However, cool helium-rich white dwarfs require a specific treatment for line broadening, owing to the high helium densities that are involved in their atmospheres (bottom of Fig. 1). New theoretical profiles were very accurately determined in a unified theory of collisional line profiles valid at very high densities using ab initio calculations of potential energy and transition dipole moments. Beyond the symmetrical Lorentzian core at low density, profiles are asymmetrical (see e.g. for the Mg I triplet: Allard et al. 2016b and top of Fig. 1). These calculations are available for dominant spectral lines. For other

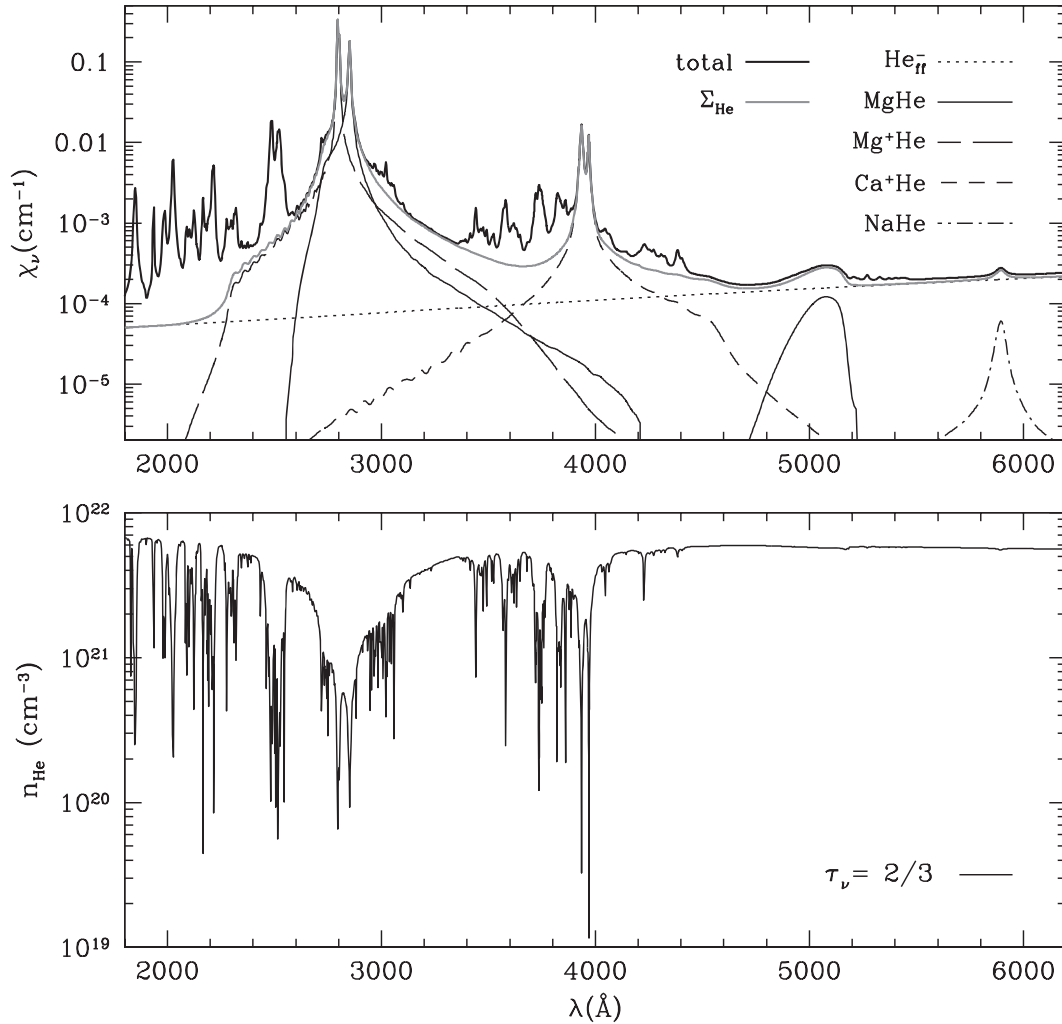


Figure 1. Top panel: Dominant opacities at $\tau_R = 0.1$, $n(\text{He}) = 3 \times 10^{21} \text{ cm}^{-3}$ in a model at $T_{\text{eff}} = 6250 \text{ K}$, and $\log g = 8.25$. Bottom panel: Neutral helium density at monochromatic optical depth $\tau_\nu = 2/3$ in the same model shown in the upper panel.

lines, we employ hydrogen line collision parameters from Barklem, Piskunov & O’Mara (2000) and scaled for helium collisions.

Fig. 1 (bottom panel) also shows the neutral helium density at a monochromatic optical depth $\tau_\nu = 2/3$, which corresponds to a photon escape probability of 50 per cent, across the optical spectrum for the same model. For example, the Mg I $\lambda 5178$ triplet and Na I $\lambda 5892$ doublet form at a density $n_{\text{He}} \approx 5 \times 10^{21} \text{ cm}^{-3}$, while the strong Ca H and K doublet forms at a range of density from 10^{19} to $5 \times 10^{21} \text{ cm}^{-3}$.

Details of the line profile calculations that include interactions with neutral helium atoms in dense atmospheres are available for Na–He, Mg–He, Mg^+ –He, Ca–He, and Ca^+ –He interactions. The optical Mg I–He 5167, 5173, 5183 Å lines show strong asymmetric blueshifted wing due to the Mg–He interaction (Allard et al. 2016b). We tabulated theoretical line profiles at 6000 K and helium density at $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 19.0$ –22.5 in steps of 0.1 dex. The tables encompass the range of neutral helium density found in the atmosphere of the cool DZ white dwarf PM J08186–3110. A single, representative temperature was adopted for the line-forming region.

The ultraviolet resonance lines Mg II 2896, 2803 Å ($P_{1/2}$, $P_{3/2}$) and Mg I 2852 Å are shaped by Mg^+ –He and Mg–He interactions, respectively (Allard et al. 2016a, 2018). The line wings extending

towards longer wavelengths are clearly detected in the UVB/X-shooter spectrum. We tabulated the Mg II and the Mg I line cross-sections at neutral helium densities from $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 19.0$ –22.0 in steps of 0.2 dex, and at 6000 K. Lorentzian profiles are adopted at lower densities.

The Ca I 4226 Å resonance line is shaped by Ca–He interactions (Blouin et al. 2019). We tabulated the line cross-sections from $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 20.3$ –23.0 in steps of 0.1 dex, and at 6000 K. Lorentzian profiles were adopted at lower densities with a full width at half-maximum adjusted to match the Ca–He profile at $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 20.3$.

The resonance Ca II H and K shaped by Ca^+ –He interactions (Allard & Alekseev 2014) were tabulated at $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 19.0$, 19.3, 19.6, 19.9, 20.0, 20.3, 20.6, 20.9, 21.0, 21.3, 21.6, 21.9, 22.0, 22.3, and 22.6, covering the range of neutral helium density encountered in the atmosphere of PM J08186–3110 (Fig. 1).

Finally, the resonance Na I is shaped by Na–He interactions (Allard 2013). We tabulated the line cross-sections at $\log(n_{\text{HeI}}/\text{cm}^{-3}) = 19.0$ –22.0 in steps of 0.5 dex at a temperature of 6000 K.

Other lines currently modelled with Lorentzian profiles should eventually be modelled with line profiles including quasi-molecular interactions, e.g. Fe–He, Ni–He, and others.

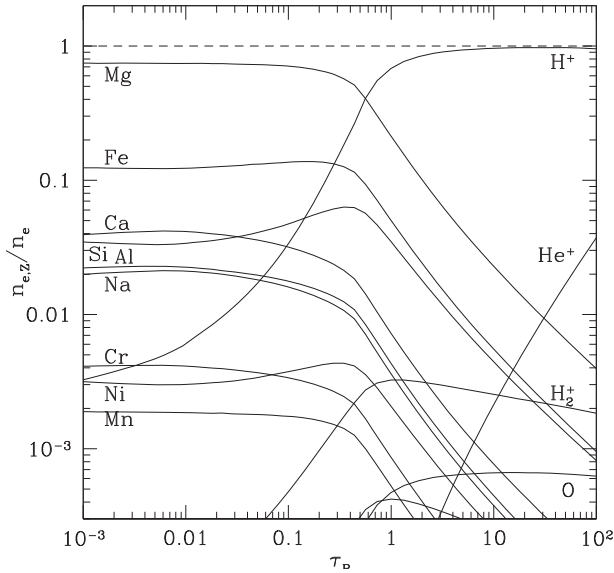


Figure 2. Electron donors expressed as a fraction of the total electron density in a reference model at $T_{\text{eff}} = 6250$ K and $\log g = 8.25$ and abundances from Table 3.

The negative helium ion opacity (He^-) dominates the optical red to IR spectrum (Fig. 1). The main contributors to the electron density are magnesium and hydrogen (Fig. 2). Lowering of the ionization potential in the high-density helium environment contributes to an increase in the electron density. We adopted a simple prescription for the ionization potential of C, Na, Mg, Ca, and Fe as a function of temperature and density described in Blouin (2019).

Individual abundances of light and heavy elements are either measured directly or, in the absence of a detection, they are scaled on iron using abundance ratios measured in chondrite meteorites (Lodders, Palme & Gail 2009). Lacking clear detections, Coutu et al. (2019) scaled the abundance of iron (-7.8) and other elements on the measured calcium abundance (-9.0) using the chondrite meteorite abundance ratios. The presence of hydrogen may be felt indirectly from its large contribution to the electron density and, consequently, the He^- opacity (see Coutu et al. 2019). The broad spectral range covered in our spectra should allow us to measure the effect of hydrogen on the continuum shape. Subasavage et al. (2017) fixed the hydrogen abundance at $\log \text{H}/\text{He} = -5$, while Coutu et al. (2019) fixed the abundance at the detection limit of $\log \text{H}/\text{He} = -3.17$. Other sources of electrons in outer atmospheric layers include elements with low first ionization potential.

A weak field of 92 kG was applied to the spectral synthesis (see Section 3.3). At the spectral resolution offered by X-shooter, this effect is apparent in the Ca II IR triplet.

3.2 Stellar parameters

We first constrained the likely effective temperature and surface gravity with the *Gaia* distance measurement and the total flux emitted by PM J08186–3110. We integrated the flux from the ultraviolet to the IR. In the ultraviolet and visual, we used the UVB and VIS X-shooter spectra scaled to the SkyMapper photometric measurements. We extended the flux to the IR with a model spectrum that is scaled to 2MASS and *WISE* photometric measurements. We then calculated the radius using the *Gaia* distance measurement for a range of effective temperatures. Finally, we used the mass–radius

Table 2. Properties of PM J08186–3110 constrained by the *Gaia* distance.

T_{eff} (K)	$\log g$	Mass (M_{\odot})	Radius (R_{\odot})
5800	8.02	0.572	0.01230
5900	8.07	0.606	0.01188
6000	8.13	0.639	0.01149
6100	8.18	0.672	0.01112
6200	8.22	0.705	0.01076
6300	8.27	0.736	0.01042
6400	8.31	0.767	0.01010
6500	8.36	0.796	0.00979

relations for hydrogen-deficient white dwarfs of Camisassa et al. (2017) to determine the corresponding mass and surface gravity. Table 2 lists the parameters that were constrained by the *Gaia* distance measurement.

We have fitted both the VLT/FORS1 and VLT/X-shooter spectra to determine the atmospheric parameters. The CTIO/R-C spectrum appeared identical to the FORS1 spectrum and was not analysed further. Fig. 3 shows the best-fitting model spectra compared to the observed FORS1 and X-shooter spectra and Table 3 summarizes the parameters of PM J08186–3110. We found that the best-fitting model to the VLT/FORS1 and X-shooter spectra corresponds to an effective temperature of 6250 K and surface gravity $\log g = 8.25$. However, the abundances in the X-shooter spectrum are systematically higher than those measured in the FORS1 spectrum by a factor of two, suggesting that the abundances vary over time. The atmosphere appears enriched in magnesium, $+0.63$ and $+0.54$ in the FORS1 and X-shooter spectra, respectively, and to a lesser extent calcium, $+0.22$ (FORS1) and $+0.28$ (X-shooter), relative to other elements. The presence of hydrogen is felt indirectly with a notable downward inflexion of the optical spectrum towards shorter wavelength. The hydrogen abundance measured in the X-shooter spectrum is a factor of 10 larger than measured in the FORS1 spectrum. We noted a discrepancy between the best-fitting calcium abundance and the strength of the Ca II IR triplet suggesting that Lorentzian profiles are inadequate in this case, and require line profiles inferring both a unified theory of spectral line broadening and accurate ab initio potential energies. The mass and cooling age were calculated using the evolutionary mass–radius relations of Camisassa et al. (2017). Although the mass and radius of Camisassa et al. (2017) and Benvenuto & Althaus (1999) are consistent, the cooling age differs significantly due to additional mechanisms being included in mass–radius relations of Camisassa et al. (2017). We estimate the errors on the temperature and surface gravity at 100 K and 0.05 dex, respectively. Error bars on abundance measurements stem from the error bars on T_{eff} and $\log g$ are estimated at 0.2 dex on average. Note that FORS1 and X-shooter abundance measurements vary in concert.

The variable abundances are most likely due to the magnetic field distribution on the white dwarf surface which can result in abundance spots. A variable magnetic field strength across the surface of the white dwarf is supported by changes in the longitudinal magnetic field noted in two spectropolarimetric measurements reported by Bagnulo & Landstreet (2019). Photometric variability will most likely be strongest in the u and v bands because this is where metal lines are strongest, although due to flux redistribution some variability should be present in the red and infrared spectral range as well. We searched for variability in the available *TESS* photometric measurements but we did not find any significant variations. Using the 2 min cadence, we measured an upper limit on the semi-amplitude of flux variations of 1.8 per cent. Binning

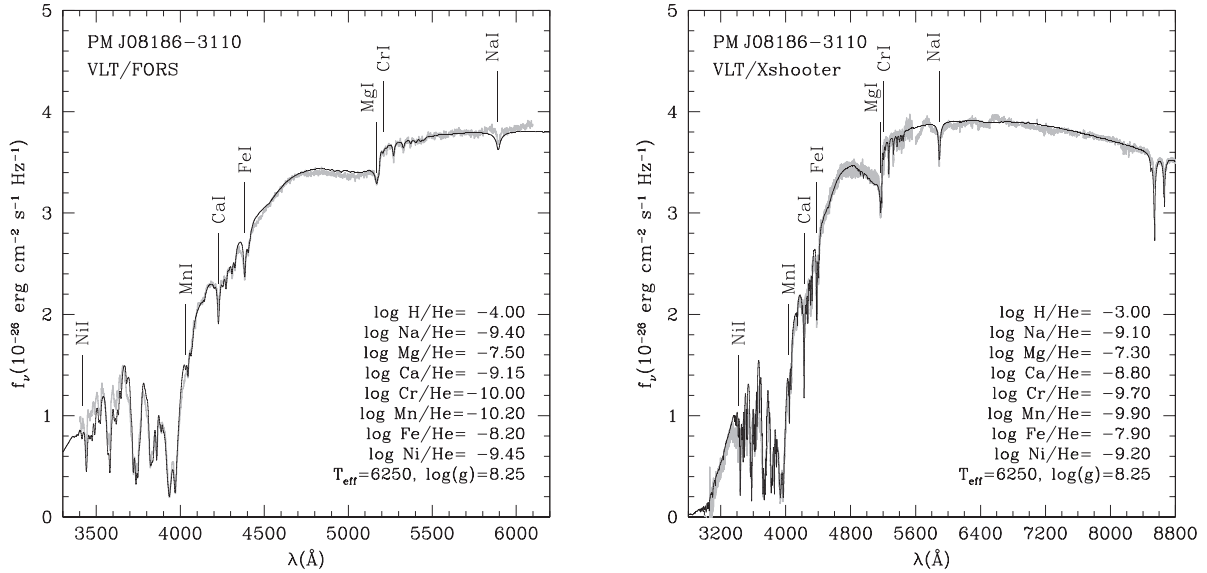


Figure 3. Left: FORS1 spectrum (grey) compared to the best-fitting model spectrum (black) with tabulated model parameters. Right: Same as left-hand panel but for the X-shooter spectrum (grey).

Table 3. Stellar and atmospheric parameters.

Parameter	Measurement	
	FORS	X-shooter
T_{eff} (K)		6250
$\log g$ (cgs)		8.25
Mass (M_{\odot})		0.72
Distance (pc)		19.4 ± 0.01
Age (Gyr)		4.2
B_l (kG)	26 ± 5	...
B_s (kG)	...	92 ± 1
$\log(\text{H/He})$	-4.00	-3.0
$\log(\text{Na/He})$	-9.40	-9.10
$\log(\text{Mg/He})$	-7.50	-7.30
$\log(\text{Ca/He})$	-9.15	-8.80
$\log(\text{Cr/He})$	-10.00	-9.70
$\log(\text{Mn/He})$	-10.20	-9.90
$\log(\text{Fe/He})$	-8.20	-7.90
$\log(\text{Ni/He})$	-9.45	-9.20

the measurements to a 10 min cadence, we reduced the limit on flux variations to 1.2 per cent. The best-fitting model spectra from the FORS1 and X-shooter data predict a 1.4 per cent variation over the *TESS* bandpass, which is consistent with the measured upper limit. Photometric variability has been detected in several magnetic white dwarfs. Rotating white dwarfs with very strong magnetic fields, magnetic dichroism can explain the photometric observations, e.g. EUVE J0317–85.5 (Vennes et al. 2003). In cool white dwarfs with weak magnetic fields, star-spots have been proposed as the likely cause (Brinkworth et al. 2013). The variations in these white dwarfs are a few per cent, comparable to our upper limit. Finally, Kilic et al. (2019) showed that the spectroscopic and photometric variations observed in G183–35 were caused by a variable magnetic field and a chemically inhomogeneous surface composition rotating on a period of about 4 h.

We compared the best-fitting model spectra to the observed photometric measurements. We used the X-shooter best-fitting spectrum to calculate model magnitudes. First, we convolved the model spectrum

with the SkyMapper (Bessell et al. 2011), 2MASS (Skrutskie et al. 2006), and *WISE* (Wright et al. 2010) bandpasses and then we calculated absolute magnitudes using the evolutionary mass–radius relations of Benvenuto & Althaus (1999). Fig. 4 shows the observed apparent magnitudes compared to the model magnitudes which were converted from absolute magnitudes to apparent magnitudes using the *Gaia* distance. The comparison shows that the short wavelength bands, SkyMapper *u* and *v*, are systematically above the X-shooter flux level and show evidence of abundance variations.

Some atmospheric parameters of PM J08186–3110 were published in the past and the effective temperatures from these studies are systematically higher than what we have obtained, although individual measurements are consistent with our own within 1σ error bars. Using low-resolution spectroscopy and assuming $\log g = 8$, Subasavage et al. (2008) measured an effective temperature of $T_{\text{eff}} = 6631 \pm 345$ K and $\log \text{Ca/He} = -9.09 \pm 0.20$. A slightly lower effective temperature of $T_{\text{eff}} = 6463 \pm 370$ K, also assuming $\log g = 8$, was determined by Giammichele et al. (2012) along with $\log \text{Ca/He} = -9.23$. Subasavage et al. (2017) measured a parallax of $\pi = 52.30 \pm 0.71$ mas and combined with *V*, *R*, *I* photometric measurements and low-resolution spectra, they constrained the parameters of PM J08186–3110 to $T_{\text{eff}} = 6480 \pm 290$ K, $\log g = 8.22 \pm 0.07$ corresponding to a mass of $0.71 \pm 0.06 M_{\odot}$. They also measured $\log \text{Ca/He} = -9.26$. Using the *Gaia* parallax, *V*, *R*, *I* photometry, and low-resolution spectroscopy, Coutu et al. (2019) constrained the parameters of PM J08186–3110 and obtained $T_{\text{eff}} = 6535 \pm 645$ K, $\log g = 8.28 \pm 0.19$, and $\log \text{Ca/He} = -8.99 \pm 0.04$, corresponding to a mass of $0.75 \pm 0.13 M_{\odot}$. The present analysis is more comprehensive than earlier ones as it benefitted from a complete spectral coverage and a detailed abundance analysis.

3.3 Magnetic field

The average surface field strength (B_s) can be estimated from the splitted Zeeman components of spectral lines (see Kawka & Vennes 2011, for details). We used the Ca II 8542 and 8662 Å lines in the X-shooter spectrum to measure $B_s = 92 \pm 1$ kG. We measured a

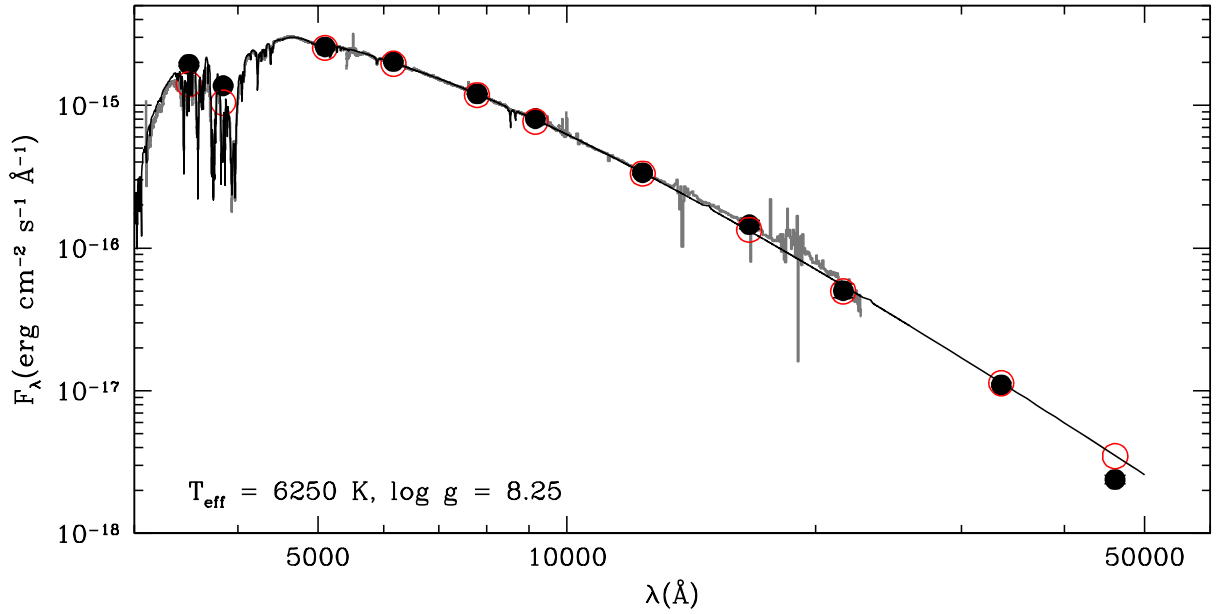


Figure 4. The best-fitting model spectrum compared to the X-shooter spectra (grey) and observed photometric measurements (black dots). The model photometric points (red circles) are calculated from the best-fitting spectrum. The ultraviolet data points differ significantly from the X-shooter flux showing evidence of abundance variations.

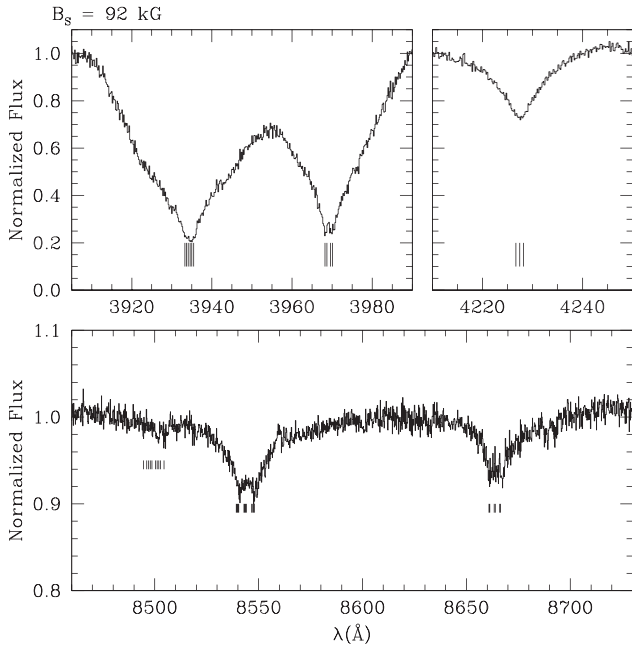


Figure 5. X-shooter spectra showing the Zeeman splitted or broadened Ca II and Ca I lines. The tick marks indicate the predicted Zeeman splitting for magnetic field strength of 92 kG. The splitting is apparent in the strongest components of the Ca II IR triplet.

barcentric corrected radial velocity of 88.0 km s^{-1} . Fig. 5 shows the Zeeman splitted or broadened Ca II and Ca I lines observed in the X-shooter spectrum. We checked the average surface field strength is consisted with other lines where the Zeeman splitting is less pronounced but we clearly see a broadened core, these include Fe I 4271.76 and Fe I 5269.537 Å.

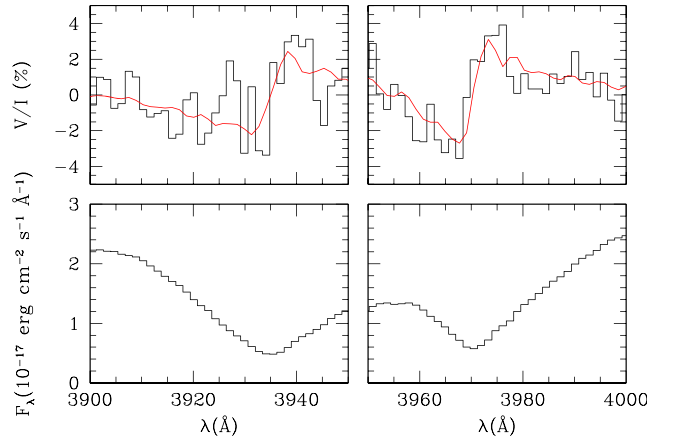


Figure 6. FORS1 circular polarization (top) and flux (bottom) spectra of the Ca II lines in PM J08186–3110.

We calculated the longitudinal magnetic field strength (B_l in G) using the circularly polarized spectra obtained with FORS1 using

$$B_l = \frac{v I}{4.67 \times 10^{-13} \lambda^2 (dI/d\lambda)}, \quad (1)$$

where $v = V/I$ is the degree of circular polarization, I is the total intensity, λ is the wavelength in Å, and $dI/d\lambda$ is the flux gradient. Fig. 6 shows the circular polarization and flux spectra of the Ca II lines with the best-fitting V/I spectrum for a longitudinal magnetic field strength of $B_l = 26 \pm 5 \text{ kG}$. Bagnulo & Landstreet (2019) measured a similar field of $20 \pm 2 \text{ kG}$ using the same set of observations. Note that the sign of circular polarization in Bagnulo & Landstreet (2019) is opposite to the sign used in this paper. The second circular polarization spectrum obtained by Bagnulo & Landstreet (2019) suggests that the magnetic field is variable supporting the likelihood of a varying abundance on the white dwarf surface.

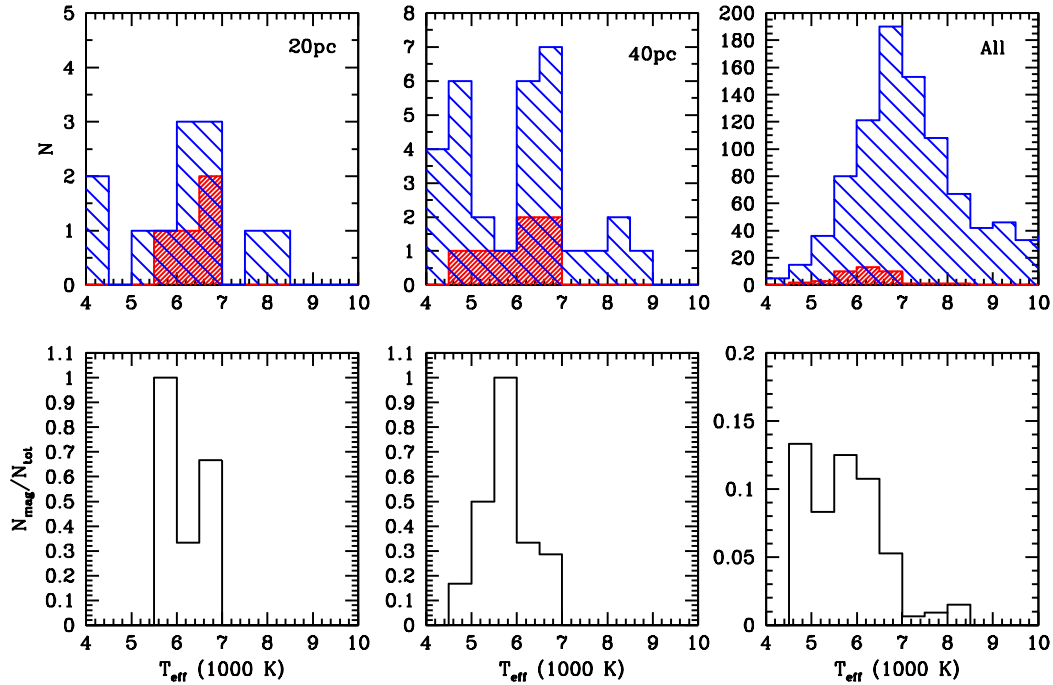


Figure 7. The incidence of magnetism in cool DZ white dwarf as a function of effective temperature.

3.4 Kinematics

We calculated the Galactic velocity components from the distance, proper motion, and radial velocity of PM J08186–3110 using Johnson & Soderblom (1987). We corrected for the Solar motion relative to the local standard of rest using $(U_{\odot}, V_{\odot}, W_{\odot}) = (11.10, 12.24, 7.25) \text{ km s}^{-1}$ (Schönrich, Binney & Dehnen 2010). We measured a barycentric corrected radial velocity of $v = 88.0 \pm 5.0 \text{ km s}^{-1}$ using the X-shooter spectrum. We subtracted a gravitational redshift of $V_{gr} = 43.3 \text{ km s}^{-1}$ to obtain a stellar velocity of 44.7 km s^{-1} . The Galactic velocity components of $(U, V, W) = (65, -54, -13) \text{ km s}^{-1}$ place PM J08186–3110 in the thick disc (Soubiran, Bienaymé & Siebert 2003). We also calculated the Galactic orbit properties using GALPY (Bovy 2015) where we use the MWPotential2014 Galactic potential. The eccentricity $e = 0.33 \pm 0.02$ and the z -component of the angular momentum $L_z = 1296 \text{ kpc km s}^{-1}$ also places PM J08186–3110 in the thick disc following Pauli et al. (2006).

The age of the Galactic thick disc is about 10 Gyr (Sharma et al. 2019) and therefore the total age of PM J08186–3110 should be comparable. However, the cooling age of PM J08186–3110 is 4.2 Gyr and assuming a thick disc metallicity, the mass and lifetime of the progenitor should be about $2.5 M_{\odot}$ and 600 Myr (Romero, Campos & Kepler 2015), respectively. Therefore, assuming single-star evolution, the total age of PM J08186–3110 should be significantly lower than 10 Gyr.

The cooling age was calculated using the evolutionary tracks of Camisassa et al. (2017) for hydrogen-deficient white dwarfs. They show that in cool helium-rich white dwarfs the high density atmosphere plays an important role in regulating their cooling rates. Although PM J08186–3110 is a cool helium-rich star, it is also polluted by heavy elements and the electrons contributed by these elements, in particular iron, help increase the He^{-} opacity and push the atmosphere to shallower depths than found in pure helium atmospheres. This is also likely to affect the cooling age estimate.

4 DISCUSSION

The number of magnetic, polluted white dwarfs is growing and the incidence of magnetism was found to be higher in cool polluted white dwarfs than in the general white dwarf population. For polluted hydrogen-rich (DAZ) white dwarfs, the incidence was found to be as high as 50 per cent for $T_{\text{eff}} \lesssim 6000 \text{ K}$ (Kawka & Vennes 2014; Kawka et al. 2019). For helium-rich white dwarfs, this incidence is 21.6 ± 3.3 per cent (Hollands et al. 2015; Hollands 2017).

4.1 Incidence of magnetism

Recently, new magnetic DZ white dwarfs have been discovered in the Solar neighbourhood (e.g. Bagnulo & Landstreet 2019; Tremblay et al. 2020), and therefore their incidence can be revisited. We have assembled a sample of known DZ white dwarfs using the extensive lists of Coutu et al. (2019) and Hollands (2017). We also included new DZ white dwarfs that lie within 40 pc of the Sun (Tremblay et al. 2020). We cross-correlated this sample with the *Gaia* DR2 catalogue to obtain parallax measurements. These measurements allow us to build volume-limited samples.

There are 12 DZ white dwarfs within 20 pc of the Sun, and of these 4 are magnetic. Fig. 7 shows that the magnetic DZs are all cooler than 7000 K and the incidence of magnetism for DZs in this temperature range is 40 per cent. Extending the volume to 40 pc, a total of 32 DZ white dwarfs are known, out of which 7 are magnetic. Again, they are all below 7000 K, however, the incidence of magnetism goes down to 27 per cent ($T_{\text{eff}} < 7000 \text{ K}$). Fig. 7 also plots the incidence of magnetism for all known DZ white dwarfs and it shows that there are few magnetic DZs with a temperature between 7000 and 8500 K. Larger volume-limited samples are needed to confirm whether the trend of an increased incidence of magnetism with decreasing temperature is real.

4.2 Abundance evolution

The kinematics of PM J08186–3110 suggest that it is an old, thick disc star, and if we assumed that the white dwarf atmosphere was polluted through the accretion or merging with a planet or a low-mass star, the abundance ratios of elements heavier than helium would depend on the age, hence composition of the parent stellar system. Spina et al. (2016) and Bedell et al. (2018) have shown that the abundance of elements lighter than Fe should be higher in older stars and this should be reflected in the composition of the accreted material on to polluted white dwarfs. Magnesium is enriched in PM J08186–3110 as compared to iron, chromium, and manganese, which is predicted in old stellar systems. However, diffusion alters the observed abundance ratios in white dwarf atmospheres relative to the abundance pattern in the accretion sources. In this regard, Heinonen et al. (2020) have shown that additional mixing criteria may have a significant effect on the diffusion time-scales of elements relative to each other. They also show that diffusion coefficients at the bottom of the deep convection zone of helium-rich white dwarfs may require considerable revision which prevents us from reaching firm conclusions on the evolution of abundance ratios as a function of the age of the source material. Moreover, the effect of magnetic field on diffusion time-scales remains largely unknown.

5 CONCLUSIONS

We have presented a spectroscopic analysis of the cool, He-rich, magnetic white dwarf PM J08186–3110, showing that it has an atmosphere enriched in magnesium relative to sodium, calcium, chromium, manganese, iron, and nickel. It is not known whether the magnesium dominance is a characteristic of an old, Fe-poor, parent environment, or it occurred later on during the accretion process. A population of Mg-rich polluted white dwarfs has already been identified and is representative of Earth-mantle material (Hollands, Gänsicke & Koester 2018). The presence of hydrogen in the atmosphere of PM J08186–3110 suggests that the accreted material, e.g. broken-up asteroids, contained ice. The recent detection of ice/water in the prototypical asteroid Ceres (Raymond et al. 2020) supports this scenario. Signatures of accreted water in white dwarfs were detected in a handful of DZ white dwarfs (Farihi, Gänsicke & Koester 2013; Gentile Fusillo et al. 2017). This is the first time an abundance pattern was measured for PM J08186–3110, with previous spectroscopic analyses resulted in the abundance measurements of calcium, only. We have also shown that the abundance pattern changes between the FORS1 and X-shooter spectra taken 10 yr apart, suggesting that PM J08186–3110 has abundance spots due to the distribution of the magnetic field on the surface of the white dwarf. These abundance spots will reveal themselves as abundance variations over the rotational period, which could be a few hours, such as was observed in G183-35 (Kilic et al. 2019). This hypothesis is supported by noted variations in the longitudinal field measured with FORS1 spectropolarimetry and, independently, with WHT/ISIS spectropolarimetry (Bagnulo & Landstreet 2019). The X-shooter spectrum allowed us to measure a weak surface average field of 92 kG.

The kinematics of PM J08186–3110 suggest that it belongs to the thick disc, however, when using evolutionary models, the total age of PM J08186–3110 is significantly lower than the age of thick disc. This could mean that either PM J08186–3110 is not part of the thick disc but rather an outlier of the old thin disc population, or that additional factors or events could slow down the cooling rate of magnetic DZ white dwarfs. The third possibility could be that

PM J08186–3110 is the result of a merger and therefore its cooling age was reset following the merging event.

We have shown that the incidence of magnetism in cool DZ white dwarfs is very high, similar to the incidence of magnetism in cool DAZ white dwarfs. Both populations are lacking counterparts in their warmer and younger counterparts which suggest that the magnetic field formation and pollution of the atmosphere are linked to an accretion event that happens late in the life of the white dwarf.

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DATA AVAILABILITY

The data underlying this article are available in the ESO Science Archive at <http://archive.eso.org>, and can be accessed under programmes 080.D-0521 and 0100.D-0531.

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