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A new magnetic white dwarf: PG 2329+267

C. Moran,[1] T. R. Marsh[1] and V. S. Dhillon[2]
[1] *University of Southampton, Department of Physics, Highfield, Southampton SO17 1BJ*
[2] *University of Sheffield, Department of Physics, Hounsfield Road, Sheffield S3 7RH*

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ABSTRACT

We have discovered that the white dwarf PG 2329+267 is magnetic, and, assuming a centred dipole structure, has a dipole magnetic field strength of approximately 2.3 MG. This makes it one of only approximately 4 per cent of isolated white dwarfs with a detectable magnetic field. Linear Zeeman splitting, as well as quadratic Zeeman shifts, is evident in the hydrogen Balmer sequence and circular spectropolarimetry reveals $\sim$10 per cent circular polarization in the two displaced σ components of Hα. We suggest from comparison with spectra of white dwarfs of known mass that PG 2329+267 is more massive than typical isolated white dwarfs, in agreement with the hypothesis that magnetic white dwarfs evolve from magnetic chemically peculiar Ap and Bp type main-sequence stars.

Key words: magnetic fields – polarization – stars: individual: PG 2329+267 – white dwarfs.

1 INTRODUCTION

The possibility that white dwarfs may possess large magnetic fields was first suggested in 1947 (Blackett 1947); however, it was not until 1970 that the first detection was made (Kemp et al. 1970). Since then 43 magnetic white dwarfs have been found, with field strengths ranging from $\sim$0.1 to $\sim$ 1000 MG. The vast majority (96 per cent) of white dwarfs have as yet shown no sign of magnetic fields (Schmidt & Smith 1995), though this percentage may drop as surveys for magnetic fields are extended to lower field strengths. Serendipitous discoveries made during spectroscopic studies may also add to the number of known magnetic systems. What the actual percentage of magnetic white dwarfs is amongst the complete population, and what the distribution of field strengths amongst this set is, remains unclear.

A more complete knowledge of the magnetic properties of these stellar remnants, particularly at low (subMG) magnetic field strengths, may allow us to deduce the role played by magnetic fields throughout the lifetime of the progenitor stars, as the magnetic fields found in white dwarfs are believed to be fossil fields preserved from earlier stages of stellar evolution. There is no known process for the generation of large-scale magnetic fields during the degenerate phase of stellar evolution, and so they are likely to be amplified versions of the fields that permeated their parent stars. White dwarfs with magnetic field strengths >1 MG may be explained by evolution from chemically peculiar, magnetic Ap and Bp stars (Angel, Borra & Landstreet 1981), which have detectable magnetic fields from 100 to 10 000 G. White dwarfs with weaker magnetic fields would require their main-sequence progenitors to have fields of only a few G, below the current observational limits. This theory is supported by the similar space density of magnetic degenerates and the expected distribution of the remnants of magnetic main-sequence stars (Sion et al. 1988), as well as the observed tendency for magnetic white dwarfs to be more massive than non-magnetic white dwarfs because of their proposed evolution from more massive progenitors.

The presence of a magnetic field has several detectable effects upon the spectrum of a white dwarf. For magnetic field strengths between 1 and 20 MG the linear Zeeman effect produces a distinctive triplet pattern for each absorption feature. Both the upper and lower atomic levels split into three energetically equidistant sublevels. This allows transitions between the upper and lower levels to occur at three different energies. The wavelength of the central π component is unaffected by the presence of the magnetic field; however, the two σ components are shifted, one to a longer (σ^-) and one to a shorter (σ^+) wavelength. The degree of this separation ($\pi - \sigma$) is determined by the strength of the magnetic field (Landstreet 1994) according to

$$\Delta\lambda_{\mathrm{L}} \simeq 4.7 \times 10^{-7} \lambda^2 B_{\mathrm{s}}, \tag{1}$$

where λ is measured in Å and the average magnetic field strength over the visible hemisphere of the white dwarf, B_{s}, is measured in MG.

Above about 20 MG the quadratic Zeeman effect dominates over the linear effect and the spectra become more and more complicated. Even at lower magnetic field strengths the quadratic Zeeman effect is noticeable as a blue shift in the wavelength of all the lines in the spectra. The size of the wavelength shift $\Delta\lambda_{\mathrm{Q}}$, given by equation (2), is different for each line in the Balmer series, with the higher lines being shifted far more than Hα (Preston 1970):

$$\Delta\lambda_{\mathrm{Q}} \simeq -5 \times 10^{-11} \lambda^2 n^4 B_{\mathrm{s}}^2, \tag{2}$$

where n is the principle quantum number of the upper level of the transition, so for the Balmer series $n = 3$ for Hα and $n = 8$ for Hζ. This simple expression is based on perturbation theory and will break down for high n values, even at quite modest field strengths (Surmelian & O'Connell 1974).

The circular polarization of the light can also be used to measure the magnetic field strength of a white dwarf. Even for weak magnetic fields (<1 MG), where the Zeeman splitting is not obvious because of the large Stark broadening of white dwarf spectral features, the line profile is still a superposition of the unshifted π component and the two shifted σ components. In a longitudinal magnetic field the two σ components have opposite circular polarizations and hence, even though the net circular polarization of the line is zero, the offset σ components produce a distinctive S-shaped feature in the circular polarization spectrum. The percentage of circular polarization ($V_{\%}$) is proportional to the longitudinal magnetic field strength B_e and the normalized flux gradient of the zero field π line, as shown below, where I_λ is the flux:

$$V_{\%}(\lambda) = 1.1B_e\left(\frac{\lambda}{4861}\right)^2\frac{1}{I_\lambda}\frac{dI_\lambda}{d\lambda}. \quad (3)$$

Hence by measuring the degree of circular polarization we can calculate B_e, the mean longitudinal magnetic field strength over the visible hemisphere of the white dwarf.

2 OBSERVATIONS

In 1995 November we observed the white dwarf PG 2329+267 as part of a spectroscopic survey to determine the masses of DA (hydrogen-dominated) white dwarfs. It was immediately clear from the characteristic Zeeman splitting of the Balmer lines that PG 2329+267 was magnetic. Follow-up observations in 1996 January, using circular spectropolarimetry, confirmed the existence of a magnetic field.

The initial discovery of the magnetic nature of PG 2329+267 was made on 1995 November 23 using the IDS spectrograph and 235-mm camera on the INT (2.5-m Isaac Newton Telescope), La Palma. The spectra cover 3682 to 5300 Å at a FWHM resolution of 2.3 Å.

We conducted follow-up observations on 1996 January 12. We used the spectropolarimeter with the blue arm of ISIS on the WHT (4.2-m William Hershel Telescope), La Palma. The set-up consisted of a quarter waveplate to convert the circular polarization into its two orthogonal components, a dekker to separate star and sky spectra, the spectrograph slit and then a calcite block to separate the two linear polarizations. Each observation yielded two spectra of the object, corresponding to the two rays split by the calcite block. In principle the intensity difference of these two spectra could yield the percentage of circular polarization; however, this would ignore any differences in the response of the spectrograph and the detector between the o and e rays. To account for any differences in instrumental response, the quarter-wave plate was rotated by 90° and a second set of observations was made. The rotation of the quarter-wave plate resulted in the reversal of the paths of the two rays. Hence by comparing the two exposures we could remove the instrumental response. We observed Hα, with the spectra covering 6362–6769 Å at a FWHM resolution of 0.7 Å.

3 RESULTS

3.1 Magnetic field strength from the Zeeman effect

The average spectrum of PG 2329+267, presented in Figs 1 and 2, shows the line splitting caused by the linear Zeeman effect. A peculiar feature exists in the Hα spectrum shown in the bottom panel of Fig. 2; while the σ^- component is apparently split into two, no such splitting is seen on the σ^+ component. The feature appears to be real but we can think of no explanation for such an asymmetry between the two σ components.

We calculated the flux-weighted average field strength over the visible hemisphere of the white dwarf (B_s) by measuring the degree

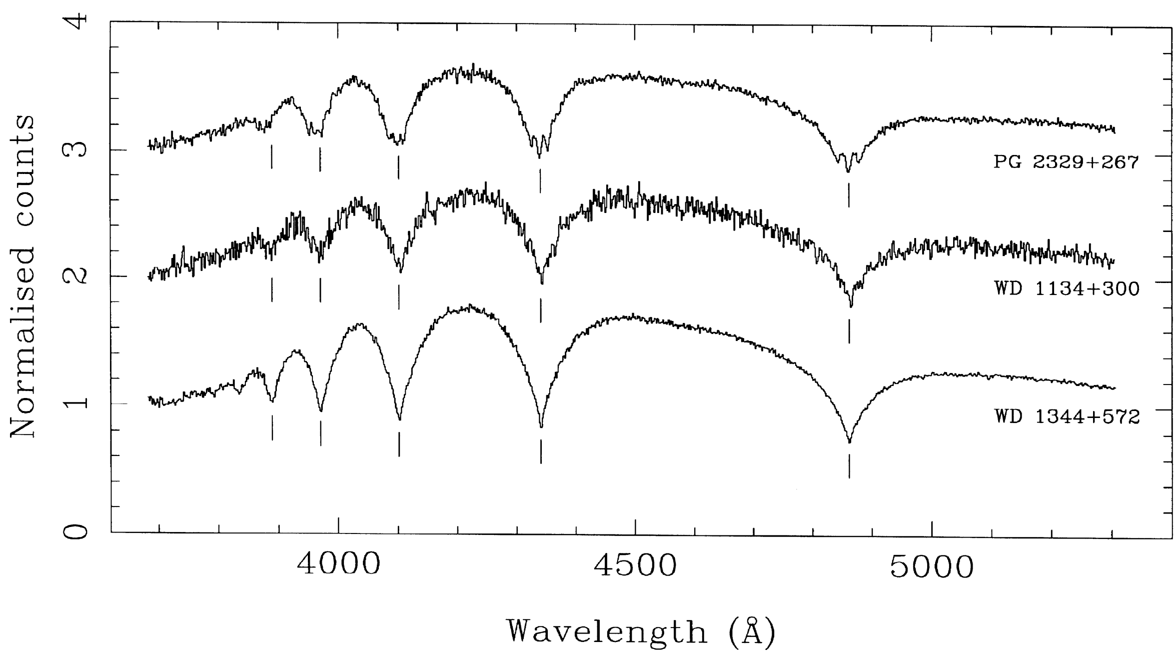

Figure 1. The spectrum of PG 2329+267 (top) taken with the INT clearly shows Zeeman splitting of the hydrogen Balmer lines caused by the presence of a magnetic field. The spectra of two non-magnetic white dwarfs are offset below for comparison. The vertical lines are placed at the rest wavelengths of the Balmer lines and aid detection of the quadratic Zeeman shift in the spectrum of PG 2329+267.

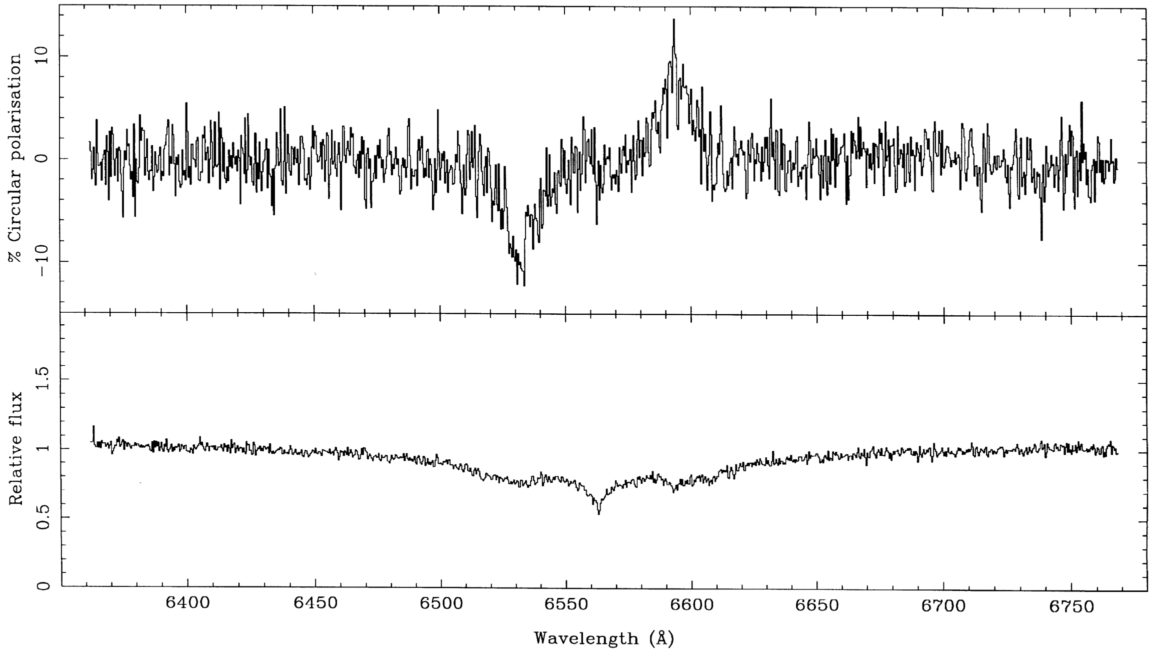

Figure 2. The lower panel shows the normalized spectrum of Hα in PG 2329+267. The upper panel shows the percentage of circularly polarized light present in the spectrum.

Table 1. Linear and quadratic Zeeman features.

Line	B_s MG (Linear)	λ_π Å	Quad shift Å	B_s MG (Quad)	Corrected B_s MG (Quad)
Hα	1.47 ± 0.07	6563.04 ± 0.10	0.28 ± 0.10	–	–
Hβ	1.57 ± 0.15	4860.55 ± 0.40	−0.78 ± 0.40	1.61 ± 0.41	2.08 ± 0.32
Hγ	1.56 ± 0.17	4339.02 ± 0.60	−1.44 ± 0.60	1.57 ± 0.33	1.81 ± 0.28
Hδ	1.45 ± 0.25	4099.08 ± 0.70	−2.65 ± 0.70	1.56 ± 0.21	1.69 ± 0.19
Hϵ	1.36 ± 0.27	3961.59 ± 0.80	−8.48 ± 0.80	2.12 ± 0.10	2.18 ± 0.10
Hζ	–	3875.31 ± 0.80	−13.75 ± 0.80	2.11 ± 0.06	2.15 ± 0.06
mean	1.58 ± 0.08			2.06 ± 0.05	2.12 ± 0.05

of wavelength splitting caused by the linear Zeeman effect. The results are shown in Table 1, column 2. For all the triplets, the line positions of the π and σ components and their corresponding uncertainties were measured by eye. The weighted mean of the measurements from all the lines is B_s = 1.58 ± 0.08 MG. This combines a measurement of the field strength from the Hα line and the higher lines of the Balmer series, even though they were taken at different times. The mean for all measurements taken from the discovery spectrum alone, i.e not including Hα, is B_s = 1.52 ± 0.10 MG

We also calculated B_s from the blue shift resulting from the quadratic Zeeman effect. The measured line centre of the π component of each triplet is shown in Table 1, column 3, the shift from the rest wavelength is shown in column 4 and the resultant magnetic field strength is shown in column 5. Note that the Hα line has a small redshift (+0.28 ± 0.10 Å) from its rest wavelength, owing to the combination of the gravitational redshift of the white dwarf and its intrinsic space motion dominating over the smaller blueshift from the quadratic Zeeman effect. If we assume a magnetic field strength of B_s = 1.58 ± 0.08 MG as measured from the linear Zeeman effect, the calculated quadratic Zeeman shift at Hα will be −0.43 ± 0.04 Å. Hence the total shift resulting from the gravitational redshift and intrinsic space motion will be +0.71 ± 0.11 Å at Hα or 32.4 ± 5.0 km s^{-1}. This velocity was used to correct the quadratic Zeeman shifts of the other spectral lines, the magnetic fields were recalculated and are shown in Table 1, column 6. The mean value of B_s, calculated from the uncorrected quadratic Zeeman shifts, is 2.06 ± 0.05 MG. Correcting the shifts with an intrinsic redshift of 32.4 ± 5.0 km s^{-1} increases the measured value of B_s to 2.12 ± 0.05 MG. Both values are inconsistent with the value of B_s determined from the linear Zeeman effect. There is an increase in the determined value of B_s from the Hϵ and Hζ lines; the mean value of B_s for the three earlier lines Hβ, Hγ and Hδ is 1.57 ± 0.16 MG when measured with the uncorrected shifts and 1.79 ± 0.14 MG with the corrected shifts, which are consistent with the mean value determined from the linear Zeeman effect. To account for a possible systematic difference between the Hα spectrum (taken with the WHT) and the Hβ−Hζ spectrum (taken with the INT) the magnetic field resulting from the quadratic Zeeman effect was calculated using a range of different velocity corrections (0 to 100 km s^{-1}). No correction yields either a self-consistent set of field strengths from the INT spectrum or a mean value consistent with the magnetic field strength measured from the linear Zeeman effect. We believe this to be the result of the breakdown of the perturbation theory used to derive equation (2).

3.2 Magnetic field strength from circular spectropolarimetry

The results of the circular spectropolarimetry are shown in Fig. 2. The bottom panel shows the normalized Hα flux while the top panel shows the percentage of circular polarization. The polarization spectrum clearly shows the S-shaped profile indicative of a magnetic field. The peak percentage of circular polarization at Hα is approximately 10 per cent. The longitudinal magnetic field strength B_e is calculated using equation (3), by a point-by-point technique (Schmidt, Stockman & Smith 1992), where in this instance the observed profile is fitted by multiple Gaussians and the flux gradient is calculated from this smooth profile in order to minimize the effect that noise in the line profile has on the magnetic field measurement. The calculated magnetic field strength is then a weighted integral of the point-by-point measurements, made across the line profile. We determined a value of B_e = + 462 ± 60 KG, though some caution should be taken with this figure, because the weak field approximation used in the equation will be breaking down as the Zeeman components are resolvable. Observations of the spectropolarimetric standard 53 Cam were used to obtain the correct sign for the magnetic field, (Angel, Mcgraw & Stockman 1973). We follow the convention that a positive circular polarization corresponds to counterclockwise rotation of the electric vector as seen by the observer.

4 DISCUSSION

4.1 Magnetic field strength and orientation of PG 2329+267

We have calculated the mean magnetic field strength over the visible hemisphere to be B_s = 1.58 ± 0.08 MG. There is no sign of rotational modulation of the magnetic field strength from our data as the measured values from the Zeeman splitting of Hα ($B_s = 1.47 \pm 0.07$ MG) and the other lines ($B_s = 1.52 \pm 0.10$ MG), which were taken on two separate occasions, are consistent with each other.

The mean longitudinal magnetic field strength has been determined to be $B_e = +462 \pm 60$ KG, hence the ratio of the longitudinal-to-mean field strength $B_e/B_s = 0.29 \pm 0.04$. This can be used to place limits on the orientation at which we observe the magnetic field. The longitudinal component of the magnetic field will be largest at the magnetic pole where $i = 0°$ and will decrease as we look closer to the magnetic equator (at $i = 90°$). We have assumed a simple centred dipole structure and calculated that we are observing the magnetic field at an inclination of $i = 60° \pm 5°$ from the magnetic axis. This result is consistent with a comparison of the Hα spectrum in Fig. 2 with computed spectra for a 3-MG dipole field (Achilleos & Wickramasinghe 1989), which suggests that we must be observing the magnetic field at an angle greater than 45°. These limits constrain the dipole magnetic field strength B_d so that $B_d = 2.31 \pm 0.59$ MG, where the dipole field strength is calculated using $B_e = 0.4 B_d \cos i$ (Schmidt & Smith 1995). This is a relatively weak magnetic field and gives PG 2329+267 the fourth lowest magnetic field strength of the 42 magnetic white dwarfs in Schmidt and Smith's (1995) list.

4.2 The mass of PG 2329+267

The discovery spectrum taken with the INT is shown in Fig. 1 along with two comparison, non-magnetic white dwarf spectra, which were taken with an identical setup. WD 1134+300 is a white dwarf with a mass of 0.9 $M_\odot$ (Bergeron, Saffer & Liebert 1992) and an effective temperature of 14 000 K, similar to that of PG 2329+267 for which the effective temperature is approximately 10 000 K (Shipman 1979). With the exception of the Zeeman features these two spectra are remarkably similar, particularly in the number of visible Balmer lines, which suggests that they have similar masses. For further comparison the spectrum of WD 1344+572 is shown at the bottom of Fig. 1. This white dwarf has a mass of 0.56 $M_\odot$, at the peak of the white dwarf mass distribution (Bergeron et al. 1992), and a temperature of 21 700 K. The increased masses of WD 1134+300 and PG 2329+267 compared with WD 1344+572 are evident from the smaller number of visible Balmer lines. The higher surface gravity of a more massive white dwarf increases the Stark broadening of the absorption lines of the hydrogen Balmer series and also reduces the number of visible absorption lines. By comparing the number of the higher Balmer lines visible in the spectra of the three white dwarfs, we can deduce that WD 2329+267 is more massive than the majority of white dwarfs and may have a mass comparable to WD 1134+300 at 0.9 $M_\odot$.

4.3 The evolution of PG 2329+267

If we consider the origin of the magnetic field in PG 2329+267, we can find evidence both for and against the hypothesis that it evolved from a chemically peculiar, magnetic Ap or Bp star. The magnetic field strength of PG 2329+267 is consistent with the theory of magnetic flux conservation from a magnetic main-sequence Ap or Bp star. As we showed with a simple qualitative argument, we believe PG 2329+267 to be more massive than the majority of white dwarfs, suggesting that it evolved from a fairly massive progenitor such as an Ap or Bp star. However, if we consider the Galactic space motion of PG 2329+267, which is given as 85.8 km s^{-1} (Sion et al. 1988), we can see that it is much larger than that found for all other magnetic white dwarfs, which themselves form a distinct low-velocity kinematic subgroup (Sion et al. 1988). The magnetic white dwarfs considered by Sion et al., with the exception of WD 0912+536, have low velocities with respect to the Sun (<50 km s^{-1}), indicating their youth and evolution from massive progenitors such as Ap and Bp stars. This is however only a statistical argument, and we do not consider the high velocity of PG 2329+267 to necessarily rule out its evolution from an Ap or Bp main-sequence star, which remains the most plausible hypothesis for the production of magnetic white dwarfs.

5 CONCLUSIONS

We have detected a magnetic field from the white dwarf PG 2329+267. The mean surface field strength measured from the degree of linear Zeeman splitting of the Balmer hydrogen lines is $B_s = 1.58 \pm 0.08$ MG. Similar measurements from the quadratic Zeeman effect yield consistent results only for the Balmer lines up to Hδ; for higher lines the perturbation theory used to calculate the magnetic field strength begins to break down. We have detected approximately 10 per cent circular polarization at Hα and have calculated the mean longitudinal magnetic field strength to be $B_e = +462 \pm 60$ KG. The ratio $B_e/B_s = 0.29 \pm 0.04$ and the shape of the Zeeman-split components suggests we are viewing the white dwarf at an inclination of $i = 60° \pm 5°$ from the magnetic axis. At this inclination the dipole magnetic field strength will be 2.31 ± 0.59 MG, making PG 2329+267 the fourth weakest known isolated magnetic white dwarf. We have suggested that PG 2329+267 is more massive than most isolated white dwarfs, which supports the hypothesis that magnetic white dwarfs evolve from chemically peculiar main-sequence Ap and Bp stars.

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