A new magnetic white dwarf: PG2329+267

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ABSTRACT

We have discovered that the white dwarf PG 2329+267 is magnetic, and assuming a centered dipole structure, has a dipole magnetic field strength of approximately 2.3 MG. This makes it one of only approximately 4% of isolated white dwarfs with a detectable magnetic field. Linear Zeeman splitting as well as quadratic Zeeman shifts are evident in the hydrogen Balmer sequence and circular spectropolarimetry reveals $\sim$10% circular polarisation in the two displaced $\sigma$ components of H\textalpha. 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: stars: individual: PG 2329+267 - white dwarfs - magnetic fields - polarisation

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%) 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 (sub MG) magnetic field strengths, may allow us to deduce the role played by magnetic fields throughout the life time 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 which 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 et al 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 Gauss, 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 due to 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 sub-levels. This allows transitions between the upper and lower levels to occur at three energetically equidistant sub-levels. This allows transitions between the upper and lower levels to occur at three different energies. The wavelength of the central \( \pi \) component is unaffected by the presence of the magnetic field, however the two \( \sigma \) components are shifted, one to a longer (\( \sigma^- \)) and one to a shorter wavelength (\( \sigma^+ \)). The degree of this separation (\( \pi - \sigma \)) is determined by the strength of the magnetic field (Landstreet 1994) according to,

\[
\Delta \lambda_L \simeq 4.7 \times 10^{-7} \lambda^2 B_s \tag{1}
\]
where $\lambda$ is measured in Angstroms and the average magnetic field strength over the visible hemisphere of the white dwarf, $B_\alpha$, is measured in MG.

Above about 20MG 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 $\Delta \lambda_Q$, given by equation 2, is different for each line in the Balmer series, with the higher lines being shifted far more than $H_\alpha$ (Preston 1970),

$$\Delta \lambda_Q \simeq -5 \times 10^{-11} \lambda^2 n^4 B_\alpha^2$$

where $n$ is the principle quantum number of the upper level of the transition, so for the Balmer series $n = 3$ for $H_\alpha$ and $n = 8$ for $H_\gamma$. 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 polarisation of the light can also be used to measure the magnetic field strength of a white dwarf. Even for weak magnetic fields ($<$1MG), where the Zeeman splitting is not obvious due to the large Stark broadening of white dwarf spectral features, the line profile is still a superposition of the unshifted $\pi$ component and the two shifted $\sigma$ components. In a longitudinal magnetic field the two $\sigma$ components have opposite circular polarisations and hence even though the net circular polarisation of the line is zero, the offset $\sigma$ components produce a distinctive $S$ shaped feature in the circular polarisation spectrum. The percentage of circularly polarisation ($V_\pi$) is proportional to the longitudinal magnetic field strength $B_\alpha$ and the normalised flux gradient of the zero field $\pi$ line, as shown below, where $I_\lambda$ is the flux.

$$V_\pi(\lambda) = 1.1B_\alpha \left(\frac{\lambda}{4861}\right)^2 \frac{1}{I_\lambda} \frac{dI_\lambda}{d\lambda}$$

Hence by measuring the degree of circular polarisation we can calculate $B_\alpha$, the mean longitudinal magnetic field strength over the visible hemisphere of the white dwarf.

2 OBSERVATIONS

In November 1995 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 January 1996, using circular spectro-polarimetry, confirmed the existence of a magnetic field.

The initial discovery of the magnetic nature of PG 2329+267 was made on 23 November 1995 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 12 January 1996. 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 polarisation 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 polarisations. 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 polarisation, 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 degrees and a second set of observations were 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 $H_\alpha$, 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 figures 1 and 2, shows the line splitting due to the linear Zeeman effect. A peculiar feature exists in the $H_\alpha$ spectrum shown in the bottom of figure 2; while the $\sigma^-$ component is apparently split into two, no such splitting is seen on the $\sigma^+$ component. The feature appears to be real but we can think of no explanation for such an asymmetry between the two $\sigma$ components.

We calculated the flux weighted average field strength over the visible hemisphere of the white dwarf ($B_\alpha$), by measuring the degree of wavelength splitting due to the linear Zeeman effect. The results are shown in table 1, column 2. For all the triplets, the line positions of the $\pi$ and $\sigma$ components and their corresponding uncertainties were measured by eye. The weighted mean of the measurements from all the lines is, $B_\alpha = 1.58 \pm 0.08$ MG. This combines a measurement of the field strength from the $H_\alpha$ 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 $H_\alpha$, is $B_\alpha = 1.52 \pm 0.10$ MG.

We also calculated $B_\alpha$, from the blue shift resulting from the quadratic Zeeman effect. The measured line center of the $\pi$ 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 $H_\alpha$ line has a small redshift (+0.28 ± 0.10 Å) from its rest wavelength, due 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 $B_\alpha = 1.58 \pm 0.08$ MG as measured from the linear Zeeman effect, the calculated quadratic Zeeman shift at $H_\alpha$ will be -0.43 ± 0.04 Å. Hence the total shift due to the gravitational redshift and intrinsic space motion will be +0.71 ± 0.11 Å at $H_\alpha$, or 32.4 ± 5.0 km/sec. 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 $B_\alpha$, calculated from the uncorrected quadratic Zeeman shifts, is 2.06 ± 0.05 MG. Correcting the shifts with an intrinsic redshift
A new magnetic white dwarf: PG2329+267

Figure 1. The spectrum of PG 2329+267 (top) taken with the INT clearly shows Zeeman splitting of the hydrogen Balmer lines due to 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.

Table 1. Linear and quadratic Zeeman features

| Line | B_s (Linear) | λ_Å | Quad shift ˚Å | B_s (Quad) | Corrected B_s (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        |
| ζ   | –            | 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 32.4 ± 5.0 km/sec 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 H_ε and H_ζ lines; the mean value of B_s for the three earlier lines H_α, H_δ, and H_ε 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 H_α spectrum (taken with the WHT) and the H_δ - H_ζ spectrum (taken with the INT) the magnetic field due to the quadratic Zeeman effect was calculated using a range of different velocity corrections (0 to 100 km/sec). 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 figure 2. The bottom panel shows the normalised H_α flux while the top panel shows the percentage of circular polarisation. The polarisation spectrum clearly shows the S shaped profile indicative of a magnetic field. The peak percentage of circular polarisation at H_α is approximately 10%. The longitudinal magnetic field strength B_l is calculated using equation 3, by a point-by-point technique (Schmidt et al 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 minimise the effect that noise in the line profile has on the magnetic field measurement.
Figure 2. The lower panel shows the normalised spectrum of $H_\alpha$ in PG2329+267. The top panel shows the percentage of circularly polarised light present in the spectrum.

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 $B_e = +462 \pm 60$ KG, though some caution should be taken with this figure as 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 polarisation 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 $B_s = 1.58 \pm 0.08$ 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 the $H_\alpha$ ($B_s = 1.47 \pm 0.07$ 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 $B_s = +462 \pm 60$ 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 $i = 0^\circ$ and will decrease as we look closer to the magnetic equator (at $i = 90^\circ$). We have assumed a simple centered dipole structure and calculated that we are observing the magnetic field at an inclination of $i = 60^\circ \pm 5^\circ$ from the magnetic axis. This result is consistent with a comparison of the $H_\alpha$ spectrum in figure 2 with computed spectra for a 3MG dipole field (Achilleos & Wickramasinghe 1989) which suggests that we must be observing the magnetic field at an angle greater than 45$^\circ$. 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 $B_d = 0.4B_e\cos i$ (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 figure 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 0.9M$_\odot$ (Bergeron et al 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 in the bottom of figure 1. This white dwarf has a mass of 0.56M⊙, at the peak of the white dwarf mass distribution (Bergeron et al 1992), and a temperature of 21,700 K. The increased mass of WD 1134+300 and PG 2329+267 compared to WD 1344+572 is 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 0.9M⊙.

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 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/sec (Sion et al 1988), we can see it is much larger than that found for all other magnetic white dwarfs, which themselves form a distinct low velocity kinematic sub-group (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 (<50km/sec) indicating their youth and evolution from massive progenitors, such as Ap and Bp stars. This is however only a statistical argument and we don’t 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 BS = 1.58 ± 0.08 MG. Similar measurements from the quadratic Zeeman effect yield consistent results only for the Balmer lines up to Hα, for higher lines the perturbation theory used to calculate the magnetic field strength begins to break down. We have detected approximately 10% circular polarisation at Hα, and have calculated the mean longitudinal magnetic field strength to be BS = + 462 ± 60 KG. The ratio BS/BD = 0.29 ± 0.04 and the shape of the Zeeman split components suggest we are viewing the white dwarf at an inclination of i = 60° ± 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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