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A dipole model for magnetic white dwarf BPM 25114

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Summary. Theoretical spectra have been computed for the magnetic DA white dwarf BPM 25114 assuming a centred-dipole field distribution. The polar field strength is deduced to be $(3.6 \pm 0.2) \times 10^7$ G. The observations suggest that the angle i between the line of sight and the magnetic axis varies by perhaps 30° during a rotation period. Detailed comparison with observations at Hα indicate more broadening than is predicted by the centred-dipole model. We predict strong variable wavelength-dependent circular (max ~ 8 per cent) and linear (max ~ 4 per cent) polarization for this star.

1 Introduction

Several polarized white dwarfs with magnetic fields in the range 1–100 MG (megagauss) have been discovered during the past few years. The magnetic DA white dwarfs GD 90 (Angel *et al.* 1974), G 99-47 (Liebert, Angel & Landstreet 1975), BPM 25114 (Wickramasinghe, Whelan & Bessell 1977), and the DBA white dwarf Feige 7 (Liebert *et al.* 1977) are particularly interesting and amenable to detailed studies, since spectroscopically they exhibit resolvable Zeeman structure. Theoretical line profiles have been computed by Kemic (1974a) for a number of hydrogen and helium lines assuming grey Milne–Eddington-type atmospheres and a model with a centred-dipole magnetic field distribution. Borra (1976) has made similar computations for Hα using centred and off-centred dipole field distributions. These results are valuable for recognizing Zeeman structure in magnetic white dwarfs and obtaining estimates of field strength.

In this article we report the results of an attempt to model the spectrum of BPM 25114 using non-grey atmospheres and allowing for polarization both in the continuum and the lines. This exercise is an improvement on previous attempts to study the gross features of the spectra of magnetic white dwarfs, but is still inadequate since we neglect the effects of the magnetic field on the temperature and pressure structure of the stellar atmosphere.

2 Model computations

The present models have been computed using the following assumptions:

(a) The field structure is assumed to be that of a centred dipole, since this is a standard model for magnetic stars and is also the simplest case which allows for magnetic broadening.

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The assumption of a dipole field also minimizes the number of independent parameters needed for the model. The two relevant parameters are the polar field stength B_p and the angle i between the line of sight and the magnetic axis. If the axis of rotation does not coincide with the magnetic axis, then i will vary as the star rotates (except in the special case when the rotation axis points towards the observer) and so different spectra can be expected. Spectrum variations are observed in BPM 25114 and Feige 7 and are readily explained with the assumption of an oblique rotator.

(b) It is assumed that the structure of the atmosphere – namely the variation of temperature T, gas pressure P_g and electron pressure P_e as a function of mean optical depth τ – remains unaltered in the presence of the magnetic field. The zero-field models have been obtained from the high-gravity ($\log g = 8.0$) model atmospheres for DA white dwarfs published by Wickramasinghe (1972).

The effects of magnetic pressure on the structure of the atmosphere could be significant if the field strength varies with depth. We have omitted this effect in this preliminary investigation in order to make the problem more tractable.

(c) Radiative-transfer equations for the Stokes parameters I, Q and V have been formulated in the manner described by Unno (1956) and Lamb & Sutherland (1974), but allowing for polarization both in the continuum and in the lines. The equations have been solved numerically using 16 integration points at optical depths $\tau_i = -\ln x_i$, where the x_i are equally spaced between 0 and 1 and assuming $I_\nu \rightarrow B_\nu$, $Q_\nu \rightarrow 0$, $V_\nu \rightarrow 0$ as $\tau_\nu \rightarrow \infty$.

(d) The strengths and shifts of the Zeeman components of Hα, Hβ, Hγ and Hδ have been obtained from the tables of Kemic (1974b). Some extrapolation for Hγ and Hδ was necessary to cover the range of field strengths of interest. When this was the case, the wavelengths were extrapolated linearly in magnetic field strength but the intensities were kept equal to the values at the highest magnetic field for which Kemic gives results. This procedure could give spurious features when fields in excess of 10–20 MG are present. Each component was Stark broadened using the Griem (1964) theory. We note, however, that this linear theory will cease to be valid once the degeneracy with l is removed.

(e) The surface integration was performed using 23 latitude points and 2–23 longitude points (depending on the latitude), where the direction of the magnetic dipole is taken as the polar axis. Because the line centre at high magnetic fields changes so rapidly with magnetic field and therefore with the changing latitude angle, in attaining the line absorption coefficient it is not satisfactory merely to sample the line profile at the individual latitude points. This procedure leads to a bumpy looking spectrum because the core of the line may or may not be sampled depending on the wavelength and particular latitude points used, as seems to be the case with previous theoretical work. Introducing a large number of latitude points was not feasible due to limits on computation time. The procedure adopted involves integrating across the appropriate portion of the line profile defined by the magnetic fields at the edges of the latitude band around a latitude point. There is some error introduced by this procedure, but it is likely to be no larger than that introduced by interpolation in the Zeeman shift tables.

(f) The continuous opacities κ_ν^0, κ_ν^+, κ_ν^- for hydrogen bound–free were computed using the theory given by Lamb & Sutherland (1974). We have adopted the same prescription for computing the continuous opacity for hydrogen free–free (Kemp 1977) and also for H^- and He following Liebert *et al.* (1977) and Landstreet & Angel (1975). We note also that the quadratic Zeeman effects are important for $B > 10^7$ G and that the Lamb–Sutherland theory which assumes 'rigidity' of the initial and final state wave functions is essentially valid only in the linear regime. However, since only the $n = 2$ and $n = 3$ levels are involved in these computations, the rigidity assumption may be valid for somewhat higher field strengths.

The computational adequacy of the present work was checked by comparison with the Hα computations of Borra (1976) for a model with $B_p = 40$ MG.

3 Analysis of BPM 25114

We use observations of BPM 25114 published by Wickramasinghe *et al.* (1977) reproduced in Fig. 1. The two spectra were taken approximately two days apart and are likely to correspond to different values of i, the angle between the magnetic axis and the line of sight. The photometric period of 2.84 day reported by Wegner (1977), if interpreted as a rotation period, is consistent with this hypothesis.

Wickramasinghe *et al.* (1977) estimated a somewhat uncertain value of 25 000 K for the effective temperature of BPM 25114 from IDS data. The *UBV* colours on the other hand suggest $T_e \sim 20\,000$ K. We have computed models with $T_e = 15\,000$, 20 000 and 25 000 K. At 15 000 K the lines are too strong and the continuum slope is unacceptable, even allowing for

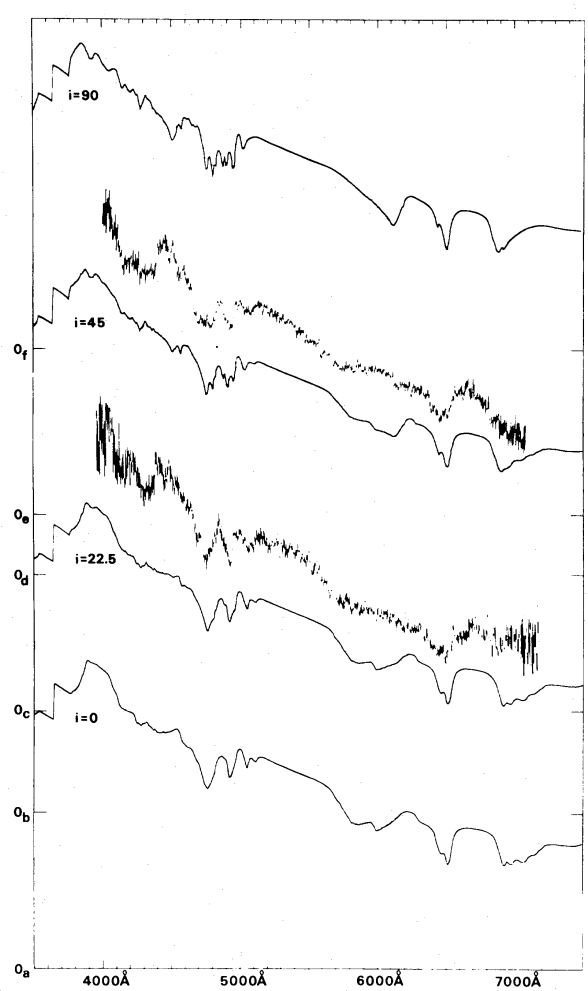

Figure 1. Observed and theoretical fluxes (f_ν) for BPM 25114. The zero points of the six curves are labelled a–f from the bottom up. The two observed spectra (c, e), from Wickramasinghe *et al.* (1977), are placed close to theoretical curves (b, d) with $B_p = 3.6 \times 10^7$ G and $i = 22.5°$ and $i = 45°$ respectively. Theoretical curves for $i = 0°$ (a) and $i = 90°$ (f) are included to show the possible range of variation for this single magnetic field. (For the theoretical curves, flux values in the continuum are normalized to those of the observed spectra.)

a reasonable margin of uncertainty in the observations. $T_e = 25\,000$ K is acceptable as far as the continuum slope is concerned, but the lines are somewhat weaker than observed. Models with $T_e = 20\,000$ K appear to give best agreement with observations.

We have computed theoretical spectra for a range of values of B_p and for $i = 0, 22.5, 45, 67.5$ and $90°$. In matching spectra we have given high weight to the Hα and Hβ components since their computation does not involve extrapolation in Kemic's (1974b) tables. From the positioning of the central component of Hα and the three strong components at Hβ we estimate $B_p = (3.6 \pm 0.2) \times 10^7$ G for the two spectra. Changes in the angle i affect the positioning of the components and also their width. However, the theoretical fluxes are relatively insensitive to changes in i and we can only suggest $i = 20 \pm 20°$ for spectrum I (c in Fig. 1) and $50 \pm 20°$ for spectrum II (e in Fig. 1). Observations of polarization should allow a much better idea of the angle i to be obtained.

In Fig. 1 the two observed spectra are presented along with two theoretical spectra which give a reasonable fit with the parameters just mentioned. Theoretical spectra with $i = 0$ and $90°$ are also presented to give an idea of the possible variation of flux with angle for this given dipole strength.

From Fig. 1 it appears that there is good agreement with observations *except* for two principal regions: $4450 \lesssim \lambda \lesssim 4600$ Å, where there is too much absorption in the theoretical spectra, and $5600 \lesssim \lambda \lesssim 6400$ Å, where the theoretical absorption is more concentrated than observations indicate. (Incidentally, any detailed agreement for $\lambda \lesssim 4400$ Å is probably partly fortuitous, since computations in this region require extrapolation of Hγ and Hδ components in Kemic's (1974b) tables.) It is noteworthy that each of the two regions of poor agreement occurs where the absorption components are varying most rapidly in wavelength with changing magnetic field. In particular, the latter of the two regions, where the theory does not predict sufficient broadening from the Hα, σ^- components, suggests that the centred-dipole model is not entirely adequate. A spread in field strength over the visible disc by a factor greater than 2 appears to be required. A possibility is that the shape of the star is not spherical as assumed, but distorted due to magnetic forces. Under these circumstances a flattened configuration in which the (magnetic) polar radius is less than the equatorial radius may be expected (Mestel 1967). The photometric variations reported by Wegner (1977) would also find a ready explanation on this hypothesis. However, to achieve significant distortion would require interior field strengths of $\sim 10^{12}$ G, which may be unreasonable on the basis of the observed field strengths.

We have investigated the effects of off-centring the dipole while retaining the spherical geometry. However, for $\Delta r/r = 0.1$ there is only a minor improvement in the $5600 \lesssim \lambda \lesssim 6400$ Å region, whereas for larger values of $\Delta r/r$ much of the earlier achieved agreement in the Hα and Hβ features seems difficult to maintain.

Other possibilities are concentrated regions of higher field strength (magnetic spots) and a different field distribution over the stellar surface where quadrupole or higher-order multipole components are present. Since the cooling time of BPM 25114 is likely to be similar to Feige 7, namely a few hundred million years, the latter suggestion is not unreasonable on the basis of the field decay times computed by Fontaine, Thomas & van Horn (1973). We note, however, that Liebert *et al.* (1977) do not find evidence for a strong (> 10 per cent) quadrupole component in Feige 7. Also the general agreement found with the dipole-type field distribution is perhaps significant.

It should be noted that our estimates of the values of B_p and i are within the assumption of a dipole field over a spherical disc. If the actual situation is different from this, as seems necessary, then a best fit between observed and theoretical spectra would probably occur at somewhat different values of B_p and i.

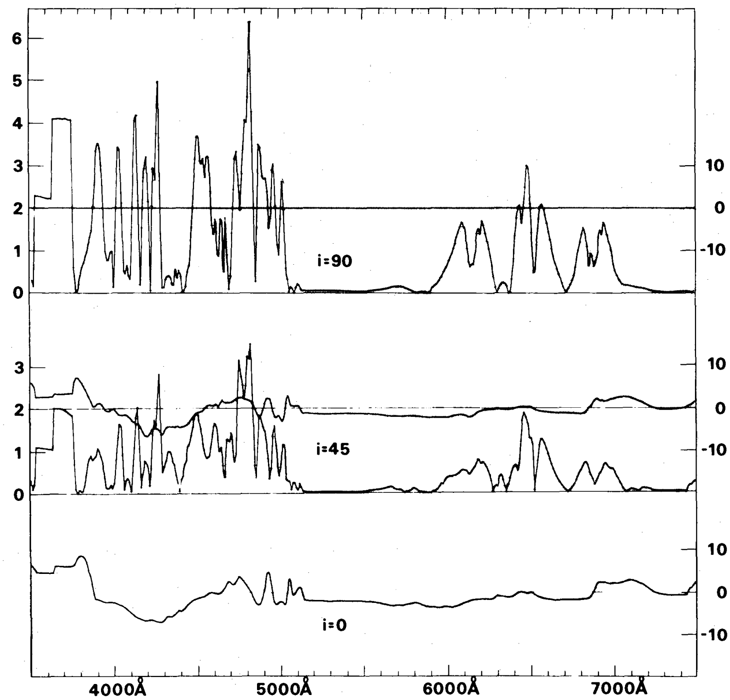

Figure 2. Polarizations for theoretical spectra for BPM 25114 with $B_p = 3.6 \times 10^7$ G. The vertical axes have units of percentage. Labelled on the left is linear polarization for $i = 45°$ (lower) and $i = 90°$ (upper). (Linear polarization for $i = 0°$ is identically zero.) Labelled on the right is circular polarization for $i = 0°$ (lower), $i = 45°$ (middle) and $i = 90°$ (upper). (Circular polarization for $i = 90°$ is marginally non-zero due to second order effects in the radiative transfer.)

4 Polarization

The increase in linear and circular polarization near the Balmer limit predicted by Lamb & Sutherland (1974) is evident in our computations (Fig. 2). The magnitude of the effect is not as high as predicted by these authors from their optically thin plane-parallel model, due to the weaker Balmer jump predicted by the detailed atmospheres and the averaging process over the stellar disc which involves the magnetic field geometry.

The strong wavelength dependent circular and linear polarization predicted from the models should be easily observable. In particular we predict a net change in circular polarization by about 10–15 per cent between 3800 and 4300 Å. (Our polarization calculations do not take into account Faraday rotation, and therefore linear polarization in particular may not be as high as we predict (Sazonov & Chernomordik 1975).)

5 Conclusions

We have computed theoretical spectra for BPM 25114 assuming a centred-dipole field distribution. Considering the various simplifying assumptions that have been made, the agreement found with observations is encouraging. However, there is indication that the factor 2 spread in field of the centred-dipole model is insufficient to explain the extent of the observed blue wing of Hα. A possibility is that the magnetic field has a dominant influence on the structure of the star resulting in a distorted configuration as suggested by Mestel (1967) for Ap stars. Other possibilities which we have not investigated are the presence of strong quadrupole or higher-order components, and local regions of enhanced field strengths (magnetic spots).

From the dipole model we deduce a polar field strength $B_p = (3.6 \pm 0.2) \times 10^7$ G. The angle between the line of sight and the magnetic axis appears to change by perhaps 30° during a rotation period. We predict strong circular polarization with a maximum of ~8 per cent in the wavelength region λλ 3500–3850 Å and somewhat weaker linear polarization.

The major uncertainties in the present work arise from (i) the neglect of magnetic forces in the hydrostatic equilibrium equations, (ii) the approximations used in computing continuous opacities at fields in excess of 10^7 G and (iii) the non-availability of Zeeman splitting computations for Hγ and Hδ for $B > 2 \times 10^7$ G and 10^7 G, respectively. Future work could advantageously concentrate on these aspects of the problem.

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