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LETTER

Letter to the Editor

Evidence for helium in the magnetic white dwarf GD 229

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Abstract. The nature of the strong absorption features in the white dwarf GD 229 has been a real mystery ever since it was found to be magnetic in 1974. All attempts to explain the spectrum by line components of hydrogen failed. With the first sets of newly calculated line data for He I in a strong magnetic field we could identify most of the absorption structures in the spectrum with stationary line components in a range of magnetic fields between 300 and 700 MG. This is much lower than previously speculated and is comparable to the highest fields found in hydrogen rich magnetic white dwarfs. The reason for the large number of spectral features in GD 229 is the extreme accumulation of stationary components of transitions in He I in a narrow interval of field strengths.

Key words: stars: white dwarfs – stars: magnetic fields – stars: individual: GD 229

1. Introduction

Magnetic fields from about 40 kG to 1 GG have been detected in about about 50 (2%) of the 2100 known white dwarfs (McCook & Sion 1998). A list of all currently known magnetic white dwarfs is found in Jordan (1997). Magnetic fields in the low field range ($\lesssim 20$ MG) in both hydrogen and helium rich magnetic white dwarfs can be detected by a relatively simple line pattern. Hydrogen line components have been identified in many objects, but until recently, helium was detected unambiguously only in the magnetic white dwarf Feige 7. Using He I line data calculated by Kemic (1974), Achilleos et al. (1992) found that the spectrum could be well reproduced with a dipole of strength 35 MG displaced by 0.15 white dwarf radii from the stellar center. Since the Kemic data were calculated by regarding the magnetic field as a small perturbation to the Coulomb interaction and are only valid up to about 20 MG, the Kemic tables had to be extrapolated for the Feige 7 analysis. The only other definite helium rich objects with fields of about 15-20 MG were discovered by Reimers et al. (1998) in the course of the Hamburg ESO survey.

Magnetic white dwarfs with field strengths $\gtrsim 100$ MG containing hydrogen could be interpreted ever since the numerical calculations of energy level shifts and transition probabilities for bound-bound transitions by groups in Tübingen and Baton Rouge (Forster et al. 1984; Rösner et al. 1984; Henry and O'Connell 1984, 1985). With the help of these data Greenstein 1984 and Greenstein et al. 1985 could identify the hitherto unidentified features in Grw $+70^\circ 8247$ with stationary components of hydrogen in fields between about 150 and 500 MG.

Since the magnetic field on the surface of a white dwarf is not homogeneous but e.g. better described by a magnetic dipole, the variation of the field strength from the pole to the equator (a factor of two for a pure dipole field) smears out most of the absorption lines at larger magnetic field strengths. However, a few of the line components become stationary, i.e. their wavelengths go through maxima or minima as functions of the magnetic field strength. These stationary components are visible in the spectra of magnetic white dwarfs despite a considerable variation of the field strengths.

About 80% of all known white dwarfs have nearly pure hydrogen atmospheres (spectral type DA). However, since most of the remaining stars have helium rich atmospheres, we would also expect a significant number of magnetic white dwarfs to belong to the spectral type DB in which He I lines are observed. Therefore it could be expected that the few magnetic white dwarfs with unidentified spectral features, that cannot be explained by the line data for hydrogen, are helium rich. The most famous example is GD 229, where Swedlund et al. (1974), Greenstein et al. (1974), Landstreet & Angel (1974), Liebert (1976), Greenstein & Boksenberg (1978), and Schmidt et al. (1996) found strong absorption features in the optical, infrared, and UV. Angel (1979) already proposed that the absorption bands in this star are due to stationary components of hydrogen or helium.

The basic difficulty in calculating energy levels and oscillator strengths for arbitrary field strengths lies in the fact that the Coulomb potential has a spherical symmetry whereas the magnetic field induces a cylindrical symmetry. This pre-

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vents a separation of variables and together with the nonlinear character of the interactions makes even the numerical solution a difficult problem. In particular the intermediate regime ($0.01 < \gamma = B/2.35 \cdot 10^9 G < 1$), in which the majority of magnetic white dwarfs is found, is very complicated, since neither the magnetic nor the Coulomb interaction dominates and we therefore encounter a so-called nonperturbative regime where none of the interaction terms can be treated by perturbation theory. In the case of the two electron system He I the situation is even more difficult, since the number of degrees of freedom is enhanced significantly and the electron-electron interaction introduces a third competitive force which makes He I a complex system with a rich variability of the spectrum with changing field strength. The particular challenge of a comparison of atomic data with observational ones lies in the fact that the energies of many excited states have to be known with a high relative accuracy (usually $\leq 10^{-4}$) and for a large number of field strengths in order to identify the stationary transitions.

Until this year the status of electronic structure calculations on He I was such (see Braun et al.1998, Jones et al. 1997, Ruder et al.1994 and references therein) that a conclusive comparison was impossible and the occurence of He I in the atmosphere of GD 229 had to be considered as a pure speculation as it was the case with respect to hydrogen in Grw $+70°8247$ until 1984.

Therefore, several alternative explanations have been proposed. Engelhardt & Bues (1995) have tried to explain the regular almost periodical structure of the GD 229 spectrum by quasi-Landau resonances of hydrogen in a magnetic field of 2.5 GG. Östreicher et al. (1987) speculated that two of the features could be due to intersections of hydrogen components in a field of about 25-60 MG.

Now, the calculations performed in Heidelberg (Becken & Schmelcher 1998) have closed that gap and for the first time precise data for a large number of energy states have become available. In this paper we will show that most of the absorption features in the optical and UV spectrum of GD 229 can be identified as stationary line transitions of He I.

2. Helium in strong magnetic field

The fixed-nucleus electronic Hamiltonian of the helium atom in a strong magnetic field oriented along the $z-$axis reads as follows

$$\mathcal{H} = \sum_{i=1,2} \left(\frac{1}{2m}\mathbf{p}_i^2 + \frac{e}{2m}BL_{z_i} + \frac{e^2}{8m}B^2(x_i^2+y_i^2) - \frac{2e^2}{|\mathbf{r}_i|} + \frac{e}{m}BS_{z_i} \right) + \frac{e^2}{|\mathbf{r}_1-\mathbf{r}_2|} \quad (1)$$

where the sum includes the one particle terms in the order: field-free kinetic, orbital Zeeman, diamagnetic, Coulomb attraction and spin Zeeman energies. The last term represents the repulsive electron-electron interaction. Effects of the finite nuclear mass can easily be taken into account by using the corresponding scaling relations (Becken & Schmelcher 1998). According to its symmetries the Hamiltonian (1) possesses four independent conserved quantities: the total spin $\mathbf{S}^2$, its $z-$component S_z, the $z-$component L_z of the total spatial electronic angular momentum and the total spatial $z-$parity Π_z (parity is a combined symmetry of the previous ones) which will be used to label the electronic states in the form $n^{2S+1}M^{(-1)^{\Pi_z}}$ where n specifies the degree of excitation within a given symmetry subspace. Calculations are performed separately for each subspace with given quantum numbers. Since the spin part of the eigenfunctions of the Hamiltonian (1) are the usual spin singlet and triplet functions we address in the following exclusively the method of investigation for the spatial part of the wave functions.

The key ingredient of our method for the ab initio calculation of the electronic structure of atoms in strong magnetic fields is a basis set of one particle functions which takes on the following appearance

$$\Phi_i(\rho,\phi,z) = \rho^{n_{\rho_i}} z^{n_{z_i}} \exp\left(-\alpha_i\rho^2 - \beta_i z^2\right) \exp\left(im_i\phi\right) \quad (2)$$

where $n_{\rho_i} = |m_i| + 2k_i, n_{z_i} = \pi_{z_i} + 2l_i$ with $k_i, l_i = 0, 1, 2, ...$ $\{\alpha_i, \beta_i\}$ are nonlinear variational parameters; π_{z_i} is the z parity of the one particle function. The basis set (2) has its precursor in a more general one (Schmelcher & Cederbaum 1988) which has successfully been applied for the investigation of the electronic structure of small molecules in strong magnetic fields (Kappes & Schmelcher 1996).

Due to the parameters $\{\alpha_i, \beta_i\}$ our basis set is extremely flexible which represents a major advantage in the presence of an external magnetic field. This allows us to accurately describe the changes in the electronic wave functions with changing field strengths. The values of the variational parameters $\{\alpha_i(B), \beta_i(B)\}$ are determined by a nonlinear optimization procedure which is performed for the spectrum of both hydrogen and He II in a magnetic field. Typically 150 one particle functions of type (2) are optimized in order to describe 15 hydrogenic states with a high accuracy. The optimization procedure has to be accomplished for each field strength separately (see Becken & Schmelcher 1998 and references therein).

The basic idea for solving the time-independent Schrödinger equation belonging to the Hamiltonian (1) is then to construct out of the above optimized one particle functions a set of spatial two electron configurations $\{\psi_i\}$ being symmetric (spin singlet) or antisymmetric (spin triplet) with respect to the interchange of the electronic coordinates and respecting the above-discussed symmetries. We represent the exact wave functions Ψ_j by a linear combination of two electron configurations $\Psi_j = \sum_i c_{ji}\psi_i(\mathbf{r}_1, \mathbf{r}_2)$. By virtue of the variational principle we arrive at a generalized eigenvalue problem whose eigenvalues and eigenvectors are excellent approximations to the exact eigenenergies and wave functions. We remark that all matrix elements of the Hamiltonian (1) with respect to the basis afunctions (2) can be evaluated analytically resulting in a complicated series of higher transcendental functions whose numerically stable and efficient implementation required a number of different techniques.

The typical number of two-electron configurations $\{\psi_i\}$, i.e. the dimension of the full Hamiltonian matrix to be diagonalized, is of the order of 2000-4000 depending on the symmetries. On a powerful workstation 10 - 20 h CPU are necessary to build up and diagonalize the Hamiltonian matrix for each field strength and symmetry subspace. Extensive calculations have been performed in the whole range $0 \leq \gamma = B/2.35 \cdot 10^9\mathrm{G} \leq 100$, for 30 electronic states the energy could be determined to an accuracy of at least 10^{-4}. For vanishing magnetic quantum number $M = 0$ many excited singlet and triplet electronic states with positive and negative $z-$parity have been determined. For nonzero angular momentum $M = +1, -1$ both singlet and triplet states have been studied for positive $z-$parity. This gives us insight into an essential part of the spectrum of the He I atom with varying field strength and allows us in particular to decide whether He I can be present in the atmosphere of magnetic white dwarfs through an extraction of the stationary components of the transitions in the corresponding regime of field strengths.

3. Interpretation of the spectrum

The strongest evidence that GD 229 does not contain hydrogen came from a HST spectrum taken by Schmidt et al. (1996): There is no evidence for components of Lyman α which do not vary very much over a very large range of magnetic field strengths. The $1s_0 \rightarrow 2p_{-1}$ transition has a maximum at 1341 Å and should always be visible even at extremely high field if significant amount of hydrogen were present.

For the first time it is now possible to compare the spectral features of GD 229 directly with the newly calculated wavelength tables for the line components of He I in a strong magnetic field (Becken & Schmelcher 1998). Since oscillator strengths are not yet available we could not directly compare the spectrum with theoretical models (see e.g. Jordan 1992). Therefore we compared the positions of stationary line components with the observed absorption bands. In total about 150 line components have been calculated of which about 40 show stationary behaviour at different field strengths.

If one looks at the helium line data up to $\gamma = 100$ (corresponding to $235\,\mathrm{GG}$) it is rather striking to see that the majority (26) of all stationary components lies in the range $300 \lesssim B/\mathrm{MG} \lesssim 700$ (see Fig. 1; note that the wavelengths were determined by spline interpolation in a still relatively crude grid). So far only 10 grid points exist for the range of magnetic field strengths plotted in Fig. 1.

In practically all cases the minimum wavelength of the large number of features seen in the optical, IR, and UV spectrum of GD 229 can be attributed to the wavelength minima of the helium components (listed in Table 1). This explains why the spectrum of GD 229 has such an extremely large number of absorption features.

Moreover, there are no clear contradictions between the predicted positions of absorptions and the observations. The only shortcoming of the current analysis is the fact that the strongest features at $4000 - 4200$ Å and at about 5280 Å can only be attributed to two line transitions ($2^1 0^+ \rightarrow 2^1 0^-$, $2^1 0^+ \rightarrow 2^1(-1)^+$). Since the identification at other wavelengths is convincing we believe that additional stationary line components are hidden in the subspaces of bound-bound transitions that have not been calculated yet (four subspaces $^1(\pm 1)^-$, $^3(\pm 1)^-$, and transitions with magnetic quantum numbers $|m| > 1$).

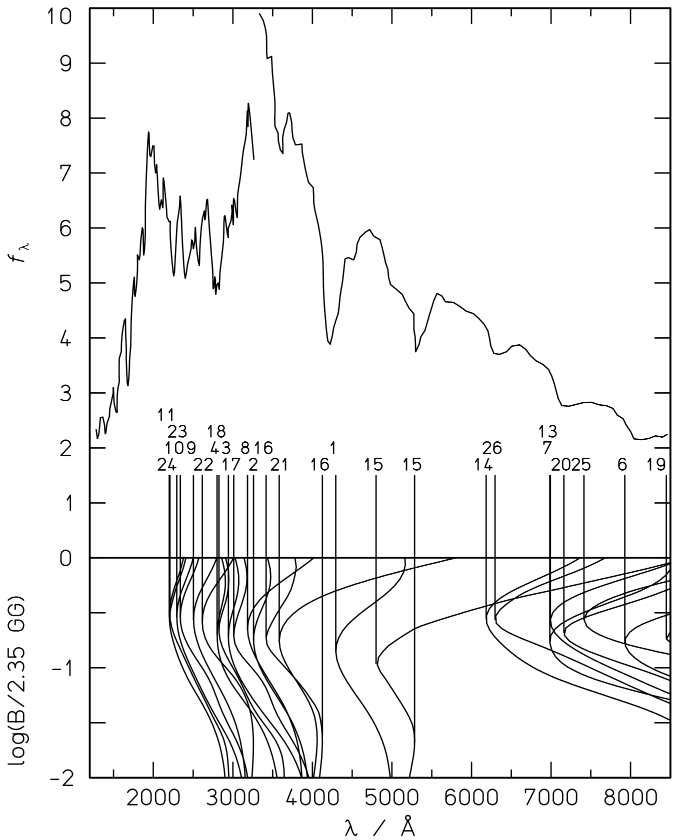

Fig. 1. The spectrum of GD 229 (Schmidt et al. 1996) is compared with the positions of He I components which are stationary in the plotted range of field strengths. The stationary wavelengths are marked and labeled with a number corresponding to the identification in Table 1. Note that additional stationary line components which are not yet theoretically calculated may contribute

In principle the wavelength maxima (also shown in the figure) of the $2^1 0^+ \rightarrow 3^1(-1)^-$ and $2^1 0^+ \rightarrow 2^1(-1)^-$ transitions would fit well to the position of the two strongest absorption. However, the corresponding field strengths of about 50 MG would be much too low compared to the result found for the other features. Such a large spread of magnetic field strengths is also rather improbable since the observed features are relatively sharp.

An alternative interpretation would be that hydrogen is additionally present in the spectrum. The strong feature at 4124 Å in the spectrum of Grw $+70°8247$ (which has a polar field strength of 320 MG, e.g. Jordan 1992) caused by the hydrogen transition $2s_0 \rightarrow 4f_0$ could also contribute to the strongest absorption feature in GD 229. However, in this case we would expect several other absorption troughs, e.g. at 5830 Å ($2s_0 \rightarrow 3p_0$) which are not present in GD 229. This is also compatible with the finding by Schmidt et al. (1996) that no Lyman α components are present in the UV spectrum.

Table 1. Components of He I which are stationary at $300 < B/\mathrm{MG} < 700$ and additionally two maxima at $\approx 50\,\mathrm{MG}$. Note that the wavelengths (and corresponding field strenghts) of the minima and maxima are interpolated in a relatively crude grid. The error range in λ was estimated from interpolations of different orders

No.	Component	Zero field trans.	$(\lambda/\text{Å})$ $\|(B/\mathrm{MG})$
1	$2^1 0^+ \to 2^1 0^-$	$2^1 S_0 \to 3^1 P_0$	4294 ±8 | 338 min
2	$2^1 0^+ \to 3^1 0^-$	$2^1 S_0 \to 4^1 F_0$	3260 ± 6 | 425 min
3	$2^1 0^+ \to 4^1 0^-$	$2^1 S_0 \to 4^1 P_0$	2943 ± 10 | 455 min
4	$2^1 0^+ \to 5^1 0^-$	$2^1 S_0 \to 5^1 F_0$	2802 ± 5 | 477 min
5	$3^1 0^+ \to 3^1 0^-$	$3^1 S_0 \to 4^1 F_0$	10692 ± 40 | 379 min
6	$3^1 0^+ \to 4^1 0^-$	$3^1 S_0 \to 4^1 P_0$	7927 ± 40 | 406 min
7	$3^1 0^+ \to 5^1 0^-$	$3^1 S_0 \to 5^1 F_0$	6984 ± 40 | 415 min
8	$1^3 0^+ \to 2^3 0^-$	$2^3 S_0 \to 3^3 P_0$	3183 ± 6 | 535 min
9	$1^3 0^+ \to 3^3 0^-$	$2^3 S_0 \to 4^3 P_0$	2504 ± 3 | 658 min
10	$1^3 0^+ \to 4^3 0^-$	$2^3 S_0 \to 4^3 F_0$	2295 ± 3 | 689 min
11	$1^3 0^+ \to 5^3 0^-$	$2^3 S_0 \to 5^3 P_0$	2200 ± 5 | 705 min
12	$2^3 0^+ \to 3^3 0^-$	$3^3 S_0 \to 4^3 P_0$	9350 ± 6 | 573 min
13	$2^3 0^+ \to 4^3 0^-$	$3^3 S_0 \to 4^3 F_0$	6990 ± 10 | 643 min
14	$2^3 0^+ \to 5^3 0^-$	$3^3 S_0 \to 5^3 P_0$	6184 ± 10 | 674 min
15	$2^1 0^+ \to 2^1(-1)^+$	$2^1 S_0 \to 3^1 P_{-1}$	5285 ± 3 | 50 max
15	$2^1 0^+ \to 2^1(-1)^+$	$2^1 S_0 \to 3^1 P_{-1}$	4812 ± 30 | 258 min
16	$2^1 0^+ \to 3^1(-1)^+$	$2^1 S_0 \to 4^1 F_{-1}$	4125 ± 3 | 56 max
16	$2^1 0^+ \to 3^1(-1)^+$	$2^1 S_0 \to 4^1 F_{-1}$	3417 ± 10 | 429 min
17	$2^1 0^+ \to 4^1(-1)^+$	$2^1 S_0 \to 4^1 P_{-1}$	3012 ± 10 | 466 min
18	$2^1 0^+ \to 5^1(-1)^+$	$2^1 S_0 \to 5^1 F_{-1}$	2825 ± 3 | 523 min
19	$3^1 0^+ \to 4^1(-1)^+$	$3^1 S_0 \to 4^1 P_{-1}$	8449 ± 150| 445 min
20	$3^1 0^+ \to 5^1(-1)^+$	$3^1 S_0 \to 5^1 F_{-1}$	7160 ± 20 | 499 min
21	$1^3 0^+ \to 2^3(-1)^+$	$2^3 S_0 \to 3^3 P_{-1}$	3582 ± 2 | 415 min
22	$1^3 0^+ \to 3^3(-1)^+$	$2^3 S_0 \to 4^3 P_{-1}$	2615 ± 5 | 629 min
23	$1^3 0^+ \to 4^3(-1)^+$	$2^3 S_0 \to 4^3 F_{-1}$	2338 ± 5 | 689 min
24	$1^3 0^+ \to 5^3(-1)^+$	$2^3 S_0 \to 5^3 P_{-1}$	2208 ± 3 | 689 min
25	$2^3 0^+ \to 4^3(-1)^+$	$3^3 S_0 \to 4^3 F_{-1}$	7413 ± 40 | 658 min
26	$2^3 0^+ \to 5^3(-1)^+$	$3^3 S_0 \to 5^3 P_{-1}$	6296 ± 40 | 658 min

4. Discussion and future prospects

For the first time we have been able to prove that GD 229 is indeed a helium rich (DB) white dwarf at a rather high magnetic field strength. From the magnetic field strengths corresponding to the extrema of the wavelengths of the line components we conclude that the range of magnetic fields is about 300-700 MG, so that it would be compatible with a dipole field with a polar field strength between 600 and 700 MG. With our analysis we could reject previous ideas that the atmosphere is hydrogen rich.

In the near future the rest of the line data for He I will be calculated. We expect that some of the missing line components will have wavelength extrema near the strong features at about 4100 and 5300 Å.

A detailed modelling of the spectrum and polarization of GD 229 will be possible as soon as oscillator strengths become available; this will enable us to determine the magnetic field structure which is impossible by our wavelength analysis.

With the new line data for He I we will also try to interpret other magnetic white dwarfs with unexplained features: e.g. HE 1211-1707 (Reimers et al. 1994, Jordan 1997), and four other newly discovered objects from the Hamburg ESO Survey (Reimers et al. 1998).

Another good candidate for such an analysis is LB 11146B for which a convincing analysis of the spectrum with hydrogen line components arrived at an approximate field strength of about 670 MG (Liebert et al. 1993, Glenn et al. 1994). Additionally a very strong and broad feature at about 5600 Å was present in the spectrum which cannot be due to hydrogen. Therefore Glenn et al. speculated that helium might be responsible. However, in our current set of line data no stationary line component of He I was found at about 670 MG.

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