# Molecular Magnetic Dichroism in Spectra of White Dwarfs

S. V. Berdyugina,[1,2] A. V. Berdyugin,[2] and V. Piirola[2]
[1]*Institute of Astronomy, ETH Zurich, CH-8092 Zurich, Switzerland**
[2]*Tuorla Observatory, FIN-21500 Piikkiö, Finland*†
(Received 15 September 2006; published 28 August 2007)

We present novel calculations of the magnetic dichroism appearing in molecular bands in the presence of a strong magnetic field, which perturbs the internal structure of the molecule and results in net polarization due to the Paschen-Back effect. Based on that, we analyze new spectropolarimetric observations of the cool magnetic helium-rich white dwarf G99-37, which shows strongly polarized molecular bands in its spectrum. In addition to previously known molecular bands of the $C_2$ Swan and CH $A$-$X$ systems, we find a firm evidence for the violet CH $B$-$X$ bands at 390 nm and $C_2$ Deslandres-d'Azambuja bands at 360 nm. Combining the polarimetric observations with our model calculations, we deduce a dipole magnetic field of $7.5 \pm 0.5$ MG with the positive pole pointing towards the Earth. We conclude that the developed technique is an excellent tool for studying magnetic fields on cool magnetic stars.

DOI: 10.1103/PhysRevLett.99.091101 PACS numbers: 97.20.Rp, 33.55.Be, 33.55.Fi, 95.75.Hi

*Introduction.*—White dwarfs are end-products of stellar evolution. The fundamental properties of the dominant group of nonmagnetic white dwarfs have been invaluable in constraining the theory of single star evolution. The progress in our understanding of the properties of magnetic white dwarfs is more difficult to achieve. It is currently apparent that significant magnetic fields are present in stars other than the Sun. If magnetic flux is conserved during stellar evolution, white dwarfs should be expected to have magnetic fields of 10–100 MG.

Indeed, fields of such strengths are quite common among magnetic white dwarfs (see the review [1]). Polarimetric surveys detected strong polarization in a variety of white dwarfs and proved beyond doubts that they are magnetic. Precise field determination was, however, possible only for objects with identified Zeeman transitions of atoms or molecules. A success in calculations of the Zeeman effect of hydrogen and neutral helium lines for very strong fields made it possible to resolve the mystery of unidentified features in spectra of many hot white dwarfs and determine their magnetic properties.

A small group of cool, helium-rich white dwarfs (DQ type) show, however, only carbon-based molecular bands (mainly $C_2$ bands) which are therefore the only indicators of their magnetic fields. It is believed that the majority of these stars are not magnetic, since no polarization was detected in $C_2$ so far. However, a famous representative of this group, G99-37, a unique white dwarf with both CH and $C_2$ molecular bands, is clearly magnetic, as indicated by prominent polarization in the CH bands [2]. G99-37 is one of the coolest DQ stars with the typical mass of 0.7 $M_\odot$ [3]. Previous spectropolarimetric observations of this star were obtained with very low resolution (16 nm), and the spectra were interpreted with simplified theories, neglecting the molecular spin or angular momentum and assuming a homogeneous field [2,4,5]. As a result, the magnetic field strength on G99-37 determined by different authors ranges from 0.3 to 20 MG. A variability of the spectrum was suspected [5] but no estimate of the rotational period is available.

Here, we present new measurements for the white dwarf G99-37 with much higher spectral resolution and polarimetric accuracy. We develop a novel diagnostic technique for measuring magnetic fields on cool stars from net polarization signatures in molecular bands based on the most advanced method of computing molecular spectra in strong magnetic fields [6]. We compare the observed and modeled Stokes parameters in several molecular bands and draw conclusions on the magnetic field strength and configuration.

*Measurements.*—G99-37 was observed at the 2.5 m Nordic Optical Telescope (NOT), La Palma, Spain, using the ALFOSC spectrograph which was upgraded with quarter- and half-wave plates enabling measurements of both circular and linear polarization. The star was observed in the wavelength interval of 320–555 nm with the resolution of 0.8 nm. The measurements were made in all four Stokes parameters. In February 2003, Stokes $I$ and $V$ were measured, while in October 2003 Stokes $I$, $Q$ and $U$ were obtained in addition. The accuracy of $\pm 0.5\%$ was achieved. To calibrate linear polarization, several standard stars with high and null polarization were observed in addition.

Our observations reveal a wealth of details in the spectrum of G99-37 (Fig. 1). In the intensity spectrum, strong, previously known molecular bands [2,7] are from $C_2$ $d\,^3\Pi_g - a\,^3\Pi_u$ Swan system at 470 nm ($\Delta v = 0$) and 520 nm ($\Delta v = 1$) and the CH $A\,^2\Delta - X\,^2\Pi$ system at 430 nm ($\Delta v = 0$). The CH bands show a remarkable signal in circular polarization: Stokes $V/I$ of $\pm 8\%$. In addition, we clearly reveal the CH $B\,^2\Sigma^- - X\,^2\Pi$ system with Stokes $V/I$ of $+5\%$ centered at 385 nm. Another new spectral feature at 360 nm is identified with the (1, 0) band of the $C_2$ $C\,^1\Pi_g - A\,^1\Pi_u$ Deslandres-d'Azambuja

 

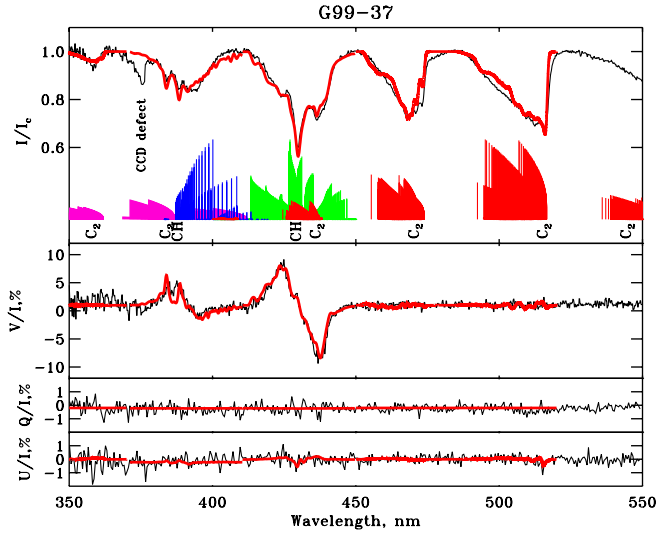


FIG. 1 (color online). Observed intensity distribution, circular, and linear polarization (Stokes $I$, $V$, $Q$, and $U$) of the white dwarf G99-37 (thin line). The CH and $C_2$ bands are identified. Synthetic spectra for a dipole field of 7 MG directed to the observer shown by thick lines.

system. Circular polarization in the continuum of about $+1\%$ was detected in the whole wavelength interval. There are no remarkable features in the linear polarization at the noise level of 0.5%.

*Method.*—If a molecule possesses a nonzero magnetic moment, it interacts with an external magnetic field that results in magnetic splitting of energy levels [8]. In the Zeeman regime, when internal coupling of the molecular angular momenta is larger than the interaction with an external magnetic field, the latter can be treated as a perturbation to the internal Hamiltonian [9]. In the strong-field regime, a transition to the Paschen-Back effect (PBE) occurs, i.e., the magnetic interaction becomes comparable or larger than the internal interactions. Thus, the diagonalization of the full Hamiltonian including both the internal and magnetic perturbation should be performed [6]. The theory described in [6] allows diagonalization of the Hamiltonian with the PBE occurring on both fine and rotational levels of any multiplicity. Based on that, we have calculated magnetic splitting of the electronic states under consideration and strengths of transitions between magnetic sublevels for fields up to 10 MG. Here, we neglect the quadratic Zeeman effect which becomes significant for much stronger fields.

In the general case of the PBE in an electronic state, only three quantum numbers remain good: the projection of the orbital momentum, $\Lambda$, spin, $S$, and projection of the total angular momentum $J$ on the magnetic field direction, $M$. Therefore, the full Hamiltonian is built for their fixed values. The values of $\Lambda$ and $S$ remain the same for a given electronic state, while $M$ defines the number of interacting levels within the state. As a result, many levels with different $J$ and $N$ quantum numbers become mixed (Fig. 2).

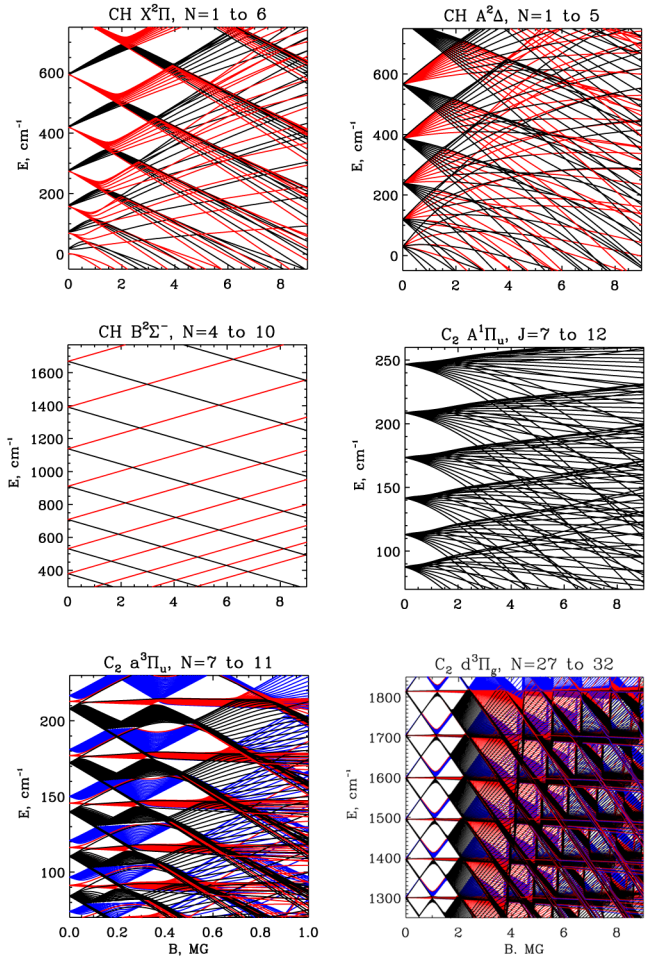


FIG. 2 (color online). Magnetic splitting of rotational levels of different electronic states of CH and $C_2$. Significant level mixture occurs for magnetic fields stronger than 0.1 MG. At weaker fields, levels are grouped according to the spin projection on the magnetic field direction.

Only one selection rule, $\Delta M = 0, \pm 1$, is used for searching for transitions in a given system between the perturbed states. As a result, many previously forbidden transitions with $|\Delta J| > \pm 1$ and $|\Delta N| > \pm 1$ become allowed.

The main feature of the molecular PBE is that Stokes line profiles become essentially asymmetric, resulting in net polarization across the line profile [6]. In a given rotational branch, many lines have the same sign of asymmetry, thus producing a net polarization signal in the band.

Using the theoretical Zeeman patterns (transition strengths and wavelength shifts) calculated with the perturbed wave functions, we carried out a spectral synthesis of the Stokes parameters of four electronic systems: CH $A\,^2\Delta - X\,^2\Pi$, CH $B\,^2\Sigma^- - X\,^2\Pi$, $C_2$ $a\,^3\Pi - d\,^3\Pi$, and $C_2$ $C\,^1\Pi - A\,^1\Pi$. Because of an enormous number of transitions involved (up to $3 \cdot 10^6$), we employed an analytical solution of the polarized radiative transfer equations, the so-called Unno-Rachkovsky solution [10], based on the Milne-Eddington stellar atmosphere. The

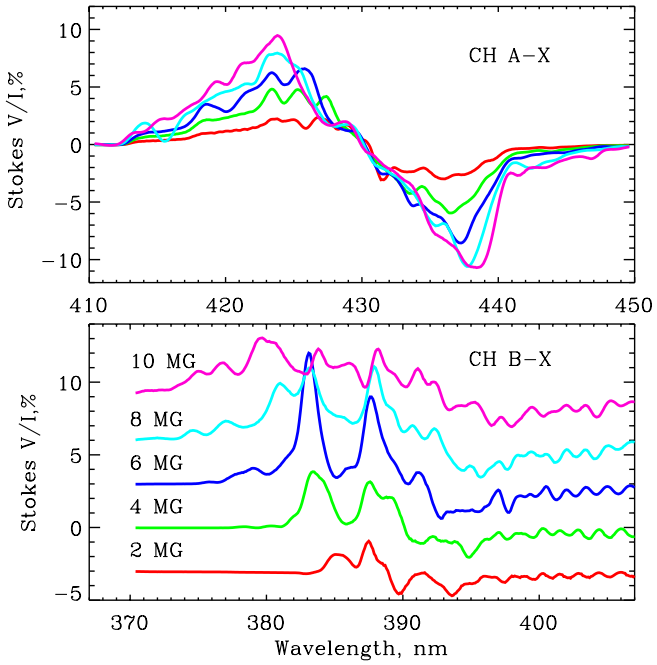


FIG. 3 (color online). Stokes $V$ profiles of the two CH band systems in a dipole magnetic field of 2 to 10 MG (in steps of 2 MG) pointing with a positive pole towards the Earth. In the upper panel, the amplitude is larger for stronger fields. In the lower panel, the profiles are shifted vertically for clarity (in steps of 3%).

model involves the following assumptions: (i) isothermal atmosphere with $T = 6100$ K [3], (ii) height-independent magnetic field, and (iii) no continuum polarization (in DQ stars it is formed due to $He^-$ and has no effect on molecular polarization [2]). Such a model allows us to separate the Stokes parameters and express them via corresponding absorption coefficients, anomalous dispersions, and angles. Line profiles are determined by the Voigt and dispersion function. This makes it possible to account for the magneto-optical effects in stronger magnetic fields. The instrumental broadening was implemented as a Gaussian profile with FWHM of 0.8 nm. The magnetic field configuration is assumed to be dipolelike.

The line list for the spectrum synthesis was compiled using the molecular database by Kurucz [11]. Wavelengths of missing lines and forbidden transitions were calculated based on the best available molecular constants and Hamiltonians. In the following, we discuss in detail the modeling of the CH and $C_2$ bands contributing to the major absorption bands and the two polarization features observed in white dwarf G99-37.

*CH.*—The strongest bands of the CH $A\,^2\Delta - X\,^2\Pi$ system are observed at 410–450 nm (bands with $\Delta v = 0$, Fig. 1). The electronic states of the system are very close to Hund's case ($b$), i.e., the total orbital momentum is coupled to the internuclear axis, whereas the spin is only loosely coupled to the orbital momentum and the molecular axis. In such a case, an increasing external magnetic field perturbs first the fine level structure and then the rotational structure of the molecule. Using molecular constants from [12] and matrix elements from [6], we have calculated the molecular level structure (up to $N = 40$) depending on the magnetic field strength (see Fig. 2). It is seen that levels become mixed due to the PBE, especially at lower rotation, and the spin cannot be neglected as was done in the earlier interpretations [2,5]. Since transition strengths and their symmetry are also modified, a broadband polarization is accumulated. It is of the opposite sign in the $P$ and $R$ rotational branches, which in the presence of a longitudinal field directed towards the observer results in an excess of positive circular polarization in the blue ($R$ branches) and of negative one in the red ($P$ branches). A cumulative effect of several vibrational bands (up to $v = 4$) produces the remarkable antisymmetric shape in Stokes $V$ at fields stronger than 1 MG, amplitude and splitting increasing with the field strength (Fig. 3). The synthetic profiles also include the contribution from the $C_2$ Swan $\Delta v = 2$ bands at 430.5 nm which noticeably absorbs the CH polarization in the red wing. A comparison with the Stokes profiles of G99-37 indicates a dipole field with the strength of 8 to 7.5 MG. A similar strength of a homogeneous field among other values was mentioned in [5]. The absence of linear polarization above 1% suggests that the dipole is pointing to the Earth within $\pm 20°$.

The CH $B\,^2\Sigma^- - X\,^2\Pi$ system is the strongest at 380–400 nm (bands with $\Delta v = 0$, Fig. 1). The upper electronic state having null orbital momentum reaches the complete PBE at rather weak magnetic fields, and the level structure reflects the independent quantization of the spin on the field direction (Fig. 2). A combination of the complete PBE on the fine structure of the upper state with the intermediate PBE on the rotational structure of the ground state produces the net circular polarization, predominantly of one sign (Fig. 3). Note that the synthetic profiles also include the contribution from the $C_2$ Deslandres-d'Azambuja $\Delta v = 0$ bands at 380 nm. The shape and polarization amplitude of the feature strongly depends on the magnetic field. The G99-37 observed Stokes profile is compatible with the dipole field of 7 MG (Fig. 1), although the fit suggests that there are probably missed transitions.

$C_2$.—The Swan system bands $a\,^3\Pi - d\,^3\Pi$ are the most prominent features in spectra of cool helium-rich white dwarfs. In the observed spectral region, three features can be identified with the $\Delta v = 0$, 1, and 2 at 520 nm, 470 nm, and 430 nm, respectively, the latter being blended with the CH $A$-$X$ system. The electronic states of the system are intermediate between Hund's cases ($a$) and ($b$). The PBE in these states occurs already at 0.1 MG, while in stronger fields, mixing of levels becomes enormous (Fig. 2). The $R$ and $P$ rotational branches are not well separated in wavelength. As a result, the polarization signal in these bands is about 1% in fields stronger than $\sim$1 MG. This indicates that the Swan $C_2$ bands may also be used for detecting

magnetic fields on cool white dwarfs but with more precise measurements and higher spectral resolution.

The $C_2$ Deslandres-d'Azambuja system at 360 nm is due to the electronic transition between the singlet levels $C\,^1\Pi - A\,^1\Pi$. Because of the null spin, the PBE occurs only on the rotation level structure in fields stronger than $\sim$1 MG (Fig. 2). Above this limit, there is no significant net polarization.

*Conclusions.*—The successful synthesis of the polarization patterns of molecular bands in a strong magnetic field, achieved with the current state of our understanding of the molecular Zeeman effect, opens up a number of astrophysical applications. The net circular polarization signatures appear due to the PBE and mixing of energy levels in the molecule. This can be employed to investigate magnetism of faint objects with low spectral resolution, in particular, of cool white, red, and brown dwarfs with strong molecular bands in their spectra. The analysis of the observed Stokes parameters of the unique magnetic white dwarf G99-37 reveals a dipolelike magnetic field of $7.5 \pm 0.5$ MG pointing to the Earth within $\pm 20°$. Further studies are needed to clarify whether the stellar rotation axis coincides with the magnetic axis.

S. V. B. acknowledges support from the ESF under the EURYI scheme, SNF Grants Nos. PE002-104552 and 200021-103696, the ETH Research Grant No. TH-2/04-3, and the Academy of Finland Grant No. 115417.

*sveta@astro.phys.ethz.ch
†andber@utu.fi, piirola@utu.fi

[1] D. T. Wickramasinghe and L. Ferrario, Publ. Astron. Soc. Pac. **112**, 873 (2000).
[2] J. R. P. Angel and J. D. Landstreet, Astrophys. J. **191**, 457 (1974).
[3] P. Dufour, P. Bergeron, and G. Fontaine, Astrophys. J. **627**, 404 (2005).
[4] R. M. E. Illing, Astrophys. J. **248**, 358 (1981).
[5] I. Bues and M. Pragal, Mem. Soc. Astron. Ital. **58**, 97 (1987).
[6] S. V. Berdyugina, P. A. Braun, D. M. Fluri, and S. K. Solanki, Astron. Astrophys. **444**, 947 (2005).
[7] J. L. Greenstein, Astrophys. J. Lett. **162**, L55 (1970).
[8] G. Herzberg, *Molecular Spectra and Molecular Structure. I. Spectra of Diatomic Molecules* (Van Nostrand Company, New York, 1950).
[9] S. V. Berdyugina and S. K. Solanki, Astron. Astrophys. **385**, 701 (2002).
[10] D. N. Rachkovsky, Izvestiya Krymskoi Astrofizicheskoi Observatorii **28**, 259 (1962).
[11] R. L. Kurucz (1993), CDROMs No. 13, 18.
[12] B. M. Krupp, Astrophys. J. **189**, 389 (1974).