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New analysis of Balmer line shapes in magnetic white dwarf atmospheres

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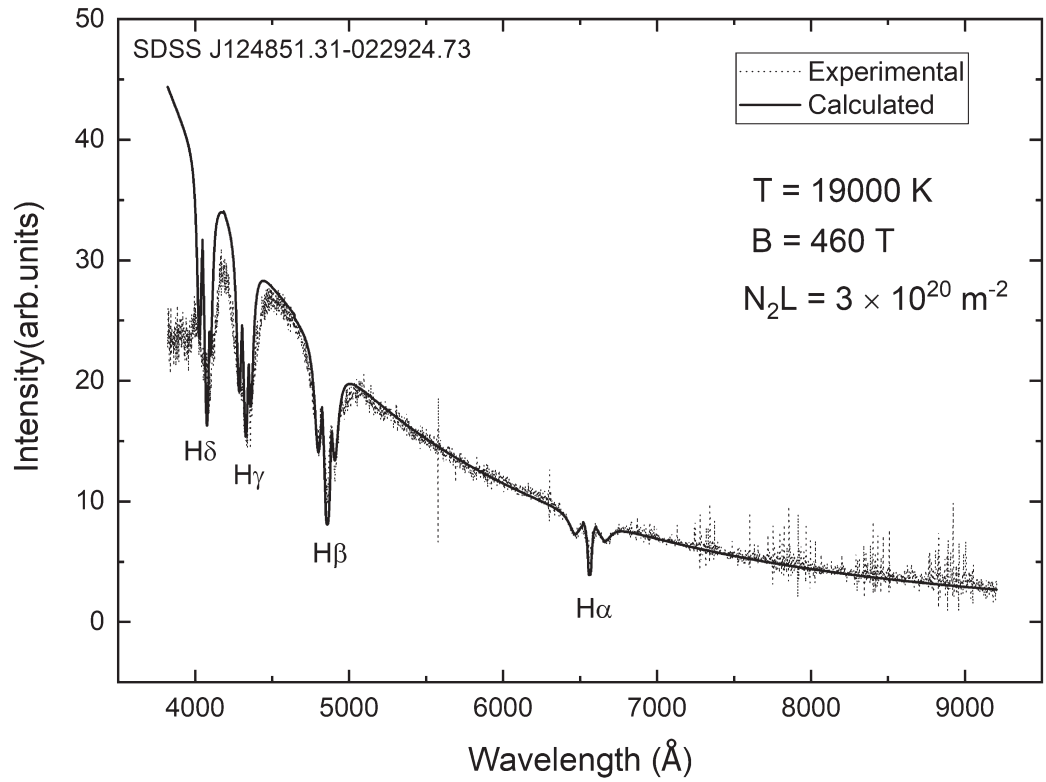
We present an analysis of hydrogen Balmer line shapes observed in a white dwarf spectrum taken from the SDSS database. The spectrum presents lines with a triplet structure, featuring the presence of a strong magnetic field. Using a spectrum fitting model, we estimate the effective temperature of the star and we estimate the magnetic field present in the atmosphere. We also estimate the electron density from Stark broadening calculations.

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New analysis of Balmer line shapes in magnetic white dwarf atmospheres

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Abstract. We present an analysis of hydrogen Balmer line shapes observed in a white dwarf spectrum taken from the SDSS database. The spectrum presents lines with a triplet structure, featuring the presence of a strong magnetic field. Using a spectrum fitting model, we estimate the effective temperature of the star and we estimate the magnetic field present in the atmosphere. We also estimate the electron density from Stark broadening calculations.

1
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1 Introduction

White dwarfs are the post-end stage of stars of low or medium mass, typically $M \lesssim 10M_{\odot}$ [1]. They are composed mostly of electron-degenerate matter, surrounded by a thin atmosphere of partially ionized plasma. Investigations have shown that the majority of white dwarfs have an atmosphere of pure hydrogen as a result of gravitational setting, which removes helium and heavier elements from the atmosphere and moves them toward inner layers [2, 3]. These atmospheres can be considered as hydrogen plasmas, which are similar to some that can be created in laboratory experiments [4]. As a rule, the physical properties of white dwarfs are inferred from spectroscopic analysis; the fitting of a spectrum can provide relevant parameters such as the surface temperature or the surface gravity, and modeling efforts are still ongoing in order to have accurate estimates [5, 6]. The electron density in a white dwarf atmosphere is high enough (up to 10^{17} cm^{-3} , and higher) so that the line shapes are affected by Stark broadening and, hence, can serve as a probe of the electron density N_e . Triplet lines, which are visible in some white dwarf spectra [7, 8], are the result of the Zeeman effect. The line splitting is proportional to the magnetic field B and, hence, provides a direct estimate of magnetic field. Following previous works [9, 10], we report on the analysis of a white dwarf spectrum where the absorption lines are subject to strong Zeeman splitting. A fitting model that accounts for continuous background and Zeeman effect is applied to the spectrum. We address the issue of Stark broadening modeling by using a computer simulation technique. An estimate of the electron density in the atmosphere is obtained based on Balmer line shape

calculations. The article is organized as follows: Sect. 2 presents the spectrum investigated in this work, Sect. 4 presents the fitting model and the inferred values for the temperature and the magnetic field, and Sect. 5 reports on Stark broadening calculations that have been carried out to infer the electron density. A discussion about the fitting results is done.

2 Presentation of the white dwarf spectrum

Many white dwarf spectra have been recorded and made available through dedicated databases, such as the Sloan Digital Sky Survey (SDSS). In this work, we investigate a spectrum observed in a white dwarf of DA type, i.e., with an atmosphere rich in hydrogen. Figure 1 shows the considered spectrum. The absorption lines correspond to the Balmer series. They are well resolved up to $n = 6$. The lines are split in triplets, which indicates a strong magnetic field. This spectrum has relatively weak noise near the lines, which makes it a suitable candidate for analysis. Although there have been many studies in white dwarf spectra, only a very few discussed the presence of a strong magnetic field [7, 8]. Here, we use a new fitting model which accounts for this, including both Stark and Zeeman effects.

3 Fitting the overall spectrum

Fitting the spectrum using an adequate model will give an estimate for the parameters characterizing the plasma in the star's atmosphere. In this section, we consider the overall spectrum. The atmosphere is described as a homogeneous slab, which absorbs the radiation

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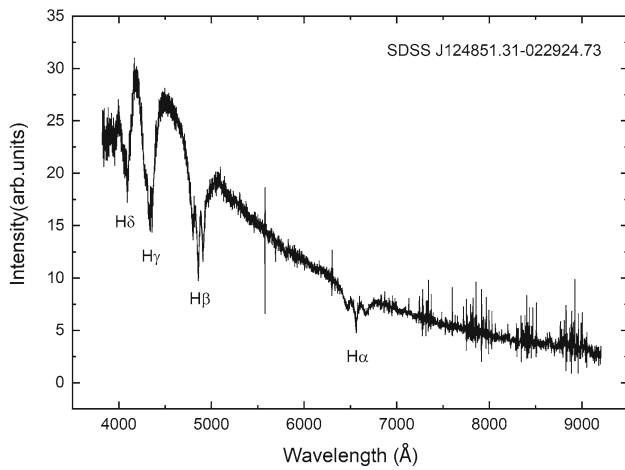


Fig. 1 Spectrum of the white dwarf considered in this work. The data were obtained from the SDSS database (www.sdss.org). The Balmer lines are split in triplets, which indicates a strong magnetic field

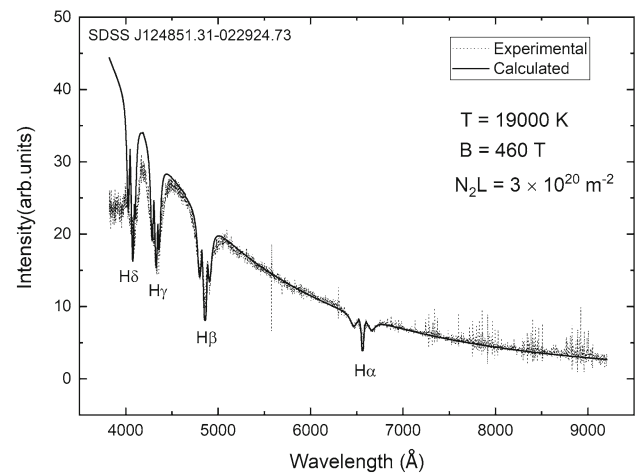


Fig. 2 Calculated best-fit spectrum for the white dwarf SDSS J124851.31-022924.73. A good agreement with the experimental white dwarf spectrum is obtained. See text for the fitting model

63 coming from the interior and re-emits it partially. The
 64 incoming radiation is described by a Planckian func-
 65 tion, the absorption is assumed to occur in spectral
 66 lines only, and the re-emission is assumed to be due
 67 both to the lines and the continuum. We define the fit-
 68 ting function from the solution of the radiative transfer
 69 equation (e.g., [11]):

$$I_\nu = B_\nu \exp(-\kappa_\nu L) + S_\nu(1 - \exp(-\kappa_\nu L)), \quad (1)$$

71 where B_ν is the Planck function, κ_ν is the extinc-
 72 tion coefficient, L is the atmosphere thickness, and S_ν
 73 denotes the re-emission contribution. Assuming local
 74 thermodynamic equilibrium (LTE), this term can be
 75 approximated as $S_\nu \simeq C_\nu \exp(-h\nu/k_B T)$ where C_ν
 76 involves the photon absorption cross sections of bound-
 77 free and free-free transitions [11]. The frequency depen-
 78 dence of C_ν is determined by Gaunt factors and is usu-
 79 ally weak; for simplicity, we will neglect this depen-
 80 dence in the analysis and leave $C_\nu \equiv C$ as an adjustable
 81 parameter. The extinction coefficient reads

$$\kappa_\nu = \sum_n \frac{h\nu}{4\pi} N_2 B_{2n} \phi_{n2}(\nu), \quad (2)$$

83 where the sum is carried out over the upper levels
 84 ($n > 2$), N_2 is the density of absorbers, i.e., the density
 85 of atom in the $n = 2$ level, B_{2n} is the Einstein coeffi-
 86 cient for absorption, and $\phi_{n2}(\nu)$ is the normalized line
 87 shape function relative to the $2 \rightarrow n$ transition. The
 88 stimulated emission has been retained through the for-
 89 mal substitution $N_2 B_{2n} \rightarrow N_2 B_{2n} [1 - \exp(-h\nu/k_B T)]$,
 90 which holds at LTE. The line shape function ϕ_{n2} is
 91 determined by the physical mechanisms that perturb
 92 the energy levels, namely the Stark effect due to the
 93 plasma microfield, the collisions with neutral atoms
 94 (both resonant and van der Waals interactions), and the
 95 Zeeman effect due to the magnetic field. There is

presently no general formula accounting for all of these
 effects and sufficiently simple so as to be applicable in a
 fast fitting routine. In particular, the modeling of Stark
 broadening is a major issue; we discuss it in the next
 section. For the sake of simplicity in the fitting here,
 we use a Lorentzian function with a width independ-
 ent of n . The only effect retained here is the Zeeman
 splitting, in such a way so as to reproduce the triplet
 structure visible in the lines. Both linear and quadratic
 Zeeman perturbations have been taken into account; for
 the quadratic Zeeman effect, analytical formulas from
 [12] have been used. Figure 2 shows the fitting result.
 From the fit, the atmospheric temperature was estimat-
 ed to be 19000 K, the magnetic field was found to
 be 460 T, and a value of $3 \times 10^{20} \text{ m}^{-2}$ was estimated
 for $N_2 L$. The inferred values for the effective temper-
 ature and the magnetic field are in good agreement
 with previous reports [7, 8] (the magnetic field values
 around 8 MG reported therein corresponds to the polar
 field, which is approximately twice the observed mag-
 netic field). Note that there is no direct estimate of the
 density N_2 through the model used here. An extension
 providing the atomic density can be devised based on
 a suitable line shape formula, accounting for collisional
 broadening; an example of such a formula is provided
 by the Lindholm impact theory and its variants [13].
 Databases providing line widths and shifts and appli-
 cable to isolated lines have precisely been developed in
 this framework, e.g., see [14, 15].

4 Stark broadening modeling

In white dwarf atmospheres, the electron density is
 usually high enough so that the Stark effect due to
 microfield provides a significant contribution to the line
 broadening. Because of its strong dependence to the

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density, this line broadening mechanism can be used as a diagnostic tool, provided a suitable model is used. The description of a Stark-broadened line amounts to solve a quantum statistical problem. We give here the main lines of the formalism. Consider an atom that emits or absorbs a photon in the presence of charged particles located at its vicinity. The line shape function is proportional to the Fourier transform of the dipole autocorrelation function [16]:

$$I(\omega) \propto \text{Re} \int_0^\infty dt \{ \text{Tr}[\rho \mathbf{d}(0) \cdot \mathbf{d}(t)] \} e^{i\omega t}. \quad (3)$$

here $\mathbf{d}(t)$ denotes the atomic dipole operator expressed in the Heisenberg picture, ρ is the density operator, $\text{Tr}(\dots)$ denotes a trace over the atomic states and the brackets $\{\dots\}$ correspond to an average over the perturbers. The dipole at time t is related to its initial value through $\mathbf{d}(t) = U^\dagger(t) \mathbf{d}(0) U(t)$, where $U(t) \equiv U(t, 0)$ is the evolution operator from time 0 to t . The latter obeys the time-dependent Schrödinger equation:

$$i\hbar \frac{dU}{dt}(t) = [H_0 + V(t)]U(t). \quad (4)$$

here H_0 is the Hamiltonian corresponding to the unperturbed atom and $V(t) = -\mathbf{d} \cdot \mathbf{E}(t)$ is the Stark effect term; $\mathbf{E}(t)$ is the electric field generated at the emitter's location by the perturbers. Several approaches have been developed for the evaluation of the spectrum (3), usually based on the separation between the time scales relative to the electrons and to the ions. For example, in the framework of the so-called standard model, the ions are assumed motionless (static approximation) and the electrons are described within a collisional picture in terms of a collision operator (impact approximation). Extensions to this model have been designed in such a way so as to retain the time-dependence of the ionic microfield (ion dynamics issue) and to account for incomplete collisions with the electrons; such extensions are usually based on kinetic theory approaches, involving either particle distribution functions (e.g., through the "unified theory" [17]) or involving ad hoc stochastic models (MMM [18, 19], FFM [20, 21]). Fully numerical simulations can also be performed; in this case, they may serve as a benchmark for models [22]. Essentially, a simulation consists in numerically integrating the time-dependent Schrödinger equation that governs the dynamics of an atom perturbed by a fluctuating electric field, itself being generated from a numerical integration of the Newtonian equations of motion for the charged particles moving in the vicinity of the emitter. We have applied the computer simulation method reported in [23] to the fitting of the shape of the $H\beta$ absorption line. One advantage of this line, with respect to the other ones, is that it is far enough from its neighbors ($H\alpha$ and $H\gamma$) so as not to overlap with them; it is also deeper than $H\alpha$, which suggests this line is less subject to re-emission. A focus has been put on Stark broadening; in particular, the broadening due to collisions

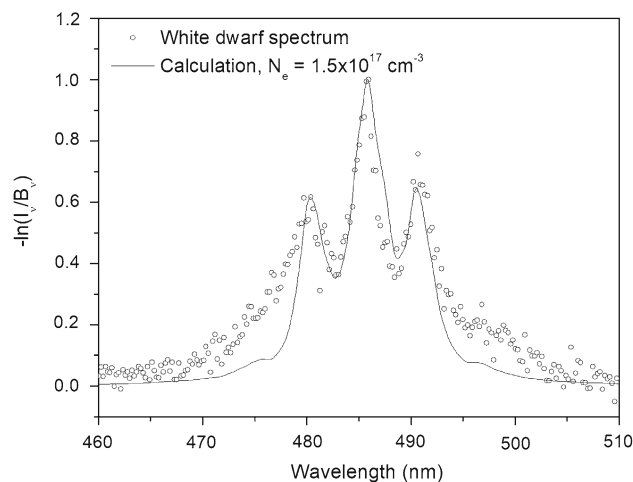


Fig. 3 A computer simulation method for Stark broadening modeling has been applied to the fitting of the $H\beta$ line shape. The inferred density was $N_e = 1.5 \times 10^{17} \text{ cm}^{-3}$

with neutrals has not been retained in the calculations. Figure 3 shows a comparison between the experimental spectrum and the best-fit result. As a first approximation, we have completely neglected the re-mission term ($S_\nu \equiv 0$); accordingly, the quantity $-\ln(I_\nu/B_\nu)$ plotted in the figure can be interpreted as being proportional to the line shape function ϕ . The fitting has been done setting the electron density as the only adjustable parameter. The other parameters have been set equal to the value inferred from the overall spectrum fitting presented in the previous section. The best-fit result is in rather good agreement with the experimental one. The inferred electron density was $N_e = 1.5 \times 10^{17} \text{ cm}^{-3}$. The main discrepancy visible in the figure concerns the slow decrease of the line wings in the experimental spectrum, which is not reproduced by the calculation. This discrepancy may be due to the presence of a population of atoms in a region of higher density, which contribute to the spectrum but are not retained here in the model. An extension of the fitting model, accounting for the spatial dependence of the plasma parameters in the atmosphere, is presently being developed.

5 Conclusion

An analysis of the lines observed in a star spectrum provides information on the chemical species present in the atmosphere and on the plasma parameters. In complement to previous works [9, 10], we have analyzed a white dwarf spectrum exhibiting strong absorption lines in the Balmer series. A fitting model has been applied to the overall spectrum. In the model, the atmosphere is described as a homogeneous slab, which absorbs the radiation coming from the interior and re-emits it partially. The temperature has been inferred from the Planck function, and an estimate for the magnetic field has been done using the separa-

219 tion between Zeeman components. These inferred val-
 220 ues are in good agreement with previous reports [7, 8].
 221 In addition, we have shown that the Stark broaden-
 222 ing of the spectral lines can be used as a probe of the
 223 electron density. Using a computer simulation method,
 224 we have obtained an estimate of the electron density
 225 from a fitting of the $H\beta$ line shape. An improvement of
 226 the spectrum fitting model, which accounts for plasma
 227 non-homogeneity, is presently ongoing. It will involve
 228 collisional-radiative calculations coupled to line transfer
 229 simulations. Specific issues such as plasma self-emission
 230 will be addressed.

231 **Data Availability Statement** This manuscript has no
 232 associated data or the data will not be deposited. [Authors'
 233 comment: ...].

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