Magnetic-Field Distribution of a White Dwarf

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14th Serbian Conference on Spectral Line Shapes in Astrophysics
Bajina Bašta, Serbia
June 19–23, 2023

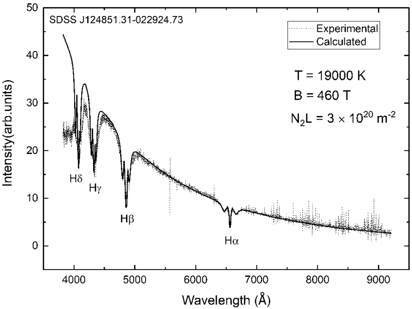
Introduction

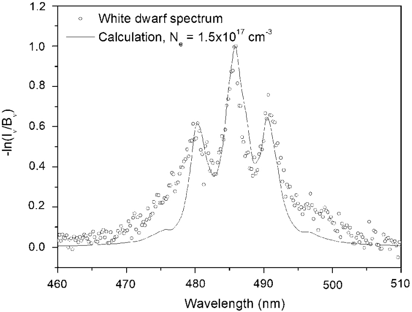
- Spectrum of the white dwarf SDSS J124851.31-022924.73.
- Hydrogen Balmer series with a clear Zeeman splitting.
- First analyzed by [Raji et al., 2021].

Used as the “experimental best fit” case at the 6th Spectral Line Shapes in Plasmas (SLSP 6) workshop (Hyères, France, October 17 – 21, 2022).

Previous study

First analyzed by [Raji et al., 2021]:



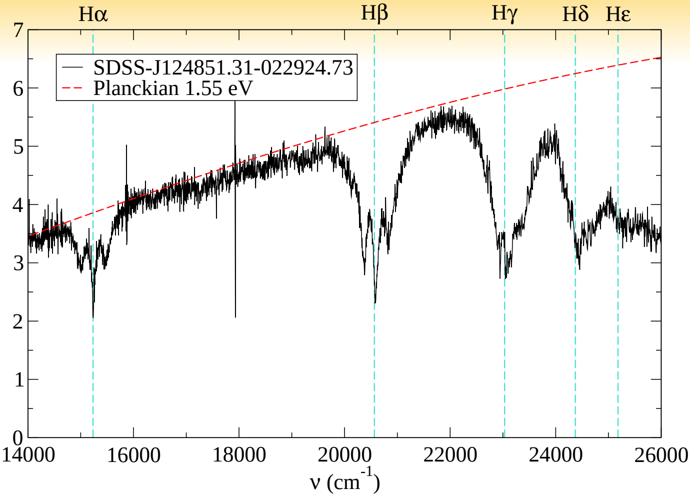


Overall fit:
$B = 460\,\mathrm{T}$.

Hβ line-shape analysis:
$n_e = 1.5 \times 10^{17}\,\mathrm{cm}^{-3}$.

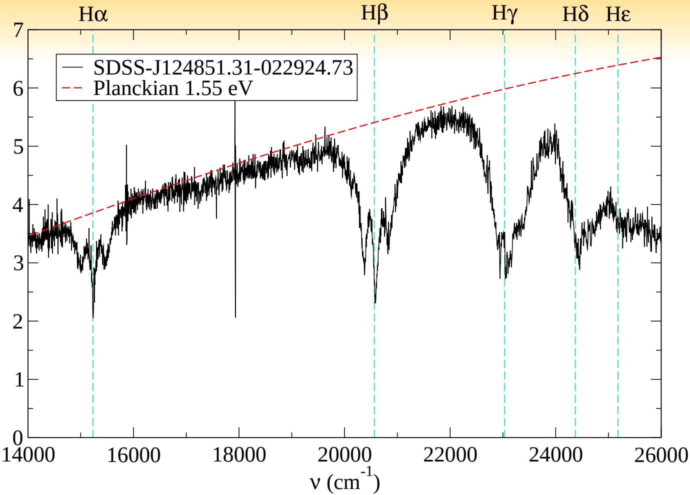
But the devil is in the details…

Data :: overview



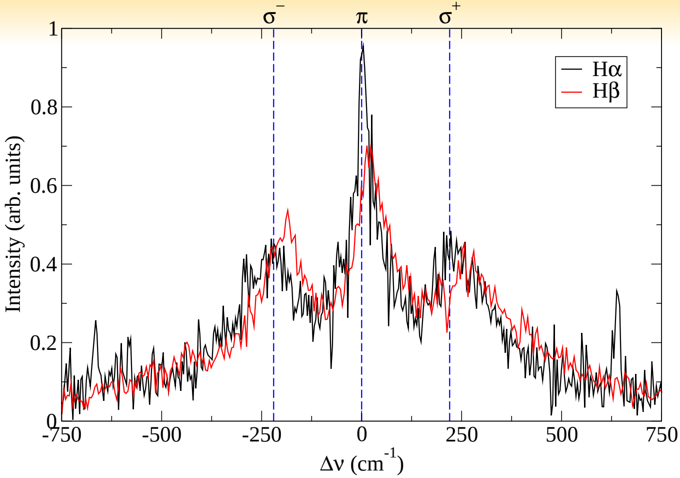
- The WD atmosphere is optically thick (at $n_e \sim 10^{17}\,\mathrm{cm}^{-3}$, $\alpha^{-1} \sim 1\,\mathrm{cm}$ and $10\,\mathrm{cm}$ for Hα and Hβ, respectively); self-absorption and re-emission take place.

Data :: overview



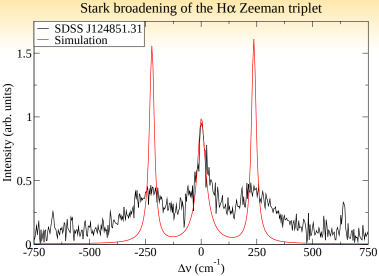
- Lines are shifted: a combined effect of the diamagnetic effect (blue shift, e.g., [Rosato, 2020]) and quadratic Stark effect (red shift, e.g., [Stambulchik et al., 2007]).

Analysis :: Hα vs Hβ

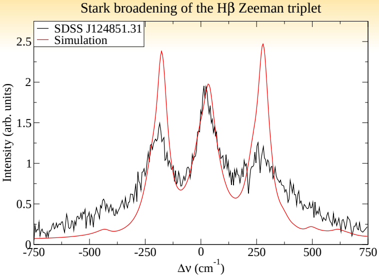


- The π (central) component of Hβ is $\sim 2\times$ wider than Hα's.
- Yet the σ (lateral) components of Hα and Hβ are similar.

Analysis :: Broadening of π and σ components



Stark broadening of the Hα Zeeman triplet

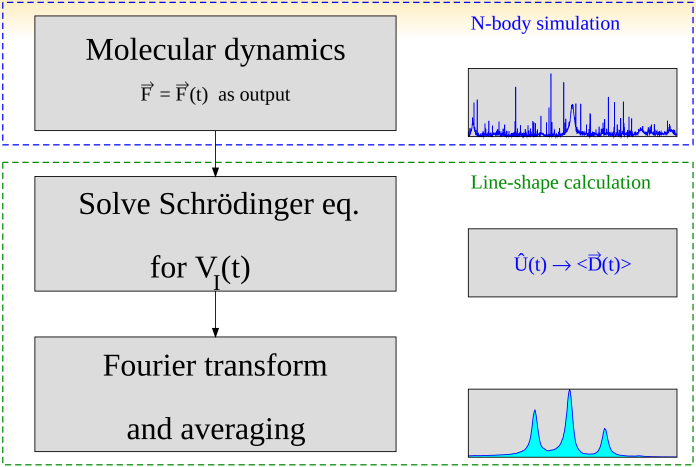


Stark broadening of the Hβ Zeeman triplet

- Contrary to the simulations (e.g., [Rosato et al., 2009]), the Stark broadening of the σ components of the Zeeman triplet is stronger than that of π.
- On the other hand, the triplet-component intensity ratios are close to $1 : 1 : 1$ – as if averaged over $\vec{B}$.

These observations suggest a wide distribution of B as a possible explanation.

Simulations :: Scheme



N-body simulation

Molecular dynamics

$\vec{F} = \vec{F}(t)$ as output

Line-shape calculation

Solve Schrödinger eq.

for $V_I(t)$

$\hat{U}(t) \to <\vec{D}(t)>$

Fourier transform

and averaging

A variant of computer simulation [Stambulchik and Maron, 2006].

Simulations :: Schrödinger solver

The Hamiltonian of the atomic system:

$$H = H_\circ + V(t).$$

The perturbation $V(t)$ is due to the plasma electric field (simulated by the MD) and external electric and magnetic[*] fields. We solve the Schrödinger equation

$$id\Psi(t)/dt = H\Psi(t)$$

using the time-development operator U in the interaction representation:

$$id\bar{U}(t)/dt = V(t)\bar{U}(t).$$

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[*] Including the quadratic (diamagnetic) term.

Simulations :: FFT and averaging

The evolution of the dipole operator is then obtained:

$$\vec{D}(t) = U(t)^{\dagger}\vec{D}(0)U(t).$$

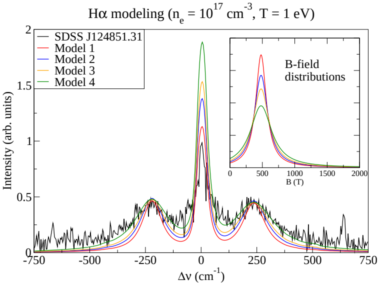
The Fourier transform of the dipole operator $\vec{D}(\omega)$ is further used to calculate the line spectrum:

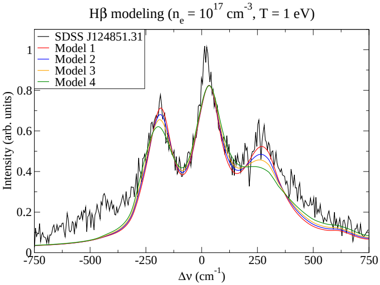
$$I^{\lambda}(\omega) \propto \sum_{i,f} \langle |\vec{e}_{\lambda} \cdot \vec{D}_{fi}(\omega)|^{2} \rangle.$$

The angle brackets denote an averaging over several runs of the code (which corresponds to the averaging over an ensemble of emitters).

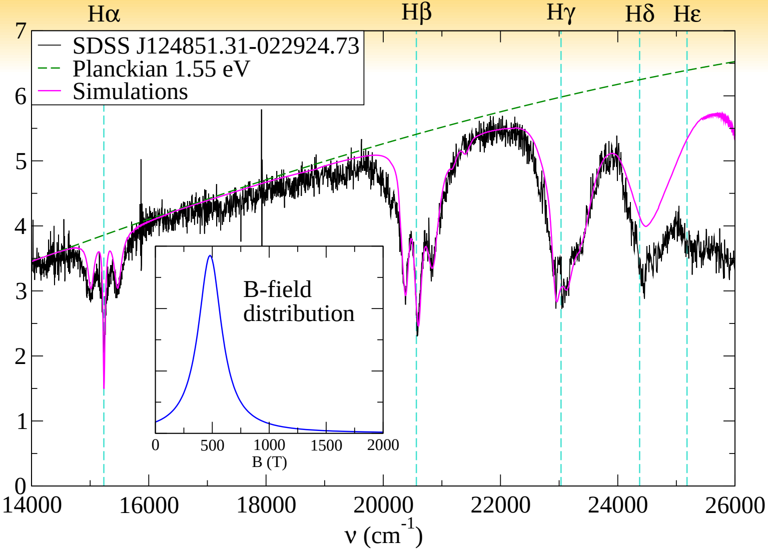
Results :: Hα and Hβ

- All states with $n = 2 \ldots 6$ are included in the Hamiltonian.
- Calculations on a wide grid of B (0 – 2000 T) are performed.
- Four models with different B-field distributions are tested: $\mathrm{FWHM}_B = 200\,\mathrm{T}, 250\,\mathrm{T}, 300\,\mathrm{T}$, and $400\,\mathrm{T}$.





Results :: Total spectrum



$n_e = 10^{17}\,\mathrm{cm}^{-3}$, $T \approx 1\,\mathrm{eV}$, $B_0 = 480\,\mathrm{T}$, $\mathrm{FWHM}_B = 250\,\mathrm{T}$.

Conclusions

- Hydrogen spectrum from a white dwarf (SDSS J124851.31-022924.73) was re-analyzed and re-modeled.
- No single set of the plasma parameters could satisfactorily explain the entire spectrum.
- A wide distribution of the magnetic field magnitudes was assumed to achieve a good overall agreement.
- Non-linear terms in the Stark and Zeeman interactions are crucial for calculating line shapes (especially the shifts).

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The work is still in progress. To be checked:

- Radiative transport effects;
- Effect of spiralling trajectories [Rosato et al., 2018, Gomez et al., 2023];
- Motional Stark effect [Rosato, 2023, Gomez et al., 2023];
- Non-dipole interaction and penetration effects [Gomez et al., 2021, Stambulchik and Iglesias, 2022].

The end

Thank you for your attention!

Bibliography

Raji, A., Rosato, J., Stamm, R., and Marandet, Y. (2021).
Eur. Phys. J. D, 75(2):63.

Rosato, J. (2020).
Atoms, 8(4):74.

Stambulchik, E., Fisher, D. V., Maron, Y., Griem, H. R., and Alexiou, S. (2007).
High Energy Density Phys., 3:272–277.

Rosato, J., Marandet, Y., Capes, H., Ferri, S., Mosse, C., Godbert-Mouret, L., Koubiti, M., and Stamm, R. (2009).
Phys. Rev. E, 79(4):046408–7.

Stambulchik, E. and Maron, Y. (2006).
J. Quant. Spectrosc. Radiat. Transfer, 99(1–3):730–749.

Rosato, J., Ferri, S., and Stamm, R. (2018).
Atoms, 6(1):12.

Gomez, T. A., Zammit, M. C., Fontes, C. J., and White, J. R. (2023).
Accepted for publication.

Rosato, J. (2023).
J. Quant. Spectrosc. Radiat. Transfer, page 108628.

Gomez, T. A., Nagayama, T., Cho, P. B., Zammit, M. C., Fontes, C. J., Kilcrease, D. P., Bray, I., Hubeny, I., Dunlap, B. H., Montgomery, M. H., and Winget, D. E. (2021).
Phys. Rev. Lett., 127(23):235001.

Stambulchik, E. and Iglesias, C. A. (2022).
Phys. Rev. E, 105(5):055210.