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Polarised line shape calculations for conditions encountered in stellar magnetic atmospheres

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Abstract. We present new investigations into spectral line shapes under conditions typical for magnetic stellar atmospheres. Our method for simulating line profiles takes into account the coupled Zeeman and Stark effects. The calculations presented here will ultimately help to correctly model the Stokes parameters of peculiar stellar objects such as the Magnetic White Dwarfs (MWDs), retrieving their magnetic field geometries from spectropolarimetric observations. For the magnetic analysis of this class of stars, in general only Stokes I profiles as a function of rotational phase have been used in the past, in a very few cases, also Stokes V. The present improved simulations of the full Stokes parameters are expected to provide a powerful tool for the analysis of strong magnetic fields like those found in the MWDs.

1. Introduction

Spectropolarimetric astronomical observations yield stellar line profiles in linear and circular polarisation, expressed with the help of the Stokes parameters. The latter are used in well-established techniques for the detection and modelling of stellar magnetic fields ([1], [2]). Whenever atomic species are immersed in a magnetic field, the energy degeneracy in the magnetic quantum number m is removed, resulting in a variety of Zeeman patterns (the simplest being a triplet). Since the polarisation of the Zeeman sub-components depends on the orientation of the magnetic field vector with respect to the line of sight, the Stokes parameters provide a powerful spectroscopic probe into stellar magnetic field geometries.

For a hydrogen plasma under physical conditions comparable to those in the atmospheres of degenerate stars, the Stark effect is of the same order of magnitude as the Zeeman effect; it is thus not formally correct to treat them separately. The simulation method applied hereafter self-consistently deals with this problem, relying on very simple principles of quantum mechanics. Applications of this technique range from the production of synthetic profiles for astrophysical purposes to the diagnosis of laboratory plasmas.

2. Method and Results

In a plasma, the emitters and/or absorbers of radiation are perturbed by the micro-field due to the presence of other ions and electrons, resulting in broadened spectral lines. According to standard plasma spectroscopy theory (see e.g, [3], [4]), a Zeeman-Stark broadened line profile is proportional to the Fourier Transform of the electric dipole autocorrelation function C(t):

$$I(\omega) \propto \frac{1}{\pi}\Re\int_0^{+\infty} C(t)e^{i\omega t}dt \tag{1}$$

$$C(t) = \sum_{\alpha,\alpha',\beta,\beta'} \rho_{\alpha\alpha'}\left(\vec{d}_{\alpha\beta}\cdot\vec{\epsilon}\right)\left(\vec{d^*}_{\alpha'\beta'}\cdot\vec{\epsilon^*}\right)\langle U_{\alpha'\alpha}(t)U^*_{\beta'\beta}(t)\rangle \tag{2}$$

Here, α and β respectively correspond to the upper and lower atomic states contributing to the line under consideration; $\vec{d}$ is the electric dipole operator; U is the time evolution operator; ρ the density matrix; $\vec{\epsilon}$ the polarisation vector; and $\langle ... \rangle$ denotes the operation of statistical averaging over the configurations of the perturbers. The time evolution operator obeys the time-dependent Schrödinger equation:

$$i\hbar\frac{dU(t)}{dt} = \left[H_0 + V(t)\right]U(t) \tag{3}$$

In this equation, H_0 contains all the time independent terms of the Hamiltonian (including the magnetic linear Zeeman effect) whereas $V(t)$ is time dependent and describes the Stark perturbation, which in the dipole approximation takes the form $V(t) = -\vec{d}\cdot\vec{E}(t)$. The $\vec{E}(t)$ function is obtained from a simulation of the particles orbiting around the emitter and computing the total field at its location. The method is the same as in [5] and [6]. The ions are simulated by means of a quasiparticle model. The electron contribution is retained within a collision operator model (GKS as in [7]). A new code has been written in Python 3. It solves equation (3) projected onto the atomic states numerically by means of a Runge-Kutta 4th order accurate algorithm, subsequently it projects amplitudes over polarisation basis vectors and computes $C(t)$ using equation (2).The profile is finally obtained by evaluating the Fourier integral numerically. Figure 1 provides an example of calculation for Lyman α and how meaningful linear polarisation can be whereas Figure 2 displays changes in the Lyman β profile due to changes in temperature. The Stokes $IQUV$ parameters returned by the code provide an experimentally/observationally convenient way of describing polarisation as each parameter corresponds to a sum or difference of measurable intensities. In order to obtain them one has to choose an appropriate reference frame for the polarisation basis vector. Here we adopt Jones notation (see [8]), so that $(\hat{x}, \hat{y})$ is the standard cartesian base, $\left(\hat{\pi/4}, \hat{-\pi/4}\right)$ a cartesian basis tilted by 45° with respect to the previous one, $\hat{l} = (\hat{x} + i\hat{y})/\sqrt{2}$ and $\hat{r} = (\hat{x} - i\hat{y})/\sqrt{2}$ the so called circular basis. In terms of these bases, the Stokes parameters can be written as follows (for details see [9]):

$$\begin{aligned} I &= \langle E_x^2\rangle + \langle E_y^2\rangle = \langle E_{\pi/4}^2\rangle + \langle E_{-\pi/4}^2\rangle = \langle E_r^2\rangle + \langle E_l^2\rangle \\ Q &= \langle E_x^2\rangle - \langle E_y^2\rangle \\ U &= \langle E_{\pi/4}^2\rangle - \langle E_{-\pi/4}^2\rangle \\ V &= \langle E_r^2\rangle - \langle E_l^2\rangle \end{aligned} \tag{4}$$

The numerical method proposed in the present work provides a capability to address the simultaneous action of Zeeman splitting and Stark broadening on the Stokes IQUV parameters. An in-depth investigation is currently ongoing and will be published in the near future.

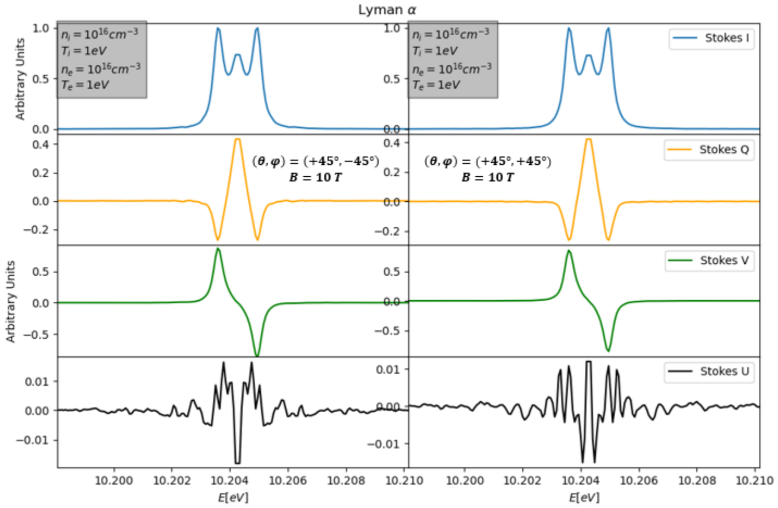

Figure 1. Lyman α Stokes $IQUV$ profiles for different magnetic field directions with respect to the observer.

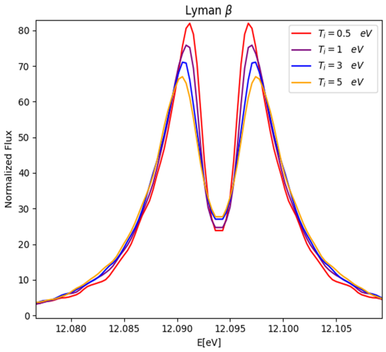

Figure 2. Temperature dependence of Lyman β. The adopted density is $n_i = 10^{17} cm^{-3}$.

3. Conclusions

The simulation method presented above has proven versatile for numerous applications in the fields of astrophysics and of laboratory plasma physics. Future investigations will be devoted to the computation of He lines, and to the analyses of both the quadratic Stark and the diamagnetic Zeeman effects, the latter being fundamental to the spectra of Magnetic White Dwarfs (MWDs) whose fields are known to reach thousands of teslas. Spectropolarimetry is a powerful observational tool in astronomy to recover magnetic field geometries, but it has yet to be applied to MWDs which mostly have only been observed in Stokes I, very rarely in Stokes V, never in Stokes Q and U. Our hope is that future observing campaigns will move towards full Stokes spectra, enabling us to decipher for the first time the complexity of the magnetic field geometries of MWDs by means of their hydrogen Balmer lines.

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