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STARK BROADENING AND WHITE DWARFS

Milan S. Dimitrijević[1,2], Andjelka Kovačević[3], Zoran Simić[1] and Sylvie Sahal-Bréchot[2]

[1] *Astronomical Observatory, Volgina 7, 11060 Belgrade 38, Serbia; mdimitrijevic@aob.bg.ac.rs, zsimic@aob.bg.ac.rs*

[2] *Observatoire de Paris, LERMA, 5 Place Jules Janssen, 92190 Meudon, France; sylvie.sahal-brechot@obspm.fr*

[3] *Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studentski Trg 16, 11000 Belgrade, Serbia; andjelka@matf.bg.ac.rs*

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Abstract. White dwarf and pre-white dwarfs are the best types of stars for the application of Stark broadening research results in astrophysics, since in the atmospheres of these stars physical conditions are very favorable for this line broadening mechanism – in hot hydrogen-deficient white dwarfs and pre-white dwarfs $T_{\rm eff}$ = 75 000–180 000 K and $\log g$ = 5.5–8 [cgs]. Even for much cooler DA and DB white dwarfs with the typical effective temperatures 10 000–20 000 K, Stark broadening is usually the dominant broadening mechanism. In this review, Stark broadening in white dwarf spectra is considered, and the attention is drawn to the STARK-B database (http://stark-b.obspm.fr/), containing the parameters needed for analysis and synthesis of white dwarf spectra, as well as for the collective efforts to develop the Virtual Atomic and Molecular Data Center.

Key words: stars: white dwarfs – Stark broadening, line profiles – databases

1. INTRODUCTION

Stellar spectroscopy is a powerful tool for investigation of stellar plasma – the temperatures in particular atmospheric layers, their chemical composition, as well as the surface gravity, spectral type and effective temperature of the star. For such purposes, in a number of cases, the influence of collisions with charged particles on emitting/absorbing atoms and ions is important in astrophysical plasmas, which results in the Stark broadening of spectral lines.

Physical conditions in the astrophysical plasmas are exceptionally different, so the Stark broadening is of interest in extreme conditions – from interstellar molecular clouds, where typical electron temperatures are $\sim$30 K or smaller and typical electron densities N_e = 2–15 cm^{-3} (see e.g. Dimitrijević 2010), to the temperatures 10^6–10^7 K and electron densities 10^{22}–10^{24} cm^{-3}. Especially favorable conditions for the Stark broadening are white dwarf and pre-white-dwarf atmospheres, where this broadening mechanism is usually dominant in comparison with the concurrent one – thermal Doppler broadening.

In this work, we will consider Stark broadening in white dwarf spectra and the corresponding results obtained by members of the Group for Astrophysical Spectroscopy at the Belgrade Astronomical Observatory, and their partners from France, Tunisia, Russia and Canada. Also, the attention will be drawn to the STARK-B database (http://stark-b.obspm.fr/), containing Stark broadening parameters needed for white dwarf spectra analysis and synthesis, as well as to the new collective effort to develop Virtual Atomic and Molecular Data Center (VAMDC - http://vamdc.org/ – Dubernet et al. 2010, Rixon et al. 2011).

2. STELLAR PLASMA RESEARCH AND STARK BROADENING

As an example of the application of Stark broadening for astrophysical plasma research, we will draw attention that line profiles enter the modeling of stellar atmospheric layers when we determine quantities such as the absorption coefficient and the optical depth τ_ν. Let us take the direction of gravity as z-direction, dealing with a stellar atmosphere. If the atmosphere is in macroscopic mechanical equilibrium, with ρ is denoted gas density, the optical depth is

$$\tau_\nu = \int_z^\infty \kappa_\nu \rho dz, \tag{1}$$

$$\kappa_\nu = N(A,i)\phi_\nu \frac{\pi e^2}{mc} f_{ij}, \tag{2}$$

where κ_ν is the absorption coefficient at a frequency ν, $N(A,i)$ is the volume density of radiators in the state i, f_{ij} is the absorption oscillator strength, m is the electron mass and ϕ_ν is spectral line profile.

Stark broadening may be also important for radiative transfer and opacity calculations, abundances, surface gravity and chemical composition determination, spectra analysis, interpretation and synthesis and astrophysical plasma modeling. In the following, we will give several examples of the investigations of Stark broadening in stellar plasma, performed in the Group for Astrophysical Spectroscopy at the Belgrade Astronomical Observatory.

In a number of papers, the influence of Stark broadening on Au II (Popović et al. 1999b), Zr II and Zr III (Popović et al. 2001a), Nd II (Popović et al. 2001b), Co III (Tankosić et al. 2003), Ge I (Dimitrijević et al. 2003a), Si I (Dimitrijević et al. 2003b), Ga I (Dimitrijević et al. 2004), Cd I (Simić et al. 2005), Cr II (Dimitrijević et al. 2007) and Te I (Simić et al. 2009) spectral lines was considered in the spectra of chemically peculiar A-type stars, and in each case deeper atmospheric layers are found where the contribution of this broadening mechanism is dominant or could not be neglected in comparison with the Doppler broadening. In order to provide the corresponding Stark broadening data for rare-earth peak in elemental abundances distribution, Popović et al. (1999a) considered the influence of collisions with charged particles on rare earth ion lines in Ap star atmospheres (La II, La III, Eu II and Eu III) and found that the errors in equivalent width synthesis and corresponding abundance determination may be important and should be taken into account.

In order to demonstrate the influence of Stark broadening in atmospheres of hot stars, Figure 1 shows the Stark widths for Te I 6s ^{5}S^o – 7p ^{5}P (5125.2 Å)

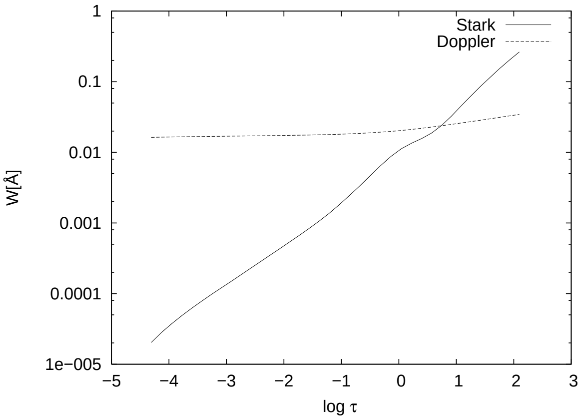

Fig. 1. Thermal Doppler and Stark widths for Te I 6s $^5S^o$ – 7p ^5P (5125.2 Å) multiplet as functions of Rosseland optical depth for an A-type star ($T_{\rm eff}$ = 10 000 K, log g = 4.5).

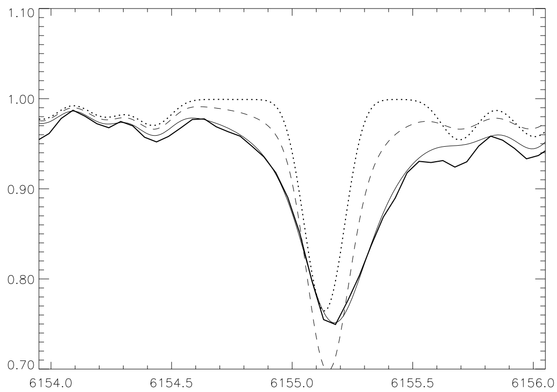

Fig. 2. A comparison between the observed Si I, 6155 Å line profile in the spectrum of Ap star 10 Aql (thick line) and synthetic spectra calculated with Stark widths and shifts from Table 1 in Dimitrijević et al. (2003b) and Si abundance stratification (thin line), with the same Stark parameters but for homogeneous Si distribution (dashed line), and with Stark width calculated by approximation formulae for the same stratification (dotted line).

multiplet (Simić et al. 2009), compared with the thermal Doppler widths for a model ($T_{\rm eff}$ = 10 000 K, log g = 4.5) of A-type star atmosphere (Kurucz 1979). Namely thermal Doppler broadening in stellar atmospheres is not a negligible broadening mechanism, and the comparison of the Stark and thermal Doppler widths may give an estimate on the importance of this effect. We note, however, that due to differences in the Gauss distribution function for the Doppler profile and the Lorentz distribution for Stark, even when the Stark width is smaller, this broadening mechanism may be significant in line widths. One can see in Figure 1, that in deeper atmospheric layers the Stark broadening mechanism becomes first comparable and than dominates in comparison with the thermal Doppler broadening.

The influence of Stark broadening and stratification on neutral silicon lines in the spectra of normal late A star HD 32115 and Ap stars HD 122970 and 10 Aql was investigated in Dimitrijević et al. (2003b). It was demonstrated that the synthetic profile of $\lambda = 6155.13$ Å Si I line fits much better to the observed one when Stark broadening is included.

3. WHITE DWARFS

From the aspect of the Stark broadening in stellar plasmas, white dwarfs are of particular interest. The first white dwarf, 40 Eridani, was discovered by W. Herschel on 1783 March 31. The second was Sirius B, the existence of which was predicted by Bessel in 1844; it was discovered by Alvan Graham Clarck in 1862. In 1950 one hundred of these stars were known, in 1999 – about 2000, and in the Sloan Digital Sky Survey more than 9000 white dwarfs are discovered.

Traditional division of white dwarfs is into hydrogen-rich (DA) and helium-rich (DB), where 'D' denotes degenerate objects. Due to gravitational separation in the absence of macroscopic motions like stellar wind or convection, the most abundant elements dominate by several orders of magnitude (Koester 2010), with rare exceptions. While the heavier elements diffuse downward, the lightest ones rest floating on the top of the atmosphere. The origin of H-deficient stars is the late helium shell flash in which white dwarf or post Asymptotic Giant Branch (AGB) star reignites helium shell burning, eliminating the rest of hydrogen in this violent event. Post AGB stars are also of great interest from the point of view of need and applicability of the Stark broadening data. Namely, AGB are stars which have terminated hydrogen and helium but not carbon burning. They form a sequence of bright red giants – AGB, and they are more luminous than the red giant branch stars, which have electron-degenerate helium cores. We note that AGB is often divided in AGB stars with carbon-oxygen cores and Super AGB (SAGB) stars with heavier elements in the cores.

White dwarfs of DA and DB types have effective temperatures between around 10 000 K and 40 000 K, so that the Stark broadening is important in analysis and modeling of their atmospheres and spectra. When the effective temperature of a cooling white dwarf becomes so low that neither helium nor hydrogen lines are present, the spectrum becomes only continuum (DC type). If in the spectra of hydrogen-rich or helium-rich atmospheres lines of various metals (but not carbon lines which will be discussed later) are seen, white dwarfs belong to DZ, DAZ or DBZ types. Such metals are considered to be accreted from outside, from interstellar matter or from some tidally disrupted asteroid (Koester 2010).

The non-DA white dwarfs are most interesting from the point of view of Stark broadening of non-hydrogen lines. They are divided to the following types: (1) DO, with 40 000 K $< T_{\rm eff} <$ 100 000 K (120 000 K according to Dreizler & Werner 1996) with the He II lines and the effective Stark broadening (Hamdi et al. 2008), (2) DB, with 12 000 K $< T_{\rm eff} <$ 40 000 K with He I lines, and (3) DQ, with 4000 K $< T_{\rm eff} <$ 12 000 K, with C lines and C_2 Swan band in the spectrum. It is assumed that carbon in the DQ white dwarfs is extracted from deeper layers by the growing convective zone (Koester 2010).

McGraw et al. (1979) discovered the first object of a new class of hot hydrogen-deficient degenerate stars, PG 1159-035. In the atmospheres of PG 1159 stars, a mixture of helium, carbon and oxygen is present. Most likely, they experienced a very late thermal pulse which eliminated the rest of hydrogen, mixed helium with carbon, oxygen and other elements from the envelope and returned them back from white dwarf phase to the post-AGB phase. PG 1195 objects are very interesting for applications of results of Stark broadening investigations (Werner et al. 1991), with effective temperatures ranging from $T_{\rm eff}$ = 100 000 K to 140 000 K. They have high surface gravity (log g = 7), and their photospheres are dominated by helium and carbon with a significant amount of oxygen (C/He = 0.5 and O/He = 0.13) (Werner et al. 1991). Their spectra, strongly influenced by Stark broadening, are dominated by He II, C IV, O VI and N V lines.

Nugent et al. (1983) discovered a faint blue star of the PG 1195 type, H 1504+65, which is not only hydrogen-, but also helium-deficient, with the atmosphere of carbon and oxygen in equal amounts. This is the hottest known star with $T_{\rm eff}$ of 170 000 ± 20 000 K, or a 'bare core of the former AGB star', according to Werner & Wolff (1999).

The need for abundant and reliable Stark broadening data for a number of trace elements, was highly stimulated by the Far Ultraviolet Spectroscopic Explorer satellite (FUSE), which provided astronomers with a great number of high resolution spectra of hot evolved stars within the wavelength range 907–1187 Å. Fontaine et al. (2008) note that FUSE range includes 'high density of transitions associated with numerous ionization levels of several elements such as: C, N, O, Si, S, P, Cl, Ne, Ar, V, Mn, Cr, Fe, Co, Ni, Ge, As, Se, Zr, Te, I and Pb among others.' For analysis and synthesis of spectra and modeling of atmospheres of hot white dwarfs, PG 1159 stars, hot B subdwarfs, post Asymptotic Giant Branch (AGB) objects such as Central Stars of Planetary Nebulae (CSPN), observed by FUSE, accurate Strak broadening data for great number of spectral lines of various atoms and their ions are needed. However, as it was pointed out in Rauch et al. (2007), line broadening data for many species and their ions are missing in the literature. Moreover, some existing data are provided within insufficient temperature and density ranges, and the extrapolation to the plasma conditions in line forming regions introduces additional errors.

A new type of hot DQ white dwarfs with $T_{\rm eff}$ = 18 000–24 000 K and carbon-rich atmospheres, has been discovered recently by Dufour et al. (2007, 2008), enabling them to propose an evolutionary sequence of white dwarfs from H 1504+65 and PG 1195 objects to hot DO, DB and DQ types. In the newly discovered class of hot DQ white dwarfs, hydrogen and helium are absent; their spectra are dominated by the C II lines, while O II lines are also present (Dufour 2011). For the investigation and modeling of these stars, and in order to understand their origin and evolution, the accurate determination of surface gravity is essential. However, the interpretation and analysis of these new objects was humped by the lack of the corresponding Stark broadening data.

Members of the Group for Astrophysical Spectroscopy considered the influence of Stark broadening for DA, DB and DO white dwarf atmospheres (Popović et al. 1999b; Tankosić et al. 2003; Milovanović et al. 2004; Simić et al. 2006; Hamdi et al. 2008) and found that for these stars Stark broadening is dominant in practically all atmospheric layers.

As an example, Simić et al. (2006) considered the influence of Stark broadening on Cu III, Zn III and Se III spectral lines in DB white dwarf atmospheres for 4s ^{2}F – 4p ^{2}G^o (λ = 1774.4 Å), 4s ^{3}D – 4p ^{3}P^o (λ=1667.9 Å) and 4p5s ^{3}P^o - 5p ^{3}D (λ = 3815.5 Å) by using the corresponding model with $T_{\rm eff}$ = 15 000 K and log g =

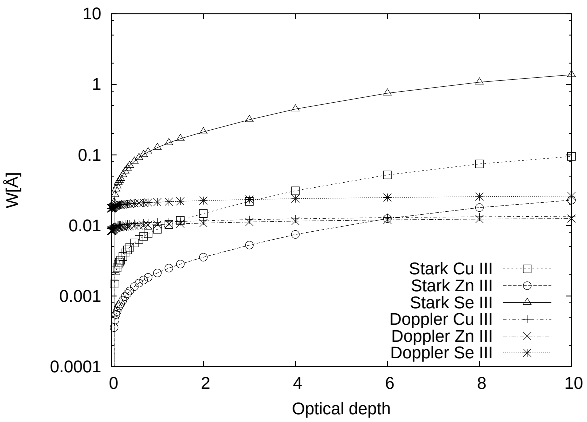

Fig. 3. Thermal Doppler and Stark widths for Cu III 4s ^{2}F – 4p ^{2}G^o (λ = 1774.4 Å), Zn III 4s ^{3}D – 4p ^{3}P^o (λ = 1667.9 Å) and Se III 4p5s ^{3}P^o – 5p ^{3}D (λ = 3815.5 Å) spectral lines for a model of the DB white dwarf atmosphere with $T_{\rm eff}$ = 15 000 K and $\log g$ = 7, as a function of the optical depth τ_{5150}.

7 (Wickramasinghe 1972). For this analysis, optical depth points at the standard wavelength λ_s = 5150 Å (τ_{5150}) are used as in Wickramasinghe (1972). One can see in Figure 3 that the thermal Doppler broadening has a much less importance in comparison with the Stark broadening mechanism. Comparing Figures 1 and 3 one can see that the importance of Stark broadening is much greater for DB white dwarf atmospheres than for A-type stars. This is the consequence of larger electron densities due to larger $\log g$ and $T_{\rm eff}$, so that electron-impacts producing Stark broadening are more effective.

For example, Figure 4 shows that the Stark width of the Se III 3815.5 Å line is larger than the Doppler width even by two orders of magnitude within the range of optical depths considered.

Hamdi et al. (2008) considered the broadening on Si VI lines in DO white dwarf spectra for 50 000 ≤ $T_{\rm eff}$ ≤ 100000 K and for 6 ≤ $\log g$ ≤ 9 atmosphere models. They found that the influence of Stark broadening increases with $\log g$ and is dominant in broad regions of the considered DO atmospheres.

Currently, within a wide international collaboration (Canada, France, Tunisia, Serbia), the work on the Stark broadening of carbon and oxygen lines in hot DQ spectra (Dufour et al. 2011) is in progress.

Reliable Stark broadening data for white dwarf research may be found in the STARK-B database (http://stark-b.obspm.fr), dedicated for modeling of stellar atmospheres, analysis and synthesis of stellar spectra, as well as for laboratory plasma research, inertial fusion plasma, laser development and investigations of plasmas in various technologies. This database enters also in the European FP7 project 'Virtual Atomic and Molecular Data Centre' (VAMDC, P.I. Marie Lise Dubernet) with the following aims: (i) to build a secure, flexible and interoperable e-science environment based interface to the existing atomic and molecular databases; (ii) to coordinate groups involved in the generation, evaluation and use of atomic and molecular data, and (iii) to provide a forum for training of potential users (Dubernet et al. 2010; Rixon et al. 2011).

In future, a mirror site will be a part of the Serbian Virtual Observatory

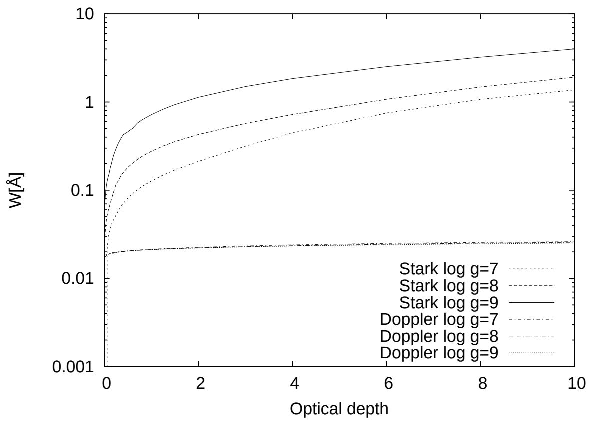

Fig. 4. Thermal Doppler and Stark widths for Se III spectral line 5s ^{3}P^o – 5p ^{3}D (λ = 3815.5 Å) for a model of the DB white dwarf atmosphere with $T_{\rm eff}$ = 15 000 K and $7 \leq \log g \leq 9$, as a function of the optical depth τ_{5150}.

(SerVO, http://www.servo.aob.rs/∼darko, P.I. Darko Jevremović). The main goal of the SerVO is to place the data, obtained by Serbian astronomers, into the VO with a compatible format, in particular the digitized photographic plates from the Belgrade Astronomical Observatory archive, in order to make them accessible to scientific community, as well as to provide astronomers in Serbia with VO tools for their research (Jevremović et al. 2009)

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