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On the Stark broadening of Cr VI spectral lines in astrophysical plasma

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Abstract. Stark broadening parameters for Cr VI lines have been calculated using semiclassical perturbation method for conditions of interest for stellar plasma. Here are presented, as an example of obtained results, Stark broadening parameters for electron- and proton-impact broadening for Cr VI 4s ^{2}S-4p ^{2}P^o $\lambda = 1430$ Å and Cr VI 4p ^{2}P^o-5s ^{2}S $\lambda = 611.8$ Å multiplets. The obtained results are used to demonstrate the importance of Stark broadening of Cr VI in DO white dwarf atmospheres. Also the obtained results will enter in STARK-B database which is included in Virtual Atomic and Molecula Data Center - VAMDC.

1. Introduction

Rauch et al. [1] have found Cr V, Cr VI and Cr VII lines in the spectrum of LS V +46o21 white dwarf, which is the central star of planetary nebula Sh 2-216. High-resolution, high-signal to noise ratio ultraviolet spectra obtained by FUSE (Far Ultraviolet Spectroscopic Explorer) and HST/STIS (Space Telescope Imaging Spectrograph aboard the Hubble Space Telescope) have been used. Rauch et al. [1] stated that: Theoretical physics should provide data which cover the astrophysical relevant temperature and density space. Better atomic and line-broadening data will then strongly improve future spectral analyses and thus, make determinations of photospheric properties more reliable.

Since the Stark broadening is usually the most important line-broadening mechanism in white dwarf atmospheres (see e.g. [10]), we will calculate, using semiclassical perturbation method [3, 4, 5], Stark broadening parameters of Cr VI spectral lines, due to collisions with electrons, protons and doubly charged helium ions, the main perturbers in white dwarfs, and an example of the obtained results will be presented here. Calculations will be performed in function of perturber density and temperature, for plasma conditions of interest for white dwarfs.

Obtained results will be used to demonstrate the importance of Stark broadening of Cr VI lines for analysis and synthesis of spectra of white dwarfs, using theoretical models of DO white dwarf atmosphere and comparing Stark and Doppler widths in function of optical depth. The obtained Stark broadening parameters of spectral lines, broadened by electron-, proton-, and He III-impacts with Cr VI emitter / absorber will be also implemented in the STARK-B database (http://stark-b.obspm.fr [6]), a part of Virtual Atomic and Molecular Data Center (VAMDC - http://www.vamdc.org [7]).

2. Theory

The theory used here for the calculations of Stark broadening parameters of Cr VI lines is the semiclassical perturbation formalism, which is described in details elsewhere with different inovations and updates [3, 4, 5]. Consequently, only short description, necessary for the understanding of the way of calculations will be presented here.

For isolated lines, the Stark broadened profile $F(\omega)$ is Lorentzian:

$$F(\omega) = \frac{W/2\pi}{(\omega - \omega_{if} - d)^2 + (W/2)^2}. \qquad (1)$$

Here,

$$\omega_{if} = \frac{E_i - E_f}{\hbar}$$

where E_i and E_f are energies of the initial and final states, (W) is width (FWHM) in angular frequency units and (d) shift

$$W = N \int v f(v) dv \left(\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} \right)$$

$$d = N \int v f(v) dv \int_{R_3}^{R_D} 2\pi \rho d\rho \sin(2\varphi_p). \qquad (2)$$

N is here the electron density, $f(v)$ the Maxwellian velocity distribution function for electrons, ρ the impact parameter of the incoming electron, and with i', f' are denoted the perturbing levels of the initial and final state. The inelastic cross section $\sigma_{jj'}(v)$, $j = i, f$

$$\sum_{i' \neq i} \sigma_{ii'}(v) = \frac{1}{2}\pi R_1^2 + \int_{R_1}^{R_D} 2\pi \rho d\rho \sum_{i' \neq i} P_{ii'}(\rho, v). \qquad (3)$$

where $P_{jj'}(\rho, v), j = i, f; j' = i', f'$ is transition probability. The elastic cross section is

$$\sigma_{el} = 2\pi R_2^2 + \int_{R_2}^{R_D} 2\pi \rho d\rho \sin^2 \delta + \sigma_r,$$

$$\delta = (\varphi_p^2 + \varphi_q^2)^{\frac{1}{2}}. \qquad (4)$$

The phase shifts due to the polarization potential φ_p (r^{-4}) and to the quadrupolar potential φ_q (r^{-3}), are explained in detail in Section 3 of Chapter 2 in [3]. The explanation of cut-offs R_1, R_2, R_3, R_D, where R_D is the Debye radius, can be found in Section 1 of Chapter 3 in [4]. Finally, the contribution of Feshbach resonances, denoted as σ_r, is introduced and explained in detail in [8].

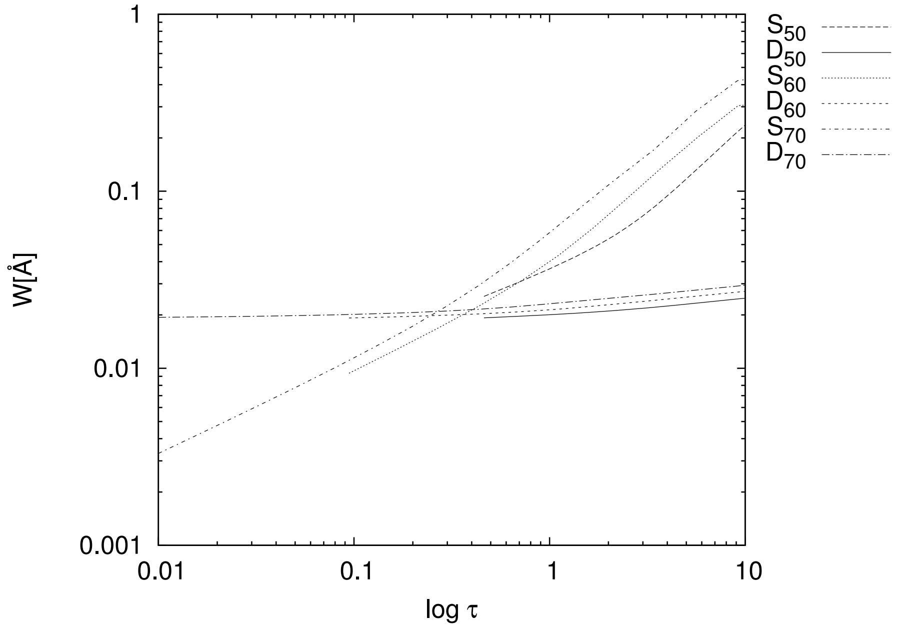

Figure 1. Stark and Doppler widths for Cr VI 4s ^{2}S-4p^{2}P^o (λ = 1430.0 Å) multiplet as a function of logarithm of Rosseland optical depth (log τ). Stark (S) and Doppler (D) widths are shown for three atmospheric models [22] with effective temperatures from T$_{eff}$ = 50 0000 K (S_{50}, D_{50}) to 70 000 K (S_{70}, D_{70}), and log g = 8.

3. Results and discussion

The Stark broadening parameters of Cr VI multiplets have been determined with the code, which is based on semiclassical perturbation theory. The energy levels, needed for present calculations have been taken from [9]. All details of the performed calculations are given e.g. in [10]. The complete obtained results will be published elsewhere. Here, in Table 1, only a sample of the results is presented. The calculations of Stark widths (FWHM) and shifts for electron-, and proton-impact broadening, have been determined for a perturber density of 10^{17} cm^{-3} and for temperatures from 50 000 K to 800 000 K.

In Table 1, a parameter C [11], provides possibility for an estimate of the maximal perturber density for which the line may be treated as isolated, when it is divided by the corresponding full width at half maximum. Denoting with V the collision volume and multiplying it by the perturber density N, for each value presented in Table, $N\,V <$ 0.1. Since this product is much less than one, the impact approximation is valid [3, 4].

Spectral lines of highly charged chromium ions, including Cr VI, have been observed in the spectra of white dwarf atmospheres where, as it has been demonstrated several times [12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 10], Stark broadening is usually dominant line broadening mechanism. With the results obtained here, we also wish to demonstrate the importance of Stark broadening in DO white dwarf atmospheres, which effective temperature is within the range 40 000 K $< T_{eff} <$ 120 000 K.

In Fig. 1 Stark (FWHM) and Doppler widths for Cr VI 4s ^{2}S-4p^{2}P^o (λ = 1430.0 Å) multiplet as a function of logarithm of Rosseland optical depth (log τ) are compared for three atmospheric models of [22], for DO white dwarf atmospheres with effective temperature T$_{eff}$ = 50 000-100 000 K and logarithm of surface gravity log g = 8.

One can notice from Fig. 1, that Stark broadening is more important or comparable to Doppler broadening for atmospheric layers which are significant for radiative transfer calculations

Table 1. This table gives electron-, and proton-impact broadening parameters for Cr VI multiplets, for a perturber density of 10^{17} cm^{-3} and temperatures from 50 000 to 800 000 K. Calculated wavelength of the transitions (in Å) and parameter C are also given. This parameter, when divided with the corresponding Stark width, gives an estimate for the maximal pertuber density for which the line may be treated as isolated. W_e: electron-impact full width at half maximum of intensity, d_e: electron-impact shift, W_p: proton-impact full width at half maximum of intensity, d_p: proton-impact shift. This table is an example of results which, in its entirety, will be published elsewhere.

Transition	T(K)	W_e (Å)	d_e (Å)	W_{H^+} (Å)	d_{H^+} (Å)
Cr VI 4s ^{2}S-4p^{2}P^o	50000.	0.159E-01	-0.278E-03	0.159E-03	-0.969E-04
1430.0 Å	100000.	0.115E-01	-0.284E-03	0.346E-03	-0.185E-03
C = 0.14E+21	150000.	0.956E-02	-0.255E-03	0.488E-03	-0.249E-03
	200000.	0.847E-02	-0.296E-03	0.575E-03	-0.303E-03
	400000.	0.650E-02	-0.348E-03	0.812E-03	-0.421E-03
	800000.	0.294E-02	-0.188E-03	0.152E-02	-0.870E-03
Cr VI 4p ^{2}P^o-5s^{2}S	50000.	0.494E-02	0.313E-03	0.684E-04	0.155E-03
611.8 Å	100000.	0.363E-02	0.291E-03	0.167E-03	0.240E-03
C = 0.10E+20	150000.	0.309E-02	0.338E-03	0.227E-03	0.292E-03
	200000.	0.277E-02	0.358E-03	0.287E-03	0.331E-03
	400000.	0.220E-02	0.330E-03	0.400E-03	0.397E-03
	800000.	0.984E-03	0.152E-03	0.921E-03	0.722E-03

and modelling of atmospheric plasma, as well as that its importance increases with the increase of the optical depth, as expected. We note also that due to differences between Lorentzian profile for Stark broadening and Gaussian for Doppler broadening, Stark broadening could be important or non negligible in the line wings even when Doppler width is larger than Stark.

It should be noted as well that the atmospheric models of [22] provide LTE models. Obviously that both NLTE and line-blanketing effects should be included to obtain correct values for the line widths, but models of [22] are tabulated with all the needed data for calculations. Looking at Fig.1, one can see that the influence of Stark broadening is so significant that the modifications due to NLTE effects and line-blanketing will not change our conclusions.

The obtained Stark broadening parameters for Cr VI multiplets will be implemented in computer readable form in the STARK-B database (http://stark-b.obspm.fr [6]), suitable especially for the diagnostics, modelling and investigations of stellar atmospheres. STARK-B is also a part of Virtual Atomic and Molecular Data Center - VAMDC (http://www.vamdc.org [7]).

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