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Stark broadening of Si II spectral lines: comparison with experimental results

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Abstract. Our calculations for Stark broadening parameters of Si II spectral lines obtained using impact semiclassical perturbation theory are compared with experimental data from the literature. Presented data are needed for the evaluation of the physical conditions of stellar plasma, siliciabundance determination, opacity calculations, stellar spectra analysis and synthesis, stellar atmosphere modelling etc.

Key words: Stark broadening – Si II – spectral lines

1. Introduction

Large cosmic abundance of silicon determines the great interest to its spectra for astrophysical and cosmological studies. From another side, it is a principal impurity chemical element in laboratory plasma and nuclear fusion, and its lines are suitable for spectroscopic diagnostics. For the evaluation of the physical conditions of stellar plasma, opacity calculations, etc. reliable data for silicon are necessary.

Silicon is one of the most experimentally investigated emitter after hydrogen, helium, and argon (see e.g. critical reviews of Konjević & Wiese 1990 and Lesage 2009). We note that the authors of NIST critical review for measured Stark broadening parameters of spectral lines, Konjević & Wiese (1990), report a large scatter in the results for Si II lines from different papers.

Spectral analysis and interpretation of electromagnetic radiation ensure valuable information about our Universe. Various cosmic light sources also contain silicon atoms and ions as emitters (Peytremann, 1972). Thus, the ionized silicon spectral lines play an important role in the plasma diagnostics within a wide range of plasma conditions in many fields of astrophysics, technology and environmental protection. Singly ionized silicon spectral lines are discovered in the emission and absorption spectra in various cosmic light sources. We mention here suitable papers emphasizing the importance of Si II lines in various fields of astrophysical plasma diagnostics. Ionized silicon lines are used for solar photosphere study in Shi et al. (2008). Using width of Si II lines, the diversity of supernovae Ia is determined in Arsenijević et al. (2008). Emission spectra of the first helium nova V445 Puppis (Iijima & Nakanishi, 2008) present prominent Si II lines. In atmospheres of A, B and O type stars, and white dwarfs, many singly charged ion lines are observed (Peytremann, 1972). The observations indicate strong visible and ultraviolet lines of ionized silicon in the spectrum of stars from type A 0 to B 3. It is known that silicon is significant in solar and stellar research. These lines provide valuable information for silicon abundance, for silicon absorption in the hot stars (Lanz et al. 1988 and references therein). With the development of space born astronomy, less intensive lines become accessible. Such lines, which originated from high energy levels, are sensitive to the plasma broadening mechanisms. According to Lanz et al. (1988), many spectra of Ap Si stars reveal such lines. Their results show that Stark broadening mechanism is a dominant one for higher transitions.

Recently, we calculated Stark width of 13 Si II multiplets for temperatures from 5000 K up to 80 000 K, and for perturber density of 10^{17} cm^{-3} using the MSE - modified semiempirical method (Dimitrijević & Konjević, 1980; Dimitrijević & Kršljanin, 1986) and Stark widths and shifts for 62 Si II multiplets, for collisions with electrons, protons and ionized helium, for a grid of temperatures and perturber densities (10^{14} - 10^{20} cm^{-3}). Semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014) has been used for calculations. The obtained results will be published elsewhere and here they have been used for comparison with available experimental data.

2. Theory

Broadening of spectral lines in a plasma is provoked by the interactions between emitting particles (atoms/ions) and environments (electrons, protons, atoms, ions, molecules). It is known in the literature as pressure broadening. Stark broadening of spectral lines arises due to interactions with electrically charged particles as electrons, protons, and ions. There are several theories applicable to this type of pressure broadening, depending on the plasma conditions. The data used for comparison with experimental data in this article have been calculated by aplying the impact semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014). For better understanding how data for comparison have been obtained, we give here briefly the basics of the theory. According to the semiclassical theory, the emitter is treated as quantum system and perturbers are examined as classical particles. The full width at half maximum (FWHM) and shift of an isolated spectral line are given by the expressions:

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

$$d = N\int vf(v)dv\int_{R_3}^{R_D}2\pi\rho d\rho\sin(2\varphi_p). \quad (1)$$

where i and f denote the initial and final level of the corresponding transition; i' and f' are perturbing levels; N perturber density; v perturber velocity, and $f(v)$ is the Maxwellian distribution of electron velocities. The cross sections $\sigma_{kk'}(v)$, $k = i, f$, concern inelastic interactions. It is presented here by an integration of the transition probability $P_{kk'}(\rho, v)$, over the impact parameter ρ as:

$$\sum_{k'\neq k}\sigma_{kk'}(v) = \frac{1}{2}\pi R_1^2 + \int_{R_1}^{R_D}2\pi\rho d\rho\sum_{k'\neq k}P_{kk'}(\rho, v). \quad (2)$$

The cross section of elastic collisions between emitting atoms (ions) and charged particles could be estimated by:

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

$$\delta = (\varphi_p^2 + \varphi_q^2)^{\frac{1}{2}}. \quad (3)$$

Here, δ gives the phase shift which components φ_p (r^{-4}) and φ_q (r^{-3}), describe emitter-perturber elastic interactions via polarization and quadrupole potentials. Explanation of the symmetrization and procedure for cut-off parameters R_1, R_2, R_3, and the Debye cut-off R_D could be found in Sahal-Bréchot (1969b). Feshbach resonances, taken into account by the third term σ_r, could be found in Fleurier (1977).

3. Results and discussion

In this paper, we compare our new calculations for Stark broadening width and shift of singly ionized silicon lines, using the semiclassical perturbation theory (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014), with measured ones. Comparatively with other chemical elements, there are many experimental data for Stark broadening of neutral and ionized silicon lines. In the next figures we present such comparison for four spectral lines which are studied in the experimental investigations, prominent in the observed spectra of

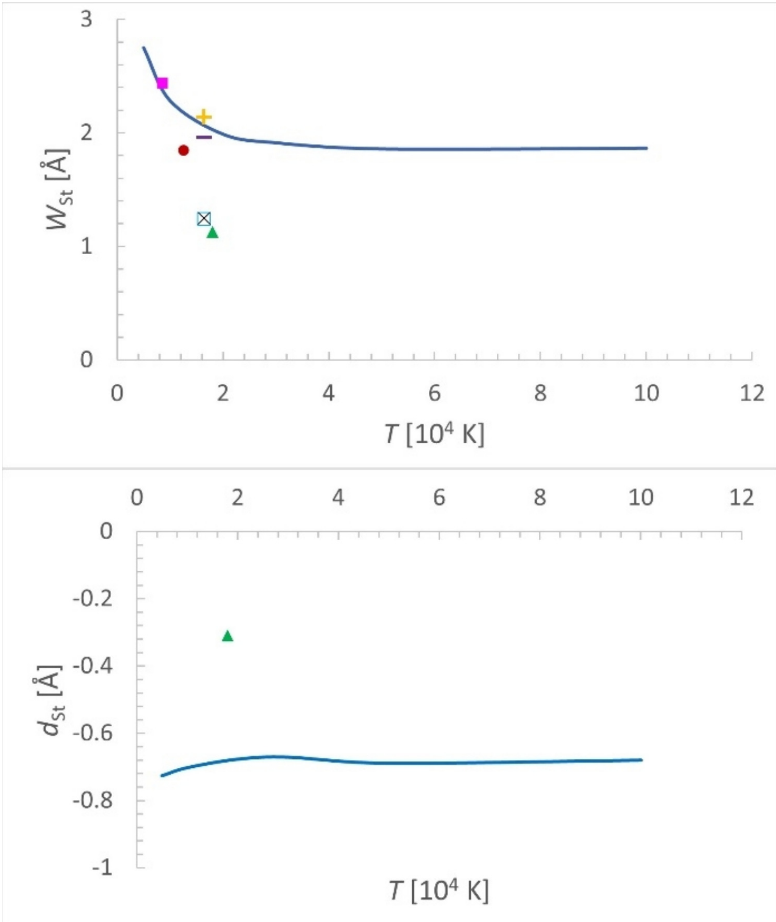

Figure 1. Comparison of the calculated temperature dependence (solid line) of Stark width (up) and shift (down) with experimental results from the literature for spectral line Si II $3s^24s$ $^2S_{1/2}$ - $3s^2$ 4p $^2P^o_{3/2}$ with λ = 6356.9 Å. The perturber density is 1.10^{17} cm^{-3}. Symbols illustrate results from: Konjević et al. (1970) (solid square); Lesage et al. (1977) (dash); Chiang & Griem (1978) (plus); Lesage et al. (1983) (open square); Pérez et al. (1993) (cross); González et al. (2002) (solid triangle) and Bukvić et al. (2008) (solid circle).

astrophysical objects and suitable for plasma diagnostics. The perturber density is 10^{17} cm^{-3}. One of the most measured spectral lines is Si II $3s^24s$ $^2S_{1/2}$ - $3s^2$ 4p $^2P^o_{3/2}$ with λ = 6356.9 Å. The reported scattering of experimental Stark width values in the publications that is noticed by Konjević & Wiese (1990), is well observable in Fig. 1 (upper part). Measurements are grouped in two parts, four widths (Konjević et al., 1970; Lesage et al., 1977; Chiang & Griem, 1978; Bukvić

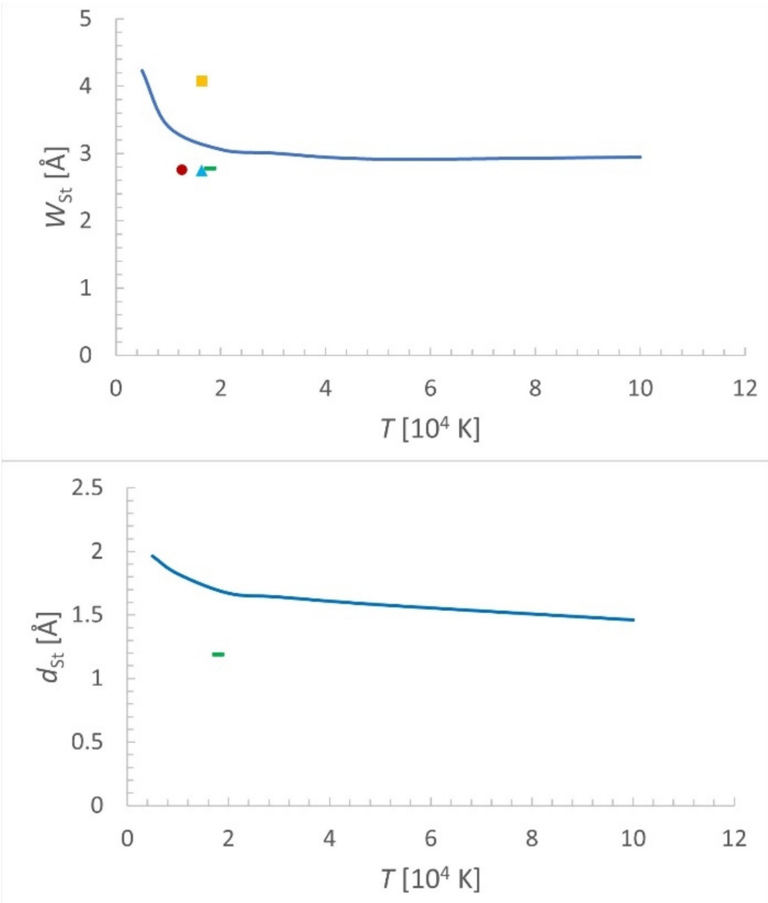

Figure 2. Comparison of the calculated temperature dependence (solid line) of Stark width (up) and shift (down) with experimental results from the literature for spectral line Si II $3s^2$ 4p $^2P^o_{3/2}$ - $3s^2$ 5s $^2S_{1/2}$ with $\lambda = 5973.4$ Å. The perturber density is 1.10^{17} cm^{-3}. Symbols illustrate results from: Kusch & Schroeder (1982) (solid square); Lesage et al. (1983) (solid triangle); González et al. (2002) (dash) and Bukvić et al. (2008) (solid circle).

et al., 2008) are close to the calculated curve and other three (Lesage et al., 1983; Pérez et al., 1993; González et al., 2002) are around two times smaller. All they fall within the temperature interval where the Stark width decreases noticeably with the temperature. There is one reference (González et al., 2002) that we found in the literature concerning shift measurements. For the first examined line both, measured and calculated values are negative. The measured value in Fig. 1 (lower part) is approximately twice lower than calculated.

Fig. 2 illustrates results for spectral line $\lambda = 5973.4$ Å, Si II $3s^2$ 4p $^2P^o_{3/2}$ -

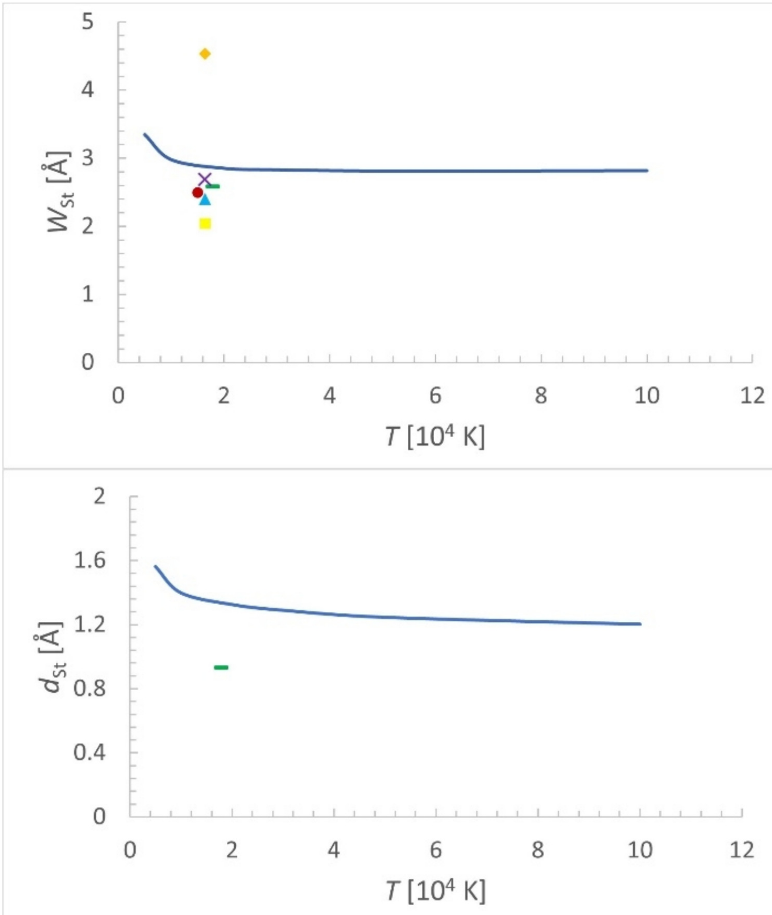

Figure 3. Comparison of the calculated temperature dependence (solid line) of Stark width (up) and shift (down) with experimental results from the literature for spectral line Si II 3s^2 4p ^{2}P$^o_{3/2}$ - 3s^2 4d ^{2}D$_{5/2}$ with $\lambda = 5052.4$ Å. The perturber density is 1.10^{17} cm^{-3}. Symbols illustrate results from: Lesage et al. (1977) (cross); Kusch & Schroeder (1982) (rhomb); Lesage et al. (1983) (solid triangle); Pérez et al. (1993) (solid square); González et al. (2002) (dash) and Bukvić et al. (2008) (solid circle).

3s^2 5s ^{2}S$_{1/2}$. There are four width measurements that we found. Three of them (Lesage et al., 1983; González et al., 2002; Bukvić et al., 2008) are grouped and closer to the calculated value, a little bit lower. The Stark width reported by Kusch & Schroeder (1982) is larger from all of them. The theory gives positive (red) shift of this line, and the experiment confirms that. Measured value is smaller again as in the previous case.

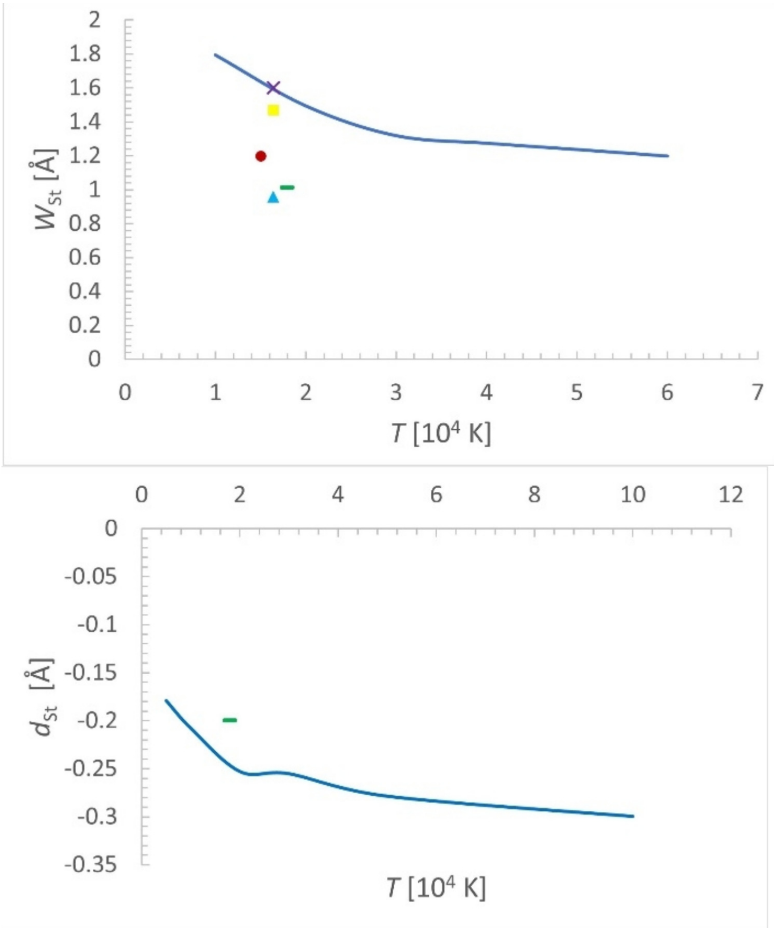

Figure 4. Comparison of the calculated temperature dependence (solid line) of Stark width (up) and shift (down) with experimental results from the literature for spectral line Si II $3s^2$ $3d$ $^2D_{5/2}$ - $3s^2 4f$ $^2F^o_{7/2}$ with $\lambda = 4130.9$ Å. The perturber density is 1.10^{17} cm^{-3}. Symbols illustrate results from: Lesage et al. (1977) (cross); Lesage et al. (1983) (solid triangle); Pérez et al. (1993) (solid square); González et al. (2002) (dash) and Bukvić et al. (2008) (solid circle).

Next spectral line in our study is in the focus of experimental works. The line is originated from 4d level, corresponding to the transition Si II $3s^2$ $4p$ $^2P^o_{3/2}$ - $3s^2$ $4d$ $^2D_{5/2}$ with $\lambda = 5052.4$ Å. Figure 3 demonstrate the behaviour of the corresponding Stark broadening parameters and comparison with experimental data. All measurements are made at close temperatures. There are six width measurements. Five results (Lesage et al., 1977, 1983; Pérez et al., 1993; González et al., 2002; Bukvić et al., 2008) are close to each other and close to the theoretical dependence except data by Kusch & Schroeder (1982) which are higher. The line shift is positive. The deviation of shift result of González et al. (2002) is practically the same as for the previous line. Its value is lower than calculated but the separation from the theoretical curve is smaller than that in Fig. 2.

There are five width measurements from different literature sources (Lesage et al., 1977; González et al., 2002; Lesage et al., 1983; Pérez et al., 1993; González et al., 2002; Bukvić et al., 2008) for line Si II 3s^2 3d $^2D_{5/2}$ - 3s^{2}4f $^2F^o_{7/2}$ with $\lambda = 4130.9$ Å. (Fig. 4, upper part). They are placed in a vertical intercept as they correspond to close temperature values. The width measured by Lesage et al. (1977) is laying on the curve, the value of Pérez et al. (1993) is close, those of Lesage et al. (1983) and González et al. (2002) are relatively far and close to each other, and the value of Bukvić et al. (2008) is in the middle of the interval where are experimental values. Both predicted shift temperature dependence and measured value (González et al., 2002) are negative, and they are relatively close. Shift comparison in the four cases shows that the disagreement is smaller for higher transitions.

4. CONCLUSION

Recent new calculations for Stark broadening widths and shifts of singly ionized silicon spectral lines for 62 multiplets, performed by using the semiclassical perturbation method (Sahal-Bréchot, 1969a,b; Sahal-Bréchot, Dimitrijević, & Ben Nessib, 2014), have been tested by comparison with experimental data. The agreement with experiments is acceptable in average and it is better for widths than for shifts. In the case of shifts agreement with experimental values is better for transitions involving higher angular momentum quantum numbers. The new Stark broadening data for Si II will be implemented in the Stark-B database (http://stark-b.obspm.fr/), which is included in Virtual Atomic and Molecular Data Center (VAMDC) (http://www.vamdc.org/).

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