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ANALYSIS OF CALCULATED STARK BROADENING PARAMETERS OF SINGLY IONIZED SILICON LINES

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Abstract. Analysis of calculated Stark broadening parameters (full width at half maximum and shift) of Si II spectral lines is presented. The importance of different interactions between emiters and perturbers (electrons, protons, and helium ions) is discussed. The conditions of interest cover temperature values 5 000 K, 10 000 K, 20 000 K, 30 000 K, 50 000 K, 100 000 K and perturber density from 10^{14} cm^{-3} to 10^{20} cm^{-3}. The results could be useful for astrophysical purposes, laboratory plasma and inertial fusion research, as well as in industrial plasma technologies.

1. INTRODUCTION

The considerable interest to the Stark broadening of Si II spectral lines arises from the large cosmic abundance of silicon, which is at the sixth place in the stellar abundance distribution of elements (SAD) (Unsöld and Bashek, 1967). The importance of some strong ion lines for the spectroscopy of solar atmosphere is outlined in Hey (1977). Singly ionized silicon lines are present in hot stars from B and A type, and also in O type stars and white dwarfs (Peytremann, 1972). Observations of Si II and Si III lines in the spectrum of peculiar stars, particularly in silicon Ap-stars are reported in (Dimitrijević, 1983 and references therein). The evaluation of the physical conditions in stellar plasma needs reliable Stark broadening data. As it is reported in Lanz et al. (1988) the silicon spectrum is dominant for stars from A0 to B3 spectral type with effective temperatures from 10 000 K to 20 000 K. Despite the resonance multiplets, strong lines are observed in the visible and ultraviolet diapason. These lines were used for silicon abundance determination in Mihalas and Henshow (1966) and Megessier (1971). Kamp (1978) and Lennon et al. (1986) investigated silicon absorption in hot stars using these strong multiplets. According to Vince et al. (1985), Stark broadening plays a role in the wings of spectral lines in solar spectrum. With the development of the instruments, reliable data are obtained for faint and less intensive lines, corresponding to higher transitions which are sensitive to the plasma conditions. As Seaton mention in his work from 1987, Stark broadening results contribute to the development of physics of stellar interiors where energy transport models require knowledge of relevant atomic process and radiative opacities.

In laboratory plasmas, silicon is a principal contaminant and silicon lines appear in the radiation spectrum (Hey, 1978; Dimitrijević, 1983). Thus, it is useful to perform spectroscopic study of silicon lines for plasma diagnostics. There are many publications on the Stark broadening measurements (Konjević et al., 1970; Purić et al., 1974; Lesage and Miller, 1975; Lesage et al., 1977; Chiang and Griem 1978; Lesage et al., 1983; Kusch and Schröder, 1982; Peréz et al., 1993; Wollschläger et al., 1997; Gonzalez et al., 2002; Lesage and Redon, 2004, Bukvić et al., 2009; Gavanski et al., 2016). It should be noted that a large scatter of experimental results is found (Konjević and Wiese, 1990). Recently, a comprehensive review on the application of silicon laser induced breakdown spectroscopy (LIBS) is published in Ivković et al. (2017). There are also many papers that deal with calculation of Stark broadening parameters of singly ionized silicon lines (Griem, 1974, Hey, 1978, Dimitrijević, 1983, Lanz et al., 1988, Gavanski et al., 2016). In Dimitrijević et al. (2023), we calculate Stark widths of 13 Si II multiplets for temperatures of 5000 K, 10 000 K, 20 000 K, 40 000 K and 80 000 K, and for perturber density of 10^{17} cm^{-3} applying modified semiempirical method (MSE) described in Dimitrijević et al. (1980, 1986). Comparison between measured Stark broadening parameters (width and shift) and our calculated results for Si II lines ($3s^24s\ ^2S_{1/2} - 3s^24p\ ^2P^o_{3/2}$, $\lambda = 6356.9$ Å; $3s^24p\ ^2P^o_{3/2} - 3s^25s\ ^2S_{1/2}$, $\lambda = 5973.4$ Å; $3s^24p\ ^2P^o_{3/2} - 3s^24d\ ^2D_{5/2}$, $\lambda = 5052.4$ Å and $3s^23d\ ^2D_{5/2} - 3s^24d\ ^2F^o_{7/2}$, $\lambda = 4130.9$ Å) is given in Dimitrijević et al. (2022).

2. THEORY

Stark broadening is a type of pressure broadening of spectral lines emitted or absorbed in plasma environment. During the process of emission (absorption) of a photon the atom (ion) interacts with surrounding charged particles as electrons, protons, and ions which broaden and shift the spectral line. We apply semiclassical perturbation theory (Sahal-Bréchot, 1969a; Sahal-Bréchot, 1969b) and further improvements (Sahal-Bréchot, 1974; Fleurier et al., 1977; Dimtrijević et al., 1991; Sahal-Bréchot, 1991; Sahal-Bréchot, 2014). The semiclassical Sahal-Bréchot theory is in the collisional approach where the atom (ion) is examined as quantum system and the charged particles as classical ones. The Stark broadening parameters (full width at half-maximum of intensity and shift of the line) are expressed by the following formulae:

$$W = 2n_e \int_0^{\infty} \mathrm{v} f(v)\, \mathrm{dv}\left[\sum_{i' \neq i} \sigma_{\mathrm{ii'}}(v) + \sum_{f' \neq f} \sigma_{\mathrm{ff'}}(v) + \sigma_{\mathrm{el}}\right]$$

$$d = \int_0^{\infty} \mathrm{v} f(v)\, \mathrm{dv} \int_{R_3}^{R_d} 2\pi\rho d\rho \sin 2\phi_p$$

where i and f denote the initial and final level of the studied transition; i' and f' are perturbing levels; n_e electron density; v velocity of the corresponding charged particle, and $f(v)$ is the Maxwellian distribution of electron velocities. The cross sections $\sigma_{ii'}(v)$ concern inelastic collisions between atoms (ions) in initial energy level and perturbers. The cross section $\sigma_{ff'}(v)$ gives inelastic collisions for transition between f and f'' atomic energy levels. These terms could be presented by an integration of the transition probability $P_{ii'}$ (respectively $P_{ff'}$), over the impact parameter ρ:

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

The contribution of elastic collisions between atoms (ions) and charged particles could be estimated by the expressions:

$$\sigma_{\mathrm{el}} = 2\pi R_2^2 + \int_{R_2}^{R_d} 8\pi\rho d\rho \sin^2\delta + \sigma_{\mathrm{r}}$$

$$\delta = \left(\phi_p^2 + \phi_q^2\right)^{1/2}$$

In the above expression δ gives the phase shift which components φ_p and φ_q, describe atom (ion)-perturber elastic collisions via polarization and quadrupole potentials, respectively. Additional clarifications on the symmetrization and cut-off parameters procedures (R_1, R_2, R_3, the Debye cut-off R_d) are available in Sahal-Bréchot, (1969b). The cross section σ_r treats Feshbach resonances (Fleurier et al., 1977; Sahal-Bréchot, 2021). To be useful for both, astrophysical purposes and laboratory spectroscopic diagnostics, our calculations for broadening parameters of Si II lines include collisions of ions with electrons, protons, and ionized helium. The proposed work includes analysis of the perturber-impact component in Stark width and shift of singly ionized silicon lines and behavior of full width and shift within a spectral series. The plasma conditions of interest are consistent with astronomical observations and laboratory measurements.

3. RESULTS

In this study we are interested in: 1) contribution of different type of collisions to the Stark broadening in the whole temperature interval; 2) behavior of width and shift within a spectral series. One of the examined spectral lines corresponds to transition $3s^2 3d\ ^2D_{5/2} - 3s^2 4d\ ^2F^o_{7/2}$, λ = 4130.9 Å. The investigated spectral series is $3s^2 3p - 3s^2 ns$ for n = 4 - 8. Temperature interval includes following values: 5 000 K, 10 000 K, 20 000 K, 30 000 K, 50 000 K, and 100 000 K. Perturber density varies from 10^{14} cm^{-3} to 10^{20} cm^{-3}.

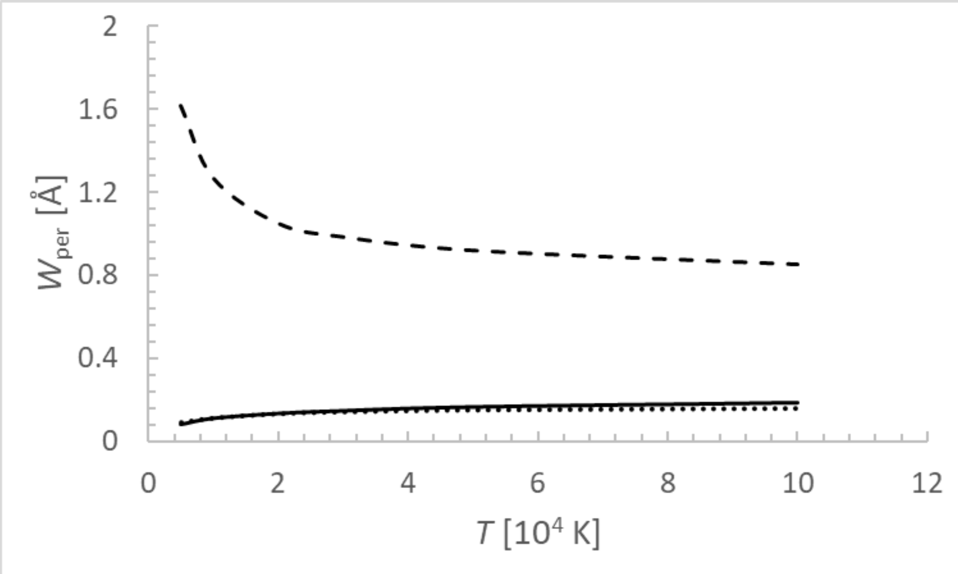

Figure 1: Behavior of electron-impact (dashed line), proton-impact (solid line) and helium ion-impact (dot line) width of Si II $3s^2 3d\ ^2D_{5/2} - 3s^2 4d\ ^2F^o_{7/2}$ spectral line (λ = 4130.9 Å) in whole temperature interval. Perturber density is 10^{17} cm^{-3}.

An example for the perturber-impact width and shift behavior versus temperature is the behavior of Stark width and shift for λ = 4130.9 Å, illustrated in figures 1 and 2. Electron-impact width is considerable for all temperatures and significantly bigger than other two width components even that it decreases with T. It's decreasing is prominent for lower temperatures, while after 20 000 K this component decreases slowly. Electron-impact width forms full width at half-maximum in whole temperature interval. Both, proton-impact, and helium ion-impact components almost coincide. They increase slowly for higher temperatures. For small temperatures interactions with helium ionized atoms are a little bit more effective, while for bigger T-values they are less effective than interactions with protons.

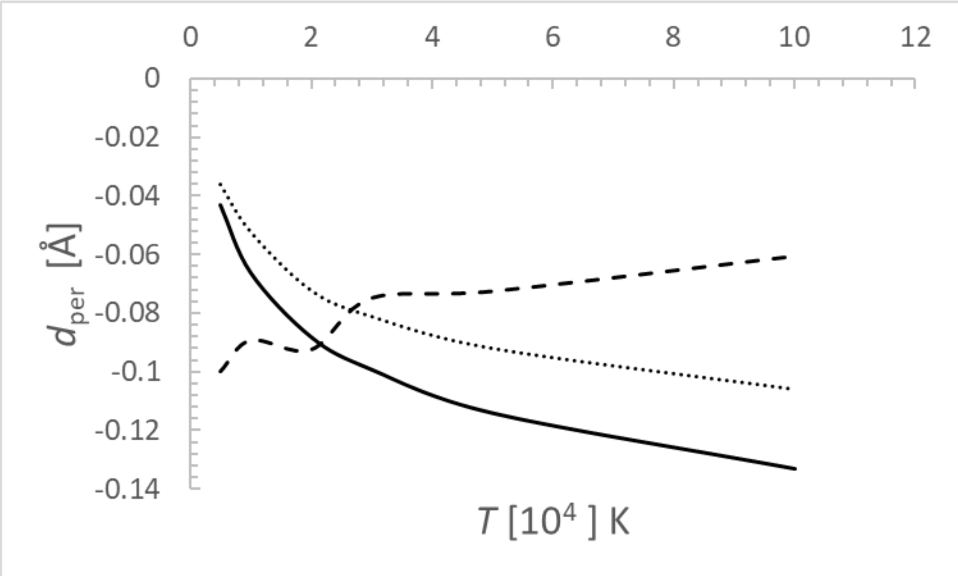

Figure 2: Behavior of electron-impact (dashed line), proton-impact (solid line) and helium ion-impact (dot line) shift of Si II $3s^23d\ ^2D_{5/2} - 3s^24d\ ^2F^o_{7/2}$ spectral line (λ = 4130.9 Å) in whole temperature interval. Perturber density is 10^{17} cm^{-3}.

Stark shift of this line is negative (blue shifted). Completely different picture is obtained for their shift components. Up to 20 000 K electron-impact shift predominates. Some oscillations of this component are observable. Around 20 000 K all three components are comparable. From 20 000 K to 100 000 K other two components, proton-impact and helium ion-impact are larger. They increase with T and follow almost same trend. Proton width component is bigger than ionized helium one for all T-values as the difference increases. The results show that the line is broadened by impacts with electrons and shifted due to interactions with all type of perturbers.

Knowledge of Stark broadening parameters for one spectral series is very important. Via interpolation or extrapolation of available results it ensures estimation of width and shift for lines which are difficult to observe, to measure or to calculate their parameters due to absence of atomic data. In the next two figures we present electron-impact width and shift for spectral lines belonging to Si II $3s^23p - 3s^2ns$ series for principal quantum number $n = 4 - 8$. For lines originated from higher energy levels (n = 7, 8) collisional approach is no longer applicable for protons and helium ions interactions with singly ionized silicon ions. It is the same for $3s^23p - 3s^26s$ transition concerning temperature up to 30 000 K. There is a notable increasing of electron impact width for $n > 6$. All shift values are positive, and the same significant increasing of electron-impact shift is demonstrated for $n > 6$.

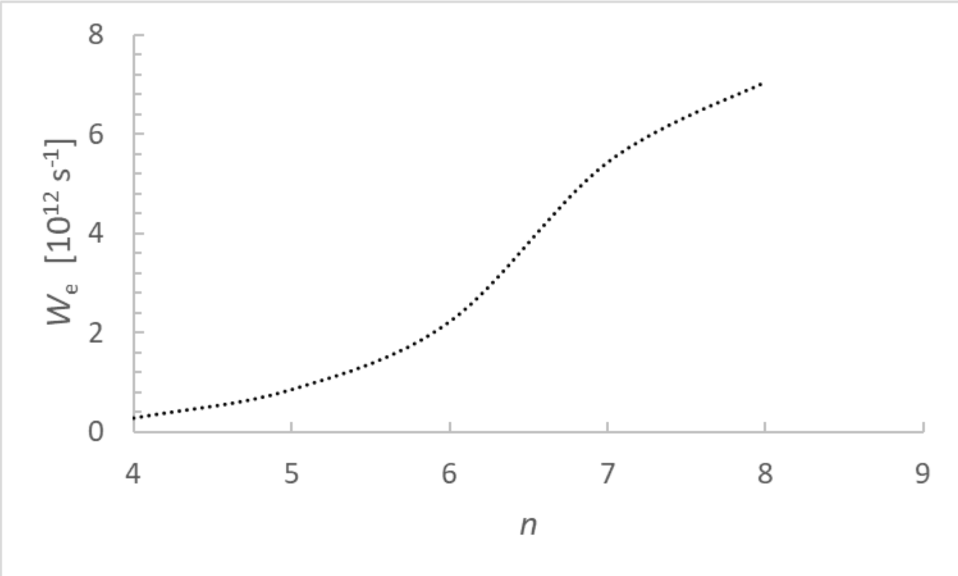

Figure 3: Electron-impact width versus principal quantum number within one spectral series $3s^23p - 3s^2ns$ for $n = 4 - 8$. The temperature is 20 000 K and the perturber density - 10^{17} cm^{-3}.

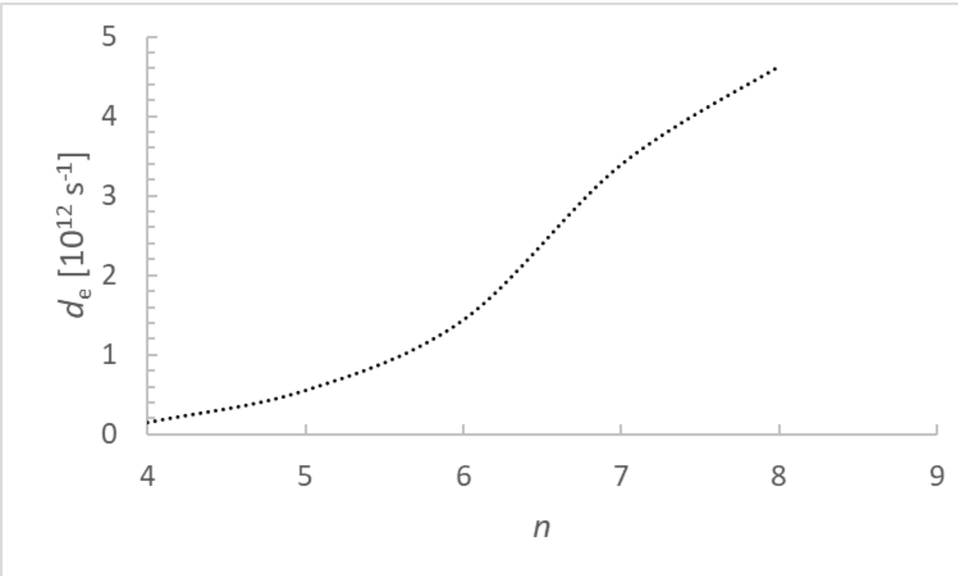

Figure 4: Electron-impact shift versus principal quantum number within one spectral series $3s^23p - 3s^2ns$ for $n = 4 - 8$. The temperature is 20 000 K and the perturber density - 10^{17} cm^{-3}.

4. CONCLUSIONS

It has been demonstrated in this work the behavior with temperature of Stark widths and shifts of Si II spectral lines, due to collisions with electrons, protons and singly charged helium ions. Also, Si II electron-impact widths and shifts behavior within a spectral series has been investigated.

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