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# Stark broadening of Zn II spectral lines

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## ABSTRACT

Stark broadening parameters, full widths at half intensity maximum, and shifts for 34 multiplets of singly charged zinc ion have been calculated using the impact semiclassical perturbation formalism. Stark broadening parameters due to collisions with electrons, protons, and helium ions have been obtained for a grid of electron densities and temperatures. The obtained results have been used to demonstrate the influence of Stark broadening mechanism on spectral lines of Zn II in stellar atmospheres.

**Key words:** atomic data – atomic processes – line: formation.

## 1 INTRODUCTION

Broadening of spectral lines by interaction with electric microfield of charged particles, or Stark broadening is the most important pressure-broadening mechanism for higher plasma temperatures and electron densities. Consequently, data for Stark broadening of different spectral lines are of importance for various plasmas in astrophysics (see e.g. Beauchamp, Wesemael & Bergeron 1997; Popović et al. 2001; Dimitrijević 2003; Dimitrijević & Sahal-Bréchet 2014), laboratory (see for example Blagojević et al. 1999; Konjević 1999; Torres et al. 2006), and inertial fusion investigations (see e.g. Griem 1992; Iglesias et al. 1998), as well as for development and investigations of lasers (see e.g. Wang et al. 1992; Csillag & Dimitrijević 2004; Dimitrijević & Sahal-Bréchet 2014) and laser-produced plasma research, modelling, and diagnostics (for example Nicolosi et al. 1978; Gornushkin et al. 1999; Serge et al. 2000).

Important applications of Stark broadening data are for plasmas in technology (Yilbas, Patel & Karatas 2015) also, as for welding, melting, and piercing of metals by lasers and plasma light sources (see for example Hoffman et al. 2006; Dimitrijević & Sahal-Bréchet 2014). For example, in order to model and design plasmas, created by evaporation of the target material with addition of the corresponding impurities, we should know profiles of spectral lines that coincide with the wavelength of the used laser. In this case, the absorption of laser radiation in plasma will be higher, and its re-emission will be with other wavelengths, where the absorption coefficient of the target is higher. Consequently, it is useful to know the profiles of spectral lines of plasma, as well as the spectrum of metal target in order to optimize the deposition of energy. Since there are many types of lasers operating at very different wavelengths, and new types will be certainly developed, line-broadening parameters for a great number of spectral lines of many atoms and ions in various ionization stages may be useful.

Stark broadening data are especially needed and used in astrophysics for abundance determinations, stellar spectra analysis and synthesis, stellar atmosphere modelling, opacity and radiative transfer calculations, determination of cosmic plasma parameters, and a number of other topics like stellar spectral-type determination, modelling of subphotospheric layers, and monitoring of thermonuclear reactions in stellar interiors. Data on Stark broadening of spectral lines are particularly needed for white dwarfs, because there, this is usually the principal pressure-broadening mechanism. For example, the influence of Stark broadening in DO dwarfs has been investigated in Dimitrijević et al. (2016), Dimitrijević & Chougule (2018), and Dimitrijević et al. (2018), in DB in Majlinger, Dimitrijević & Simić (2018), Majlinger, Dimitrijević & Srećković (2020a) and Majlinger, Dimitrijević & Srećković (2020b), in DA in Majlinger et al. (2020a) and Majlinger et al. (2020b), and in B subdwarfs in Hamdi et al. (2017) and Chougule et al. (2020). Such data may be also of interest in the case of the main-sequence stars, in particular, for A and late B spectral types (Majlinger et al. 2020a,b).

Atomic data for zinc, including Stark broadening, are of interest in astrophysics because they are often needed for abundance determination of A- and late B-type stars and white dwarfs. Sneden, Crocker & Cooper (1988) underline the importance of determination of zinc abundances for Galactic stars since the nucleosynthesis of zinc is not well understood (Barbuy et al. 2015). Moreover, this is one of the key elements enabling to understand the star formation rate and chemical enrichment of the Galactic bulge (da Silveira et al. 2018). It is also important to probe the contribution of hypernovae at the lower metallicities during the bulge chemical enrichment process (see e.g. Barbuy et al. 2015; da Silveira et al. 2018, and references therein).

Also, zinc can be observed in damped Lyman- $\alpha$  systems (DLAs), where, as the assumed proxy for Fe, it is of great importance for investigation of the chemical evolution of the Universe at high redshifts by studying abundances in DLAs (Pettini et al. 1999; Rafelski et al. 2012, 2014; da Silveira et al. 2018).

The spectral lines of neutral and ionized zinc are observed in spectra of various stars. For example, Tautvaišienė et al. (2020) analyzed spectra of 277 stars ( $T_{\text{eff}}$  between 3700 and 6600 K and

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log  $g$ , where  $g$  is the surface gravity, from 0.8 to 4.5) obtained by the NASA Transiting Exoplanet Survey Satellite (TESS) space telescope and found Zn I lines. Takeda et al. (2016) report on abundance determination of zinc for 239 GK giants and 160 FGK dwarfs. Using Zn I lines, Baratella et al. (2020) determined zinc abundance in a sample of nine stars and the Sun; Mikolaitis et al. (2020) for 249 F, G, and K dwarf stars; Chen, Nissen & Zhao (2004) for 44 thin galactic discs, 10 thick discs, and eight halo dwarf stars; Bihain et al. (2004) for 38 FGK stars; da Silveira et al. (2018) for 23; Sneden et al. (1988) for five bright, very metal deficient Population II stars, HD 19445, HD 103095, HD 122563, HD 165195, and HD 175305; and Barbuy et al. (2015) for a number of stars, as well as others. Zn I spectral lines are more investigated since there are strong and convenient lines in the visible part of the spectrum, but their existence is the confirmation that Zn II lines also exist, especially in deeper, as well as subphotospheric layers, where Stark broadening is particularly important. Zn II lines are also observed in stellar spectra. For example, Roederer & Barklem (2018) found Zn I and Zn II spectral lines in six warm ( $5766 \text{ K} \leq T_{\text{eff}} \leq 6427 \text{ K}$ ), metal-poor dwarf and subgiant ( $3.64 \leq \log g \leq 4.44$ ) stars.

Stark broadening parameters of Zn II spectral lines have been measured and calculated several times. The experimental results have been published by Kusch & Oberschelp (1967), Djeniže et al. (1991), and Mayo & Ortiz (2008). Using the modified semiempirical method (Dimitrijević & Konjević 1980; Dimitrijević & Kršljanin 1986), Popović, Vince & Dimitrijević (1993) calculated Stark widths and shifts for 12 Zn II multiplets using the semiempirical method of Griem (1968). Additionally, they calculated, when applicable, Stark widths using the low temperature limit of the semiempirical formula (Griem 1968) and of modified semiempirical formula (Dimitrijević & Konjević 1987). Moreover, using regularities and systematic trends, Lakićević (1983) estimated Stark width of the resonance Zn II line.

Our objective in this work is to calculate Stark broadening parameters, full width at half-maximum of intensity (FWHM –  $W$ ), and shift  $d$  using the semiclassical perturbation formalism (Sahal-Bréchet 1969a,b) to compare the obtained results with existing experimental and theoretical data and to use them to demonstrate the influence of Stark broadening in stellar atmospheres.

## 2 THE IMPACT SEMICLASSICAL PERTURBATION METHOD

For the calculation of Stark broadening parameters of spectral lines of singly charged zinc ion, the semiclassical perturbation formalism (Sahal-Bréchet 1969a,b) has been used (different later innovations and optimizations are described in Sahal-Bréchet 1974; Fleurier, Sahal-Bréchet & Chappelle 1977; Dimitrijević, Sahal-Bréchet & Bommier 1991; Sahal-Bréchet 1991; Dimitrijević & Sahal-Bréchet 1996; Sahal-Bréchet, Dimitrijević & Ben Nessib 2014). According to this method the FWHM –  $W$  and the shift ( $d$ ) of an isolated spectral line of a non-hydrogenic ion may be expressed as:

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

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

where  $i$  and  $f$  are initial and final levels of the corresponding transition,  $i'$  and  $f'$  are their perturbing levels,  $N$  is perturber density,  $v$  velocity of perturber,  $f(v)$  the Maxwellian velocity distribution, and

$\rho$  the impact parameter of the perturber colliding with the emitting ion.

The inelastic cross-sections  $\sigma_{kk'}(v)$ ,  $k = i, f$ , are presented here as an integration of the transition probability  $P_{kk'}(\rho, v)$ , over the impact parameter  $\rho$  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 contribution of elastic collisions and resonances to the line width is expressed as:

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

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

In the equation above,  $\sigma_{el}$  is the elastic cross-section and  $\varphi_p$  ( $r^{-4}$ ) and  $\varphi_q$  ( $r^{-3}$ ) are phase shifts due to the polarization and quadrupolar potential. They are defined in Section 3 of chapter 2 in Sahal-Bréchet (1969a). The symmetrization procedure and cut-offs  $R_1, R_2, R_3$ , and  $R_D$  are described in Section 1 of chapter 3 in Sahal-Bréchet (1969b). The explanation of the term describing the contribution of Feshbach resonances,  $\sigma_r$ , is given in Fleurier et al. (1977). We note that in analogous formulae for perturbing ions, the Coulomb force is not attractive but repulsive, so that trajectories are different. Additionally, in such a case there is no contribution of Feshbach resonances.

If we know line width and shift, it is easy to obtain the line profile  $F(\omega)$ , since Stark broadened isolated line has a Lorentzian form and it is given by:

$$F(\omega) = \frac{W/(2\pi)}{(\omega - \omega_{if} - d)^2 + (W/2)^2}. \quad (4)$$

Here,

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

where  $E_i, E_f$  are the energies of initial and final atomic energy levels, respectively. Consequently, if we know Stark broadening parameters, we have all needed for Stark broadening contribution to the profile of an isolated line of non-hydrogenic ion.

## 3 STARK BROADENING PARAMETER CALCULATIONS

Using the semiclassical perturbation theoretical approach (Sahal-Bréchet 1969a,b), here are calculated electron-, proton-, and helium ion-impact broadening parameters, FWHM –  $W$ , and shift ( $d$ ) for singly charged zinc ion (Zn II). The calculations are performed for temperatures of 5000 K, 10 000 K, 20 000 K, 30 000 K, 50 000 K, and 100 000 K for perturber densities from  $10^{14}$  to  $10^{19} \text{ cm}^{-3}$ .

Atomic energy levels for singly charged zinc ion, needed for present calculations, have been taken from Sugar & Musgrove (1995). The needed oscillator strengths have been calculated using Bates & Damgaard (1949) method, the tables of Oertel & Shomo (1968), and the method of Van Regemorter, Hoang Binh & Prud'homme (1979) for higher levels, when the method of Bates & Damgaard (1949) is not convenient.

The obtained results for 34 Zn II multiplets are given in electronic, computer-readable form, as Tables S1–S6, in the online journal edition as additional data, for perturber densities from  $10^{14} \text{ cm}^{-3}$  (Table S1) up to  $10^{19} \text{ cm}^{-3}$  (Table S6). As an example of the content of Tables S1–S6, here are given in Table 1, the results for two multiplets in order to show the form of additional data.

**Table 1.** This table gives electron-, proton-, and helium ion-impact broadening parameters for Zn II lines. 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 perturber density for which the line may be treated as isolated. The validity of impact approximation is checked by the calculation of the value of  $NV$ , where  $V$  is the collision volume and  $N$  the perturber density. If  $NV < 0.1$ , the impact approximation is valid. In the case that  $NV > 0.5$ , the corresponding results for FWHM and  $d$  are not presented. When  $0.1 < NV \leq 0.5$ , before the corresponding Stark broadening parameters an asterisk is placed in order to notice that this result is on the limit of validity of impact approximation. The Stark broadening parameters for 34 Zn II multiplets are available in its entirety in machine-readable form in the online journal as additional data. Results for perturber densities  $10^{14} \text{ cm}^{-3}$  to  $10^{19} \text{ cm}^{-3}$  are in Tables S1–S6 in additional data. In all tables, temperatures are from 5000 to 100 000 K. A positive shift is towards the red part of the spectrum. A portion, for a perturber density of  $10^{17} \text{ cm}^{-3}$ , is shown here for guidance regarding its form and content.

Perturber density =		1E + 17 cm <sup>-3</sup>					
Transition	T(K)	Electrons width (Å)	Shift(Å)	Protons width (Å)	Shift (Å)	Ionized width (Å)	Helium shift (Å)
Zn II 4s-4p	5000.	0.743E-01	−0.178E-03	0.893E-03	−0.577E-05	0.139E-02	−0.577E-05
2038.2 Å	10000.	0.542E-01	−0.287E-04	0.173E-02	−0.129E-04	0.226E-02	−0.129E-04
C = 0.16E+21	20000.	0.392E-01	−0.128E-03	0.257E-02	−0.269E-04	0.308E-02	−0.267E-04
	30000.	0.326E-01	−0.145E-03	0.304E-02	−0.399E-04	0.332E-02	−0.386E-04
	50000.	0.265E-01	−0.845E-04	0.336E-02	−0.618E-04	0.363E-02	−0.571E-04
	100000.	0.215E-01	−0.153E-03	0.378E-02	−0.966E-04	0.401E-02*	−0.833E-04
Zn II 4s-5p	5000.	0.489E-01	−0.245E-02	0.294E-02	−0.786E-03	*0.357E-02	−0.688E-03
984.9 Å	10000.	0.380E-01	−0.145E-02	0.412E-02	−0.126E-02	*0.440E-02	−0.108E-02
C = 0.45E+19	20000.	0.311E-01	−0.202E-02	0.478E-02	−0.175E-02	0.504E-02	−0.143E-02
	30000.	0.287E-01	−0.173E-02	0.516E-02	−0.196E-02	0.537E-02	−0.161E-02
	50000.	0.269E-01	−0.135E-02	0.559E-02	−0.229E-02	0.563E-02	−0.186E-02
	100000.	0.252E-01	−0.142E-02	0.607E-02	−0.268E-02	0.586E-02	−0.218E-02

We note as well that the wavelengths given in tables are calculated from atomic energy levels and may differ from the experimental ones. It is also worth to note that the Stark broadening parameters depend on relative positions of atomic energy levels and not on their absolute positions, if we express them in angular frequency units. We can transform Stark width in Å in angular frequency units by the expression:

$$W(\text{Å}) = \frac{\lambda^2}{2\pi c} W(s^{-1}), \quad (5)$$

where  $c$  is the speed of light. If we need to correct the width or shift for the difference between calculated and experimental/observed wavelength, we can do this, for example for the width and similarly for the shift as:

$$W_{\text{cor}} = \left( \frac{\lambda_{\text{exp}}}{\lambda} \right)^2 W. \quad (6)$$

Here,  $W_{\text{cor}}$  is the corrected width,  $\lambda_{\text{exp}}$  is the experimental or observed,  $\lambda$  the calculated wavelength, and  $W$  the width from tables in this paper.

The quantity  $C$  (Dimitrijević & Sahal-Bréchet 1984), given in Tables S1–S6, divided by the corresponding width ( $W$ ) shows the maximal perturber density when the line may be considered as isolated. During the calculations, the validity of impact approximation is checked by the calculation of the value of  $NV$ , where  $V$  is the collision volume and  $N$  the perturber density. If  $NV < 0.1$ , the impact approximation is valid (Sahal-Bréchet 1969a,b). In the case that  $NV > 0.5$ , the corresponding results for FWHM and  $d$  are not presented because the impact approximation is not valid. When the value of the condition of validity of the impact approximation is  $0.1 < NV \leq 0.5$ , before the corresponding Stark broadening parameters an asterisk is placed in order to notice that this result is on the limit of validity of impact approximation.

When the impact approximation is not valid for ion impacts, one can calculate the ion broadening contribution using a formula within the quasi-static approach (Griem 1974; Sahal-Bréchet 1991). In the

case of intermediate conditions between the impact and quasi-static approximation, the unified-type theory, as for example, the method of Barnard, Cooper & Smith (1974) can be applied.

## 4 RESULTS AND DISCUSSION

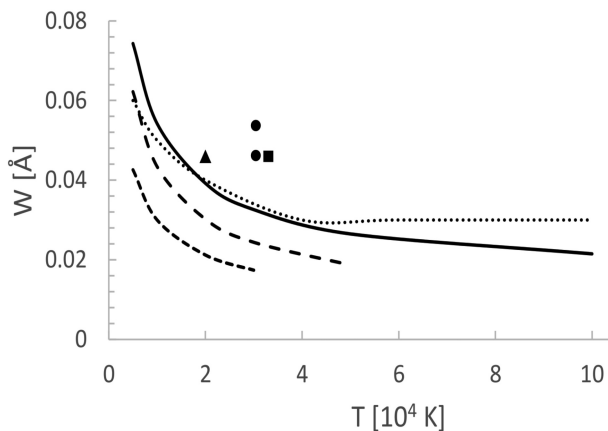
In Table 2 and in Figs 1 and 2, our results are compared with semiclassical results of Blagojević & Konjević (2017), results obtained by Popović et al. (1993) with the help of the modified semiempirical method (Dimitrijević & Konjević 1980; Dimitrijević & Kršljanin 1986), and results of Djeniže et al. (1991) obtained by using the semiempirical method (Griem 1968). One can see that the agreement with the semiclassical results of Blagojević & Konjević (2017) is relatively good for the widths. In the case of Zn II 5s-5p, shown in Fig. 2, there is an unusual increase of the Stark width at higher temperatures ( $T > 40\,000$  K) in the results of Blagojević & Konjević (2017), which is probably the consequence of some numerical difficulties in the calculation. The agreement is worse for the shifts. We note that while for widths all contributions from various perturbations are positive, in the case of shifts they are positive and negative, so that when a lot of mutual cancellations are present, the obtained results are less accurate. In the case of modified semiempirical results, the agreement of widths for s-p transitions is within mutual limits of accuracy. The agreement is better for lower temperatures and worse for higher. For p-d and d-f transitions, results are different up to the two times. This is maybe the consequence of the fact that d and f orbitals are more elliptical, so that optical electron comes closer to the nucleus, where quantum effects are more prominent. Shifts are not in agreement, even the sign is different. The agreement with Stark widths calculated by Djeniže et al. (1991) by using the semiempirical method (Griem 1968) is within the mutual limits of accuracy. We note a strange increase of the Stark widths of Djeniže et al. (1991) for higher temperatures. We suppose that this is the consequence of the jump between the semiempirical formula and its asymptotic expression used for high temperatures. We would like to note as well that the temperature dependence of Stark broadening

**Table 2.** Comparison of our results for FWHM (WSCP) and shift (dSCP) with semiclassical results of Blagojević & Konjević (2017) (WBK, dBK), results obtained by Popović et al. (1993) (WMSE, dMSE) by using the modified semiempirical method (Dimitrijević & Konjević 1980; Dimitrijević & Kršljanin 1986), and results of Djeniže et al. (1991) (WSE) obtained by using the semiempirical method (Griem 1968). Electron density is  $10^{17} \text{ cm}^{-3}$ .

Transition	$T$ (K)	WSCP(A)	dSCP(A)	WBK (A)	dBK (A)	WMSE (A)	dMSE (A)	WSE (A)
Zn II 4s-4p	5000.	0.743E-01	-0.178E-03	0.6E-01	-0.2E-01	0.622E-01	0.950E-02	0.426E-01
2038.2 Å	10000.	0.542E-01	-0.287E-04	0.5E-01	-0.2E-01	0.434E-01	0.685E-02	0.300E-01
$C = 0.16E+21$	20000.	0.392E-01	-0.128E-03	0.4E-01	-0.1E-01	0.302E-01	0.504E-02	0.212E-01
	30000.	0.326E-01	-0.145E-03			0.244E-01	0.428E-02	0.174E-01
	40000.	0.289E-01	-0.756E-04	0.3E-01	-0.1E-01	0.210E-01	0.386E-02	0.15E-01
	50000.	0.265E-01	-0.845E-04			0.187E-01	0.360E-02	
	60000.	0.249E-01	-0.964E-04	0.3E-01	-0.1E-01			
	100000.	0.215E-01	-0.153E-03	0.3E-01	-0.1E-01			
Zn II 4s-5p	5000.	0.489E-01	-0.245E-02			0.328E-01	0.390E-02	
984.9 Å	10000.	0.380E-01	-0.145E-02			0.228E-01	0.298E-02	
$C = 0.45E+19$	20000.	0.311E-01	-0.202E-02			0.164E-01	0.244E-02	
	30000.	0.287E-01	-0.173E-02			0.144E-01	0.232E-02	
	40000.	0.276E-01	-0.150E-02			0.135E-01	0.258E-02	
	50000.	0.269E-01	-0.135E-02			0.122E-01	0.291E-02	
	60000.	0.264E-01	-0.137E-02					
	100000.	0.252E-01	-0.142E-02					
Zn II 5s-5p	5000.	3.76	-1.15	3.55	-1.95	3.24	-0.469	3.44
7638.0 Å	10000.	2.85	-0.861	2.95	-1.61	2.24	-0.346	2.64
$C = 0.27E+21$	20000.	2.32	-0.664	2.7	-1.4	1.62	-0.269	2.46
	30000.	2.18	-0.601			1.42	-0.255	2.78
	40000.	2.12	-0.543	2.69	-1.25	1.34	-0.235	3.23
	50000.	2.08	-0.501			1.32	-0.214	
	60000.	2.07	-0.469	2.75	-1.18			
	100000.	2.02	-0.398	2.83	-1.1			
Zn II 4p-5s	5000.	0.263	0.107	0.25	0.13	0.244	0.814E-01	0.193
2539.8 Å	10000.	0.186	0.829E-01	0.2	0.11	0.170	0.606E-01	0.136
$C = 0.84E+20$	20000.	0.132	0.622E-01	0.17	0.9E-01	0.120	0.476E-01	0.112
	30000.	0.118	0.554E-01			0.116	0.449E-01	0.113
	40000.	0.110	0.510E-01	0.16	0.8E-01	0.922E-01	0.442E-01	0.138
	50000.	0.105	0.469E-01			0.866E-01	0.439E-01	
	60000.	0.102	0.436E-01	0.15	0.7E-01			
	100000.	0.948E-01	0.368E-01	0.15	0.6E-01			
Zn II 4p-6s	5000.	0.212	0.964E-01			0.272	0.108	
1528.2 Å	10000.	0.150	0.926E-01			0.197	0.870E-0	
$C = 0.13E+20$	20000.	0.126	0.762E-01			0.156	0.819E-01	
	30000.	0.119	0.691E-01			0.147	0.776E-01	
	40000.	0.114	0.663E-01			0.144	0.704E-01	
	50000.	0.110	0.617E-01			0.142	0.645E-01	
	60000.	0.109	0.578E-01					
	100000.	0.108	0.489E-01					
Zn II 4p-4d	5000.	0.165	0.528E-01			0.928E-01	0.112E-01	
2088.7 Å	10000.	0.126	0.408E-01			0.642E-01	0.899E-02	
$C = 0.20E+20$	20000.	0.100	0.322E-01			0.452E-01	0.814E-02	
	30000.	0.893E-01	0.269E-01			0.386E-01	0.851E-02	
	40000.	0.841E-01	0.249E-01			0.360E-01	0.921E-02	
	50000.	0.806E-01	0.236E-01			0.348E-01	0.111E-01	
	60000.	0.780E-01	0.219E-01					
	100000.	0.721E-01	0.187E-01					
Zn II 4p-5d	5000.	0.296	0.465E-01			0.137	0.180E-01	
1451.0 Å	10000.	0.252	0.359E-01			0.964E-01	0.153E-01	
$C = 0.15E+19$	20000.	0.222	0.267E-01			0.726E-01	0.150E-01	
	30000.	0.210	0.223E-01			0.656E-01	0.156E-01	
	40000.	0.204	0.198E-01			0.632E-01	0.173E-01	
	50000.	0.199	0.189E-01			0.622E-01	0.161E-01	
	60000.	0.195	0.182E-01					
	100000.	0.183	0.150E-01					
Zn II 4d-4f	5000.	2.56	0.529	3.33	1.35	1.28	0.323	2.60
4920.4 Å	10000.	2.11	0.421	2.62	1.02	0.912	0.275	1.93

**Table 2** – *continued*

Transition	$T$ (K)	WSCP(A)	dSCP(A)	WBK (A)	dBK (A)	WMSE (A)	dMSE (A)	WSE (A)
$C = 0.17E+20$	20000.	1.81	0.314	2.18	0.78	0.768	0.296	1.68
	30000.	1.69	0.303			0.764	332	1.80
	40000.	1.62	0.291			0.762	0.346	1.765
	50000.	1.58	0.276			0.760	0.346	
	60000.	1.54	0.258					
	100000.	1.45	0.213	1.69	0.45			



**Figure 1.** Comparison of different theoretical and experimental Stark full widths for Zn II 4s-4p transition. Solid line WSCP (present semiclassical perturbation calculations); dotted line WBK (Blagojević & Konjević 2017); dashed line WMSE (Popović et al. 1993); and short dashed line WSE (Djeniže et al. 1991). Experimental results: circle – Mayo & Ortiz (2008), square – Djeniže et al. (1991), and triangle – Lakićević (1983). Electron density is  $10^{17} \text{ cm}^{-3}$ .

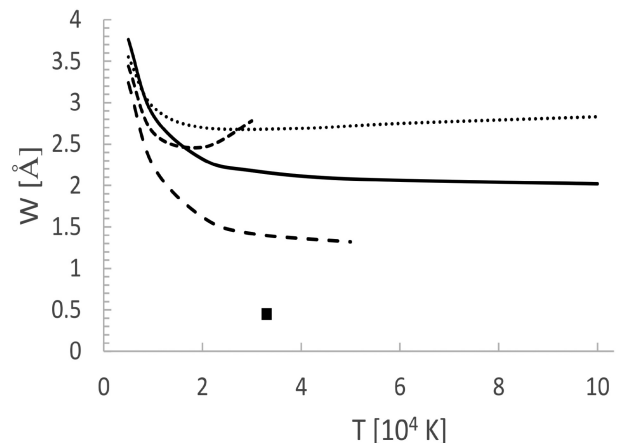
width for Zn II 4s-4p transition (see Fig. 1 and Table 2) has a same trend for WSCP, WMSE, and WSE, almost parallel one to other.

Fig. 3 presents results for Stark shift for Zn II 5s-5p multiplet compared with results obtained using semiclassical approach (dBK) and modified semiempirical method (dMSE). Both have negative values as our results. The behaviour with temperature is practically the same for considered theoretical methods.

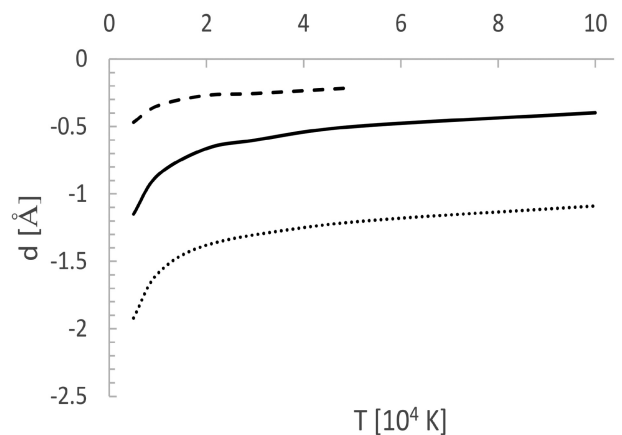
In Figs 1 and 2 and in Table 3, our results are compared with existing experimental data of Djeniže et al. (1991) (WDJ), Mayo & Ortiz (2008) (WMO), and Kusch & Oberschelp (1967) (WKO) at an electron density of  $10^{17} \text{ cm}^{-3}$ . The best agreement is with results of Mayo & Ortiz (2008). For six lines, the average ratio of their and our Stark widths,  $WMO/WSCP$ , is equal to 1.01. On the other hand, average  $WDJ/WSCP$  from four lines is 0.46 and  $WKO/WSCP$  is 2.75 from four lines. The worst agreement is with results of Kusch & Oberschelp (1967). However, Konjević & Wiese (1976) stated that they did not check for self-absorption, which is probably high.

We can conclude that Stark broadening data presented here are in relatively good agreement with other calculated and reliable experimental results. Further experimental measurements in a wide temperature interval will be a better indication for the accuracy of calculated Stark broadening parameters.

We also used the obtained data to demonstrate the importance of such Stark broadening data for stellar plasma investigation and modelling. In Fig. 4, ratio of Stark and Doppler widths of Zn II  $\lambda = 2539.8 \text{ Å}$  line ( $4p \ ^2P_{3/2}^o - 5s \ ^2S_{1/2}$ ) as a function of temperature of atmospheric layer is presented for different effective temperatures and  $\log g = 4$ . Models of stellar atmospheres were taken from Kurucz



**Figure 2.** Comparison of different theoretical and experimental Stark full widths for Zn II 5s-5p transition. Solid line WSCP (present semiclassical perturbation calculations); dotted line WBK (Blagojević & Konjević 2017); dashed line WMSE (Popović et al. 1993); and short dashed line WSE (Djeniže et al. 1991). Experimental results: square – Djeniže et al. (1991). Electron density is  $10^{17} \text{ cm}^{-3}$ .

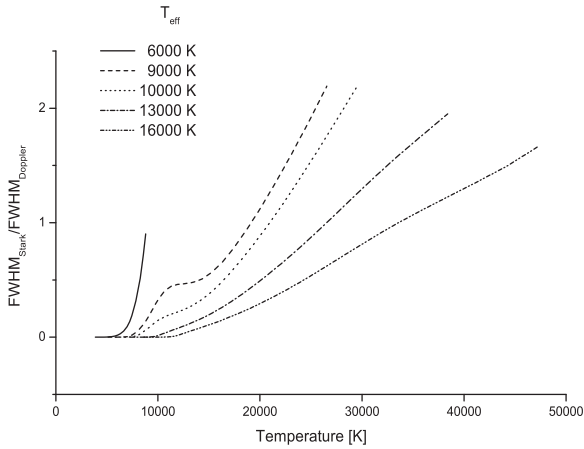


**Figure 3.** Comparison of different theoretical and experimental Stark line shifts for Zn II 5s-5p transition. Solid line WSCP (present semiclassical perturbation calculations); dotted line WBK (Blagojević & Konjević 2017); and dashed line WMSE (Popović et al. 1993). Electron density is  $10^{17} \text{ cm}^{-3}$ .

(1979). The considered effective temperatures correspond to F type ( $T_{\text{eff}} = 6000 \text{ K}$ ), A type ( $T_{\text{eff}} = 9000$  and  $10\,000 \text{ K}$ ), and B type ( $T_{\text{eff}} = 13\,000$  and  $16\,000 \text{ K}$ ) of stellar atmospheres. We can see that for F-type stars, Stark broadening may be non-negligible in comparison with Doppler broadening while in A- and B-type stars, there are atmospheric layers where Stark broadening is dominant. Also, we can see that in comparison with B type and F type, Stark broadening is most important for A-type stars.

**Table 3.** Comparison of our results for FWHM (WSCP) with experimental results of Djeniže et al. (1991) (WDJ), citetMa08 (WMO), and Kusch & Oberschelp (1967) (WKO). Electron density is  $10^{17} \text{ cm}^{-3}$ .

Transition	$\lambda$ (Å)	$T$ (K)	WSCP (Å)	WDJ (Å)	WMO (Å)	WKO (Å)
Zn II $4s^2S-4p^2P^o$	2025.48	30400	0.0320		0.0537	
	2061.91	30400	0.0332		0.0462	
		33000	0.0320	0.046		
Zn II $5s^2S-5p^2P^o$	7588.48	33000	2.13	0.446		
Zn II $4p^2P^o-5s^2S$	2502.0	11000	0.173			0.64
		30400	0.115		0.085	
	2557.96	11000	0.181			0.88
		30400	0.120		0.093	
Zn II $4p^2P^o-4d^2D$	2064.23	30400	0.0870		0.0665	
	2099.94	30400	0.0901		0.0653	
		33000	0.117	0.102		
Zn II $4d^2D-4f^2F^o$	4911.66	11000	2.05			2.45
		33000	1.68	0.366		
	4924.0	11000	2.06			2.55

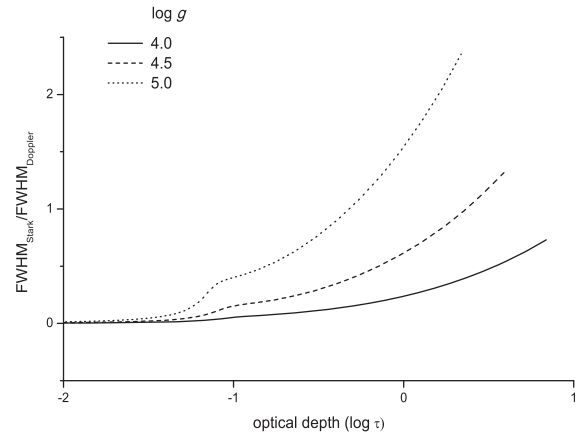
**Figure 4.** Ratio of Stark and Doppler widths of Zn II  $\lambda = 2539.8 \text{ \AA}$  line ( $4p^2P^o_{3/2}-5s^2S_{1/2}$ ) as a function of temperature of atmospheric layer for different effective temperatures and  $\log g = 4$ . Models of stellar atmospheres were taken from Kurucz (1979).

In Fig. 5 is shown the ratio of Stark and Doppler widths as a function of logarithm of Rosseland optical depth ( $\tau$ ) for different logarithms of surface gravities  $\log g$  and  $T_{\text{eff}} = 10\,000 \text{ K}$ , which is an effective temperature corresponding to earliest A stars or latest B stars. Models of stellar atmospheres were taken from Kurucz (1979). We can see that the influence of Stark broadening increases with the increase of surface gravity, as expected, since the electron density also increases with the increase of  $g$ .

The fact, that there are so many papers dedicated to observations and applications of Zn II spectral lines in different scientific and technological field from one side, and several calculations of Stark broadening parameters from another, manifests the need of such data.

## 5 CONCLUSIONS

We obtained new Stark broadening parameters for 34 multiplets of Zn II within the frame of the semiclassical perturbation formalism. For majority of them there are no other theoretical or experimental results.

**Figure 5.** Ratio of Stark and Doppler widths of Zn II  $\lambda = 2539.8 \text{ \AA}$  line ( $4p^2P^o_{3/2}-5s^2S_{1/2}$ ) as a function of logarithm of Rosseland optical depth ( $\tau$ ) for different logarithms of surface gravities  $\log g$  and  $T_{\text{eff}} = 10\,000 \text{ K}$ . Models of stellar atmospheres were taken from Kurucz (1979).

The performed comparison of Stark broadening parameters with available ones, experimental and calculated from the literature, presented here shows that they could be useful for plasma diagnostics and modelling. The obtained results for Stark broadening of Zn II spectral lines are of interest for analysis and synthesis of stellar spectra, for the modelling of stellar atmospheres, radiative transfer calculations, and other astrophysical problems. We used the obtained data to show the importance of Stark broadening data for stellar atmospheres of B, A, and F types. Such data are also of interest for laboratory plasma diagnostics, for lasers, and technological plasmas.

Stark widths and shifts for Zn II spectral lines will also be implemented in the STARK-B data base (Sahal-Bréchet et al. 2010; Sahal-Bréchet, Dimitrijević & Moreau 2012, 2015a; Sahal-Bréchet et al. 2015b), which is a part of Virtual Atomic and Molecular Data Center (VAMDC) (Dubernet et al. 2010; Rixon et al. 2011; Dubernet et al. 2016; Albert et al. 2020). We note as well that a link to STARK-B is in the Serbian Virtual Observatory (SerVO, <http://servo.aob.rs>) (Jevremović et al. 2009; Jevremović et al. 2012).

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## DATA AVAILABILITY

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

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## SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

## suppl\_data

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