INFLUENCE OF ASTROPHYSICAL PLASMA ON SPECTRAL LINESHAPES

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Abstract. A review of astrophysical problems where Stark broadening data are of interest is given. Also, the results of Stark broadening study relevant to astrophysical problems and to the laboratory plasma research have been reviewed and discussed. Particular attention has been paid to the semiclassical method and the modified semiempirical method as well as to the use in astrophysics of results and achievements in Stark broadening research of the Belgrade school.

1. Needs in astrophysics for an extensive set of Stark broadening data

It is difficult to state in general terms which spectral lines are important for the analysis, research and modelling of astrophysical plasma and in particular astrophysical spectra, since the atmospheric composition of a star is not known a priori, and many interesting groups of stars exist with very peculiar abundances as compared to the Sun. Consequently, stellar spectroscopy depends on very extensive list of elements and line transitions with their atomic and line broadening parameters.

The interest for a very extensive list of line broadening data is additionally stimulated by the development of space astronomy where an extensive amount of spectroscopic information over large spectral regions of all kind of celestial objects has been and will be collected, stimulating the spectral-line-shape research.

Development of computers also stimulated the need for a large amount of atomic and spectroscopic data. Particularly large number of data is needed for example for opacity calculations. An illustrative example might be the article on the calculation of opacities for classical Cepheid models [1], where 11 996 532 spectral lines have been taken into account (45 lines of H, 45 of He, 638 of C, 54 of N, 2 390 of O, 16 030 of Ne, 50 170 of Na, 105 700 of Mg, 145 200 of Al, 133 700 of Si, 12 560 of Ar and 11 530 000 of Fe), and where Stark broadening is included.
Interesting investigations which become possible with the development of computer technology, are calculations of equivalent width changes with the age in starburst stellar clusters and galaxies [2]. In this Ref. the change of particular hydrogen and helium lines equivalent widths during 500 million years, has been calculated and compared with observations of stellar clusters of the Large Magellanic Clouds, the super-star clusters in the starburst galaxy NGC 205, the nucleus of the dwarf elliptic galaxy NGC 205, and a luminous “E+A” galaxy. Calculations have been done in two steps. First, the population of stars of different spectral types, as a function of age are calculated, and then the profiles of the lines are synthesized by adding the different contributions from stars. For spectral line profiles synthesis the effects of natural, Stark, Van der Waals and thermal Doppler broadening have been taken into account.

For the estimation of radiative transfer through stellar plasmas, especially in subphotospheric layers as well as for the determination of chemical abundances of elements from equivalent widths of absorption lines, an as much as possible complete set of Stark broadening data for an as much as possible larger number of spectral lines for different emitters is needed, since we do not know a priori the chemical composition of a star.

2. Applications of semiclassical method for Stark broadening research in Serbia and astrophysical significance of obtained results

In spite of the fact that the most sophisticated theoretical method for the calculation of a Stark broadened line profile is the quantum mechanical strong coupling approach, due to its complexity and numerical difficulties, only a small number of such calculations exist (see e.g. references in [3]). As an example of the contribution of the Belgrade school, the first calculation of Stark broadening parameters within the quantum mechanical strong coupling method for a nonhydrogen neutral emitter spectral lines is for Li I $2s^2S - 2p^2P^o$ transition [4].

In a lot of cases such as e.g. complex spectra, heavy elements or transitions between highly excited energy levels, the more sophisticated quantum mechanical approach is very difficult or even practically impossible to use and, in such cases, the semiclassical approach remains the most efficient method for Stark broadening calculations.

The existing large scale calculations of Stark broadening parameters were performed by using three different computer codes, basically developed by (i) Jones, Benett and Griem [5–7], (ii) Sahal-Bréchet [8,9] and (iii) Bassalo, Cattani and Walder [10].

Using the computer code developed by Jones, Benett and Griem for neutrals and singly charged ions and adapted by Dimitrijević for multiply charged ions, Belgrade school provided Stark broadening data for Br I, Ge I, Hg I, Pb I, Rb I,
Cd I, Zn I, O II, O III, C III, C IV, N II, N III, N IV, S III, S IV, Cl III and Ti II, Mn II.

In order to complete as much as possible Stark broadening data needed for astrophysical and laboratory plasma research and stellar opacities calculations we are making a continuous effort to provide Stark broadening data for a large set of atoms and ions. In a series of papers we have performed large scale calculations of Stark broadening parameters for a number of spectral lines of various emitters (see e.g. [3] and references therein), within the semiclassical-perturbation formalism [8,9], for transitions when a sufficiently complete set of reliable atomic data exists and a good accuracy of obtained results is expected. Extensive calculations have been performed, up to now (see Ref. [3] and references therein) for a number of radiators, and consequently, Stark broadening parameters for: 79 He, 62 Na, 51 K, 61 Li, 25 Al, 24 Rb, 3 Pd, 19 Be, 270 Mg, 31 Sc, 33 Sr, 14 Ba, 189 Ca, 32 Zn, 6 Au, 48 Ag, 3 Ar, 28 Ca II, 30 Be II, 29 Li II, 66 Mg II, 64 Ba II, 19 Si II, 3 Fe II, 2 Ni II, 32 Ne II, 101 In II, 12 B III, 23 Al III, 10 Sc III, 27 Be III, 11 Ne III, 32 Y III, 20 In III, 2 Ti III, 5 O III, 2 Ne IV, 10 Ti IV, 39 Si IV, 90 C IV, 5 O, 114 P IV, 2 Pb IV, 19 O V, 30 N V, 25 C V, 51 P V, 34 S V, 26 V V, 30 O VI, 21 S VI, 2 F VI, 14 O VII, 10 F VII, 10 Cl VII, 20 Ne VIII, 4 K VIII, 9 Ar VIII, 6 Kr VIII, 4 Ca IX, 30 K IX, 8 Na IX, 57 Na X, 48 Ca X, 4 Sc X, 7 Al XI, 4 Si XI, 18 Mg XI, 4 Ti XI, 10 Sc XI, 9 Si XII, 27 Ti XII, 61 Si XIII and 33 V XIII multiplets become available.

Data for particular lines of F I, B II, C III, N IV, Ar II, Ga II, Ga III, Cl I, Br I, I I, Cu I, Hg II, N III, F V and S IV also exist.

The obtained semiclassical result have been compared with critically selected experimental data for 13 He I multiplets (see references in [3]). The agreement between experimental and semiclassical calculations is within the limits of ±20%, what is the predicted accuracy of the semiclassical method [7].

Our semiclassical Stark broadening parameters, were used for different astrophysical problems. Since the helium has the largest cosmical abundance after hydrogen, it is naturally that our He Stark broadening data have been often used for different investigations in astrophysics. They have been used for the considerations of following astrophysical problems: non LTE model analysis of the interacting binary β Lyrae; variability investigations of Balmer lines in Ap stars; investigations of peculiar helium-strong stars δ Orionis C and HD 58260, the chemical composition of the northern double cluster h and χ Persei and the loose association Cepheus OBIII; the role of blending in the He singlet lines formation in Bp star atmospheres; the critical analysis of the ultraviolet temperature scale and the effective temperature calibration of white dwarfs; the investigation of extreme helium star BD-90-4395; the ionization and excitation in cool giant stars; the constitution of the atmospheric layers and the extreme ultraviolet-spectrum of hot hydrogen rich white dwarfs; spectral properties of hot hydrogen rich white dwarfs with stratified H/He model; radiative accelerations on iron; radiative acceleration of helium in
the atmospheres of sdOB stars; research of stars with peculiar helium and noble gases abundances; a spectroscopic analysis of DAO and hot DA white dwarfs. They entered in a spectrum synthesis program for binary stars and have been used for atmosphere research, helium surface mapping and spectrum variability considerations of ET Andromedae, for the investigation of the He I \( \lambda 10830 \) Å formation mechanism in classical cepheids, for the consideration of hot white dwarfs in the Extreme-Ultraviolet Explorer survey, for the search for forced oscillations in the eclipsing and spectroscopic binary V436 Persei-1 Persei, for investigations of helium abundance in He rich stars and white dwarfs; a study of the effect of diffusion and mass-loss on the helium abundance in hot white dwarfs and subdwarfs, for the spectral analysis of the low gravity extreme helium stars LSS 4357, LS II+3305 and LSS 99 and the field horizontal-branch B-type star Feige 86, for comparison with theoretical results obtained within the Stark broadening theory of solar Rydberg lines in the far infrared spectrum, for a discussion of He I 2P-nD line formation in \( \lambda \) Eridani, for a study of the atmospheric variations of the peculiar B(\( \epsilon \)) star HD 45677 (FS Canis Majoris), for a new method for fitting observations with synthetic spectra, for the consideration of the abundance of He\(_3\) isotope in HgMn star atmospheres, and investigation of the helium stratification in the atmospheres of magnetic helium peculiar stars.

Our semiclassical Stark broadening results which have the highest impact in astrophysics, concern ionized silicon spectral lines. Results of our semiclassical investigations have been used for silicon abundance analyses with co-added DAO spectrograms, of the HgMn stars \( \phi \) Herculis, 28 Herculis, HR 7664, \( \nu \) Capricri, \( \iota \) Coronae Borealis, HR 8349, \( \pi \) Bootis, \( \nu \) Herculis, HR 7361, HR 4072, HR 7775, B stars \( \pi \) Ceti, 134 Tauri, 21 Aquilae, \( \nu \) Capricorni, \( \gamma \) Pegasi, \( \iota \) Herculis, \( \zeta \) Draconis, \( \eta \) Lyrae, 8 Cygni, 22 Cygni, B and A stars \( \gamma \) Geminorum, 7 Sextantis, HR 4817, HR 5780, HD 60825, Merak, \( \pi \) Draconis, \( \kappa \) Cephei, early A type stars 68 Tauri, 21 Lyncis, \( \alpha \) Draconis, 2 Lyncis, \( \omega \) Ursae Majoris, \( \phi \) Aquilae, 29 Vulpeculae, \( \sigma \) Aquarii normal F main sequence stars \( \theta \) Cygni, \( \iota \) Piscium, \( \sigma \) Bootis, the metallic lined stars 15 Vulpeculae, 32 Aquarii, HR 4072B, 60 Leonis, 6 Lyrae, silicon abundance analyses with Complejo Astronomico el Leoncito REOSC echelle spectrograms of \( \kappa \) Cancri, HR 7245, ksi Octantis, HR 4487, 14 Hydrae, 3 Centauri A, silicon abundance studies of CP stars HD 43819, HD 147550, \( \chi \) Lupi, 21 Canum Venaticorum, HD 133029, HD 192913, silicon abundance determination for \( \gamma \) Geminorum, HR 1397, HR 2154, HR 60825 and 7 Sextantis. Our data have also been used for a discussion on the future of stellar spectroscopy, investigation of blue stragglers of M 67, determination of the effective temperature of B-type stars from the Si II lines of the UV multiplet 13.04 at 130.5–130.9 nm, analysis of the red spectrum of Ap stars, NLTE Analysis of subluminous O type hot subdwarf in the binary system HD 128220, a discussion of the role of spectral line Stark shifts for stellar chemical composition determination with the method of atmospheric model, a discussion of the nature of the F str \( \lambda 4077 \) type stars and have been used for
atmosphere research, He surface mapping and spectrum variability considerations of ET Andromedae.

Semiclassical Stark broadening data on N II, N III and N IV lines have been used for the investigation of the chemical composition of the young open cluster NGC 6611. Our data for Ga II have been used for gallium abundance analysis of κ Cancri, normal late B and HgMn stars and for a discussion on anomalous gallium line profiles in HgMn stars as a possible evidence for chemically stratified atmospheres. Our semiclassical results for lithium have been used for a study of the non-LTE formation of Li I lines in cool stars. Results for C IV have been used for the consideration of the influence of gravitational settling and selective radiative forces in PG 1159 stars, high resolution UV spectroscopy of two hot (pre-) white dwarfs (KPD 0005+5106 and RXJ 2117+3412) with the Hubble Space Telescope, spectral energy-distribution and the atmospheric properties of the helium-rich white-dwarf MCT 0501-2858 and for an investigation of stellar masses, kinematics, and white dwarf composition for three close DA+dMe binaries. Stark broadening data for N V spectral lines have been used for the spectral analysis of the planetary nebula K 1-27 and data for O VI for spectral analysis of the multiple-shell planetary nebula LoTr4 and for very hot hydrogen-deficient central stars of both nebulae. They have been used also for the study of the EUV spectrum of the unique bare stellar core H1504+65. Our Stark-broadening parameters of ionized mercury spectral lines of astrophysical interest, have been used for determination of Hg abundances in normal late-B and HgMn stars from co-added IUE spectra; our data for Ca II for abundance analyses of the double-lined spectroscopic binary α Andromedae, and our data for Mg I for a non-LTE analysis of Mg I in the solar atmosphere.

3. Modified semiempirical method for Stark broadening and astrophysical applications

It is twenty two years from the formulation of the modified semiempirical (MSE) approach [11] for the calculation of Stark broadening parameters for non-hydrogenic ion spectral lines. Within this period the considered method has been applied successfully many times for different problems in astrophysics and physics. According to the modified semiempirical (MSE) approach [11–17] the electron impact full width (FWHM) of an isolated ion line is given as

$$W_{MSE} = N \frac{8\pi}{3} \frac{\hbar^2}{m^2} \left( \frac{2m}{\pi kT} \right)^{1/2} \frac{\chi^2}{\sqrt{3}} \frac{2\pi c}{\sqrt{3}} \left( \sum_{\ell_i \pm 1} \sum_{A_i, J_i} \tilde{R}^2 \left[ n_{i\ell_i} A_i J_i, n_{i(\ell_i \pm 1)} A_i J_i \right] \tilde{g}(x_{\ell_i, \ell_i \pm 1}) + \sum_{\ell_f \pm 1} \sum_{A_f, J_f} \tilde{R}^2 \left[ n_{f\ell_f} A_f J_f, n_{f(\ell_f \pm 1)} A_f J_f \right] \tilde{g}(x_{\ell_f, \ell_f \pm 1}) \right)$$

(1)
where the initial level is denoted as matrix element
\[ \text{energy difference between levels} \]
In Eqs. (1) and (2)\[ \ell \]
Also,\[ E \]
and the final one as
\[ \text{energy difference between levels} \]
Also,\[ E \]
and the square of the
\[ \text{energy difference between levels} \]
Also,\[ E \]
and the corresponding Stark shift as
\[ d_{\text{MSK}} = \frac{N \pi^2}{3^2 m^2} \left( \frac{2 \pi}{\pi kT} \right)^{1/2} \pi^2 \text{c} \]
\[ \left\{ \sum_{\ell_i \ell_i'} \sigma_{\ell_i \ell_i'} \overline{R}^2 \left[ n_i \ell_i A_i J_i, n_i (\ell_i + 1) A_i J_i \right] \bar{g}_{sh} (x_i, \ell_i + 1) \right. \]
\[ - \sum_{\ell_i \ell_i'} \sigma_{\ell_i \ell_i'} \overline{R}^2 \left[ n_i \ell_i A_i J_i, n_i (\ell_i - 1) A_i J_i \right] \bar{g}_{sh} (x_i, \ell_i - 1) \]
\[ - \sum_{\ell_i \ell_i'} \sigma_{\ell_i \ell_i'} \overline{R}^2 \left[ n_f \ell_f A_f J_f, n_f (\ell_f + 1) A_f J_f \right] \bar{g}_{sh} (x_f, \ell_f + 1) \]
\[ + \sum_{\ell_i \ell_i'} \sigma_{\ell_i \ell_i'} \overline{R}^2 \left[ n_f \ell_f A_f J_f, n_f (\ell_f - 1) A_f J_f \right] \bar{g}_{sh} (x_f, \ell_f - 1) \]
\[ + \left( \sum_{\ell_i} \overline{R}^2 \right)_{\Delta n \neq 0} g_{sh} (x_n, n_i + 1) - \]
\[ - 2 \sum_{\ell_i' (\Delta E_{\ell_i'} < 0)} \sum_{\ell_i \ell_i'} \overline{R}^2 \left[ n_i \ell_i A_i J_i, n_i \ell_i' A_i J_i' \right] g_{sh} (x_i, \ell_i') \]
\[ - \left( \sum_{\ell_i' \ell_i'} \overline{R}^2 \right)_{\Delta n \neq 0} g_{sh} (x_n, n_i + 1) \]
\[ + 2 \sum_{\ell_i' (\Delta E_{\ell_i'} < 0)} \sum_{\ell_i \ell_i'} \overline{R}^2 \left[ n_f \ell_f A_f J_f, n_f \ell_f' A_f J_f' \right] g_{sh} (x_f, \ell_f') + \sum_k \delta_k \right\} \]
where the initial level is denoted as \( i \) and the final one as \( f \) and the square of the
\[ \overline{R}^2 \left[ n_k \ell_k A_k J_k, n_k (\ell_k \pm 1) A_k J_k' \right] = \frac{\ell_\ell}{2 J_k + 1} Q [\ell_k A_k, (\ell_k \pm 1) A_k'] Q (J_k, J_k' [P_n^k (\ell_k \pm 1)]^2. \]
Also, \( \ell_\ell = \text{max} (\ell_k, \ell_k \pm 1) \) and
\[ \left( \sum_{\ell_i} \overline{R}^2 \right)_{\Delta n \neq 0} = \left( \frac{3n_k^*}{2 \pi} \right)^2 \frac{1}{9} (n_k^* 2 + 3 \ell_k^2 + 3 \ell_k + 11). \]
In Eqs. (1) and (2)
\[ x_{\ell_k \ell_k'} = \frac{E}{\Delta E_{\ell_k \ell_k'}}, \quad k = i, f; \]
and \( E = \frac{3}{2} kT \) is the electron kinetic energy and \( \Delta E_{\ell_k \ell_k'} = |E_{\ell_k} - E_{\ell_k'}| \) is the
energy difference between levels \( \ell_k \) and \( \ell_k \pm 1 (k = i, f), \)
\[ x_{n_k, n_k + 1} \approx \frac{E}{\Delta E_{n_k, n_k + 1}}. \]
where for $\Delta n \neq 0$, the energy difference between energy levels with $n_k$ and $n_k + 1$, $\Delta E_{n_k,n_k+1}$ is estimated as $\Delta E_{n_k,n_k+1} \approx 2Z^2E_H/n_k^3$. $n_k^* = [E_H Z^2/(E_{\text{ion}} - E_k)]^{1/2}$ is the effective principal quantum number, $Z$ is the residual ionic charge (for example $Z = 1$ for neutrals) and $E_{\text{ion}}$ is the appropriate spectral series limit.

If we have an oscillator strength, e.g. from literature, the corresponding matrix element may be calculated as

$$\tilde{\mathbf{R}}^2_{k,k'} \approx \frac{E_H}{E_k'} - E_k - \frac{k'}{2k + 1} \cdot f_{k'k} \quad (E_k' > E_k), \quad k = i, f$$

or

$$\tilde{\mathbf{R}}^2_{k,k'} \approx \frac{E_H}{E_k'} - E_k - \frac{k'}{2k + 1} \cdot f_{k'k} \quad (E_k' < E_k), \quad k = i, f$$

where $f_{k'k}$ (for $E_k' > E_k$) and $f_{k'k}$ (for $E_k' < E_k$) are oscillator strengths and $E_H$ is the hydrogen ionization energy.

Possible configuration mixing may be taken into account (see e.g., Ref. [15]) if one represents $\tilde{\mathbf{R}}^2_{\alpha\beta}$ as

$$\tilde{\mathbf{R}}^2_{\alpha\beta} = K_{\alpha} \cdot \tilde{\mathbf{R}}^2_{\alpha'\alpha} + K_{\beta} \cdot \tilde{\mathbf{R}}^2_{\beta'\beta},$$

where $K_{\alpha}$ and $K_{\beta}$ are mixing coefficients for two configurations and $K_{\alpha} + K_{\beta} = 1$.

In Eqs. (1–4) $N$ and $T$ are electron density and temperature, respectively, while $Q(A, \ell' A')$ and $Q(J, J')$ are multiplet and line factors. The value of $A$ depends on the coupling approximation (see e.g., [15]). In the case of the $LS$ coupling approximation, applied here, $A = L$, for the $jK$ approximation $A = K$ and for the $jj$ approximation $A = j$. The $[R^2_{n_k,t_k}]$ is the radial integral, and with $g(x)$ [7], $\tilde{g}(x)$ [11] and $g_{sh}(x)$ [7], $\tilde{g}_{sh}(x)$ [14] are denoted the corresponding Gaunt factors for width and shift, respectively. The factor $\sigma_{kk'} = (E_{k'} - E_k)/(E_{k'} - E_k)$, where $E_k$ and $E_{k'}$ are the energy of the considered and its perturbing level. The sum $\sum_k \delta_k$ is different from zero only if perturbing levels with $\Delta n \neq 0$ strongly violating the assumed approximations exist, so that they should be taken into account separately, and may be evaluated as

$$(3) \quad \delta_i = \pm \tilde{\mathbf{R}}^2_{i',i} \left[ g_{sh} \left( \frac{E}{\Delta E_{i,i'}} \right) \mp g_{sh} (x_{n_i,n_i+1}) \right],$$

for the upper level, and

$$(4) \quad \delta_f = \mp \tilde{\mathbf{R}}^2_{f,f'} \left[ g_{sh} \left( \frac{E}{\Delta E_{f,f'}} \right) \mp g_{sh} (x_{n_f,n_f+1}) \right],$$

for the lower level. In eqs. (3) and (4) the lower signs correspond to $\Delta E_{kk'} < 0$, $k = i, f$.

In comparison with the full semiclassical approach [5–10] and the Griem’s semiempirical approach [18] who needs practically the same set of atomic data as the more sophisticated semiclassical one, the modified semiempirical approach [11–17] needs a considerably smaller number of such data. In fact, if there are no perturbing levels strongly violating the assumed approximation, for e.g. the line
width calculations, we need only the energy levels with $\Delta n = 0$ and $\ell_{i,f} = \ell_{i,f} \pm 1$, since all perturbing levels with $\Delta n \neq 0$, needed for a full semiclassical investigation or an investigation within the Griem’s semiempirical approach [18], are lumped together and approximately estimated. Here, $n$ is the principal and $\ell$ the orbital angular momentum quantum numbers of the optical electron and with $i$ and $f$ are denoted the initial and final state of the considered transition.

Due to the considerably smaller set of needed atomic data in comparison with the complete semiclassical [5–10] or Griem’s semiempirical [18] methods, the MSE method is particularly useful for stellar spectroscopy depending on very extensive list of elements and line transitions with their atomic and line broadening parameters where it is not possible to use sophisticated theoretical approaches in all cases of interest.

The MSE method is also very useful whenever line broadening data for a large number of lines are required, and the high precision of every particular result is not so important like e.g. for opacity calculations or plasma modeling. Moreover, in the case of more complex atoms or multiply charged ions the lack of the accurate atomic data needed for more sophisticated calculations, makes that the reliability of the semiclassical results decreases. In such cases the MSE method might be very interesting as well.

For the astrophysical purposes, of particular interest might be the simplified semiempirical formula [13] for Stark widths of isolated, singly, and multiply charged ion lines applicable in the cases when the nearest atomic energy level ($j' = i'$ or $f'$) where a dipolly allowed transition can occur from or to initial ($i$) or final ($f$) energy level of the considered line, is so far, that the condition $x_{j,j'} = E/(E_{j'} - E_j) \leq 2$ is satisfied. In such a cases full width at half maximum is given by the expression [13]:

$$W(\AA) = 2.2151 \times 10^{-8} \frac{\lambda^2(\text{cm})N(\text{cm}^{-3})}{T^{1/2}(\text{K})} \left(0.9 - \frac{1.1}{Z}\right) \sum_{j=i,f} \frac{(3n_j^* - \ell_j^2 - \ell - 1)}{2n_j^*} \left(n_j^* - \ell_j^2 - \ell - 1\right).$$

Here, $N$ and $T$ are the electron density and temperature respectively, $E = 3kT/2$ is the energy of perturbing electron, $Z - 1$ is the ionic charge and $n$ the effective principal quantum number. This expression is of interest for abundance calculations, as well as for stellar atmospheres research, since the validity conditions are often satisfied for stellar plasma conditions.

Similarly, in the case of the shift

$$d(\AA) = 1.1076 \times 10^{-8} \frac{\lambda^2(\text{cm})N(\text{cm}^{-3})}{T^{1/2}(\text{K})} \left(0.9 - \frac{1.1}{Z}\right) \frac{9}{4Z^2} \sum_{j=i,f} \frac{n_j^2 \ell_j}{2\ell_j + 1} \left\{ (\ell_j + 1)[n_j^* - (\ell_j + 1)^2] - \ell_j (n_j^* - \ell_j^2) \right\}.$$
If all levels $\ell_{ji,f} \pm 1$ exist, an additional summation may be performed in Eq. (5) to obtain

$$d(\text{Å}) = 1.1076 \times 10^{-8} \frac{\lambda^2 (\text{cm}) N(\text{cm}^{-3})}{T^{1/2}(K)} \left(0.9 - \frac{1.1}{Z} \right) \frac{9}{4Z^2} \times \sum_{j=i,f} n_j^2 \varepsilon_j + 1 \left(n_j^2 - 3\ell_j^2 - 3\ell_j - 1\right),$$

where $\varepsilon_j = +1$ if $j = i$ and $-1$ if $j = f$.

The modified semiempirical approach has been tested several times on numerous examples. In order to test this method, critically selected experimental data for 36 multiplets (7 different ion species) of doubly- and 7 multiplets (4 different ion species) of triply-charged ions were compared with theoretical line widths. The averaged values of the ratios of measured to calculated widths are as follows [11]: for doubly charged ions $1.06 \pm 0.32$ and for triply-charged ions $0.91 \pm 0.42$. The assumed accuracy of the MSE approximation is about $\pm 50\%$, but it has been shown in Refs. [16] and [17] that the MSE approach, even in the case of the emitters with very complex spectra (e.g., Xe II and Kr II), gives very good agreement with experimental measurements (in the interval $\pm 30\%$). For example for Xe II, $6s-6p$ transitions, the averaged ratio between experimental and theoretical widths is $1.15 \pm 0.5$ [16].

In order to complete as much as possible the needed Stark broadening data, Belgrade group (Milan S. Dimitrijević, Lukać Popović, Vladimir Kršljunin, Dragan Tankosić, Nenad Milovanović and Zoran Simić) used the modified semiempirical method to obtain the Stark width and in some cases shift data for a large number of spectral lines for the different atom and ion species. Up to now:

- 6 Fe II, 4 Pt II, 16 Bi II, 12 Zn II, 8 Cd II, 18 As II, 10 Br II, 18 Sb II, 8 I II, 20 Xe II, 138 Ti II, 3 La II, 16 Mn II, 14 V II, 6 Eu II, 37 Kr II, 6 Y II, 6 Sc II, 4 Be III, 4 B III, 13 S III, 8 Au II, 8 Zr II, 53 Ra II, 3 Mn III, 10 Ga III, 8 Ge III, 4 As III, 3 Se III, 6 Mg III, 6 La III, 5 Sr III, 8 V III, 210 Ti III, 9 C III, 7 N III, 11 O III, 5 F III, 6 Ne III, 8 Na III, 10 Al III, 5 Si III, 3 P III, 16 CI III, 6 Ar III, 30 Zr III, 2 B IV, Cu IV, 30 V IV, 14 Ge IV, 7 C IV, 4 N IV, 4 O IV, 2 Ne IV, 4 Mg IV, 7 Si IV, 3 P IV, 2 S IV, 2 Cl IV, 4 Ar IV, 3 C V, 50 O V, 12 F V, 9 Ne V, 3 Al V, 6 Si V, 11 N VI, 28 F VI, 8 Ne VI, 7 Na VI, 15 Si VI, 6 P VI, and 1 Cl VI transitions have been calculated (see Ref. [17] and references therein). The shift data for 16 Bi II, 12 Zn II, 8 Cd II, 18 As II, 10 Br II, 18 Sb II, 8 I II, 20 Xe II, 5 Ar II, 6 Eu II, 14 V II, 8 Au II, 14 Kr II and 138 Ti II transitions have been calculated (see Ref. [17] and references therein). Moreover, 286 Nd II Stark widths have been calculated within the simplified modified semiempirical approach.

Calculations within the modified semiempirical approach, for comparison with experimental data or testing of the theory have been performed also for Stark widths for 14 Al I, 46 Al II, 12 Al III, 1 C IV, 1 N V, 1 O VI, 1 Ne VIII, 3 N III, 3 O IV, 3 F V, 2 Ne VI, 12 C IV, 4 C II, 5 N II, 3 O II, 4 F II, 3 Ne II, 1 N II, 8
The modified semiempirical method and Stark broadening parameters calculated within this approach have been applied in astrophysics e.g. for the determination of carbon, nitrogen and oxygen abundances in early B-type stars magnesium, aluminium and silicon abundances in normal late-B and HgMn stars, from co-added IUE spectra and elemental abundances in hot white dwarfs, investigations of abundance anomalies in stars, elemental abundance analyses with DAO spectrograms for 15-Vulpeculae and 32-Aquarii, radiative acceleration calculation in stellar envelopes, consideration of radiative levitation in hot white dwarfs, quantitative spectroscopy of hot stars, non-LTE calculations of silicon - line strengths in B-type stars, stellar opacities calculations and study, atmospheres and winds of hot stars investigations, investigation of Ga II lines in the spectrum of Ap stars. Stark broadening data calculated within the modified semiempirical method entered in a critical overview of atomic data for stellar abundance analysis, and a catalogue of atomic data for low-density astrophysical plasma, design and development of new lasers, spectroscopic diagnostics of railgun plasma armatures, 3d photoabsorption investigations in Zn III, Ge IV, Zn II, Ga III and Ge IV, Stark broadening parameter regularities and systematic trends research, radiative emission coefficients calculations for thermal plasmas, plasma-wall contact considerations, particle-velocity distribution and expansion of a surface flashover plasma examined in the presence of magnetic fields... The modified semiempirical method entered also in computer codes, as e.g. OPAL opacity code, handbooks and monographs.

In order to make the application and usage of our Stark broadening data obtained within the semiclassical and modified semiempirical approaches more easier, we are organizing them now in a database BELDATA.

At the end, it is interesting to emphasize that the Stark broadening research is a developed research field in Yugoslavia, which has a critical mass of scientists. In Ref. [19] reviewing spectral line shapes investigations in Yugoslavia and Serbia within 1962–2000 period, it is shown that during this period 1427 (1222 by serbian authors) bibliographic items have been published by 179 Yugoslav authors (152 from Serbia, 26 from Croatia and 1 living in France). Majority of these articles concern Stark broadening.

References


