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Astronomical spectra and collisions with charged particles

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Abstract. We analyze here the significance of Stark broadening for analyzis, interpretation and synthesis of stellar spectra, and analyzis, diagnostics and modeling of stellar plasma. It was considered for which types of stars and for which investigations Stark broadening is significant and methods for theoretical determination of Stark broadening parameters are discussed. Such investigations on Belgrade Astronomical Observatory are reviewed as well.

Key words. Stark broadening, line profiles, stellar atmospheres, white dwarfs, radio recombination lines, neutron stars, atomic data, data bases

1. Introduction

By analysis of stellar spectral lines, we can determine their temperatures, the temperature in particular atmospheric layers, the chemical composition of stellar plasma, surface gravity. We can understand better nuclear processes in stellar interiors, and determine the spectral type and effective temperature by comparing the considered stellar spectrum with the standard spectra for particular types.

In comparison with laboratory plasma sources, plasma conditions in astrophysical plasmas are exceptionally various. So that line broadening due to interaction between absorber/emitter and charged particles (Stark broadening) is of interest in astrophysics in plasmas of such extreme conditions like in the interstellar molecular clouds or neutron star atmospheres.

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In interstellar molecular clouds, typical electron temperatures are around 30 K or smaller, and typical electron densities are 2-15 cm^{-3}. In such conditions, free electrons may be captured (recombination) by an ion in very distant orbit with principal quantum number (n) values of several hundreds and deexcite in cascade to energy levels n-1, n-2,... radiating in radio domain. Such distant electrons are weakly bounded with the core and may be influenced by very weak electric microfield, so that Stark broadening may be important.

In interstellar ionized hydrogen clouds, electron temperatures are around 10 000 K and electron density is of the order of $10^4 cm^{-3}$. Corresponding series of adjacent radio recombination lines originating from energy levels with high (several hundreds, even more than thousand) n values are influenced by Stark broadening.

For temperatures larger than around 10 000 K, hydrogen, the main constituent of stellar atmospheres is mainly ionized, and among collisional broadening mechanisms for spectral lines, the dominant is the Stark effect. This is the case for white dwarfs and hot stars in particular of A and late B types, since due to high temperature, stars of O and early B types have smaller surface gravity so that the electron density is smaller. Even in cooler star atmospheres as e.g. Solar one, Stark broadening may be important, since the influence of Stark broadening within a spectral series increases with the increase of the principal quantum number of the upper level, and also in subphotospheric layers electron density and temperature increase and Stark broadening becomes dominant.

The density and temperature range of interest for the radiative envelopes of A and F stars is $10^{14}\mathrm{m}^{-3} \leq \mathrm{N}_e \leq 10^{16}\mathrm{m}^{-3}$; $10^4 \leq \mathrm{T} \leq 4\ 10^5$ (Stehleé 1994).

White dwarfs of DA and DB type have effective temperatures between around 10 000 K and 30 000 K so that Stark broadening is of interest for their spectra investigation and plasma research, analysis and modeling. Spectra of DA white dwarfs are characterized by broad hydrogen lines, while those of DB white dwarfs are dominated by the lines of neutral helium. White dwarfs of DO type have effective temperatures from approximately 45000 up to around 120 000 (Dreizler and Werner 1996) and Stark broadening may be very important for the investigation of their spectra (Hamdi et al. 2008).

For applications of results of Stark broadening investigations, very interesting are PG1159 stars, hot hydrogen deficient prewhite dwarfs, with effective temperatures ranging from T_{eff} = 100 000 K to 140 000 K, where of course Stark broadening is very important (Werner et al. 1991). These stars have high surface gravity (log g= 7), and their photospheres are dominated by helium and carbon with a significant amount of oxygen present (C/He = 0.5 and O/He = 0.13) (Werner et al. 1991). Their spectra, strongly influenced by Stark broadening, are dominated by He II, C IV, O VI and N V lines.

The densities of matter and electron concentrations and temperatures in atmospheres of neutron stars are orders of magnitude larger than in atmospheres of white dwarfs, and are typical for stellar interiors. Surface temperatures for the photospheric emission are of the order of 10^6 - 10^7 K, and electron densities of the order of 10^{24} cm^{-3} (Paerels 1997).

In this work we will consider the significance of Stark broadening for investigations of astrophysical plasma and some results obtained in the Group for Astrophysical Spectroscopy on Belgrade Astronomical Observatory.

2. Stellar plasma research

Line shapes enter in the modelisation of stellar atmospheric layers by the determination estimation of the quantities such as absorption coefficient κ_ν, Rosseland optical depth τ_{Ross} and the total opacity cross-section per atom σ_ν.

Let we take the direction of gravity as z-direction, dealing with a stellar atmosphere. If the atmosphere is in macroscopic mechanical equilibrium and with *rho* is denoted gas density, the optical depth is

$$\tau_\nu = \int_z^\infty \kappa_\nu \rho dz, \tag{1}$$

$$\kappa_\nu = N(A,i)\phi_\nu \frac{\pi e^2}{mc} f_{ij}, \tag{2}$$

where κ_ν is the absorption coefficient at a frequency ν, $N(A,i)$ is the volumic density of radiators in the state i, f_{ij} is the absorption oscillator strength, m is the electron mass and ϕ_ν spectral line profile. The total opacity cross-section per atom is

$$\sigma_\nu(op) = M\kappa_\nu, \tag{3}$$

where M is the mean atom mass, and the opacity per unit length is

$$\rho\kappa_\nu = N\sigma_\nu(op), \tag{4}$$

Let us introduce an independent variable, a mean optical depth

$$\tau_{Ross} = \int_z^\infty \kappa_{Ross} \rho dz. \tag{5}$$

For the Rosseland mean optical depth τ_{Ross}, κ_{Ross} is defined as

$$\frac{1}{\kappa_{\rm Ross}}\int_0^\infty \frac{dB_\nu}{dT}d\nu = \int_0^\infty \frac{1}{\kappa_\nu}\frac{dB_\nu}{dT}d\nu, \quad (6)$$

where

$$B_\nu(T) = \frac{2h\nu^3}{c^2}(e^{h\nu/kT} - 1)^{-1}. \quad (7)$$

Now the Rosseland-mean opacity cross-section is

$$\sigma_{Ross} = M\kappa_{Ross}. \quad (8)$$

Stark broadening parameters are needed as well for the determination of the chemical composition of stellar atmospheres i.e. for stellar elemental abundances determination. The method which uses synthetic and observed spectra and adjustment of atmospheric model parameters to obtain the best agreement is well developed and applied to many stars. It has been found that exist chemically peculiar stars especially within the spectral class interval F0-B2 (see e.g. (Khokhlova 1994)) with abundances for particular elements for several order of magnitude different from solar ones. It has been found as well that the CP stars surface is chemically inhomogeneous so that local chemical composition depending on coordinates on the stellar surface has been introduced. Such anomalies are explained mainly by diffusion mechanism occurring in stellar envelopes and (or) atmospheres and differences in radiative acceleration of particular elements (LeBlanc and Michaud 1995). The radiative acceleration g_r at ν, in the frequency interval $d\nu$, acting on the element A (with density $N(A)$ and mass m_A) is (Stehlé 1995)

$$m_A g_r = \frac{\kappa_\nu(A)}{N(A)}\Phi_\nu\frac{d\nu}{c}, \quad (9)$$

where $\kappa_\nu(A)$ is the contribution of A to the monochromatic absorption coefficient, and Φ_ν the radiative flux. In the opaque envelope of the radius r, the radiative flux is approximately equal to (Stehlé 1995)

$$\Phi_\nu = \frac{4\pi}{3}\frac{1}{\rho\kappa_\nu}\frac{\partial B_\nu}{\partial T}(\frac{-\partial T}{\partial r}), \quad (10)$$

$$\kappa_\nu = \kappa_\nu(A) + \kappa_{rest}, \quad (11)$$

where κ_{rest} are other contributions to the total absorption coefficient apart $\kappa_\nu(A)$. The majority of CP stars are A and B type stars where Stark broadening is the main pressure broadening mechanism.

With the improved sensitivity of space born X-ray instruments, spectral lines originating from neutron star atmospheres are of increasing interest. Since the characteristic density in the atmosphere is directly proportional to the acceleration of gravity at the stellar surface, measurement of the pressure broadening of absorption lines will yield a direct measurement of M/R^2, where M and R are the stellar mass and radius. When this is coupled with a measurement of the gravitational redshift (proportional to M/R) in the same, or any other, line or set of lines, the mass and radius can be determined separately. These mass and radius measurements do not involve the distance to star, which is usually poorly determined, or the size of the emitting area (Paerels 1997).

The Stark width for a hydrogen - dominated plasma ($z = 1, N_{pert} = N_e, \mu = 1/2$), assuming that electron and proton broadening are comparable in the static approximation (Griem et al. 1979) is (Paerels 1997)

$$W_{Stark}[eV] = 163 \cdot Z^{-1} M_{1.4}^{2/3} R_6^{-4/3} T_6^{-2/3} \mathrm{eV}. \quad (12)$$

Here, Z is the ionic nuclear charge, $M_{1.4}$ the stellar mass in units of 1.4 solar masses, R_6 the radius in units of 10^6 cm, and T_6 the atmospheric temperature in units of 10^6 K.

In Paerels (1997) a typical Stark width of 20 eV has been found for H-like oxygen Lyα, and a Stark width of 60 eV has been predicted for oxygen Lyβ.

3. Application of the semiclassical method for Stark broadening investigation on Belgrade Astronomical Observatory

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 Dimitrijević and Sahal-Bréchot (1996)). An example of the contribution of the Group for Astrophysical Spectroscopy on Belgrade Astronomical Observatory is the first calculation of Stark broadening parameters within the quantum mechanical strong coupling method for a nonhydrogen neutral emitter for Li I 2s ^{2}S - 2p ^{2}P^o transition (Dimitrijević et al. 1981).

In a lot of cases such as e.g. complex spectra, heavy elements or transitions between highly excited energy levels, the more sophysticated 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.

In order to complete as much as possible Stark broadening data needed for astrophysical and laboratory plasma research and stellar opacities determinations, we have performed in a series of papers large scale calculations of Stark broadening parameters for a number of spectral lines of various emitters (see e.g. (Dimitrijević and Sahal-Bréchot 1996) references therein and (Jevremović et al. 2009)), within the semiclassical perturbation formalism (Sahal-Bréchot 1969a,b) optimized and updated several times ((Fleurier et al. 1977; Dimitrijević and Sahal-Bréchot 1984, 1996) and references therein), for transitions when a sufficiently complete set of reliable atomic data exists and a good accuracy of obtained results is expected.

Up to now are published Stark broadening parameters for 79 He, 62 Na, 51 K, 61 Li, 25 Al, 24 Rb, 3 Pd, 19 Be, 270 Mg, 31 Se, 33 Sr, 14 Ba, 189 Ca, 32 Zn, 6 Au, 48 Ag, 18 Ga, 70 Cd I, 9 Cr I, 4 Te I, 25 Ne I, 28 Ca II, 30 Be II, 29 Li II, 66 Mg II, 64 Ba II, 19 Si II, 3 Fe II, 2 Ni II, 22 Ne II, 5 F II, 1 Cd II, 1 Kr II, 2 Ar II, 7 Cr II, 12 B III, 23 Al III, 10 Sc III, 27 Be III, 5 Ne III, 32 Y III, 20 In III, 2 Tl III, 5 F III, 2 Ne IV, 10 Ti IV, 39 Si IV, 90 C IV, 5 O IV, 114 P IV, 2 Pb IV, 19 O V, 30 N V, 25 C V, 51 P V, 34 S V, 16 Si V, 26 V V, 26 Ne V, 30 O VI, 21 S VI, 2 F VI, 15 Si 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 particular spectral lines and multiplets.

The obtained semiclassical result have been compared with critically selected experimental data for 13 He I multiplets (Dimitrijević and Sahal-Bréchot 1985). The agreement between experimental and semiclassical calculations is within the limits of ± 20%, that is the predicted accuracy of the semiclassical method (Griem 1974).

4. Application of semiclassical Stark broadening parameters for the consideration of its influence on stellar spectral lines

In a number of papers, the influence of Stark broadening on Au II (Popović et al. 1999a), Co III (Tankosić et al. 2003), Ge I (Dimitrijević et al. 2003a), Ga I (Dimitrijević et al. 2004), Cd I (Simić et al. 2005) and Te I (Simić et al. 2009) on spectral lines in chemically peculiar A type stellar atmospheres was investigated and for each investigated spectrum are found atmospheric layers where the contribution of this broadening mechanism is dominant or could not be neglected. In mentioned papers as the model for a chemically peculiar star atmosphere of A type star was used model with plasma conditions close to χ Lupi HgMn star of Ap type. Such investigations were also performed for DA, DB and DO white dwarf atmospheres (Popović et al. 1999a; Tankosić et al. 2003; Hamdi et al. 2008) and it was found that for such stars Stark broadening is dominant compared to Doppler in practically all relevant atmospheric layers.

As an example of the influence of Stark broadening in atmospheres of hot stars in Fig. 1 is given Stark widths for Te I 6s ^{5}S^o - 6p ^{5}P (9903.9 Å) multiplet (Simić et al. 2009) compared with Doppler widths for a model (T$_{eff}$=10000 K, log g= 4.5) of A type star atmosphere (Kurucz 1979). Namely Doppler broadening is in hot atmospheres an important concurrent broadening mechanism and by comparison of Stark and Doppler widths one

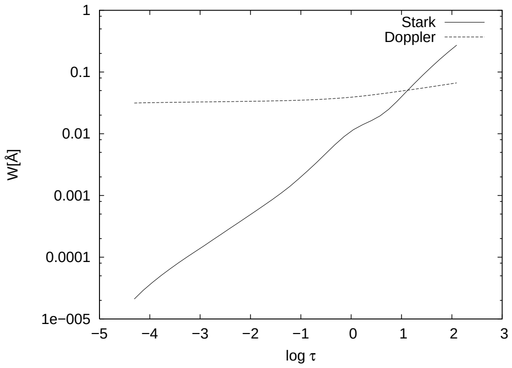

Fig. 1. Thermal Doppler and Stark widths for Te I 6s $^5S^o$ - 6p ^5P (9903.9 Å) multiplet as functions of optical depth for an A type star (T_{eff} = 10000 K, log g = 4.5).

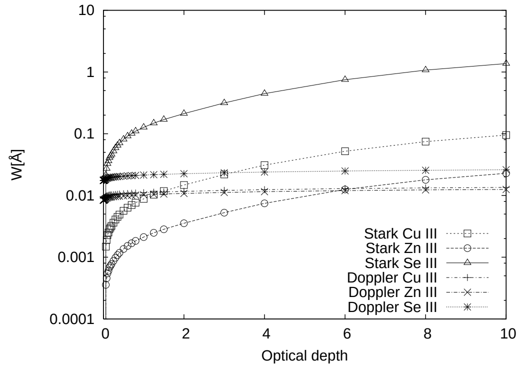

Fig. 2. Thermal Doppler and Stark widths for Cu III 4s ^{2}F - 4p ^{2}G^o (λ=1774.4 Å), Zn III 4s ^{3}D - 4p ^{3}P^o (λ=1667.9 Å) and Se III 4p5s ^{3}P^o - 5p ^{3}D (λ=3815.5 Å) spectral lines for a DB white dwarf atmosphere model with T_{eff} = 15,000 K and *log* g = 7, as a function of optical depth τ_{5150}.

can conclude on the importance of this mechanism. One should take into account however, that due to differences in Gauss distribution function for Doppler profile and Lorentz distribution for Stark, even if the Stark width is smaller, this broadening mechanism may influence line wings. Our results are presented in Fig. 1 as a function of Rosseland optical depth - log τ. One can see that the Stark broadening mechanism is absolutely dominant in comparison with the thermal Doppler mechanism in deeper layers of stellar atmosphere.

The influence of the Stark broadening on Cu III, Zn III and Se III spectral lines in DB white dwarf atmospheres was investigated also in Simić et al. (2006) for 4s ^{2}F - 4p ^{2}G^o (λ=1774.4 Å), 4s ^{3}D - 4p ^{3}P^o (λ=1667.9 Å) and 4p5s ^{3}P^o - 5p ^{3}D (λ=3815.5 Å) by using the corresponding model with T_{eff} = 15000 K and $\log g$ = 7 (Wickramasinghe 1972). For the considered model atmosphere of the DB white dwarfs the prechosen optical depth points at the standard wavelength λ_s=5150 Å(τ_{5150}) are used in Wickramasinghe (1972) and in Simić et al. (2006). As one can see in Fig. 2 for the DB white dwarf atmosphere plasma conditions, thermal Doppler broadening has much less importance in comparison with the Stark broadening mechanism. For example Stark width of the considered Se III 3815.5 Å line is larger than Doppler one up

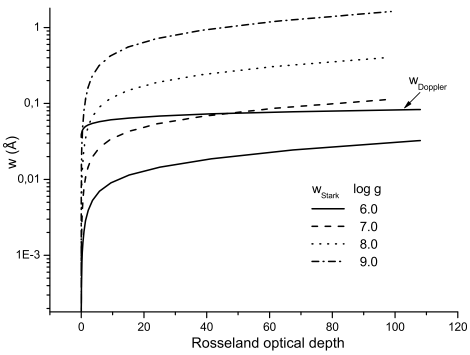

Fig. 3. Stark and Doppler width for Si VI 2p^4(^{3}P)3s ^{2}P-2p^4(^{3}P)3p ^{2}D^o(λ = 1226, 7Å) spectral line as a function of Rosseland optical depth. Stark and Doppler width are given for four models of DO white dwarfs with log g = 6–9 i T$_{eff}$ = 80 000 K.

to two orders of magnitude within the considered range of optical depths. Much larger Stark widths in DB white dwarf atmospheres in comparison with A type stars are the consequence of larger electron densities due to much larger $\log g$ and larger T_{eff}, so that electron-impact (Stark) broadening mechanism is more effective.

Hamdi et al. (2008) investigated the influence of Stark broadening on Si VI lines in

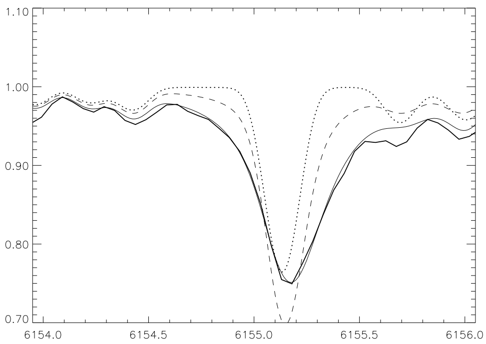

Fig. 4. A comparison between the observed Si I, 6155 Å line profile in the spectrum of Ap star 10 Aql (thick line) and synthetic spectra calculated with Stark widths and shifts from Table 1 in Dimitrijević et al. (2003b) and Si abundance stratification (thin line), with the same Stark parameters but for homogeneous Si distribution (dashed line), and with Stark width calculated by approximation formulae for the same stratification (dotted line).

DO white dwarf spectra for 50000 K ≤ T_{eff} ≤ 100000 K and 6 ≤ log g ≤ 9. It was found that the influence increases with log g and that is dominant in broad regions of the cosidered atmospheres (Fig. 3).

An example of the application of Stark broadening data in astrophysics may be found in Dimitrijević et al. (2003b) where the influence of Stark broadening and stratification on neutral silicon lines in spectra of normal late type A star HD 32115, and Ap stars HD 122970 and 10 Aql was investigated. They found that synthetic line profile of λ = 6155.13 Å Si I line fit much better to the observed one when it was calculated with Stark width and shift. Also authors reproduced the asymmetric and shifted profile of this line in HD 122970 reasonably well using the uniform distribution of neutral silicon and their results for Stark broadening parameters. Authors stressed that with their theoretical Stark broadening parameters the sensitivity of Si I λ 6155.13 Å asymmetry to Si abundance changes in the 10 Aql atmosphere, can be successfully used in empirical studies of abundance stratification. They found also that for considered Si I lines the contribution of electron impacts is dominant but, impacts with protons and He II ions should be taken into account as well.

Dimitrijević et al. (2007) have investigated Cr II lines in the spectrum of the Ap star HD 133792, for which careful abundance and stratification analysis has been performed (Kochukhov et al. 2006). HD133792 has an effective temperature of T_{eff}=9400 K, a surface gravity of log g = 3.7, and a mean Cr overabundance +2.6 dex relative to the solar Cr abundance (Kochukhov et al. 2006). All calculations were carried out with the improved version SYNTH3 of the code SYNTH for synthetic spectrum calculations. Stark broadening parameters were introduced in the spectrum synthesis code. The stratified Cr distribution in the atmosphere of HD133972 derived in Kochukhov et al. (2006) was used. Figure 5 shows a comparison between the observed line profiles of Cr II lines 3403.30 Å and synthetic calculations with the Stark damping constants from Kurucz (Kurucz 1993) line lists and with the data by Dimitrijević et al. (2007). Good agreement between observations and calculations for a set of weak Cr II lines proves the use of the stratified Cr distribution, while all four strong Cr II lines demonstrate a good accuracy for obtained theoretical Stark broadening parameters (Dimitrijević et al. 2007).

This opens a new possibility, to check the theoretical and experimental Stark broadening results additionally with the help of stellar spectra, which will be particularly interesting with the development of space born spectroscopy, building of giant telescopes of the new generation and increase of accuracy of computer codes for modellisation of stellar atmospheres. The Cr II lines analyzed in Dimitrijević et al. (2007) are particularly suitable for such purpose since they have clean wings where the influence of Stark broadening is the most important.

5. Modified semiempirical method for Stark broadening and astrophysical applications

The modified semiempirical (MSE) approach (Dimitrijević and Konjević 1980; Dimitrijević

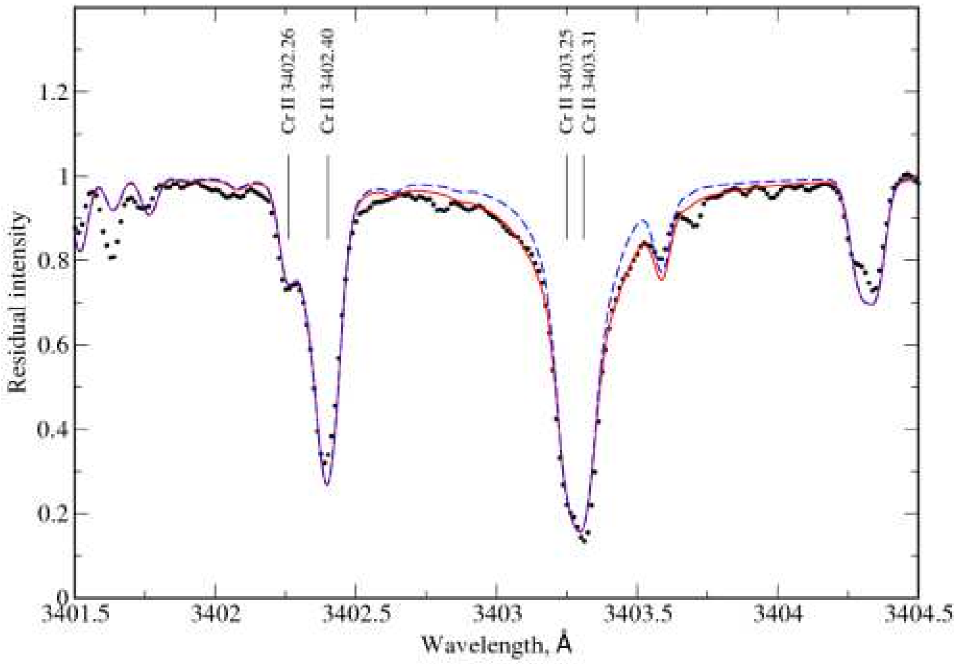

Fig. 5. Comparison between the observed Cr II 3403.30 line profile (dots) and synthetic calculations with the Stark parameters from paper by Dimitrijević et al. (2007) (full line) and those from Kurucz (1993) (dashed line).

and Kršljanin 1986; Dimitrijević and Konjević 1987; Dimitrijević and Popović 1993, 2001; Popović and Dimitrijević 1996a) for the calculation of Stark broadening parameters for non-hydrogenic ion spectral lines, has been applied successfully many times for different problems in astrophysics and physics.

In comparison with the full semiclassical approach (Sahal-Bréchot 1969a,b; Griem 1974) and the Griem's semiempirical approach (Griem 1968) who needs practically the same set of atomic data as the more sophysticated semiclassical one, the modified semiempirical approach 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 the difference of the principal quantum numbers n for the upper and lower level of transition forming the considered spectral line, $\Delta n = 0$, since all perturbing levels with $\Delta n \neq 0$, needed for a full semiclasical investigation or an investigation within the Griem's semiempirical approach (Griem 1968), are lumped together and approximately estimated.

Due to the considerably smaller set of needed atomic data in comparison with semiclassical and semiempirical methods (Sahal-Bréchot 1969a,b; Griem 1974, 1968), 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

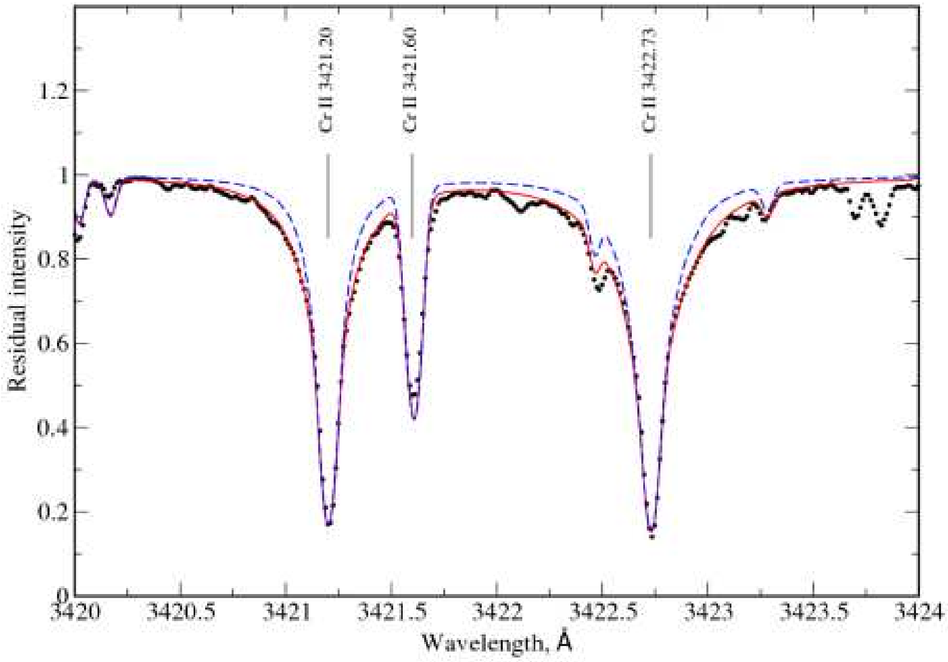

Fig. 6. The same as in Fig.5 but for the Cr II 3421.20, 3422.73 Å lines.

atoms or multiply charged ions the lack of the accurate atomic data needed for more sophysticated calculations, makes that the reliability of the semiclassical results decreases. In such cases the MSE method might be very interesting as well.

The modified semiempirical approach has been tested several times on numerous examples (Dimitrijević and Popović 2001). In order to test this method, selected experimental data for 36 multiplets (7 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 (Dimitrijević and Konjević 1980): for doubly charged ions 1.06 ± 0.32 and for triply-charged ions 0.91 ± 0.42. The assumed accuracy of the MSE method is about ±50%, but it has been shown in Popović and Dimitrijević (1996b), Popović and Dimitrijević (1998) and Popović et al. (2001a) 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 ± 30%.). For example for Xe II, 6s-6p transitions, the averaged ratio between experimental and theoretical widths is 1.15 ± 0.5 (Popović and Dimitrijević 1996b).

Stark widths, and in some cases also and shifts are determined for spectral lines of the following emitters/absorbers: Ar II, Fe II, Pt II, Bi II, Zn II, Cd II, As II, Br II, Sb II, I II, Xe II, Mn II, La II, Au II, Eu II, V II, Ti II, Kr II, Na II, Y II, Zr II, Sc II, Nd II, Be III, B III, S III, C III, N III, O III, F III, Ne III, Na III, Al III, Si III, P III, S III, Cl III, Ar III, Mn III, Ga III, Ge III, As III, Se III, Zn III, Mg III, La III, V III, Ti III, Bi III, Sr III, Cu III, Co III, Cd III, B IV, Cu IV, Ge IV, C IV, N IV, O IV, Ne IV, Mg IV, Si IV, P IV, S IV, Cl IV, Ar IV, V IV, Ge IV, C V, O V, F V, Ne V, Al V, Si V, N VI, F VI, Ne VI, Si VI, P VI and Cl VI.

An example of the application of the MSE method is the consideration of so called ”zirconium conflict” in χ Lupi star atmosphere (Popović et al. 2001a). Namely, the zirconium abundance determination from weak Zr II optical lines and strong Zr III lines (detected in UV) is quite different (see e. g. Sikström (1999)) in HgMn star χ Lupi. Sikström (1999) supposed that this difference is probably due to non adequate use of stellar models, e.g. if the influence of non-LTE effects or if diffusion is not taken into account.

In Popović et al. (2001a), the electron-impact broadening parameters calculation of two astrophysically important Zr II and 34 Zr III lines has been performed, in order to test the influence of this broadening mechanism on determination of equivalent widths and to discuss its possible influence on zirconium abundance determination. Obtained results have been used to see how much the electron-impact broadening can take part in so called "zirconium conflict" in the HgMn star χ Lupi.

Popović et al. (2001a) have calculated the equivalent widths with the electron-impact broadening effect and without it for different abundances of zirconium. The obtained results for ZrIII[194.0nm] and ZrII[193.8nm] lines show that the electron-broadening effect is more important in the case of higher abundance of zirconium. The equivalent width increases with abundance for both lines, but the equivalent width for ZrIII[194.0nm] line is more sensitive than for ZrII[193.8nm] line. It may cause error in abundance determination in the case when the electron-impact broadening effect is not taken into account. In any case synthesizing of these two lines in order to measure the zirconium abundance without taking into account the electron-impact widths will give that with the ZrIII[194.0nm] the abundance of zirconium is higher than with the ZrII[193.8nm] line. However, this effect cannot cause the difference of one order of magnitude in abundance. Although the "zirconium conflict" in HgMn star χ Lupi cannot be explained only by this effects, one should take into account that this effect may cause errors in abundance determination.

Another example of the applicability of MSE method in astrophysics is the investigation of rare earth element (REE) spectral lines in the spectra of CP stars. In Popović et al. (1999b), the Stark widths and shifts for six Eu II lines and widths for three La II and six La III multiplets have been calculated by using the MSE method. The influence of the electron-impact mechanism on line shapes and equivalent widths in hot star atmospheres has been considered. It has been shown that Stark broadening is significant in hot stars, and it should be taken into account in the analysis of stellar spectral lines for the $T_{eff} > 7000$ K, in particular if europium is overabundant.

In Popović et al. (2001b) Stark widths for 284 Nd II lines have been determined within the symplified MSE approach. The lines of Nd II are observed in spectra of CP stars as well as in spectra of other stars (see e.g. Cowley et al. (2000); Guthrie (1985); Adelman (1987), etc.). Due to conditions in stellar atmospheres, the Nd II lines are dominant in comparison with Nd I and Nd III lines, e.g. in spectra of HD101065, a roAp star, Cowley et al. (2000) found 71 lines of Nd II and only 6 and 7 lines of Nd I and Nd III, respectively.

It is the reason why for determination of Neodymium abundance in spectra of CP and other stars the Nd II lines are usually used. On the other side, due to complexity of Nd II spectrum, it is very difficult to obtain atomic data (oscillator strengths, Stark widths, etc.) needed for astrophysical purposes.

Popović et al. (2001b) used for Stark width calculation the simplified MSE approach of Dimitrijević and Konjević (1987). This formula gives better results than older approximate formula of Cowley (1971) often used for Stark width estimations when more sophisticated methods are not applicable.

In order to test the importance of the electron-impact broadening effect in stellar atmospheres, Popović et al. (2001b) have synthesized the line profiles of 38 Nd II lines using SYNTH code (Popović et al. 1999c) and the Kurucz's ATLAS9 code for stellar atmosphere models (Kurucz 1993) in the temperature range of $6000 \leq T_{eff} \leq 16000$ K, and $3.0 \leq \log g \leq 5.0$.

They have synthesized the line profiles with and without taking the electron-impact broadening mechanism for different types of stellar atmospheres. First, they have synthesized all considered line profiles for

Neodymium abundance of A = log[Nd/H]=-7.0, and two values of log g=4.0 and 4.5 for different effective temperatures (T_{eff}= 6000 – 16000). All considered lines have similar dependence on effective temperature.

In order to point out the type of stars where the electron-impact broadening effect is the most important, Popović et al. (2001b) summarized this influence in different types of stellar atmospheres, considering the minimal and maximal influence for all studied lines. They found that the most important influence of Stark broadening mechanism is in the A-type stellar atmospheres. Taking into account that Stark width depends on electron density, the effect is dominant in hot star atmospheres where electron density is higher, since hydrogen becomes ionized. However for stars of O and early B type the surface gravity is smaller and electron density decreases in spite of higher temperatures. Starting from the fact that ionization potential of Nd II is 10.73 eV and consequently the layers where Nd II ion density is maximal have electron temperature between 7000 K and 9000 K, Popović et al. (2001b) have calculated the averaged electron density in these layers of stellar atmosphere for different stellar types for log g=4.0 and they found that the averaged electron density decreases with effective temperature. This is the reason why the maximal influence of Stark broadening effect in the case of Nd II is in A-type stellar atmospheres.

6. Serbian Virtual Observatory, STARK-B Database and VAMDC FP7 project

Serbian virtual observatory (SerVO) is a new project whose objectives are to publish in VO compatible format data obtained by Serbian astronomers in order to make them accessible to scientific community, as well as to provide astronomers in Serbia with VO tools for their research. The project objectives are:

- establishing SerVO and join the EuroVO and IVOA;
- establishing SerVO data Center for digitizing and archiving astronomical data obtained at Belgrade Astronomical Observatory;
- development of tools for visualization of data.

One of the aims of this project, is to publish together with Observatoire de Paris, in collaboration with Sylvie Sahal-Bréchot, Marie Lise Dubernet and Nicolas Moreau, STARK-B - Stark broadening data base containing as the first step Stark broadening parameters obtained within the semiclassical perturbation approach by Sylvie Sahal-Bréchot and myself in VO compatible format, and make two mirror sites - in Paris and Belgrade.

In this database which is also included in the database MOLAT of Paris Observatory and in the European Virtual Atomic and Molecular Data centre (VAMDC) FP7 project, enter just Stark broadening data on which was written in this paper. We will note that the precursor of SerVO was BELDATA and its principal content was database on Stark broadening parameters. The history of BELDATA may be followed in Popović et al. (1999c,d); Milovanović et al. (2000); Dimitrijević et al. (2003c) and Dimitrijević and Popović (2006). After intensification of collaboration with French colleagues around MOLAT database of Paris observatory BELDATA became STARK-B. (see http://stark-b.obspm.fr/elements.php).

This database is dedicated for modellisation of stellar atmospheres, stellar spectra analysis and synthesis, as well as for laboratory plasma research, inertial fusion plasma, laser development and plasmas in technology investigations.

The simple graphical interface to the data is provided. User first chooses the element of interest from the periodic system of elements. After that the ionization stage, perturber (s), perturber density, transition and plasma temperature can be set and page with description of data and table with shifts and widths is generated.

This database enters also in european FP7 project Virtual Atomic and Molecular Data Centre - VAMDC. In Consortium are 15 institutions from 9 countries. Its objective is to build accessible and interoperable einfrastructure for atomic and molecular data upgrading and integrating extensive portfolio of database services and catering for the needs of variety of data users from academia and industry.

7. Conclusions

One can conclude that the multidisciplinary research field of Stark broadening of Spectral lines, gives many possibilities for scientific research. Such investigations in astronomy have and its conference in Serbia. I-III Yugoslav conference on spectral line shapes were organized 1995, 1997 and 1999, in Krivaja at Bačka Topola, Bela Crkva and Brankovac on Fruška Gora, IV Serbian conference on spectral line shapes in Arandjelovac 2003, and V-VII Serbian conference on spectral line shapes in astrophysics 2005, 2007 and 2009, in Vršac, Sremski Karlovci and Zrenjanin.

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