Influence of Collisions with Charged Particles on Astronomical Spectra

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Abstract. Collisions of emitters and absorbers with charged particles influence on the spectral line profiles of stellar plasma, due to splitting and shifting of atomic energy levels in electric field (Stark effect) resulting in broadening and shift of spectral lines. Here is analyzed the importance of Stark broadening for analyzis, interpretation and synthesis of stellar spectra, and analyzis, diagnostics and modeling of stellar plasma, and discussed the significance of such results in other research fields. 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
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INTRODUCTION

Collisions of emitter or absorber with charged particles result in broadedning and shift of spectral lines, since in electric field atomic energy levels are splitted and shifted. Since during collisions electric microfield vary, when we make an average in order to obtain the influence of an ansamble of perturbing charged particles we will obtain a distribution of line intensities as a function of wavelengths, i.e. a broadened line profile.

It is interesting how many data on stars we could obtain by analysis of their 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 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.

CONDITIONS IN ASTROPHYSICAL PLASMAS AND STARK BROADENING

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.

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 $10^{14}\ cm^{-3} \leq N_e \leq 10^{16}\ cm^{-3}$; $10^4\ K \leq T \leq 4\ 10^5\ K$ [1].

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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 K up to around 120 000 K [2] and Stark broadening may be very important for the investigation of their spectra [3].

For applications of results of Stark broadening investigations, very interesting are PG1159 stars, hot hydrogen deficient pre-white dwarfs, with effective temperatures ranging from T_{eff} = 100 000 K to 140 000 K, where of course Stark broadening is very important [4]. 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) [4]. 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} [5].

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.

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. [6]) 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 [7]. For the determination of radiative acceleration, line profiles are also needed [7] so that Stark broadening parameter data may be useful, in particular since the majority of CP stars are of A and B type where this broadening mechanism is of interest.

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 [8].

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 [8]). 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 ^2S - 2p $^2P^o$ transition [9].

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. [8] references therein and [10]), within the semiclassical perturbation formalism [11,12] optimized and updated several times ([13-15] 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 [16]. The agreement between experimental and semiclassical calculations is within the limits of ± 20%, what is the predicted accuracy of the semiclassical method [17].

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 [18], Co III [19], Ge I [20], Ga I [21], Cd I [22] and Te I [23] 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 [18,19,24] and it was found that for such stars Stark broadening is dominant compared to Doppler in practically all relevant atmospheric layers.

An example of the application of Stark broadening data in astrophysics may be Ref. [25] 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. [26] have investigated Cr II lines in the spectrum of the Ap star HD 133792, for which careful abundance and stratification analysis has been performed [27]. HD133792 has an effective temperature of $T_{\rm eff}$=9400 K, a surface gravity of log g = 3.7, and a mean Cr overabundance +2.6 dex relative to the solar Cr abundance [27]. 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 Ref. [27] was used. Figure 1 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 [28] line lists and with the data by Dimitrijević et al. [26]. 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 [26].

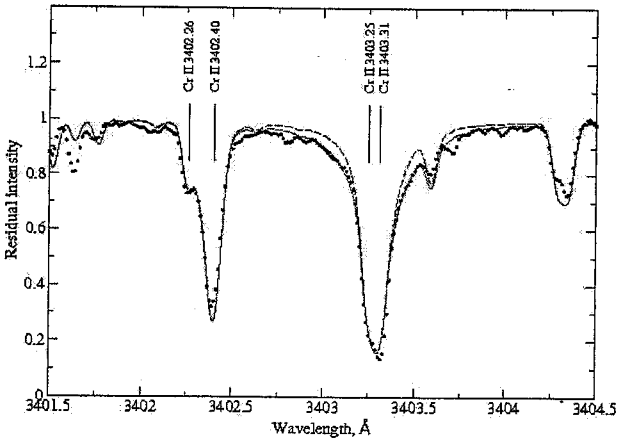

FIGURE 1. Comparison between the observed Cr II 3403.30 line profile (dots) and synthetic calculations with the Stark parameters from paper by Dimitrijević et al. [26] (full line) and those from Kurucz [28] (dashed line).

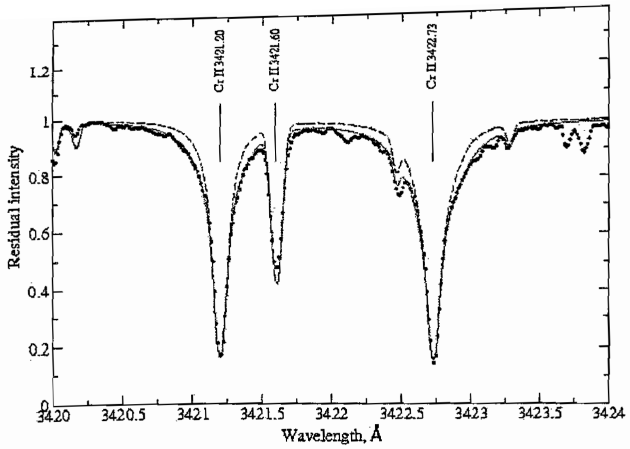

FIGURE 2. The same as in Fig.5 but for the Cr II 3421.20, 3422.73 Å lines.

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 Ref. [26] are particularly suitable for such purpose since they have clean wings where the influence of Stark broadening is the most important.

MODIFIED SEMIEMPIRICAL METHOD FOR STARK BROADENING AND ASTROPHYSICAL APPLICATIONS

The modified semiempirical (MSE) approach [29-34] 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 [11,12,17] and the Griem's semiempirical approach [35] 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 [35], are lumped together and approximately estimated.

Due to the considerably smaller set of needed atomic data in comparison with semiclassocal and semiempirical methods [11,12,17,35], 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 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 [33]. In order to test this method, selected experimental data for 36 multiplets (7 different ion species) of triply-charged ions were compared with theoretical linewidths. The averaged values of the ratios of measured to calculated widths are as follows [29]: 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 [36,37] and, Dimitrijević and Popović [38] 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 [36].

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 [38]. 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. [39]) in HgMn star χ Lupi. Sikström et al. [39] 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. [38], 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. [38] synthesized the line profiles of Zr II, λ=193.8 nm and Zr III, λ=194.0 nm using the stellar model with similar characteristics as in the case of χ Lupi (T_{eff}=10650 K and log g=3.8). These lines have been choosen, because they have been usually used for abundance determination, since they have small wavelength displacement and are well resolved.

Popović et al. [38] 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.

An other 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. [40], 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. [41] 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. [42-44], etc.). Due to conditions in stellar atmospheres, the Nd II lines are dominant in comparison with Nd I and Nd III lines. For example, in the spectrum of HD101065, a roAp star, Cowley et al. [42] found 71 lines of Nd II and only 6 and 7 lines of Nd I and Nd III, respectively. This 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 the corresponding atomic data (oscillator strengths, Stark widths, etc.) needed for astrophysical purposes.

Popović et al. [41] used for Stark width calculations of Nd II lines the simplified MSE approach of Dimitrijević and Konjević [31]. This formula gives better results than older approximate formula of Cowley [45] 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. [41] have synthesized the line profiles of 38 Nd II lines using SYNTH code [46] and the Kurucz's ATLAS9 code for stellar atmosphere models [28] 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 K). 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. [41] 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. [41] 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 the increase of effective temperature, for stellar types earlier than A. This is the reason why the maximal influence of Stark broadening effect in the case of Nd II is in A-type stellar atmospheres.

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. One part of it is the database on Stark broadening STARK-B, made together with French colleagues, containing, as the first step, Stark broadening parameters obtained by Sylvie Sahal-Bréchot and author of this article within the semiclassical perturbation approach during 30 yers of French-Serbian collaboration.

In this database which is aldso 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 Refs. [46-50]. 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).

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