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STARK BROADENING IN ASTROPHYSICS

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Abstract. Significance for astrophysical plasma research and modelling of broadening of spectral lines by collisions with charged particles, or Stark broadening, is considered and analyzed here, as well as the corresponding applications of Stark broadening data.This line broadening mechanism is particularly of interest e.g. for the research of white dwarfs and hot stars of A and B type, and for the analysis and synthesis of their spectra. For example, a large number of data is needed for calculations of stellar opacities and modeling and investigation of stellar atmospheres. Data on Stark broadening of spectral lines are also important for diagnostics and research of laboratory, fusion, laser produced and technological plasmas.

Also, we will review and consider some results of Stark broadening research on Belgrade Astronomical observatory, as well as the organization of Stark broadening data in STARK-B database, a part of VAMDC (Virtual Atomic and Molecular Data Center).

1. INTRODUCTION

In comparison with laboratory plasmas, the plasma conditions in astrophysical plasmas are incomparably more various, so that broadening due to interaction between emitter and charged particles (Stark broadening) is of interest in astrophysics in plasmas of such extreme conditions like in the interstellar molecular clouds (electron temperatures Te around 30 K or smaller, typical electron density, Ne, 2-15 cm^{-3}) or neutron star atmospheres (T is 10^6 - 10^7 K and Ne of the order of 10^{24} cm^{-3}).

Here, we will consider astrophysical importance of Stark broadening investigations, theoretical methods for the determination of Stark broadening parameters, namely Full Width at Half Maximum (FWHM) of intensity of spectral line (W) and the shift (d), and results obtained by us. Also, we will consider the organization of Stark broadening data, obtained by us in STARK-B database (http://stark-b.obspm.fr - Sahal-Bréchot et al. 2014b) which is a part of VAMDC (Virtual Atomic and Molecular Data Center - http://www.vamdc.eu/, see Dubernet et al. 2010 and Rixon et al. 2011), founded and developed as an FP-7 european project.

2. STARK BROADENING IN ASTROPHYSICS

The importance of Stark broadening data for stellar plasma research obviously follows from the fact that line profiles enter the modeling of stellar atmospheric layers since they are needed to determine the absorption coefficient κ_ν at a frequency ν, and the optical depth τ_ν. If the atmosphere is in macroscopic mechanical equilibrium and we denote with ρ the gas density, and with z the direction of gravity, 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 $N(A,i)$ is the volume density of radiators in the state i, f_{ij} is the absorption oscillator strength, m the electron mass and ϕ_ν spectral line profile, which, if plasma conditions are favorable, is influenced by Stark broadening mechanism.

In astrophysics, plasma conditions, favorable for Stark broadening, may be very different. For example in interstellar molecular clouds, where, as we stated earlier, typical Te are around 30 K or smaller, and typical Ne electron densities are 2-15 cm^{-3}, free electrons may be recombined in very distant orbit with principal quantum number (n) values of several hundreds and then deexcite in cascade to energy levels $n-1, n-2, ...$ radiating in radio domain. Since they are weakly bounded with the core, even very weak electric microfield may have a considerable influence, so that Stark broadening may be non-negligible. Similar situation is also in interstellar ionized hydrogen clouds, where Te are around 10 000 K and Ne is of the order of 10^4 cm^{-3}.

Favorable conditions for Stark broadening are also in atmospheres of hot stars. Namely, since for $T_{\rm eff} > 10^4$K, hydrogen, the main constituent of ordinary stellar atmospheres is mainly ionized, Stark broadening is the dominant among collisional broadening mechanisms for spectral lines. Such conditions are in atmospheres of white dwarfs and hot stars of O, B and A type. However, since Stark broadening depends not only on Te but also on Ne, the best conditions are in white dwarfs and in A-type stars, since towards B and O type, the temperature increases but electron density decreases. But Stark broadening may be of interest and for cooler stars, since its influence within a spectral series increases with the increase of the principal quantum number of the upper level and also is important for subphotospheric layers modelling and research.

Another type of astrophysical objects where Stark broadening is important are neutron stars, where 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}.

Of particular interest for Stark broadening applications in astrophysics are white dwarfs and the post Asymptotic Giant Branch (AGB) stars. AGB stars, with terminated hydrogen and helium but not carbon burning, forming a sequence of bright red giants. They are more luminous than the ordinary Red Giant Branch stars with electron-degenerate helium cores. AGB are often divided in AGB stars with carbon-oxygen cores and Super AGB, or SAGB, stars with heavier cores.

The principal division of white dwarfs is in the hydrogen-rich DA type, with spectra characterized by broade hydrogen lines and helium-rich DB type, with spectra dominated by neutral helium lines. Most of observed white dwarfs have the effective temperatures between around 8,000 K and 40,000 K so that Stark broadening is of interest for their spectra, particularly since the corresponding electron densities are much higher than in ordinary star atmospheres. White dwarfs cooled to so low effective temperatures that only continuum without helium or hydrogen lines is present in the spectrum, are of DC type. Sometimes, the spectra of DZ white dwarfs contain the lines of metal, introduced by accretion from the matter from outside. They are denoted as DZ, DAZ or DBZ type.

White dwarfs of DB type, now are divided in: DO type, with 40,000 K $< T_{eff} <$ 120,000 K (see e.g. Dreizler and Werner (1996), DB, with 12,000 K $< T_{eff} <$ 40,000 K, and DQ, with 4,000 K $< T_{eff} <$ 12,000 K (C lines and C_2 Swan band in the spectrum). The presence of carbon lines in the DQ white dwarfs is explained by convection from the deeper layers (Koester 2010).

We could add that in astrophysics, Stark broadening is of interest for many different problems, as for example for radiative transfer, opacity calculations, abundances, surface gravity and chemical composition determination, spectra analysis, interpretation and synthesis and astrophysical plasma modelling.

We note that for astrophysical applications we need an as much as possible large set of reliable Stark broadening data for, before not astrophysically important trace elements, due to development of space born spectroscopy. For example, according to Fontaine et al. (2008) FUSE Far Ultraviolet Spectroscopic Explorer satellite provided a great number of high resolution spectra within the wavelength range 907-1187 Å, associated with numerous ionization levels of several elements such as: C, N, O, Si, S, P, Cl, Ne, Ar, V, Mn, Cr, Fe, Co, Ni, Ge, As, Se, Zr, Te, I and Pb among others.

Researchers at Belgrade Astronomical observatory, investigated the influence of Stark broadening on Au II (Popović et al. 1999d), Zr II and Zr III (Popović et al. 2001a), Nd II (Popović et al. 2001b), Co III (Tankosić et al. 2003), Ge I (Dimitrijević et al. 2003a), Si I (Dimitrijević et al. 2003c), Ga I (Dimitrijević et al. 2004), Cd I (Simić et al. 2005), Cr II (Dimitrijević et al. 2007, Simić et al. 2013),Te I (Simić et al. 2009) and Nb III (Simić et al. 2014) spectral lines in the A type Star spectra, and found in all examined cases atmospheric layers where this broadening mechanism is of importance or at least should be taken into account. Investigating the influence of Stark broadening of rare-earth peak elements La II, La III, Eu II and Eu III, Popović et al. (1999c) found that serious errors in abundance determination for Ap stars occures if we neglect the Stark broadening contribution. In Dimitrijević et al. (2003c), the Si I lines in spectra of normal late type A star HD 32115, and Ap stars HD 122970 and 10 Aql have been investigated and it has been demonstrated that the synthetic profile of $\lambda = 6155.13$ Å Si I line fits much better with the observed one when Stark broadening is taken into account.

The significance of Stark broadening for DA, DB and DO white dwarfs, has been considered by Popović et al. 1999d, Tankosić et al. 2003, Milovanović et al. 2004, Simić et al. 2006, 2013, and Hamdi et al. 2008. it has ben shown that, for the difference from A typre stars, in the case of white dwarfs, Stark broadening is practically dominant in all atmospheric layers of interst.

Hamdi et al. (2008) analyzed Stark broadening of Si VI spectral lines for 50,000 K $\leq T_{eff} \leq$ 100,000 K and for $6 \leq \log g \leq 9$ DO white dwarf atmosphere models. It is shown that the influence of Stark broadening increases with log g and is dominant in broad atmospheric layers.

We note as well that for the interpretation and analysis of the newly discovered hot DQ white dwarfs with T_{eff} 18000 - 24000 K, and carbon atmospheres, we determined the corresponding Stark broadening parameters for C II lines (Dufour et al. 2011, Larbi-Terzi et al. 2012).

3. THEORETICAL METHODS

In the Group of Astrophysical Spectroscopy, we use for the calculation of Stark broadening parameters the semiclassical perturbation method (Sahal-Bréchot, 1969a,b). which for the full width at half-maximum intensity (FWHM), W, and the shift, d, of a Stark broadened line gives the expression (Sahal-Bréchot, 1969a,b, see also Sahal-Bréchot et al. 2014a):

$$W = N_P \int v f(v) dv \left(\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} \right). \tag{1}$$

Here, the perturbing levels of the initial level i and the final level f are denoted as i' and f'. The inelastic collision contribution is denoted as $\sigma_{jj'}, j = i, f$, and the elastic one as σ_{el}.

The shift, d, is given by (the dipolar interaction potential is the only one to be taken into account):

$$d = N_P \int v f(v) dv \int 2\pi \rho d\rho \sin(2\varphi_p), \tag{2}$$

where the phase shift φ_p is due to the dipolar potential, namely the polarization potential in the adiabatic approximation.

We developed also in Belgrade the modified semiempirical (MSE) approach (Dimitrijević and Konjević 1980, Dimitrijević and Kršljanin 1986, Dimitrijević and Popović 2001) for the calculation of Stark broadening parameters for non-hydrogenic ion spectral lines, which is especially useful when there is no corresponding set of reliable atomic data for the application of the full semiclassical perturbation method. According to the MSE, FHWM of an isolated ion line is given as

$$w_{MSE} = N \frac{4\pi}{3c} \frac{\hbar^2}{m^2} \left(\frac{2m}{\pi kT}\right)^{1/2} \frac{\lambda^2}{\sqrt{3}} \cdot \Big\{ \sum_{\ell_i \pm 1} \sum_{L_{i'} J_{i'}} \vec{\Re}^2_{\ell_i,\ell_i \pm 1} \widetilde{g}(x_{\ell_i,\ell_i \pm 1}) +$$

$$+ \sum_{\ell_f \pm 1} \sum_{L_{f'} J_{f'}} \vec{\Re}^2_{\ell_f,\ell_f \pm 1} \widetilde{g}(x_{\ell_f,\ell_f \pm 1}) + \Big(\sum_{i'} \vec{\Re}^2_{ii'} \Big)_{\Delta n \neq 0} g(x_{n_i,n_i+1}) +$$

$$+ \Big(\sum_{f'} \vec{\Re}^2_{ff'} \Big)_{\Delta n \neq 0} g(x_{n_f,n_f+1}) \Big\},$$

where the $\vec{\Re}^2_{\ell_k,\ell_{k'}}$, $k = i, f$ is the square of the matrix element, and

$$\Big(\sum_{k'} \vec{\Re}^2_{kk'} \Big)_{\Delta n \neq 0} = \left(\frac{3n_k^*}{2Z}\right)^2 \frac{1}{9} (n_k^{*2} + 3\ell_k^2 + 3\ell_k + 11).$$

Here,

$$x_{l_k,l_{k'}} = \frac{E}{\Delta E_{l_k,l_{k'}}}, k = i, f,$$

where $E = \frac{3}{2}kT$ is the electron kinetic energy and $\Delta E_{l_k,l_{k'}} = |E_{l_k} - E_{l_{k'}}|$ is the energy difference between levels l_k and l_k ±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 leves with n_k and n_k+1, $\Delta E_{n_k,n_k+1}$, is estimated as $\Delta E_{n_k,n_k+1} \approx 2Z^2 E_H/n_k^{*3}$. $n_k^* = [E_H Z^2/(E_{ion} - E_k)]^{1/2}$ is the effective principal quantum number, Z is the residual ionic charge, for example Z=1 for neutral atoms and E_{ion} is appropriate spectral series limit.

With $g(x)$ (Griem 1968) and $\widetilde{g}(x)$ (Dimitrijević and Konjević 1980) are denoted the corresponding Gaunt factors.

In comparison with the full semiclassical approach (Sahal-Bréchot 1969ab) and the simpler Griem's semiempirical approach (Griem 1968) a considerably smaller set of input data is needed for the application of MSE, so that this method is particularly useful for stellar spectroscopy which needs a very extensive list of elements and line transitions with their Stark broadening parameters where it is not always possible to use the more sophysticated semiclassical perturbation approach.

Of particular interest for astrophysics could be the simplified semiempirical formula (Dimitrijević and Konjević 1987) for Stark widths of isolated, singly, and multiply charged ion lines, which is 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 $x_{\mathrm{jj'}} = E/|E_{\mathrm{j'}} - E_{\mathrm{j}}| \leq 2$ is satisfied. In such a case FWHM is (Dimitrijević and Konjević 1987):

$$W(\mathring{A}) = 2.2151 \times 10^{-8} \frac{\lambda^2(\mathrm{cm}) N(\mathrm{cm}^{-3})}{T^{1/2}(\mathrm{K})} (0.9 - \frac{1.1}{Z}) \sum_{\mathrm{j=i,f}} (\frac{3n_{\mathrm{j}}^*}{2Z})^2 (n_{\mathrm{j}}^{*2} - \ell_{\mathrm{j}}^2 - \ell - 1). \quad (20)$$

Here, $E = 3kT/2$ is the energy of perturber, $Z - 1$ is the ionic charge and n the effective principal quantum number. This expression is of interest for a number of topics in astrophysics, like for example abundance calculations, or stellar atmospheres research.

4. STARK-B DATABASE AND VAMDC

Our results for Stark broadenning parameters, published in more than 150 papers, we have organized in the database STARK-B (formerly called BELDATA). It was initiated in the Astronomical Observatory of Belgrade (AOB) and the history of BELDATA can be followed in Popović et al. (1999a,b), Milovanović et al. (2000a,b), Dimitrijević et al. (2003b) and Dimitrijević and Popović (2006). Since the end of 2008, the STARK B database, is on-line in free access (http://stark-b.obspm.fr Sahal-Bréchot et al. 2014), and it is maintained and developed at Paris Observatory.

In the database STARK-B are Stark line widths W and shifts d as a function of temperatures and densities and for different perturbers. The accuracy of the Stark line widths varies from about 15-20 percent to 35 percent, and in some cases up to 50 percent.

Actually (1st of September of 2014) Stark broadening parameters obtained by using the SCP method for 79 transitions of He, 61 Li, 29 Li II, 19 Be, 30 Be II, 27 Be III, 1 B II, 12 B III, 148 C II, 1 C III, 90 C IV, 25 C V, 1 N, 7 N II, 2 N III, 1 N IV,

30 N V, 4 O I, 12 O II, 5 O III, 5 O IV, 19 O V, 30 O VI, 14 O VII, 8 F I, 5 F II, 5 F III, 2 F V, 2 F VI, 10 F VII, 25 Ne I, 22 Ne II, 5 Ne III, 2 Ne IV, 26 Ne V, 20 Ne VIII, 62 Na, 8 Na IX, 57 Na X, 270 Mg, 66 Mg II, 18 Mg XI, 25 Al, 23 Al III, 7 Al XI, 3 Si, 19 Si II, 39 Si IV, 16 Si V, 15 Si VI, 4 Si XI, 9 Si XII, 61 Si XIII, 114 P IV, 51 P V, 6 S III, 1 S IV, 34 S V, 21 S VI,2 Cl, 10 Cl VII, 18 Ar, 2 Ar II, 9 Ar VIII, 32 Ar III, 51 K, 4 K VIII, 30 K IX, 189 Ca, 28 Ca II, 8 Ca V, 4 Ca IX, 48 Ca X, 10 Sc III, 4 Sc X, 10 Sc XI,10 Ti IV, 4 Ti XI, 27 Ti XII, 26 V V, 33 V XIII, 9 Cr I, 7 Cr II, 6 Mn II, 3 Fe II, 2 Ni II, 9 Cu I, 32 Zn, 18 Ga, 11 Ge, 3 Ge IV, 16 Se, 4 Br, 11 Kr, 1 Kr II, 6 Kr VIII, 24 Rb, 33 Sr, 32 Y III, 3 Pd, 48 Ag, 70 Cd, 1 Cd II, 18 In II, 20 In III, 4 Te, 4 I, 14 Ba, 64 Ba II, 6 Au, 7 Hg II, 2 Tl III and 2 Pb IV are in STARK-B.

With the inclusion of all our SCP results the stage one of the STARK-B database is finished. The stage two started with the development and implementation of the formulae enabling to fit the tabulated data with temperature. We also started to implement Stark broadening parameters calculated by using the Modified semiempirical method (MSE) (Dimitrijević and Konjević 1980, Dimitrijević and Kršljanin 1986, Dimitrijević and Popović 2001). This method is used when the needed atomic data set is not sufficiently complete to perform an adequate semiclassical perturbation calculation. Stark line widths and, in some cases shifts of the following emitters have been determined by us:

Ag II, Al III, Al V, Ar II, Ar III, Ar IV, As II, As III, Au II, B III, B IV, Ba II, Be III, Bi II, Bi III, Br II, C III, C IV, C V, Ca II, Cd II, Cl III, Cl IV, Cl VI, Co II, Cu III, Cu IV, Eu II, Eu III, F III, F V, F VI, Fe II, Ga II, Ga III, Ge III, Ge IV, I II, Kr II, Kr III, La II, La III, Mg II, Mg III, Mg IV, Mn II, N II, N III, N IV, N VI, Na III, Na VI, Nb III, Nd II, Ne III, Ne IV, Ne V, Ne VI, O II, O III, O IV, O V, P III, P IV, P VI, Pt II, Ra II, S II, S III, S IV, Sb II, Sc II, Se III, Si II, Si III, Si IV, Si V, Si VI, Sn III, Sr II, Sr III, Ti II, Ti III, V II, V III, V IV, Xe II, Y II, Zn II, Zn III, and Zr II.

Up to 1st of September 2014, have been implemented the MSE results for the following emitters :

Al V, P VI, Cl IV, Cl VI, Ar IV, Mn III, Co III, Ga III, Ge III, Ge IV, Cd III and Ra II.

STARK-B database may be used for modelling and spectroscopic diagnostics of stellar atmospheres and envelopes, as well as for laboratory plasmas, laser equipment and technological plasmas investigations but could be used for a much larger number of topics in astrophysics, physics and technology.

In Dimitrijević and Sahal-Bréchot (2014a), the analysis of citations of Stark broadening data obtained by semiclassical perturbation method, which are in STARK-B databases is performed. It is shown that the largest number of citations of these data is for astrophysical applications. Stark broadening parameters of He I, Na I, C IV, Si II, Si IV, Li I, N V, Hg II, O VI, S VI, Mg I, Mg II, Ba I, Ba II, Ca I and Ca II have been used for various investigations in astrophysics.

If we do not take into account the usage of Stark broadening data for theoretical and experimental research of Stark broadening, the applications of Stark broadening parameters obtained by semiclassical perturbation method are not so numerous in physics as in astrophysics. Semiclassical Stark broadening parameters of He I, Li II, Be II, Na I, Ca I, Ca II, Mg I, Mg II, Sr I, Ba I, Ba II, Zn I, Ag I, Cd I, Cu I, Ar I, Ar VIII, Al III, C IV and S V have been used for various physical problems.

From the analysis of aplications of Stark broadening parameters calculated using semiclassical perturbation method (Sahal-Bréchot, 1969a,b) one can conclude that principal users of such data are astronomers, using them especialy for the investigation of A and B type stars, white dwarfs and hot stars in evolved evolution stages (especialy PG1195 type). The most used data are for spectral lines of He I and Si II. Concerning plasmas in physics and technology, the most frequent applications concern laser produced plasma, and the most used data are Stark broadening parameters of Zn I.

The STARK-B database enters also in European FP7 project Virtual Atomic and Molecular Data Centre - VAMDC (Dubernet et al. 2010, Rixon et al. 2011). In Consortium are 15 institutions from 9 countries. Its objective is to build accessible and interoperable e-infrastructure for atomic and molecular data upgrading and integrating various existing database services containing atomic and molecular data.

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