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Stark broadening of B I spectral lines within $2s^2 2p$ - $2s^2 nd$ Spectral Series

Magdalena Christova[1], **Milan S. Dimitrijević**[2,3] **and**
Sylvie Sahal-Bréchot[3]

[1] *Department of Applied Physics, Faculty of Applied Mathematics and Informatics, Technical University - Sofia, Kl. Ohridski Blvd 8, 1000 Sofia, Bulgaria, (E-mail: mchristo@tu-sofia.bg)*

[2] *Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia, (E-mail: mdimitrijevic@aob.rs)*

[3] *Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, LERMA, F-92190, Meudon, France, (E-mail: mdimitrijevic@aob.rs, sylvie.sahal-brechot@obspm.fr)*

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Abstract. Stark broadening parameters of neutral boron spectral lines within one series $2s^2 2p$ - $2s^2 nd$ (n = 3 - 8) have been presented. The dependence of: temperature, electron density and principal quantum number has been studied. The contribution in Stark width and shift of different perturbers (electrons, protons and ionized helium ions) has been obtained. Results are applicable for astrophysical and laboratory plasma diagnostics.

Key words: Atomic data – Atomic processes – Line: profiles – Plasmas

1. Introduction

The study reports calculated Stark broadening parameters (widths and shifts) of boron spectral lines. The impact semi-classical perturbation formalism has been applied (Sahal-Bréchot, 1969a,b). Data on boron lines, including Stark broadening, are of interest in astrophysics but also for laboratory (Blagojević et al., 1999), fusion (Iglesias et al., 1997) and laser produced (Nicolosi et al., 1978) plasmas investigations as well as for laser research and development (Wang et al., 1992).

The story of origin of the formation of LiBeB trio starts from the middle of the twentieth century (Burbridge et al., 1957; Penzias, 1978) and stays unsolved up to now (Lyubimkov, 2018). In the whole nuclear realm, the light elements LiBeB are exceptional since they are both, simple and rare. A general trend in nature is that the abundance of the elements versus the mass number draws a globally decreasing curve (Vangioni-Flam & Cassé, 1999; Vangioni-Flam et al., 2000). Lithium, beryllium, and boron are of great interest for two sets of reasons, which might be categorized as cosmological and related to stellar structure (Duncan et al., 1998). Heretofore, it was reported in the literature, that the rare and fragile light nuclei, lithium, beryllium and boron are not generated in the normal course of stellar nucleosynthesis (except ^{7}Li, in the galactic disk) and are, in fact, destroyed in stellar interiors. The standard Big Bang nucleosynthesis (BBN) theory is not effective to explain the generation of ^{6}Li, ^{9}Be, ^{10}B, ^{11}B (Schramm, 1993; Thomas et al., 1993), what is reflected in the low abundance of these simple species. Recently, according to Lyubimkov (2018), there are modern data indicating that first chemical elements up to oxygen are formed in Big Bang nucleosynthesis. Nevertheless, the abundance questions are among unsolved problems. Lithium, beryllium, and boron are a unified group of elements from the standpoint of evolution, since they burn up in stars in the same process, (p, α) reactions. The stellar structure interest stems from the fact that Li, Be and B undergo nuclear reactions at relatively low temperatures, approximately 2.5, 3.5, and 5x10^{6} K at densities similar to those in the Sun. Since these temperatures are reached not far below the convection zone and well outside the core in solar-type stars, circulation and destruction of the light elements can result in observable abundance changes. Observations of these changes can provide an invaluable probe of stellar structure and mixing. Both Li and Be abundances are greatly reduced in the giants from their initial main-sequence values. Duncan et al. (1998) report the B abundance of two giants and one dwarf in the Hyades, the latter included to evaluate explicitly the boron abundance prior to giant-branch evolution. They demonstrate empirically that boron contributes to the absorption spectra of cool stars. HST measurements of boron abundances of these objects have permitted a test of one of the basic predictions of stellar evolution theory: the growth of the convection zone as a star evolves up the giant branch.

On the basis of Hubble Space Telescope Goddard High Resolution Spectrograph, the boron abundance has been derived for the young Orion solar-type member BD - 05^{o}1317 and reported by Cunha et al. (1999). According to their conclusion, the real interstellar boron abundance and its comparison with the stellar values remains uncertain. The boron abundance derived from spectra of B-type stars of the Orion association is consistent with the expectation that it should be similar to those of the solar system, but it is considerably higher than the interstellar boron abundance for several lines of sight, including some toward Orion. Question of low boron abundance emerges, why interstellar gas and young stars have boron abundance lower 4 or 5 times since the Solar system was formed (Cunha et al., 1999). The light trace elements lithium, beryllium, and boron play a major and significant role in the formation of the primordial fireball, interstellar, intergalactic space, stellar surfaces and interiors (Venn et al., 2002). This role arises because boron nuclei are destroyed by warm protons, and thus even quite shallow mixing of the atmosphere with the interior reduces the surface abundance by bringing boron-depleted material to the surface. The importance of latest nuclei data, including boron to carbon ratio, from space station experiment Alpha Magnetic Spectrometer (AMS-02) is outlined by Niu & Li (2018). Using the abundant information carried by cosmic rays about their sources and propagation environments, the properties of the structure of the Galaxy, the interstellar medium (ISM) and even dark matter (DM) in the Galaxy could be investigated.

In hot stars, boron alone is observable and a study on boron abundance of B-type stars has been presented in Venn et al. (2002). Stark broadening is important for hot stars. The present-day boron abundance is a principal goal of most of studies on hot stars since it could improve our understanding of the Galactic chemical evolution of boron. It is shown that boron is a tracer of some various processes affecting a surface composition of hot stars that are not included in the standard models of stellar evolution. Boron abundances are a clue to unraveling the nonstandard processes that affect young hot stars. Stark broadening is often needed for abundances determination of hot stars. In Popović et al. (1999b) errors in abundances have been analyzed, in the case that Stark broadening is not taken into account, especially for A-type stars.

In Duncan et al. (1998) the importance of light element abundance for the giant-branch evolution is underlined. Spectral lines of boron ions have been observed in stellar spectra. B I lines have been observed in F and G stars (Duncan et al., 1997). Especially for white dwarfs, Stark broadening mechanism is usually the principal one and Stark broadening data for various atomic and ionic lines are of particular interest for WDs (Popović et al., 1999b; Tankosić et al., 2003; Milovanović et al., 2004; Simić et al., 2006; Dimitrijević et al., 2011; Dufour et al., 2011; Simić et al., 2013, 2014). For A type and late B type stars from the main sequence this broadening mechanism may be of interest (Lanz et al., 1988; Popović et al., 1999a,b, 2001a,b; Dimitrijević et al., 2003a,b; Tankosić et al., 2003; Dimitrijević et al., 2004; Milovanović et al., 2004; Dimitrijević et al., 2005; Simić et al., 2005a,b, 2009, 2013, 2014).

The increasing astrophysical importance of Stark broadening data for various atoms and ions of trace elements, arises with the development of satellite born telescopes. They provide high-resolution spectra of earlier inaccessible quality. Well-resolved line profiles for many white dwarfs, where Stark broadening is important, have been and will be registered by the Space Telescope Imaging Spectrograph (STIS), Cosmic Origins Spectrograph (COS) and Goddard High Resolution Spectrograph (GHRS), Far Ultraviolet Spectroscopy Explorer (FUSE), the International Ultraviolet Explorer and others.

Consequently the origin and evolution of boron, are of particular interest and the corresponding Stark broadening data are needed (Tankosić et al., 2003).

Recently, we have calculated Stark broadening parameters for 157 multiplets of helium-like boron (B IV) multiplets (Dimitrijević et al., 2014, 2016). To complete as much as possible the corresponding Stark broadening data needed in astrophysics, laboratory-, technological- , fusion-, and laser produced-plasma physics, our aim is to present in this work new theoretical determinations of Stark broadening parameters (full widths at half intensity and shifts) within the impact semi-classical perturbation approach for B I multiplets and to study their regularities within a spectral series.

2. Theory

Interactions between an atom (ion, or molecule) and surrounding particles (perturbers) in a gas or plasma provoke broadening and shift of spectral line profile when this atom emits or absorbs light. This broadening is known as pressure broadening. The width of the profile at half maximum of the intensity and the shift of spectral line profile are broadening parameters. They depend from the temperature and density of the medium and could be used for spectroscopic diagnostics. When the perturbers are charged particles the observed broadening is called Stark broadening. The plasma in the Universe exists in a huge interval of temperatures and densities and Stark broadening could be notable or dominant in many domains. At temperatures of the order of 10^4 K and densities of 10^{13} - 10^{15} cm^{-3}, Stark broadening is powerful for modelling and analysing spectra of moderately hot (A) and hot (B) types of stars (Sahal-Bréchot, 2010). Especially, Stark broadening is the dominant collisional line broadening process in all layers of the atmosphere of white dwarfs. Stark broadening theory is successfully applied for the purposes of spectroscopic diagnostics and modelling. For such purposes the knowledge of numerous atomic data and spectral profiles is required. The white dwarfs are very faint objects and observed profiles of trace elements, as boron in the present case, are useful probes for modern spectroscopic diagnostics. Interpretation of the spectra of white dwarfs allows to understand the evolution of these very old stars, which are close to death.

Sahal-Bréchot theory of Stark broadening (Sahal-Bréchot, 1969a,b) has been applied in this study. The theory is based on the semi-classical perturbation formalism. According to this theory, the full half width (W) and the shift (d) of an isolated line originating from the transition between the initial level i and the final level f is expressed as:

$$W = 2N \int v f(v) dv \left(\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} \right) \tag{1}$$

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

where i' and f' are perturbing levels, n_e and v are the electron density and the velocity of perturbers respectively, and $f(v)$ is the Maxwellian distribution of electron velocities.

The inelastic contribution in the width (cross sections $\sigma_{ii'}(v)$, and $\sigma_{ff'}(v)$) can be expressed by an integration of the transition probability $P_{ii'}$ over the impact parameter ρ:

$$\sum_{i' \neq i} \sigma_{ii'}(v) = \frac{1}{2}\pi R_1^2 + \int_{R_1}^{R_D} 2\pi \rho d\rho \sum_{i' \neq i} P_{ii'}(\rho, v). \tag{3}$$

The elastic collision cross section for the width is given by

$$\sigma_{el} = 2\pi R_2^2 + \int_{R_2}^{R_D} 2\pi\rho d\rho \sin^2 \delta, \tag{4}$$

$$\delta = (\varphi_p^2 + \varphi_q^2)^{\frac{1}{2}}. \tag{5}$$

The phase shifts ϕ_p and ϕ_q are caused by the polarization and quadrupole potential interactions, respectively. The symmetrization procedure, cut-off parameters R_1, R_2, R_3 and Debye cut-off R_d are described in Sahal-Bréchot (1969a,b). This theoretical method has been developed by later innovations and optimizations, described in details in Sahal-Bréchot et al. (2014).

3. Results

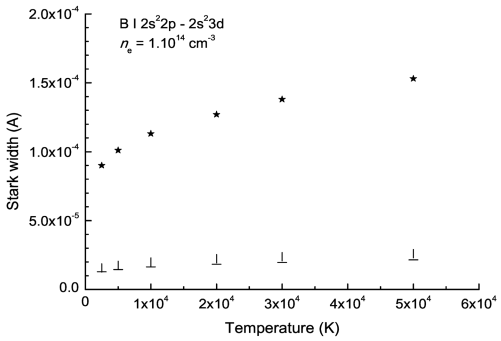

Figure 1. Stark broadening width for $2s^22p$ - $2s^23d$ transition for electron density 10^{14} cm^{-3} *versus* temperature from different type of perturbers: electrons - star; protons - vertical dash; ionized helium ions - horizontal dash.

Stark broadening impact parameters, full width at half maximum of intensity (FWHM - W) and shift (d) for B I lines within one spectral series have been calculated. Semi-classical perturbation method (Sahal-Bréchot, 1969a,b), has been applied. Electrons, protons, and helium ions have been examined as perturbers and their contribution to the total Stark broadening parameters has been discussed. The temperature interval of interest is (2500 - 50 000) K, and those for electron density is 10^{11} - 10^{20} cm^{-3}. The role of temperature and electron density has been studied. Energy levels needed for these calculations, have been taken from Kramida & Ryabtsev (2007), while for the needed oscillator

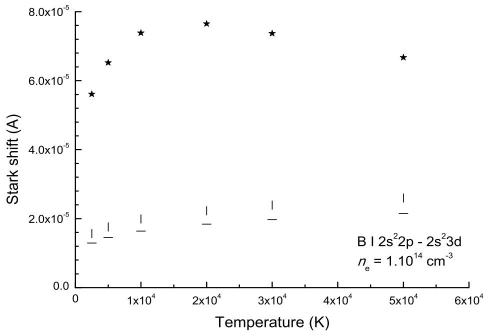

Figure 2. Same as in Fig. 1 but for the shift.

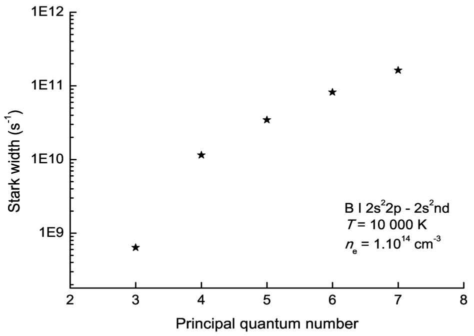

Figure 3. Electron broadening width for spectral lines within 2s^{2}2p - 2s^{2}nd (n = 3 - 8) spectral series *versus* principal quantum number. The electron density is 10^{14} cm^{-3} and the temperature - 10 000 K.

strengths Bates & Damgaard (1949) method has been used, together with the tables of Oertel & Shomo (1968).

Studied lines belong to one spectral series 2s^{2}2p - 2s^{2}nd for n = 3 - 8. The Stark width and shift of 2s^{2}2p - 2s^{2}3d spectral line have been illustrated in Figs.1 and 2 respectively. The total Stark width and shift are due to interactions with electrons, protons and ionized helium ions. The contribution of every type of perturbers has been estimated and shown in the figure. All components of the width slowly increase with the temperature. The proton width is almost the same as the width from He$^+$ ions, while the electron width is more than five times greater. The proton-impact shift as well as shift from He$^+$ ion impacts

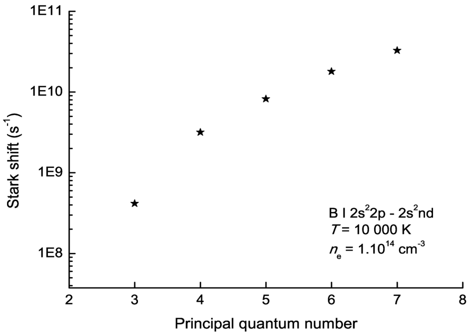

Figure 4. Same as in Fig. 5 but for the shift.

also increase with the temperature, while electron shift reach a maximum at 20000 K and slowly decreases for higher values.

The variation of electron width and shift versus principal quantum number within one spectral series has been presented in Figs. 3 and 4 respectively. We can see a regular increase of widths and shifts with the increase of principal quantum number, as expected. This regular behavior can be used for interpolation of new data if we have spectral series where Stark broadening parameters are not known for all transitions.

4. Conclusion

Stark broadening impact parameters of B I spectral lines within the series 2s^{2}2p - 2s^{2}nd (n = 3 - 8) have been calculated. The role of the: temperature, electron density and principal quantum number has been studied. The contribution to Stark width and shift of different perturbers (electrons, protons and ionized helium ions) has been obtained. Results are applicable for astrophysical and laboratory plasma diagnostics.

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