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Stark Broadening of Neutral Boron Lines

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Abstract: Stark broadening parameters, width and shift, of lines within B I $2s^22p$–$2s^2ns$ spectral series have been calculated. Semi-classical theory in impact approximation has been applied. Temperature dependence of Stark parameters has been studied. The presented results could be applied for plasma diagnostics.

Keywords: atomic data; atomic processes; line formation

1. Introduction

In astrophysics, Stark broadening data for various atomic and ionic lines are of particular interest for white dwarfs, where this line broadening mechanism is usually the principal one [1–8]. This broadening mechanism may be of interest for the main sequence stars, especially for A type and late B type [9–19]. It could be mentioned the increasing astrophysical importance of Stark broadening data for various atoms and ions of trace elements. The development of satellite born telescopes as 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, ensure high-resolution spectra and well-resolved line profiles for many white dwarfs, where Stark broadening is important.

Stark broadening and other data on boron lines are of interest also for laboratory [20], fusion [21] and laser produced [22] plasmas investigations as well as for laser research and development [23]. In astrophysics, the light elements lithium, beryllium, and boron are of great interest for two sets of reasons, which might be categorized as cosmological and related to stellar structure [24]. 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 [25,26]. 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 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 [27–29], what is reflected in the low abundance of these simple species. Recently, according to [30], 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 5×10^6 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. Authors of [24] report the B abundance of two giants and one dwarf in the Hyades, the latter included evaluating 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 spectra, the research [31] reports the boron abundance derived for the young Orion solar-type member BD—05o1317. They note that, the real interstellar boron abundance and its comparison with the stellar values remains uncertain. Determinations of boron abundance for Orion associations provide unexpected results. The boron abundance derived from spectra of B-type stars is consistent with the expectation that the boron abundance of the Orion association should be similar to that of the solar system, but is considerably higher than the interstellar boron abundance for several lines of sight, including some toward Orion. A low boron abundance raises the question as to how the boron abundance of interstellar gas and young stars has decreased by a factor of 4 or 5 since the Solar system was formed [31]. The light trace elements lithium, beryllium, and boron are at the center of astrophysical puzzles involving topics as diverse as the primordial fireball, interstellar (IS) or even intergalactic space, and stellar surfaces and interiors [32]. This is 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. In [32], a study on boron abundance of B-type stars has been presented. Boron alone is observable in hot stars where Stark broadening is not negligible or important. A principal goal of most of these studies of hot stars was to establish the present-day boron abundance in order to improve our understanding of the Galactic chemical evolution of boron. Boron in hot stars, like lithium in cool stars, is shown to be a tracer of some of the various processes affecting a stars surface composition that are not included in the standard models of stellar evolution. If the initial boron abundances of local hot stars are similar from star to star and association to association, then the large spread in boron abundances, a factor of at least 30 across their sample, shows that boron abundances are a clue to unraveling the nonstandard processes that affect young hot stars. In hot stars Stark broadening is often needed for the determination of abundances and in [1] are analyzed errors in abundances if it is not taken into account, especially for A-type stars.

The importance of light element abundance for the giant-branch evolution is underlined in [24]. Spectral lines of boron ions have been observed in stellar spectra. B I lines have been observed in F and G stars [33], B II in hotter stars [34] and B III in early B stars [34,35]. For example, in [36] are reported B III lines in 44 early B stars. Since, the origin and evolution of boron are of particular interest new atomic data, including Stark broadening, are needed [2].

In [37,38], we have calculated Stark broadening parameters for B IV multiplets. To complete as much as possible the corresponding Stark broadening data needed in astrophysics, laboratory-, technological-, fusion-, and laser produced-plasma physics, we present in this work new theoretical Stark broadening parameters (full widths at half intensity and shifts) within the impact semi-classical perturbation approach for one spectral series.

2. Theory

Pressure broadening of spectral lines arises when an atom, ion, or molecule which emits or absorbs light in a gas or plasma, is perturbed by its interactions with the other particles of the medium. Interpretation of this phenomenon is currently used for modelling of the medium and for spectroscopic diagnostics, since the broadening of the lines depends on the temperature and density of the medium. The physical conditions in the Universe are very various, and collisional broadening with charged particles (Stark broadening) appears to be important in many domains. For example, at temperatures around 10^4 K and densities 10^{13}–10^{15} cm^{-3}, Stark broadening is efficient for modelling and analysing spectra of moderately hot (A) and hot (B) types of stars [39]. Stark broadening is also an important diagnostic tool for studying the solar chromosphere: in the quiet Sun at electron densities ~10^{11} cm^{-3} and in solar flares at the electron densities ~10^{13} cm^{-3}, it is efficient for diagnostics of solar plasmas [40–42]. Especially in white dwarfs, Stark broadening is the dominant collisional line broadening process in all layers of the atmosphere. The theory of Stark broadening is well applied for accurate spectroscopic diagnostics and modelling. This requires the knowledge of numerous line profiles of trace elements, as boron in the present case, which is used as useful probes for modern spectroscopic diagnostics. Interpretation of the spectra of white dwarfs, which are very faint, allows understanding the evolution of these very old stars, which are close to death.

The primary results for Stark broadening parameters of B I lines from one spectral series have been calculated using Sahal-Bréchot theory based on the semi-classical perturbation formalism [43,44]. Within the Sahal-Bréchot 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:

$$W = 2n_e \int_0^\infty vf(v)dv \left[\sum_{i' \neq i} \sigma_{ii'}(v) + \sum_{f' \neq f} \sigma_{ff'}(v) + \sigma_{el} \right] \quad (1)$$

$$d = \int_0^\infty vf(v)dv \int_{R_3}^{R_d} 2\pi\rho d\rho \sin\varphi_p \quad (2)$$

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 cross sections $\sigma_{ii'}$ (v) (respectively $\sigma_{ff'}$ (v)) can be expressed by an integration of the transition probability $P_{ii'}$ over the impact parameter ρ:

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

The elastic collision contribution to the width is given by:

$$\sigma_{el} = 2\pi R_2^2 + \int_{R_2}^{R_d} 8\pi\rho d\rho (\sin\delta)^2 \quad (4)$$

$$\delta = \left(\varphi_p^2 + \varphi_q^2\right)^{1/2} \quad (5)$$

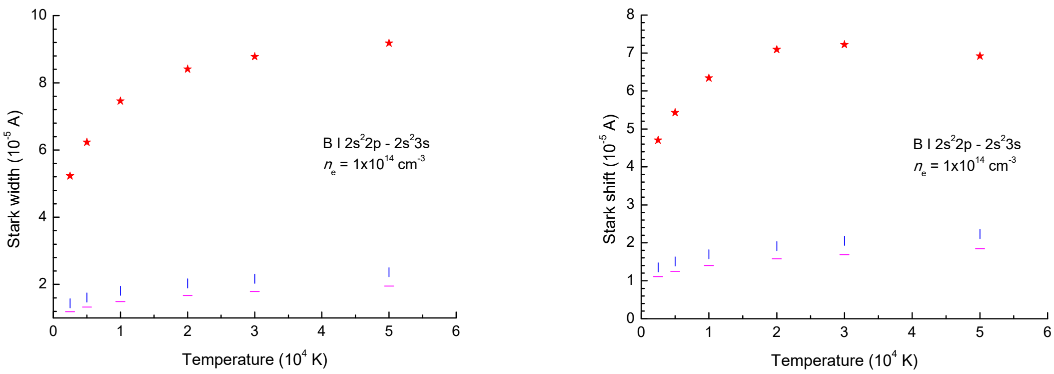
The phase shifts φ_p and φ_q are due to the polarization and quadrupole potential, respectively. The cut-off parameters R_1, R_2, R_3, the Debye cut-off R_d and the symmetrization procedure are described in [43,44]. The collisons of emitters with electrons, protons and ionized helium have been examined, and the contribution of different perturbers to the total Stark broadening parameters has been discussed.

We note that different later innovations and optimizations of this theoretical method have been described in details in [45–50].

3. Results and Discussion

In this paper, new results for Stark broadening parameters of boron lines, width and shift, have been reported. The study have been performed on the spectral lines within one series, B I $2s^22p$–$2s^2ns$, n = 3–8 for temperatures from 2500 K to 50,000 K and electron densities from 10^{11} cm^{-3} to 10^{20} cm^{-3}. Energy levels needed for these calculations, have been taken from [51], while for the needed oscillator strengths [52] method has been used, together with the tables of [53]. The average error of the semiclassical-perturbation method, used here, is estimated to be ±30% [50] but for simple atoms like boron it is better than 20% [54].

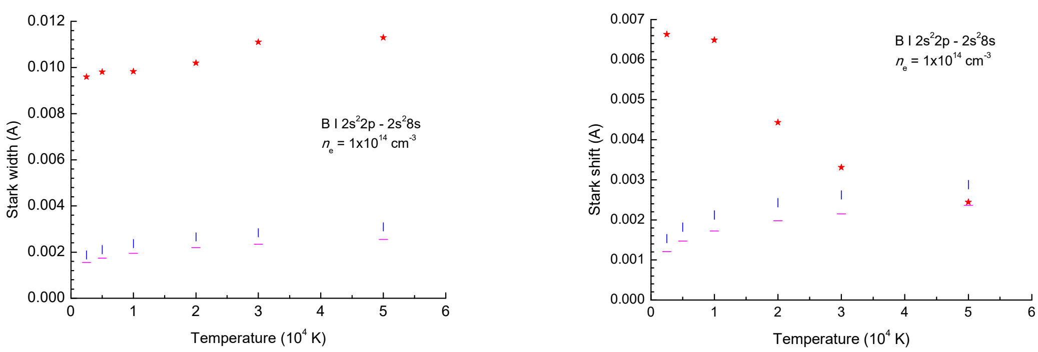
In Figure 1, temperature dependence of width and shift of spectral lines from B I $2s^22p$–$2s^23s$ multiplet has been illustrated. The contribution of every type of perturbers has been shown. The main broadening and shifting of the profile is caused by the electrons. Electron-impact width and shift slowly increase with temperature. The values of proton width are close to ionized helium width and both increase with temperature very slowly. They are four times lower than the electron-impact width. The electron-impact shift slowly increases up to 30,000 K and starts to decrease for higher values. The proton and ionized helium shifts are close to each other, notably lower than electron-impact one and very slowly increase for higher temperatures.



(**a**) (**b**)

Figure 1. Stark broadening width (**a**) and shift (**b**) of spectral line of $2s^22p$–$2s^23s$ transition versus temperature from different type of perturbers: electrons–red star; protons–vertical blue dash; ionized helium ions–horizontal magenta dash. Electron density is 1×10^{14} cm^{-3}.

Different behavior of Stark broadening parameters and their components have been observed for spectral line of higher initial energy level, B I $2s^22p$–$2s^28s$ (see Figure 2). All components of Stark width increase slowly in the examined temperature interval. The electron-impact width is dominant, almost five times greater in the whole temperature interval. The electron-impact shift decreases with *T*, while shifts from protons and helium ions increase. All shift component converge to one value from 30,000 to 50,000 K. The demonstrated sensitivity of the shift of this line could be applied for plasma temperature diagnostics.

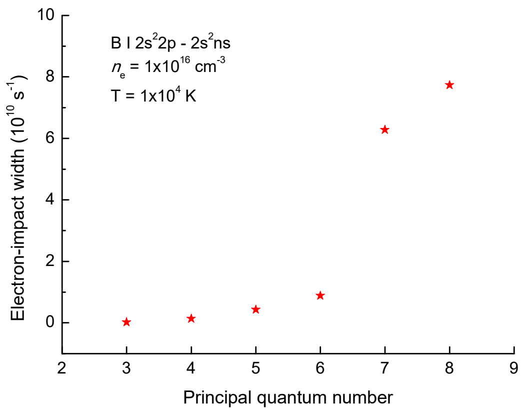


(**a**) (**b**)

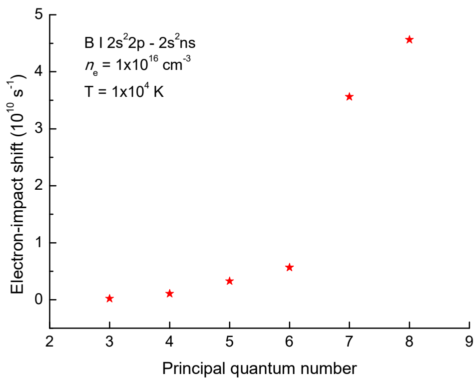
Figure 2. Stark broadening width (**a**) and shift (**b**) of spectral line of $2s^22p$–$2s^28s$ transition versus temperature from different type of perturbers: electrons–red star; protons–vertical blue dash; ionized helium ions–horizontal magenta dash. Electron density is 1×10^{14} cm^{-3}.

All shift values for all lines in this series are positive, red shifts. The theory predicts a linear dependence of Stark broadening parameters on the electron density. On the basis of the obtained results, B I $2s^22p$–$2s^28s$ and B I $2s^22p$–$2s^27s$ spectral lines could be applied for diagnostics up to 10^{16} cm^{-3}. The analyze shows that $2s^22p$–$2s^26s$ and $2s^22p$–$2s^25s$ spectral lines are useful up to 10^{17} cm^{-3} for all temperatures. B I $2s^22p$–$2s^24s$ is suitable for densities up to 10^{18} cm^{-3} in whole temperature interval. We found a little difference for $2s^22p$–$2s^25s$ at density 10^{18} cm^{-3}, which could be used for temperatures above 20,000 K. For electron density of order (10^{19}–10^{20}) cm^{-3} only $2s^22p$–$2s^23s$ spectral line is applicable.

The variation of electron-impact width and shift versus principal quantum number within one spectral series have been observed. In Figure 3, results for electron density 1×10^{16} cm^{-3} and temperature 10,000 K have been shown. The values vary from 2.3×10^8 s^{-1} to 7.7×10^{10} s^{-1} for the width and, from 1.9×10^8 s^{-1} to 4.6×10^{10} s^{-1} for the shift. The notable increasing of two parameters have been marked for lines from higher energetic levels, where the change is two orders. Such behavior is in accordance with the theory. The obtained dependences could be useful for transitions from higher energetic levels ($n > 8$) where new broadening parameters could be extrapolated.



(**a**)



(**b**)

Figure 3. Electron-impact broadening width (**a**) and shift (**b**) for spectral lines within $2s^22p$–$2s^2ns$ (n = 3–8) spectral series versus principal quantum number. Electron density is 1×10^{16} cm^{-3} and temperature is 1×10^4 K.

4. Conclusions

New calculated results for Stark broadening parameters of boron lines within one spectral series B I $2s^22p$–$2s^2ns$ (n = 3–8) have been presented in this work. The role of the temperature, electron density and the principal quantum number dependence within series have been studied. The presented Stark widths and shifts are measurable, sensitive to all three variables and could be used for further modelling and diagnostics. The conditions to apply for plasma diagnostics have been discussed for every line.

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