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Stark Broadening of B I Lines Belonging To Low Energetic Transitions

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Abstract. Stark broadening parameters of neutral boron spectral lines have been presented. The studied lines correspond to low energetic level transitions. The temperature dependence has been obtained and the contributions of electrons, protons and ionized helium ions have been illustrated. The obtained results are applicable for astrophysical and laboratory plasma.

INTRODUCTION

The story of origin of the formation of LiBeB trio starts from the middle of the twenty century [1,2] and stays unsolved up to now [3]. 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 [4,5]. Lithium, beryllium, and boron are of great interest for two sets of reasons, which might be categorized as cosmological and related to stellar structure [6]. 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 6Li, 9Be, 10B, 11B [7-9], what is reflected in the low abundance of these simple species. Recently, according to [3], 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 $5\text{x}10^6$ 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. The authors in [6] 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.

Based on Hubble Space Telescope Goddard High Resolution Spectrograph spectra, the boron abundance has been presented in [10], 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 [10]. 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 [11]. 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. A study on boron abundance of B-type stars has been presented in [11]. 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. We note that in hot stars Stark broadening is often needed for the determination of abundances and in [12] 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 [6]. Spectral lines of boron ions have been observed in stellar spectra. B I lines have been observed in F and G stars [13], B II in hotter stars [14] and B III in early B stars [14,15]. For example, B III lines in 44 early B stars were found in [16].

In astrophysics, Stark broadening data for various atomic and ionic lines are of particular interest especially for white dwarfs, where this line broadening mechanism is usually the principal one [12,17-23]. This broadening mechanism may be of interest and for the main sequence stars, especially for A type and late B type [12,13,18,22-34].

We note as well the increasing astrophysical importance of Stark broadening data for various atoms and ions of trace elements, without astrophysical meaning before the development of satellite born telescopes which now are providing high-resolution spectra of earlier inaccessible quality. Well-resolved line proles for many white dwarfs, where Stark broadening is important, have been and will be provided for example 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.

Data on boron lines, including Stark broadening, are of interest in astrophysics but also for example for laboratory [35], fusion [36] and laser produced [37] plasmas investigations as well as for laser research and development [38].

Consequently the origin and evolution of boron, are of particular interest and the corresponding Stark broadening data are needed [17].

Recently, we have calculated Stark broadening parameters for B IV multiplets [39,40]. 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.

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 [41]. 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 profiles, particularly for trace elements, as boron in the present case, which are used as useful probes for modern spectroscopic diagnostics. Interpretation of the spectra of white dwarfs, which are very faint, allows to understand the evolution of these very old stars, which are close to death.

The primary results for Stark broadening parameters of B I lines from two spectral series have been calculated using Sahal-Bréchot theory based on the semi-classical perturbation formalism [42,43]. 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:

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

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

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 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:

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

The elastic collision contribution to the width is given by:

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

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

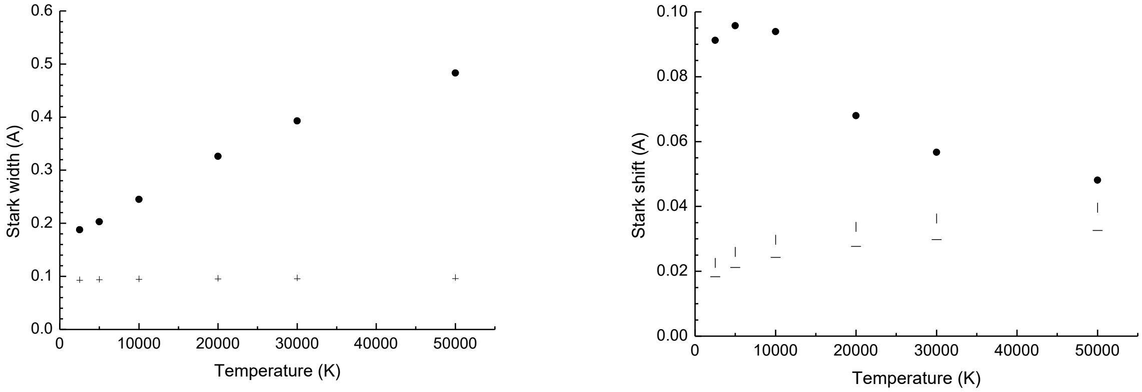
The phase shifts φ_p and φ_q are due to the polarization and quadrupole potential, respectively. The cut-offs parameters R_1, R_2, R_3, the Debye cut-off R_d and the symmetrization procedure are described in [42,43]. The collisons of emitters with electrons, protons and ionized helium have been examined, 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 Sahal-Bréchot [44-49].

RESULTS

We have calculated here, within the frame of semiclassical perturbation method [42,43], electron-, proton-, and helium ion-impact broadening parameters, full width at half maximum of intensity (FWHM - W) and shift (d) for B I multiplets. The examined temperature varies from 2500 to 50 000K, and perturber density is 10^{16} cm^{-3}. Energy levels needed for these calculations, have been taken from [50], while for the needed oscillator strengths [51] method has been used, together with the tables of [52].

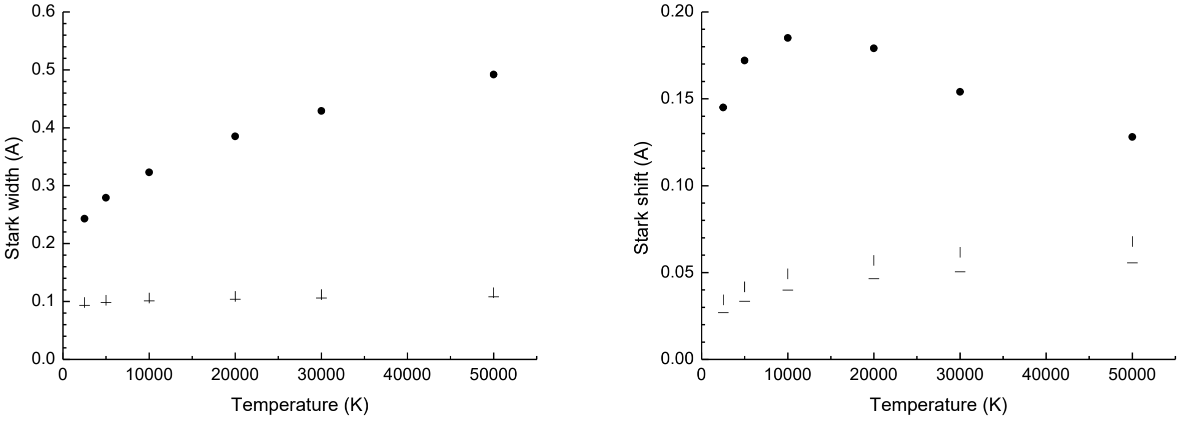
All studied lines correspond to low energetic transitions. The Stark width and shift of $2s^23s$ - $2s^23p$; $2s^24s$ - $2s^23p$ and $2s^24s$ - $2s^24p$ transitions have been illustrated in Fig.1, Fig.2 and Fig.3, respectively. The contribution of every type of perturbers has been estimated and discussed.



(a) (b)

FIGURE 1. Stark broadening width (a) and shift (b) of spectral line of $2s^23s$ - $2s^23p$ transition versus temperature from different type of perturbers: electrons - solid circle; protons – vertical dash; ionized helium ions – horizontal dash.

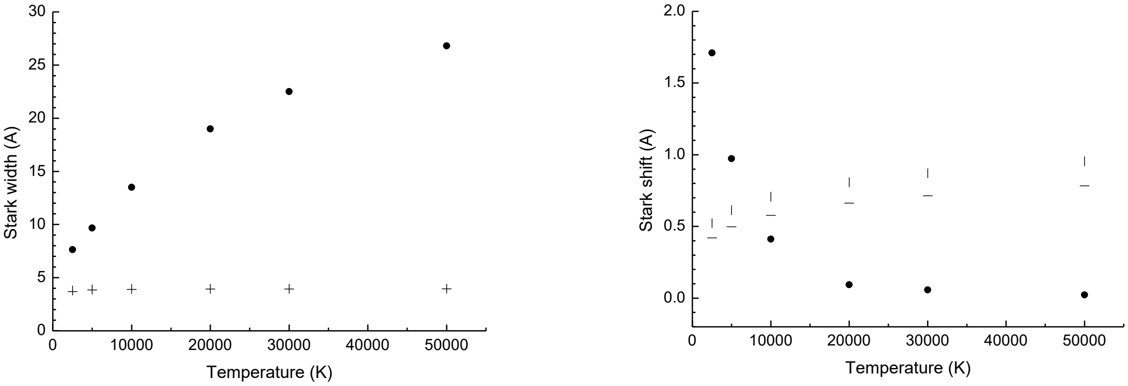
For the spectral line ($2s^23s$ - $2s^23p$) presented in Fig.1, the major contribution in both broadening parameters is given by the electrons. The electron width and shift are sensitive to the plasma temperature. The Stark width almost linearly increases, while the shift decreases for temperatures above 10 000 K. The widths produced by protons and ionized helium ions overlap and stay constant with temperature. The values for proton and ionized helium ions shift are close in value and slowly increase with temperature. The three shifts converge to one value at the end of the temperature interval. Figure 2 shows the broadening parameters of spectral line by $2s^24s$ - $2s^23p$ multiplet. The behavior of the width and shift by protons and ionized helium ions versus temperature is almost the same as in $2s^23s$ - $2s^23p$ transition case. Here, the difference between proton width and ionized helium ion width is observable. The decreasing of electron shift starts above 20 000 K and at 50 000 K is more than twice greater than proton's and He^+ ones.



(a) (b)

FIGURE 2. Stark broadening width (a) and shift (b) of spectral line of $2s^24s$ - $2s^23p$ transition versus temperature from different type of perturbers: electrons - solid circle; protons – vertical dash; ionized helium ions – horizontal dash.

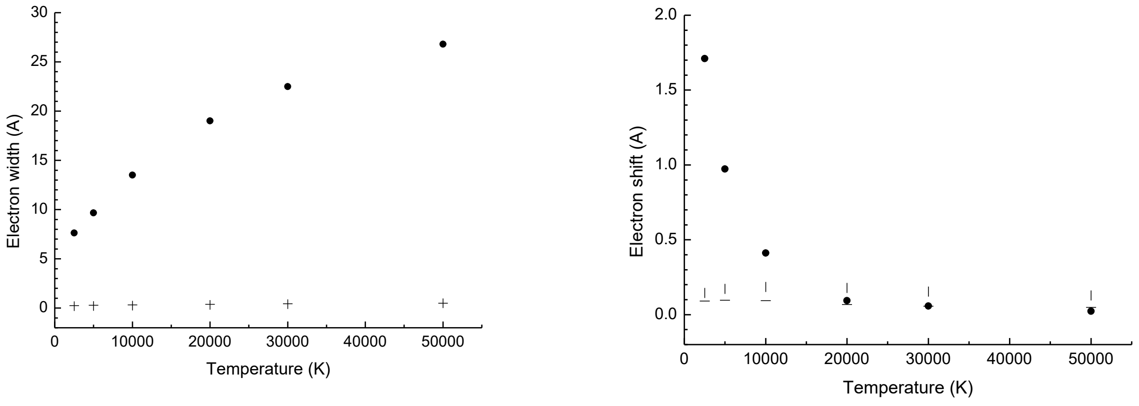
Dramatic changes of Stark shift of line corresponding to $2s^24s$ - $2s^24p$ spectral transition have been demonstrated in Fig.3. For the shift, all three values converge at 5000 K. Above that temperature, proton shift and He^+ shift are predominant while electron shift reaches zero. The three broadenings start with similar values, the proton and He^+ ones does not change within the temperature interval, while the electron one increases more than 5 times.



(a) (b)

FIGURE 3. Stark broadening width (a) and shift (b) of spectral line of $2s^24s$ - $2s^24p$ transition versus temperature from different type of perturbers: electrons - solid circle; protons – vertical dash; ionized helium ions – horizontal dash.

Since, the broadening by electrons is dominant for three presented lines, comparison of electron Stark widths and shifts has been shown in Fig. 4. The broadening of the spectral profile of $2s^24s$ - $2s^24p$ transition in whole temperature interval is notable. The broadening of this line is suitable for temperature diagnostics due to the temperature sensitivity. The shift shows temperature sensitivity for lower temperatures up to 20 000 K. In fact, it is not measurable above 20 000 K. In contrast, two other transitions $2s^23s$ - $2s^23p$; $2s^24s$ - $2s^23p$ have spectral profiles where shifting is measurable and sensible to the temperature.



(a) (b)

FIGURE 4. Electron Stark broadening width (a) and shift (b) of spectral lines versus temperature for studied transitions: $2s^23s$ - $2s^23p$ (vertical dash); $2s^24s$ - $2s^23p$ (horizontal dash) and $2s^24s$ - $2s^24p$ (solid circle).

CONCLUSION

The obtained results for Stark broadening parameters of examined spectral transitions in this work are measurable and could be applied for further modelling and diagnostics. The presented results for Stark broadening parameters, width and shift, are sensitive to the temperature. Observations and measurements of Stark widths and shifts provide temperature diagnostics of studied plasmas.

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REFERENCES

[1] Burbidge, E. M., Burbidge, G. R., Fowler, W. A., and Hoyle, F., 1957, Rev. Mod. Phys. 29, 547

[2] Penzias A., Nobel Lecture 1978, The origin of the elements

[3] Lyubimkov, L.S. Light Chemical Elements in Stars: Mysteries and Unsolved Problems. *Astrophysics* **2018**, *61*, 262–285, doi:10.1007/s10511-018-9533-x

[4] Vangioni-Flam, E.; Cassé, M. Cosmic Lithium-Beryllium-Boron story. *Astrophys. Space Sci.* **1999**, *265*, 77–86.

[5] Vangioni-Flam, E.; Cassé, M.; Audouze, J. Lithium-beryllium-boron: Origin and evolution. *Phys. Rep.* **2000**, *333–334*, 365–387, doi:10.1016/S0370-1573(00)00030-2.

[6] Duncan, D.K.; Peterson, R.C.; Thorburn, J.A.; Pinsonneault, M.H. Boron abundances and internal mixing in stars I the Hyades giants. *Astrophys. J.* **1998**, *499*, 871–882, doi:10.1086/305649.

[7] Delbourgo-Salvador, P.; Vangioni-Flam, E. Primordial abunances of Be and B from standard Big-Bang nucleosynthesis, in *Origin and Evolution of Elements*; eds. Prantzos, N.; Vangioni-Flam, E.; Casse, M., Cambridge University Press: London, UK, 1993, 132-138.

[8] Schramm, D.N. Primordial Nucleosynthesis, in: *Origin and Evolution of the Elements*; eds. Prantzos, N.; Vangioni-Flam, E.; Casse, M., Cambridge University Press: London, UK, 1993, 112-131.

[9] Thomas, D.; Schramm, D.N.; Olive, K.A.; Fields, B.D. Primordial nucleosynthesis and the abundances of beryllium and boron. *Astrophys. J.* **1993**, *406*, 569, doi:10.1086/172469.

[10] Cunha, K.; Smith, V.V.; Lambert, D.L. The boron abundance of the Orion G-dwarf member BD-05 1317. *Astrophys. J.* **1999**, *519*, 844–849.

[11] Venn, K.A.; Brooks, A.M.; Lambert, D.L.; Lemke, M.; Langer, N.; Lennon, D.J.; Keenan, F.P. Boron abundances in B-type stars: A test of rotational depletion during main-sequence evolution. *Astrophys. J.* **2002**, *565*, 571–586, doi:10.1086/324435.

[12] Popović, L.Č.; Dimitrijević, M.S.; Tankosić, D. The Stark broadening effect in hot star atmospheres: Au I and Au II lines. *Astron. Astrophys. Suppl. Ser.* **1999**, *139*, 617–623, doi:10.1051/aas:1999113.

[13] Duncan, D.K.; Primas, F.; Rebull, L.M.; Boesgaard, A.M.; Deliyannis, C.P.; Hobbs, L.M.; King, J.R.; Ryan, S.G. The evolution of galactic boron and the production site of the light elements. *Astrophys. J.* **1997**, *488*, 338–349, doi:10.1086/304683.

[14] Cunha, K.; Lambert, D.L.; Lemke, M.; Gies, D.R.; Roberts, L.C. Boron abundances of B stars of the Orion association. *Astrophys. J.* **1997**, *478*, 211–224, doi:10.1086/303791.

[15] Proffitt, C.R.; Jönsson, P.; Litzén, U.; Pickering, J.C.; Wahlgren, G.M. Goddard high-resolution spectrograph observations of the B III resonance doublet in early B stars: Abundances and isotope ratios. *Astrophys. J.* **1999**, *516*, 342–348.

[16] Proffitt, C.R.; Quigley, M.F. Boron abundances in early B stars: Results from the B III resonance line in IUE data. *Astrophys. J.* **2001**, *548*, 429–438, doi:10.1086/318673.

[17] Tankosić, D.; Popović, L.Č.; Dimitrijević, M.S. The electron-impact broadening parameters for Co III spectral lines. *Astron. Astrophys.* **2003**, *399*, 795–797, doi:10.1051/0004-6361:20021801.

[18] Milovanović, N.; Dimitrijević, M.S.; Popović, L.Č.; Simić, Z. Importance of collisions with charged particles for stellar UV line shapes: Cd III. *Astron. Astrophys.* **2004**, *417*, 375–380, doi:10.1051/0004-6361:20034162.

[19] Simić, Z.; Dimitrijević, M.S.; Popović, L. Č.; Dačić, M.D. Stark broadening parameters for Cu III, Zn III and Se III lines in laboratory and stellar plasma. *New Astron.* **2006**, *12*, 187–191, doi:10.1016/j.newast.2006.09.001.

[20] Dimitrijević, M.S.; Kovačević, A.; Simić, Z.; Sahal-Bréchot, S. Stark broadening of several NeII, Ne III and OIII spectral lines for the Stark-B database. *Balt. Astron.* **2011**, *20*, 580–586.

[21] Dufour, P.; Ben Nessib, N.; Sahal-Bréchot, S.; Dimitrijević, M.S. Stark broadening of carbon and oxygen lines in hot DQ White Dwarf stars: Recent results and applications. *Balt. Astron.* **2011**, *20*, 511–515.

[22] Simić, Z.; Dimitrijević, M.S.; Sahal-Bréchot, S. Stark broadening of resonant Cr II 3d 5-3d 4 4p spectral lines in hot stellar atmospheres. *Mon. Not. R. Astron. Soc.* **2013**, *432*, 2247–2251, doi:10.1093/mnras/stt634.

[23] Simić, Z.; Dimitrijević, M.S.; Popović, L.Č. Stark broadening data for spectral lines of rare-earth elements: Nb III. *Adv. Space Res.* **2014**, *54*, 1231–1234, doi:10.1016/j.asr.2013.11.025.

[24] Lanz, T.; Dimitrijević, M.S.; Artru, M. Stark broadening of visible Si II lines in stellar atmospheres. *Astron. Astrophys.* **1988**, *192*, 249–254.

[25] Popović, L.Č.; Dimitrijević, M.S.; Ryabchikova, T. The electron-impact broadening effect in CP stars: The case of La II, La III, Eu II, and Eu III lines. *Astron. Astrophys.* **1999**, *350*, 719–724.

[26] Popović, L.Č.; Milovanović, N.; Dimitrijević, M.S. The electron-impact broadening effect in hot star atmospheres: The case of singly- and doubly-ionized zirconium. *Astron. Astrophys.* **2001**, *365*, 656–659, doi:10.1051/0004-6361:20000013.

[27] Popović, L.Č.; Simić, S.; Milovanović, N.; Dimitrijević, M.S. Stark broadening effect in stellar atmospheres: Nd II lines. *Astrophys. J. Suppl. Ser.* **2001**, *135*, 109–114, doi:10.1086/321778.

[28] Dimitrijević, M.S.; Jovanović, P.; Simić, Z. Stark broadening of neutral germanium spectral lines. *Astron. Astrophys.* **2003**, *410*, 735–739, doi:10.1051/0004-6361:20031176.

[29] Dimitrijević, M.S.; Ryabchikova, T.; Popović, L.Č.; Shulyak, D.; Tsymbal, V. On the influence of Stark broadening on Si I lines in stellar atmospheres. *Astron. Astrophys.* **2003**, *404*, 1099–1106, doi:10.1051/0004-6361:20030561.

[30] Dimitrijević, M.S.; Dačić, M.; Cvetković, Z.; Simić, Z. Stark broadening of Ga I spectral lines. *Astron. Astrophys.* **2004**, *425*, 1147–1152, doi:10.1051/0004-6361:20047066.

[31] Dimitrijević, M.S.; Ryabchikova, T.; Popović, L.Č.; Shulyak, D.; Khan, S. On the influence of Stark broadening on Cr I lines in stellar atmospheres. *Astron. Astrophys.* **2005**, *435*, 1191–1198, doi:10.1051/0004-6361:20042318.

[32] Simić, Z.; Dimitrijević, M.S.; Popović, L.Č.; Dačić, M.D. Stark broadening of F III lines in laboratory and stellar plasma. *J. Appl. Spectrosc.* **2005**, *72*, 443–446, doi:10.1007/s10812-005-0095-4.

[33] Simić, Z.; Dimitrijević, M.S.; Milovanović, N.; Sahal-Bréchot, S. Stark broadening of Cd I spectral lines. *Astron. Astrophys.* **2005**, *441*, 391–393, doi:10.1051/0004-6361:20052701.

[34] Simić, Z.; Dimitrijević, M.S.; Kovačević, A. Stark broadening of spectral lines in chemically peculiar stars: Te I lines and recent calculations for trace elements. *New Astron. Rev.* **2009**, *53*, 246–251, doi:10.1016/j.newar.2009.08.005.

[35] Blagojević, B.; Popović, M.V.; Konjević, N.; Dimitrijević, M.S. Stark broadening parameters of analogous spectral lines along the lithium and beryllium isoelectronic sequences. *J. Quant. Spectrosc. Radiat. Transf.* **1999**, *61*, 361–375, doi:10.1016/S0022-4073(98)00002-8.

[36] Iglesias, E.; Griem, H.; Welch, B.; Weaver, J. Uv Line Profiles of B IV from a 10-Ps KrF-Laser-Produced Plasma. *Astrophys. Space Sci.* **1997**, *256*, 327–321.

[37] Nicolosi, P.; Garifo, L.; Janisitti, E.; Malvezzi, A.M.; Tondello, G. Broadening and self-absorption of the resonance lines of H-like light ions in laser-produced plasmas. *IL Nuov. Cim. B* **1978**, *48*, 133–151, doi:10.1007/BF02743638.

[38] Wang, J.S.; Griem, H.R.; Huang, Y.W.; Böttcher, F. Measurements of line broadening of L B V Hα and Lδ in a laser-produced plasma. *Phys. Rev. A* **1992**, *45*, 4010–4014, doi:10.1103/PhysRevA.45.4010.

[39] Dimitrijević, M.S.; Christova, M.; Simić, Z.; Kovačević, A.; Sahal-Bréchot, S. Stark broadening of B IV lines for astrophysical and laboratory plasma research. *Adv. Space Res.* **2014**, *54*, 1195–1202, doi:10.1016/j.asr.2013.08.021.

[40] Dimitrijević, M.S.; Christova, M.; Simić, Z.; Kovačević, A.; Sahal-Bréchot, S. Stark broadening of B IV spectral lines. *Mon. Not. R. Astron. Soc.* **2016**, *460*, 1658–1663, doi:10.1093/mnras/stw1023.

[41] Sahal-Bréchot, S. Case studies on recent Stark broadening calculations and STARK-B database development in the framework of the European project VAMDC (Virtual Atomic and Molecular Data Center). *J. Phys. Conf. Ser.* **2010**, *257*, 012028, doi:10.1088/1742–6596/257/1/012028.

[42] Sahal-Bréchot, S. Impact Theory of the Broadening and Shift of Spectral Lines due to Electrons and Ions in a Plasma, *Astron. Astrophys.* **1969**, *1*, 91–123.

[43] Sahal-Bréchot, S. Broadening of ionic isolated lines by interactions with positively charged perturbers in the quasistatic limit, *Astron. Astrophys.* **1969**, *2*, 322–354.

[44] Sahal-Bréchot, S. Stark Broadening of Isolated Lines in the Impact Approximation, *Astron. Astrophys.* **1974**, *35*, 319-321.

[45] Sahal-Bréchot, S. Broadening of ionic isolated lines by interactions with positively charged perturbers in the quasistatic limit, *Astron. Astrophys.* **1991**, *245*, 322-330.

[46] Fleurier, C.; Sahal-Bréchot, S.; Chapelle, J. Stark profiles of some ion lines of alkaline earth elements. *J. Quant. Spectrosc. Radiat. Transf.* **1977**, *17*, 595–604, doi:10.1016/0022-4073(77)90019-X.

[47] Dimitrijević, M.S.; Sahal-Bréchot, S.; Bommier, V. Stark broadening of spectral lines of multicharged ions of astrophysical interest. *Astron. Astrophys.* **1991**, *89*, 581.

[48] Dimitrijević, M.S.; Sahal-Bréchot, S. Stark broadening of Li II spectral lines. *Phys. Scr.* **1996**, *54*, 50–55, doi:10.1088/0031-8949/54/1/008.

[49] Sahal-Bréchot, S.; Dimitrijević, M.S.; Ben Nessib, N. Widths and shifts of isolated lines of neutral and ionized atoms perturbed by collisions with electrons and ions: An outline of the semiclassical perturbation (SCP) method and of the approximations used for the calculations. *Atoms* **2014**, *2*, 225–252, doi:10.3390/atoms2020225.

[50] Kramida, A.E.; Ryabtsev, A.N. A critical compilation of energy levels and spectral lines of neutral boron. *Phys. Scr.* **2007**, *76*, 544–557, doi:10.1088/0031-8949/76/5/024.

[51] Bates, D.R.; Damgaard, A. The calculation of the absolute strengths of spectral lines. *Philos. Trans. R. Soc. Lond. Ser. A* **1949**, *242*, 101–122.

[52] Oertel, G.K.; Shomo, L.P. Tables for the Calculation of Radial Multipole Matrix Elements by the Coulomb Approximation. *Astrophys. J. Suppl. Ser.* **1968**, *16*, 175.