Stark Width Regularities within Beryllium Spectral Series

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Abstract: The dependences of Stark width on the upper-level ionization potential within different series of the neutral beryllium spectral lines have been studied. The dependences previously observed for electron impact contribution to the Stark widths were also obtained for the proton impact contribution. The emphasis is on the fine structure influence on the studied Stark parameter dependences. The influence of temperature on the dependences of Stark width parameters has been demonstrated. The relations found can be used in both cases for prediction of new Stark broadening data, thus avoiding much more complicated procedures.

1 Introduction

Progress in studying different kinds of Stark broadening regularities of astrophysical interest was enabled by a monograph by Griem (1974) and a series of critical review papers devoted to the theoretical and experimental investigation of Stark broadening of numerous spectral lines from different atoms and ions (Konjević, Dimitrijević & Wiese 1984a, 1984b; Konjević & Wiese 1976a, 1976b, 1990; Konjević et al. 2002; Lesage 2009). This, together with the Stark B database prepared by Dimitrijević & Sahal-Bréchot (1992, 1993, 1994), opens an opportunity for studying different kinds of Stark broadening parameter regularities more seriously within similar spectra (Purić & Šćepanović 1999; Šćepanović & Purić 2003; Purić et al. 2008; Tapalaga, Dojčinović & Purić 2011; Elabidi & Sahal-Brechot 2011). This includes studies of regularities within multiplets and super-multiplets, spectral series, transition arrays, isoelectronic sequences, isonuclear sequences, homologous sequences, particular transitions (e.g., resonance and off-resonance) along the periodic table within a single stage of ionization, or within several ionization stages, as far as the influence of the atomic structure is concerned. However, the dependence of the Stark parameters on plasma parameters — electron density and temperature — has been investigated in a great number of papers, theoretically and experimentally. It was found that the Stark line widths of nonhydrogenic atoms and ions are linearly dependent on the electron density (N_e) and are also weak functions of the electron temperature (T_e). Therefore, in order to study regularities it is of great interest to have as accurate data as possible for a specific electron density and temperature.

In many reviews (see, e.g., Lanz & Artru 1985, Seaton 1987, Iglesias et al. 1990, Reyna et al. 2009) it is indicated that the experimentally determined Stark widths, as well as the existing theoretical data, cannot fulfil the necessity for many observed stellar lines used for opacity calculations and the relative radiation transfer modelling in different studies of astrophysical interest, although it is an active field of research. Such data are of interest also for the estimation of radiative transfer through stellar plasmas for some classes of hot stars, for the determination of chemical abundances of elements from equivalent widths of the absorption lines, and for other astrophysical topics. Generally speaking, there is a need for Stark broadening parameters of many lines of different elements in various ionisation stages over a very broad range of plasma parameters, such as electron density and electron temperature. Therefore, it is of interest to exploit any possible theoretical approach that might provide simple relations from the systematic trends found in the Stark broadening data, both in simple and complex spectra. In several previous papers (Purić et al. 1991; Purić, Miller & Lesage 1993; Purić et al. 2008; Tapalaga et al. 2011; Elabidi & Sahal-Brechot 2011) it has been shown that physics-based interpretation of the Stark broadening regularities could provide Stark parameters with an appropriate combination of reliability and computational simplicity.

Beryllium was first observed in the Sun in 1895 (Rowland and Tatnall 1895). The beryllium Stark broadening parameters are important to astrophysicists since the surface content (abundance) of light elements involves problems correlated with nucleogenesis, mixing the atmosphere with the interior and stellar structure and evolution (Castilho et al. 1999). The abundance of light elements, especially Li and Be, are key diagnostics of stellar structure and evolution in cool stars, because they are effectively destroyed by nuclear reactions in stellar interiors (Boesgaard 1988; Boesgaard and King 2002). Also, beryllium is used as a chronometer for the early evolution of the galaxy (Gratton 2007).

All relevant papers can be divided in two groups according to their approach in studying different regularities. The first group of papers (see Purić et al. 2008 and

references therein) is devoted to the evaluation of different types of regularities, such as dependence on atomic charge number, upper level ionization potential, atomic polarizability, principal quantum number and rest core charge of the emitter (seen by an electron undergoing transition), based on the Stark width and shift theoretical formulas obtained in different approximations: semiclassical, semiempirical and adiabatic. In the second group of papers (Wiese & Konjević 1982, 1992) regularities are examined among the experimental results, and conclusions are drawn on the basis of studying the configuration of the atomic energy levels and the transition probabilities. Namely, the expected regularities were studied and discussed, comparing the existing experimental and theoretical data within similar spectra, without any attempt to find a functional relation between Stark parameters and a particular atomic structure parameter.

An approach based on the systematic trends found in Stark broadening parameters has been developed in a series of articles devoted to the Stark parameter dependences on the upper-level ionization potential and rest core charge of the emitter (see Purić et al. 2008 and references therein). Such an approach differs from earlier trend analyses of Stark broadening parameters, primarily in the choice of the variable that conveys information regarding the atomic structure to the Stark broadening parameters (Purić et al. 1993). In this way the influence of atomic structure on such dependences is described appropriately. On the other hand, the work of several other authors (Wiese & Konjević 1982, 1992) was based on the hydrogenic model, which uses integer principle quantum numbers instead of the upper-state ionization potential χ chosen here. Both variables take into account the density of states perturbing the emitting state. However, some advantages of the present method are: (i) χ-based trend analyses achieve better fits (compared to those obtained when integer quantum number is used instead; Purić et al. 1987); (ii) using χ-values, the lowering of the ionization potential (Inglis & Teller 1939) can be taken into account, predicting merging with continuum when the plasma environment causes the line's upper-state ionization potential to approach zero; and (iii) the dependence of the Stark width (w) on χ is theoretically expected (Purić et al. 1993; Purić et al. 2008).

The proposed method is based on the fact that Stark widths in angular frequency units exhibit a certain function dependence on the upper-level ionization potential of the corresponding transition. In fact, the upper-level ionization potential is the bounding energy of the electron on the upper level of the corresponding transition. In order to avoid misunderstanding the positive value of this quantity, χ is called the upper-level ionization potential. Moreover, a systematic dependence has also been found on the rest core charge (Z_c) of the ionized emitter as seen by the electron undergoing transition. Simple relations based on such trends may be useful in astrophysics, when Stark broadening data for many lines are needed. Therefore, the Stark parameter dependencies on χ and Z_c were

deduced from the large scale of semiclassical (Griem 1974) or semiempirical (Griem 1968) and modified semiempirical calculations (Dimitrijević & Konjević 1980). The obtained relations were verified using the existing experimental and theoretical data (Purić et al. 2008).

The accuracy of the obtained data using the described procedure is expected to be comparable with that of the data used in the verification of Stark width dependencies on the upper-level ionization potential. Therefore, it is very important for this method to have as large as possible a set of data, calculated or measured, for the same plasma conditions, in particular the electron temperature and density. It is then possible to avoid the influence of density and temperature scaling, Debye screening effects and the contributions of different ions to the Stark widths used in the trends analyses. Otherwise, the existing data have to be normalized to the particular electron density and temperature in order to be used in trend analysis. Stark width data of spectral lines originated from neutral beryllium is the case studied here. They are taken from the Stark B database prepared by Dimitrijević & Sahal-Bréchot (1992, 1993, 1994) and from theoretical results calculated by Griem (1974).

In the Stark B database one can find Stark width data calculated separately for electron and proton impact contribution to the width of different atoms and ions and among them neutral beryllium spectral lines. It gives an opportunity to study in more detail the Stark parameter regularities of spectral lines originating from neutral beryllium. The emphasis is on the regularities within different BeI spectral series, and the fine structure influence such as different multiplicities (e.g. singlets and triplets) on the Stark parameter dependences upon the upper-level ionization potentials. The electron and proton impact contribution to the Stark broadening were simultaneously studied. It was found in both cases (electron and proton impact contribution) that these functions are different and therefore various singlet series have to be fitted and studied separately. It was not possible to divide them into several groups with a common correlation factor as was found in the case of the MgI singlet series (Tapalaga et al. 2011). Unfortunately, there is a lack of triplet series data, so a similar analysis could not be performed.

Finally, the well-determined Stark width dependences on the upper-level ionization potential are used to predict electron and proton impact contributions to the Stark widths of 27 BeI spectral lines not calculated or measured so far, to demonstrate the method of prediction.

2 Stark Widths Regularities

2.1 Theoretical Background

The theoretical relations for the Stark width of a spectral line as the function of the upper-level ionization potential and the rest core charge of the emitter were evaluated (Puric et al. 1993) starting from equation 77 of Griem (1974). These relations were successfully fitted to the

Stark parameters of a great number of spectral lines, as shown in a series of articles (see e.g. Purić et al. 1993, Purić & Šćepanović 1999 and Purić et al. 2008), and found to be of the form:

$$w = Z_c^{c_1} a_1 N_e f(T_e) \chi^{-b_1}, \qquad (1)$$

where w is the line width, χ is the corresponding upper-level ionization potential, Z_c is the rest core charge of the emitter, as seen by the electron undergoing transition ($Z_c = 1, 2, 3 \ldots$ for neutrals, singly charged ions, …, respectively) and a_1, b_1 and c_1 are coefficients independent of temperature, electron density, ionization potential for a particular transition and the rest core charge of the emitter.

Equation 1 can be used: (i) in the case of the lines originating from the same type of transitions (e.g. resonances or off-resonances; Purić, Ćuk & Lakićević 1985); multiplets, supermultiplets, spectral series and transition array within one stage of ionization ($Z_c = $ constant), or within several stages of ionization ($Z_c \neq$ const; Purić et al. 1991; Purić et al. 1993; Purić & Šćepanović 1999; Purić et al. 2008); (ii) within particular isoelectronic sequences (Purić et al. 1988a); and (iii) within a given isonuclear sequence (Purić et al. 1988b). In the case of a particular transition within a given homologous group of atoms or ions, it is more convenient to use a slightly different relation as the function of the nuclear charge number Z of the emitter (Purić et al. 1987).

For the same plasma conditions and for the exactly analogous transitions within the different atomic spectra, corresponding a_1 and b_1 constants are the same. Consequently, one can determine empirically, from experimental or more sophisticated calculations, averaged values for $a = a_1 N_e f(T_e)$ and $b = b_1$. Therefore, it was found that a general form of that dependence in the case of the particular transition array within the same stage of the ionization ($Z_c = $ constant) of the different emitters is of the following form:

$$w = Z_c^{c_1} a \chi^{-b}. \qquad (2)$$

In the case of a particular transition array, for the emitters in different ionization stages ($Z_c \neq$ const) the general form of Equation 1 can be rearranged:

$$w^* = w/Z_c^{c_1} = a_1 N_e f(T_e) \chi^{-b_1} = a \chi^{-b}. \qquad (3)$$

Here w^* is the reduced value of the Stark width of the spectral line in angular frequency units; the corresponding upper-level ionization potential (χ) is expressed in eV. It was found that coefficient c_1 is a universal constant approximately equal to 5.20 (Purić et al. 2008). A comprehensive set of Stark broadening data of the investigated ions has been used elsewhere (Purić & Šćepanović 1999), to demonstrate the existence of Stark width data regularities for the spectral lines originating from different transition arrays. This was extended towards as high as

possible ionisation stages, but for the lines originating from the particular 3s–3p transition arrays (Purić et al. 2008). It is important to stress that these dependences are universal and applicable for all types of transitions (Purić & Šćepanović 1999). However, the accuracy of predicted Stark widths values from such functional dependences is higher when obtained by the study of Stark broadening regularities within the lines originating from particular types of arrays, for example from 3s–3p transition arrays for as large as possible a range of electron temperatures and densities (Purić et al. 2008).

In the case of neutral spectra, such as that of BeI, $Z_c = 1$ and consequently Equation 2 can be written as

$$w = a\chi^{-b}. \qquad (4)$$

Comparing Equations 3 and 4 one can conclude that they are of the same form.

In order to investigate different Stark parameter regularities, an accurate set of theoretical and experimental data is necessary, being normalised to the particular electron density and temperature. The normalisation to the same N_e can be done by linear scaling due to the linear dependence of Stark widths on N_e. However, Stark width dependence on the electron temperature is different for each line in the spectrum. Therefore, the correction to the temperature dependence must be performed with great care for all data used for a given type of above-mentioned dependencies and regularities. For instance, instead of the commonly adopted temperature dependence of $T^{-1/2}$ for ion lines, one has to use, for both ion and neutral spectral lines, for each line in the spectra (Purić & Šćepanović 1999; Purić et al. 2008; Tapalaga et al. 2011), a set of functions given by:

$$f(T) = A + BT^{-C}, \qquad (5)$$

for a large temperature range (Grim 1974) given by:

$$10^{-2}\chi_0 \leq kT_e \leq \chi_0. \qquad (6)$$

The coefficients A, B and C are independent of the electron temperature and χ_0 is the ionisation potential of a given emitter. It was found that the same type of functions can be used in the case of neutral spectral lines, and consequently in the case of BeI spectral lines.

As far as the procedure for Stark broadening data predictions is concerned, it has been described in detail elsewhere (Purić et al. 2008), hence only a few details are given here for the sake of completeness. A comprehensive set of Stark broadening data of the investigated BeI lines has been used to demonstrate the existence of Stark width data regularities within its spectral line series, as is predicted by Equations 1–4. Finally, using the obtained Stark widths dependences on χ, Stark widths are predicted for 27 BeI lines not calculated or measured so far, to demonstrate such a possibility in any other case.

Table 1. The obtained *a* and *b* coefficients and corresponding correlation factor R^2 for the electron and proton impact contributions to the Stark widths for beryllium spectral series

Spectral series	$T = 5000$ K			$T = 10{,}000$ K			$T = 50{,}000$ K		
	a (rad s^{-1})	b	R^2	a (rad s^{-1})	b	R^2	a (rad s^{-1})	b	R^2
Electron impact broadening (Stark B)									
2p–nd (1)	1.79E+11	2.6178	N/A	2.11E+11	2.7368	N/A	2.98E+11	2.7843	N/A
2p–ns (1)	3.55E+11	2.3481	N/A	3.79E+11	2.3041	N/A	4.35E+11	2.2232	N/A
2s–np (1)	2.05E+11	2.3920	0.9947	2.43E+11	2.4470	0.9958	3.65E+11	2.4376	0.9986
3d–np (1)	2.14E+11	2.2361	1.0000	2.67E+11	2.2417	1.0000	4.63E+11	2.1020	0.9997
3p–nd (1)	1.70E+11	2.8728	N/A	2.12E+11	2.7909	N/A	3.57E+11	2.3328	N/A
3s–np (1)	2.07E+11	2.2963	0.9994	2.58E+11	2.2844	1.0000	4.40E+11	2.1222	0.9993
3s–np (3)	3.01E+11	2.5835	N/A	3.60E+11	2.5060	N/A	5.22E+11	2.1635	N/A
4d–np (1)	3.50E+11	1.8114	N/A	4.21E+11	1.8613	N/A	6.74E+11	1.8133	N/A
4s–np (1)	2.44E+11	2.0346	0.9962	3.32E+11	1.9765	0.9964	6.01E+11	1.8366	0.9973
Electron impact broadening (Griem 1974)									
2p–nd (1)	2.17E+11	3.0552	1.0000	2.70E+11	2.9583	1.0000	4.06E+11	2.7645	0.9997
2p–ns (1)	4.31E+11	2.3755	1.0000	4.95E+11	2.3572	1.0000	6.53E+11	2.2747	1.0000
2s–np (1)	4.87E+11	3.2996	N/A	5.83E+11	3.2591	N/A	7.59E+11	3.0206	N/A
Proton impact broadening (Stark B)									
2p–nd (1)	5.19E+10	2.3412	N/A	5.35E+10	2.3130	N/A	5.93E+10	2.2328	N/A
2p–ns (1)	7.78E+10	2.3062	N/A	8.76E+10	2.3177	N/A	1.15E+11	2.3449	N/A
2s–np (1)	7.32E+10	2.1734	0.9977	7.52E+10	2.1633	0.9979	8.11E+10	2.1422	0.9975
3d–np (1)	6.62E+10	2.1789	0.9995	6.75E+10	2.1804	0.9995	7.24E+10	2.1685	0.9992
3p–nd (1)	4.58E+10	2.5990	N/A	4.70E+10	2.6302	N/A	5.14E+10	2.7449	N/A
3s–np (1)	7.45E+10	2.0909	0.9995	7.56E+10	2.1023	0.9994	7.93E+10	2.1211	0.9987
3s–np (3)	8.99E+10	2.3411	N/A	9.71E+10	2.4181	N/A	1.14E+11	2.5266	N/A
4d–np (1)	6.90E+10	2.0551	N/A	7.30E+10	2.0226	N/A	8.72E+10	1.9038	N/A
4s–np (1)	7.52E+10	2.0410	1.0000	7.58E+10	2.0512	1.0000	7.83E+10	2.0598	1.0000

2.2 Results and Discussion

The main task of this paper is to investigate the relations between Stark widths of spectral lines (FWHM) and the upper-level ionization potential of the corresponding transition within spectral series of BeI spectral lines which can be used for the prediction of Stark widths for missing spectral lines from these series. For this purpose, the Stark width data from the Stark B database (Dimitrijević & Sahal-Bréchot 1992, 1993, 1994) and data calculated by Griem (1974) were collected and matched with their corresponding energy levels taken from the NIST database.[1] Namely, a collection of 38 BeI spectral lines with their corresponding Stark width values was taken from the Stark B database and used in further study of Stark width dependence on the upper-level ionization potential at different temperatures for the lines originating from the following BeI spectral series: 2s–np (1), 2p–ns (1), 2p–nd (1), 3s–np (1), 3p–nd (1), 3d–np (1), 4s–np (1), 4d–np (1) and 3s–np (3). In addition, Stark width data was taken from Griem (1974) for the following BeI spectral series: 2s–np (1G), 2p–ns (1G) and 2p–nd (1G), as well as for two triplet lines, 2p–3d (3G) and 2p–3s (3G), that are used in this analysis for the sake of comparison. Next to the series notation a number in parenthesis is given (1 or 3), standing for singlet or triplet series, respectively, and G for the data taken from Griem (1974).

For all the studied series it was found that the relation given by Equation 4 is appropriate for any particular temperature for both the electron impact and proton impact contributions to the Stark widths. During these analyses, one must use Stark width data in angular frequency units. The expected temperature dependences (Equation 5) were verified for all 38 spectral lines used in the analysis. The Stark width dependences on the upper-level ionization potential were verified for all nine spectral series studied here. In order to obtain data for any missing line from the series, one has to use the obtained functional dependence expected according to Equation 4 knowing only the upper-level ionization potential, and to substitute it in the same equation. Using this procedure and the temperature dependence of the Stark width given by the Equation 5, it is possible to obtain Stark broadening data by extrapolation or interpolation for any temperature of interest from the range defined by Equation 6. An appropriate computer program was developed in order to be able to get the Stark width temperature dependence of any particular spectral line originating from the above-mentioned series of neutral beryllium. This enables the obtaining of Stark width data dependences on the upper-level ionization potential at any temperature, as given in Table 1. In Table 1 the appropriate coefficients *a* and *b* are given for 5000 K, 10,000 K and 50,000 K, together with the corresponding correlation factors R^2 for both the electron and proton impact contributions to the Stark widths for all studied beryllium spectral series ($N_e = 10^{22}$ m^{-3}). For some series, correlation factors R^2 are
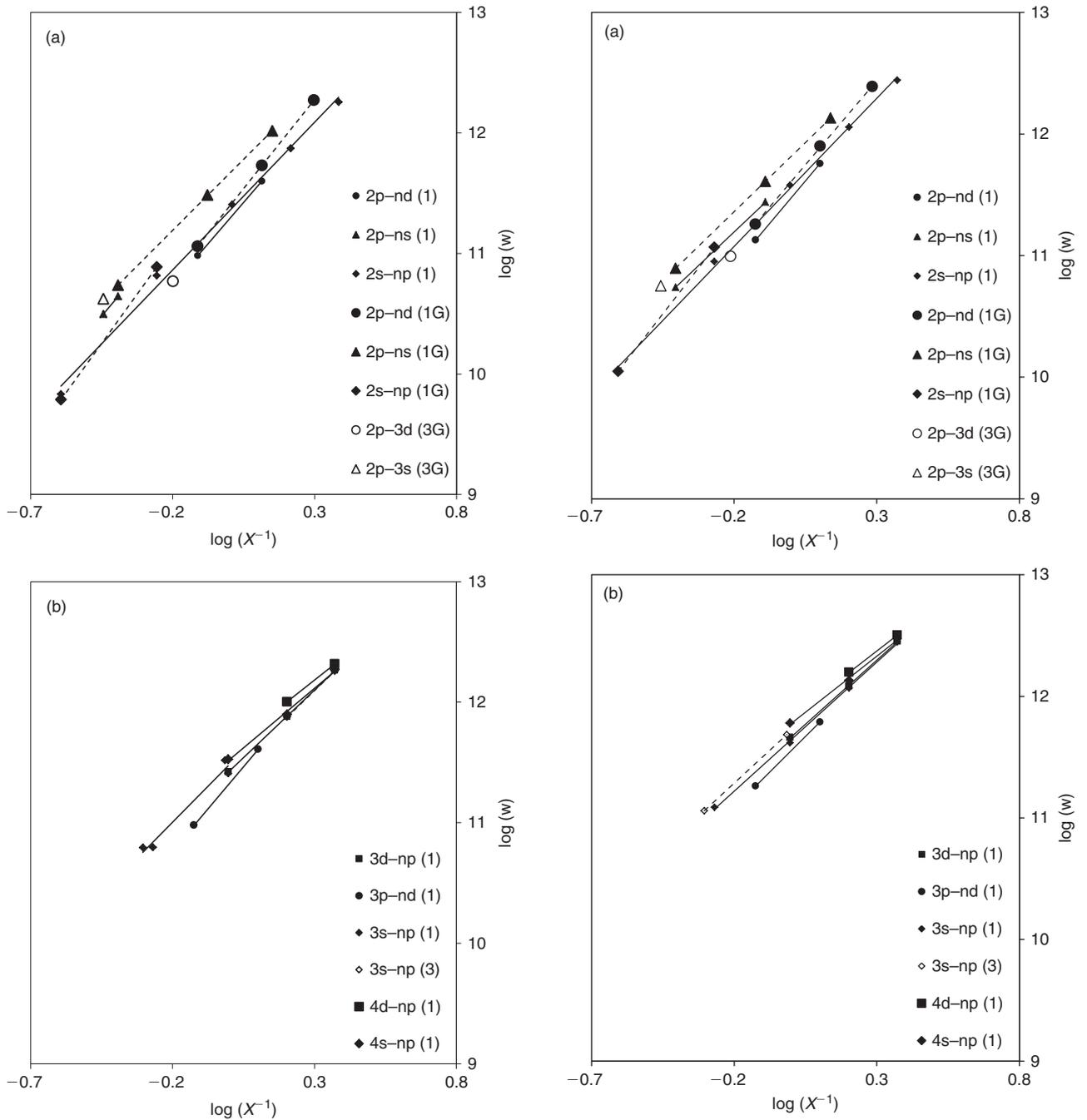
Figure 1 The electron impact contributions to Stark width dependences versus inverse upper-level ionisation potential at 10,000 K temperature for different BeI spectral series with principal quantum number of lower level of (a) $n = 2$; (b) $n = 3, 4$. The numbers (1) and (3) indicate singlets or triplets, respectively. Values taken from Griem (1974) are specified with 3G for triplets and 1G for singlets.

Figure 2 The electron impact contributions to Stark widths dependences versus inverse upper level ionisation potential at 50,000 K temperature for different BeI spectral series with principal quantum number of lower level of (a) $n = 2$; (b) $n = 3, 4$. The numbers (1) and (3) indicate singlets or triplets, respectively. Values taken from Griem (1974) are specified with 3G for triplets and 1G for singlets.

not available (N/A) because there were only two points in that series so R^2 would have a trivial value. However, the parameters of linear best-fitting, a and b, are listed because, based on available series, we assume that all series have a high value of R^2, so two points are enough to predict the behaviour of other lines that belong to these particular series. Influence of the fine structure on the obtained dependences (singlets or triplets) was also observed in this analysis. Namely, it was found that in the case of lines

originating from singlet series the temperature dependences are increasing functions. For triplet series these dependences are increasing or decreasing functions. Having found these temperature dependences for any spectral line, one can also find the corresponding Stark width dependences on the upper-level ionization potential within the spectral series studied here for every temperature. This is shown in Figures 1–4. For this purpose a special computer program was developed.
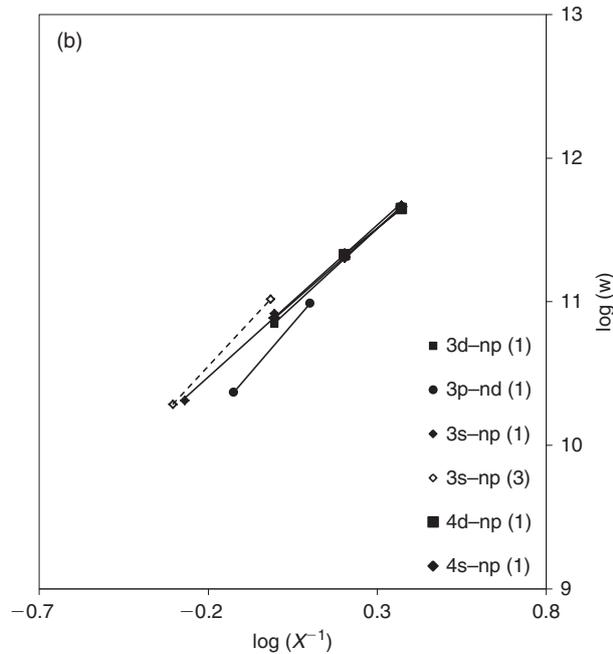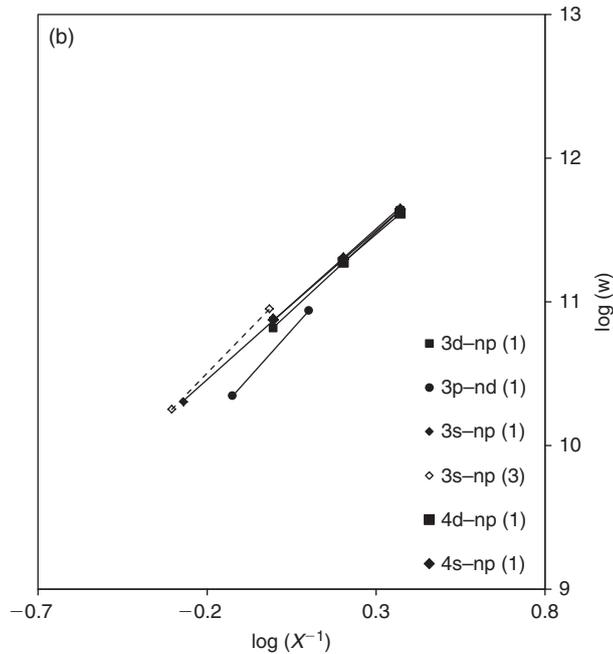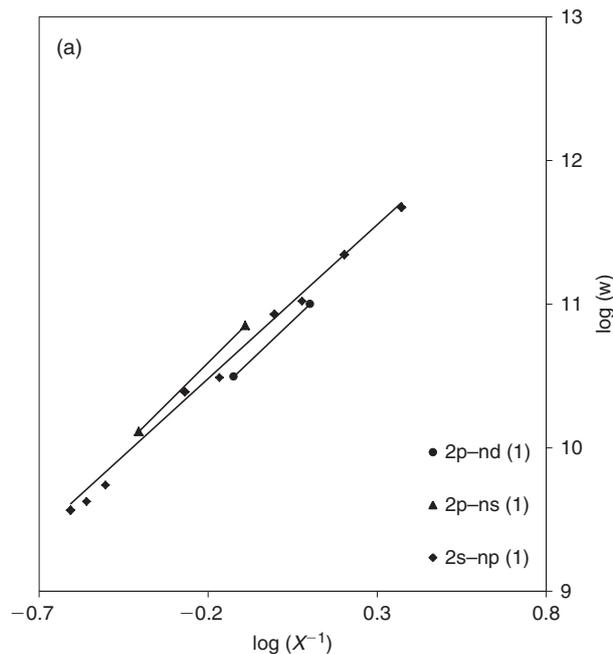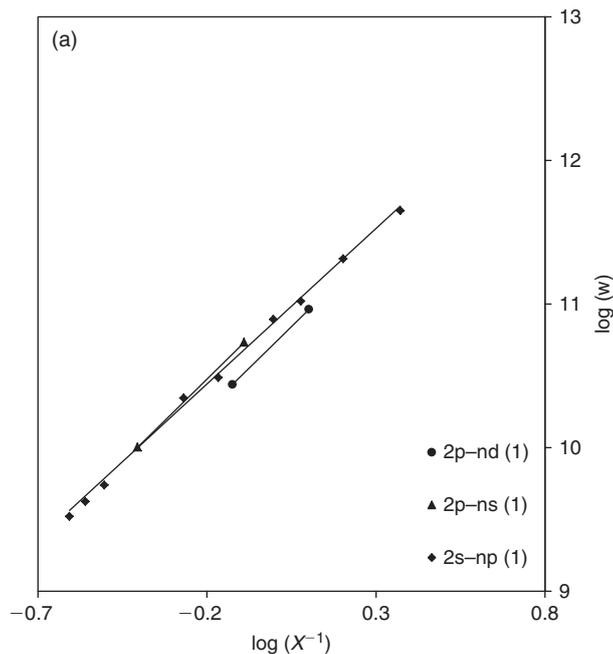
Figure 3 The proton impact contributions to Stark widths dependences versus inverse upper level ionisation potential at 10,000 K temperature for different BeI spectral series with principal quantum number of lower level of (a) $n = 2$; (b) $n = 3, 4$. The numbers (1) and (3) indicate singlets or triplets, respectively.

Figure 4 The proton impact contributions to Stark widths dependences versus inverse upper level ionisation potential at 50,000 K temperature for different BeI spectral series with principal quantum number of lower level of (a) $n = 2$; (b) $n = 3, 4$. The numbers (1) and (3) indicate singlets or triplets, respectively.

In Figures 1 and 2, electron impact contributions to the Stark width dependences versus inverse value of the upper level ionisation potential are shown for all investigated spectral series at two different electron temperatures, 10,000 K and 50,000 K. For example, it was found that for five spectral lines of BeI belonging to the 2s–np singlet series, the corresponding correlation factors in both cases (electron and proton impact contribution) are equal to one. The same behaviour is observed for all other series studied here. Values taken from Griem

(1974) are also included in Figures 1a and 2a for the sake of comparison. The trend analysis done using the Stark B database and theoretical data calculated by Griem (1974) have shown the same slope, although data calculated by Griem (1974) are systematically larger (up to 15%). Also, in Figures 1a and 2a the Stark width values of two triplet lines, 2p–3d (3G) and 2p–3s (3G), taken from Griem (1974) are given for the sake of comparison. Analysing these figures it is obvious that these Griem's Stark width values are in good agreement
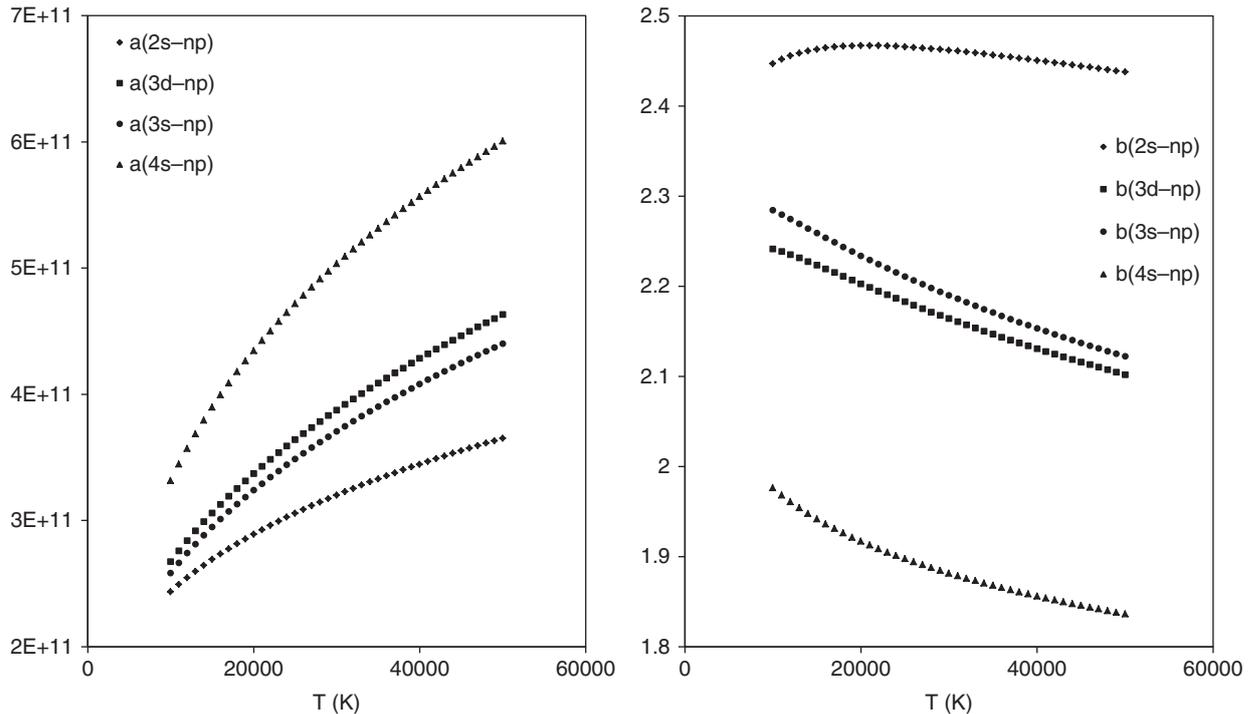
Figure 5 Temperature dependences of Stark width coefficients *a* and *b*.

with trends obtained for the 2p–nd (1G) and 2p–ns (1G) singlet spectral series.

The proton impact contribution dependences on the upper-level ionisation potential found at two different temperatures (10,000 K and 50,000 K) are graphically presented in Figures 3 and 4. One can conclude that the found dependences are similar to the electron impact contribution dependences obtained in this analysis. All studied spectral series (singlets and triplets) were treated separately and in all cases the corresponding correlation factors R^2 were better than 0.99, as shown in Table 1.

In Figure 5, the influence of temperature on the dependences of Stark width coefficients *a* and *b* from Equation 4 has been demonstrated. From this figure one can conclude that the coefficients *a* and *b* are increasing and decreasing functions of temperature, respectively.

The obtained Stark width dependences on the upper-level ionisation potential are used for prediction of Stark width data for the lines not investigated so far and given in Table 2. In this table, predicted Stark width (FWHM) values for 27 BeI spectral lines missing so far from the studied series are given for electron and proton impact contributions at $T = 5000$ K, $T = 10,000$ K and $T = 50,000$ K, normalized to an electron density of $N_e = 10^{22}$ m^{-3}. The total Stark widths are given in Table 2 for the sake of comparison. Based on the above-described analysis it is possible to predict Stark widths at any temperature, although the results in this paper are given only for $T = 5000$ K, $T = 10,000$ K and $T = 50,000$ K, as presented in Table 2. The predicted Stark width values are given at several temperatures starting from 5000 K, since it is the relevant photospheric stellar temperature for cool

stars (Primas et al. 2000; Garcia Lopez, Rebolo and Perez de Taoro 1995).

It is expected that the accuracy of the predicted data has the same accuracy as the data (experimental and theoretical) used in the verification of the Stark width theoretical dependences on the upper-level ionisation potential. The existing theoretical data (Griem 1974) are in good agreement (within quoted theoretical uncertainty) with the obtained Stark width regularities based on the theoretical data used in this analysis (Dimitrijević & Sahal-Bréchot 1992, 1993, 1994).

3 Conclusion

Searching for different types of regularities and systematic trends which can simplify complicated theoretical calculations, especially ones used in astrophysics, is of great interest. Therefore the aim of this paper was to establish as precisely as possible the dependence of the Stark parameters on the upper-level ionisation potential for nine BeI spectral series in order to demonstrate the capabilities of the described method.

This work successfully proves the existence of strong functional Stark width dependences on the upper-level ionisation potential for lines originating from the same series. These dependences were obtained and found to be of the type given by Equation 4. It was found that temperature dependences are very important for studying the Stark parameters of BeI spectral lines originating from different regularities. Therefore we have used theoretical values obtained by different authors for nien series in order to determine the temperature dependence of Stark

Table 2. The calculated values for the electron and proton impact contribution to the Stark widths of BeI spectral lines normalized to an electron density of $N_e = 10^{22}$ m^{-3}

BeI spectral lines			Electron impact widths (nm) at different temperatures			Proton impact widths (nm) at different temperatures			Total Stark widths (nm) at different temperatures		
λ (Å)	Transition	Terms	5000 K	10,000 K	50,000 K	5000 K	10,000 K	50,000 K	5000 K	10,000 K	50,000 K
3516.55	2p–5d	1P°–1D	0.066	0.084	0.123	0.123	0.016	0.017	0.082	0.100	0.140
3368.60	2p–6d	1P°–1D	0.154	0.205	0.304	0.304	0.034	0.035	0.188	0.239	0.339
3283.85	2p–7d	1P°–1D	0.324	0.448	0.674	0.674	0.065	0.065	0.390	0.513	0.739
3737.36	2p–5s	1P°–1S	0.056	0.059	0.066	0.066	0.012	0.018	0.068	0.073	0.084
3477.56	2p–6s	1P°–1S	0.129	0.134	0.145	0.145	0.028	0.042	0.157	0.165	0.187
3346.39	2p–7s	1P°–1S	0.270	0.275	0.290	0.290	0.057	0.087	0.327	0.340	0.377
1375.48	2s–7p	1S–1P°	0.035	0.044	0.066	0.066	0.010	0.010	0.045	0.054	0.076
1364.08	2s–8p	1S–1P°	0.068	0.087	0.129	0.129	0.018	0.019	0.085	0.105	0.147
1356.68	2s–9p	1S–1P°	0.119	0.155	0.229	0.229	0.029	0.031	0.148	0.185	0.260
1208.68	3d–7p	1D–1P°	0.023	0.029	0.043	0.043	0.007	0.007	0.030	0.036	0.051
1125.95	3d–8p	1D–1P°	0.038	0.048	0.068	0.068	0.011	0.012	0.049	0.059	0.080
1077.46	3d–9p	1D–1P°	0.060	0.076	0.104	0.104	0.017	0.018	0.077	0.093	0.122
9246.42	3p–5d	1P°–1D	0.513	0.607	0.756	0.756	0.115	0.143	0.628	0.728	0.899
8289.17	3p–6d	1P°–1D	1.146	1.318	1.395	1.395	0.234	0.305	1.380	1.566	1.700
7794.18	3p–7d	1P°–1D	2.430	2.724	2.508	2.508	0.457	0.622	2.887	3.214	3.130
5547.99	3s–7p	1S–1P°	0.514	0.631	0.887	0.887	0.149	0.160	0.662	0.780	1.047
5366.98	3s–8p	1S–1P°	0.920	1.126	1.512	1.512	0.244	0.272	1.164	1.379	1.784
5254.27	3s–9p	1S–1P°	1.536	1.876	2.421	2.421	0.388	0.436	1.924	2.277	2.857
5560.35	3s–5p	3S–3P°	0.161	0.186	0.231	0.231	0.043	0.059	0.204	0.234	0.290
5089.14	3s–6p	3S–3P°	0.373	0.418	0.454	0.454	0.091	0.135	0.464	0.523	0.589
4850.51	3s–7p	3S–3P°	0.795	0.868	0.842	0.842	0.179	0.282	0.974	1.079	1.123
2550.41	4d–7p	1D–1P°	0.103	0.132	0.199	0.199	0.028	0.029	0.131	0.159	0.228
2208.07	4d–8p	1D–1P°	0.129	0.167	0.249	0.249	0.036	0.037	0.165	0.204	0.286
2029.00	4d–9p	1D–1P°	0.169	0.221	0.326	0.326	0.050	0.049	0.219	0.272	0.376
1341.12	4s–7p	1S–1P°	0.026	0.033	0.050	0.050	0.008	0.009	0.034	0.041	0.059
1240.02	4s–8p	1S–1P°	0.039	0.049	0.072	0.072	0.012	0.013	0.052	0.062	0.086
1181.46	4s–9p	1S–1P°	0.059	0.072	0.103	0.103	0.018	0.020	0.077	0.091	0.122

parameters, by introducing coefficients *A, B* and *C* for these lines. These coefficients were obtained via a systematic trends analysis for temperature data normalization. Normalization on the electron density was performed using a linear function for non-hydrogenic emitters.

On the basis of the above-given results one can draw the following conclusions. Firstly, Equation 4 can be used successfully for Stark width prediction with the appropriate coefficients *a* and *b* and corresponding upper-level ionisation potential. Secondly, the influence of fine structure (singlet and triplet) on Stark width dependences on the upper-level ionisation potential is very important. Thirdly, in general the best precision can be obtained using Equation 4 for any particular series separately. The obtained theoretical dependence has been compared with theoretically determined Stark widths published so far. The agreement was found to be within the theoretical uncertainty.

After analysing the relationship between the Stark width of spectral lines and the upper-level ionization potential, the same conclusions can be drawn for the behaviour of both electron and proton impact contributions. An almost linear (in log–log scale) relation between FWHM and upper-level ionisation potential can be established according to Equation 4 within particular series of spectral lines. The influence of temperature on the studied dependences of Stark width parameters has been demonstrated. Finally, the obtained Stark width dependences on the upper-level ionization potential were used for prediction of Stark width values for 27 beryllium spectral lines belonging to the same series studied here, but not measured or theoretically calculated so far. It is expected that the accuracy of the obtained data using the described procedure is comparable to the accuracy of the data used in the verification of Stark width dependences on the upper-level ionization potential, taking into account the quality of the fitting procedure (i.e., very high correlation factors).

Acknowledgments

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