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CONTRIBUTION OF ION TO THE ASTROPHYSICAL IMPORTANT 471.32 nm He I SPECTRAL LINE BROADENING

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Abstract. Ion contribution of the astrophysical important Stark broadened 471.32 nm He I spectral line profiles have been measured at electron densities between $4.4\,10^{22}$ and $8.2\,10^{22}$ m^{-3} and electron temperatures between 18 000 and 33 000 K in plasmas created in five various discharge conditions using a linear, low-pressure, pulsed arc as an optically thin and reproductive plasma source operated in a helium-nitrogen-oxygen gas mixture. On the basis of the observed asymmetry of the line profiles we have obtained their ion broadening parameters (A) caused by influence of the ion microfield and also the influence of the ion dynamic effect (D) to the line shape. Our A and D parameters represent the first data obtained experimentally by the use of the line profile deconvolution procedure. We have found stronger influence of the ion contribution to this He I line profiles than the semiclassical theoretical approximation provides. This can be important for some astrophysical plasma modelling or diagnostics.

1. Introduction

After hydrogen, helium is the most abundant element in the universe. The 471.32 nm (2p ^{3}P$^0_{2,1}$ - 4s ^{3}S$_1$ transition) neutral helium (He I) spectral line are the most investigated in the helium spectrum. This line has been used by various investigations of the radiation emitted by cosmic light sources like: white dwarfs, variables, supergiants and galaxies (Rupke et al. 2002, Bergeron et al. 2002, Peimbert et al. 2002, Thuan et al. 2002, Bresolin et al. 2002, Benjamin et al. 2002, Drissen et al. 2001, Cuesta and Phillips 2000). Therefore, the use of this He I spectral line for diagnostical purposes in astrophysics understands the knowledge of its line profile characteristics. A significant number of theoretical and experimental works has been dedicated to the He I Stark FWHM (full-width at half intensity maximum, W) investigations (Lesage and Fuhr 1999, and references therein). The aim of this work is to present the measured Stark broadening parameters of the He I 471.32 nm spectral line at (18 000 - 33 000) K electron temperatures (T) and at (4.4 - 8.2) 10^{22} m^{-3} electron densities (N). The used T values are typical for many cosmic light sources. Using a deconvolution procedure described by Milosavljević and Poparić (2001) we have obtained, for the first time, on the basis of the observed line profile asymmetry, the ion contribution to the line shape expressed due to the quasistatic ion (parameter A) and ion dynamic effect (coefficient D) (Griem 1974, Barnard et al. 1974, Bassalo et al. 1982) and, also, the separate electron (W_e) and ion (W_i) contributions to the total Stark width (W_t). As a plasma source we have used a linear, low-pressure, pulsed arc operated in five various discharge conditions. Our measured W_t, W_e, W_i and A values have been compared to all available theoretical and experimental data.

2. Experiment

The modified version of the linear low pressure pulsed arc (Djeniže et al. 1998, 2002) has been used as a plasma source. The working gas was helium - nitrogen - oxygen mixture (90% He + 8% N_2 + 2% O_2). The used tube geometry and corresponding discharge conditions are presented in Table. 1.

Table 1: Various discharge conditions. C-bank capacity, U-bank voltage, H-plasma length, Φ-tube diameter, P-filling pressure. N and T denote electron density and temperature, respectively obtained at a 25^{th} μs after the beginning of the discharge when the line profiles were analyzed.

C (μF)	U (kV)	H (cm)	Φ (mm)	P (Pa)	N (10^{22}m^{-3})	T (K)
8	4.5	6.2	5	267	6.1	33000
14	4.2	14.0	25	267	8.2	31500
14	3.4	14.0	25	267	6.7	30000
14	2.6	14.0	25	267	4.4	28000
14	1.5	7.2	5	133	5.0	18000

Spectroscopic observation of spectral lines was made end-on along the axis of the discharge tube described in details in Djeniže (2002).

The line profiles were recorded by a step-by-step technique using a photomultiplier (EMI 9789 QB and EMI 9659B) and a grating spectrograph (Zeiss PGS-2, reciprocal linear dispersion 0.73 nm/mm in the first order) system. The instrumental FWHM of 8 pm was obtained by using narrow spectral lines emitted by the hollow cathode discharge.

The plasma reproducibility was monitored by the He I (501.56 nm, 388.86 nm and 587.56 nm) lines radiation and, also, by the discharge current using the Rogowski coil signal (it was found to be within ±5%). Using the double plasma length method, described by Milosavljević (2001), the correction of the line profiles was performed in order to eliminate the influence of self-absorption on the line shapes.

The plasma parameters were determined using standard diagnostics methods. Thus, the electron temperature was determined from the ratios of the relative line intensities of four N III spectral lines (409.74 nm, 410.34 nm, 463.42 nm and 464.06 nm) to the 463.05 nm N II spectral line with an estimated error of ±10%, assuming the existence of the LTE (Griem 1974). All the necessary atomic data were taken from NIST (2002) and Glenzer et al. (1994). The electron density decay was measured using a well known single wavelength He-Ne laser interferometer technique for the 632.8 nm transition with an estimated error of ±9%. The electron densities and temperatures, obtained at the moment when the line profiles were analyzed, are presented in Table 1.

3. Numerical procedure for deconvolution

The proposed functions for various line shapes, eq. (1) is of the integral form and include several parameters. Some of these parameters can be determined in separate experiments, but not all of them. Furthermore, it is impossible to find an analytical solution for the integrals and methods of numerical integration to be applied. This procedure, combined with the simultaneous fitting of several free parameters, causes the deconvolution to be an extremely difficult task and requires a number of computer supported mathematical techniques. Particular problems are the questions of convergence and reliability of deconvolution procedure, which are tightly connected with the quality of experimental data.

$$K(\lambda) = K_o + K_{max} \int_{-\infty}^{\infty} exp(-t^2) \cdot [\int_0^{\infty} \frac{\mathrm{H_R}(\beta)}{1 + (2\frac{\lambda - \lambda_o - \frac{\mathrm{W_G}}{2\sqrt{\ln 2}} \cdot t}{\mathrm{W_e}} - \alpha \cdot \beta^2)^2} \cdot d\beta] \cdot dt \quad (1)$$

Here K_o is the baseline (offset) and K_{max} is the maximum of intensity (intensity for $\lambda = \lambda_o$) (Milosavljević and Poparić 2001). $\mathrm{H}_R(\beta)$ is an electric microfield strength distribution function of normalized field strength $\beta = \mathrm{F}/\mathrm{F}_o$, where F_o is the Holtsmark field strength. A ($\alpha = \mathrm{A}^{4/3}$) is the static ion broadening parameter as a measure of the relative importance of ion and electron broadenings. R is the ratio of the mean distance between the ions to the Debye radius, i.e. the Debye shielding parameter and W_e is the electron width (FWHM) in the $\mathrm{j}_{A,R}$ profile (2).

For the purpose of deconvolution iteration process we need to know the value of K function (1) as a function of λ for every group of parameters (K_{max}, λ_o, W_e, W_G, R, A). The function $\mathrm{K}(\lambda)$ is in integral form and we have to solve a triple integral in each step of iteration process of varying the above group of parameters. The first integral in the "K" function is the micro field strength distribution function, $\mathrm{H}_R(\beta)$ the second one is the $\mathrm{j}_{A,R}(\lambda)$ function eq. (2) and the third is the convolution integral of a Gaussian and a plasma broadened spectral line profile $\mathrm{j}_{A,R}(\lambda)$, denoted by $\mathrm{K}(\lambda)$ equation (1). All these integrals have no analytic solution and must be solved using the numerical integration.

$$j_{A,R}(\lambda) = j_o + j_{max} \cdot \int_0^{\infty} \frac{\mathrm{H_R}(\beta)}{1 + (2\frac{\lambda - \lambda_o}{\mathrm{W}_e} - \alpha \cdot \beta^2)^2} \cdot d\beta \quad (2)$$

The most difficult integral to deal with is the micro field strength distribution function, because this is a multidimensional integral. Straightforward manner would be the estimates of multidimensional integral by Monte Carlo method of integration. The numbers of random samples of points must be large in order to achieve satisfactory accuracy. That would lead to the increased processor time (Milosavljević 2001).

In general, the base line K_o in functions (1) is a function of wavelength. In many cases it is nearly constant, or linear function.We have included in our procedure the fitting of background by cubic polynomial, as independent step, in order to prepare experimental data for the main deconvolution procedure.

The upper limits of numerical conditionality of this method are minimum twenty experimental points per line (the border of line is ($-3/2 \cdot \mathrm{W}_e + \lambda_o < \lambda < +3/5 \cdot \mathrm{W}_e + \lambda_o$), where W_e is electron FWHM), and maximal statistical indeterminacy in intensity is 5% at every experimental point. Poor experimental measurements weaken the conditionality of the system of equations, and lead to non-applicability of this method. This has been concluded by testing the sensitivity of the algorithm by generating random statistical noise with Gaussian distribution in every point involved in theoretical profiles.

4. Results and discussion

The plasma broadening parameters (W_t, W_e, W_i, A, D) obtained by our deconvolution procedure of the recorded line profile at a measured N and T values are presented in Table 2 together with other author's results. Various theoretical (G, BCW, DSB) predictions of the W_e, W_i, and A are also given. By the normalization of the A^G and A^{BCW} values to our electron density the well known $N^{1/4}$ numerical factor (Griem 1974) was used.

Table 2: Measured line broadening characteristics of the 471.32 nm spectral line. Total Stark FWHM (W_t^{exp} in pm within ±12% accuracy), electron Stark width (W_e^{exp} in pm within ±12% accuracy), ion Stark width (W_i^{exp} in pm within ±12% accuracy), static ion broadening parameter (A^{exp}, dimensionless within ±15% accuracy) and ion dynamic coefficient (D^{exp}, dimensionless within ±20% accuracy) at a given electron temperature (T in 10^3 K) and electron density (N in $10^{22}\mathrm{m}^{-3}$). Here Tw present the values given in this work and those used from other authors: RS, Roder and Stampa (1964); K, Kelleher (1981); B, Berg et al. (1962); W, Wulff (1958); Gr, Griem et al. (1962); L, Lincke (1964); P, Pérez et al. (1991); M, Mijatović et al. (1995).The index G, BCW and DSB denote theoretical data taken from Griem (1974), Bassalo et al. (1982) and Dimitrijević and Sahal – Bréchot (1990), respectively at a given T and N.

T	N	W_t^{exp}	W_e^{exp}	W_i^{exp}	A^{exp}	D^{exp}	Ref.	W_e^G	W_e^{BCW}	W_e^{DSB}	W_i^{DSB}	A^G	A^{BCW}
33.0	6.1	542	371	171	0.343	1.0	Tw	554	483	398	95	0.146	0.162
31.5	8.2	713	481	232	0.368	1.0	Tw	740	648	533	125	0.157	0.175
30.0	6.7	595	407	188	0.352	1.0	Tw	603	528	430	99	0.150	0.166
28.0	4.4	372	261	111	0.317	1.0	Tw	394	341	281	65	0.136	0.151
18.0	5.0	403	286	117	0.335	1.0	Tw	428	370	319	69	0.142	0.161
16.5	1.7				0.20*		RS						
20.9	1.03	96			0.095	1.36	K						
20.0	13.0	1400					B						
30.0	3.2	290					W						
30.0	2.6	300					Gr						
22.7	9.3	91					L						
30.2	3.23	295					P						
19.3	0.25	23					M						

In order to make the comparison among measured (W_t^{exp}) and calculated (W_t^{th}) total (electron + ion) width values easier, the W_t^{exp}/W_t^{th} dependence on the electron temperature is presented graphically in Figure 1 for the investigated lines.

The G (Griem 1974) and BCW (Bassalo et al. 1982) W_t values are calculated using the Eq.(226) from Griem (1974) with the W_e and A values predicted by the G and BCW theoretical approaches, respectively. The W_t^{exp}/W_t^{th} ratios related to the Dimitrijević and Sahal–Bréchot (1990) (DSB) data have been calculated only for our experimental values. Namely, for the calculations of the W_i^{DSB} it is necessary to know the helium ion concentration connected to the plasma composition. We have performed this for our discharge conditions only.

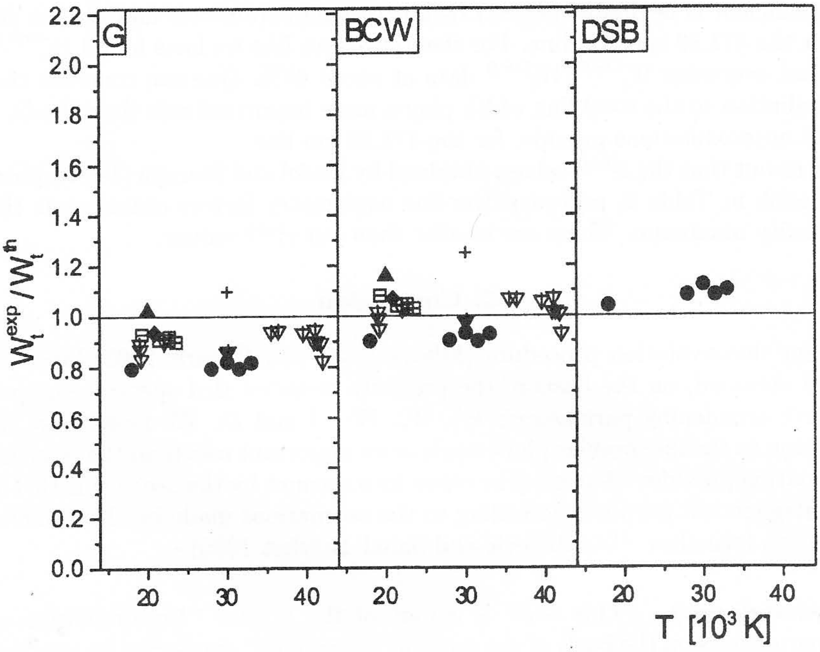

Fig. 1: Ratios of the experimental total Stark FWHM (W_t^{exp}) to the various theoretical (W_t^{th}) predictions vs. electron temperature for the He I 471.32 nm line. ∘, +, ⋄, △, ▽+, ⩡and+ represent our experimental data and those from Griem et al. (1962), Kelleher (1981), Berg et al. (1962), Wulff (1958), Lincke (1964), Pérez et al. (1991) and Mijatović et al. (1995), respectively. G, BCW and DSB represent the ratios related to the theories taken from Griem (1974), Bassalo et al. (1982) and Dimitrijević and Sahal - Bréchot (1990), respectively.

It turns out that our W_e^{exp} and W_i^{exp} are the first separated experimental electron and ion Stark width data obtained by using our deconvolution procedure. Our W_e^{exp} data are smaller than the G, BCW and DSB approximations provide for the investigated lines. Approximations BCW and DSB provide smaller W_e values than the G approximation.

By the inspection of the Figure 1 one can conclude that Griem's (1974) W_t values lie above most of the experimental values and also above BCW and DSB theoretical data. Theoretical W_t values presented by Bassalo et al. (1982) lie about 10% - 15% below Griem's values. The W_t values ($W_e + W_i$) presented by Dimitrijević and Sahal-Bréchot (1990) agree with ours (W_t^{exp}) within 3% - 10% (on average).

We have found evident contribution of the ion influence to the line broadening due to the quasistatic ion effect expressed with the ion broadening parameter (A). Our

A^{exp} values are the first data obtained directly by the use of the line deconvolution procedure. They are higher than the G and BCW approaches provide at about 135% and 110%, respectively. We have found that the ion dynamic effect, expressed due to the D coefficient is negligible ($D \simeq 1$) by our plasma parameters and plasma composition for the 471.32 spectral line. For the 471.32 nm line we have found W_i^{exp}/W_t^{exp} values that overvalue W_i^{DSB}/W_t^{DSB} data at about 65%. One can conclude that the ion contribution to the total line width play a more important role than the G, BCW and DSB approximations provide, for the 471.32 nm line.

It turns out that the A^{exp} values, obtained by Rodel and Stampa (1964), presented with asterisk in Table 2, represent the line asymmetry factors obtained at the line half intensity maximum. These are smaller than our A^{exp} values.

5. Conclusion

Using line deconvolution procedure (Milosavljević and Poparić 2001, Milosavljević 2001) we obtained, on the basis of the precisely recorded He I spectral line profiles, their Stark broadening parameters: W_t, W_e, W_i, A and D. We found that the ion contribution to the line profiles plays much more important role than the semiclassical approximation provides what must be taken into account by the use of this He I line to plasma diagnostical purposes according to the estimations made by the semiclassical perturbation formalism (Dimitrijević and Sahal-Bréchot 1990).

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