Proceedings of the IX Bulgarian-Serbian Astronomical Conference: Astroinformatics (IX BSACA) Sofia, Bulgaria, July 2-4, 2014,
Editors: M. K. Tsvetkov, M. S. Dimitrijević, O. Kounchev, D. Jevremović and K. Tsvetkova
Publ. Astron. Soc. "Rudjer Bošković" No 15, 2015, 63-66

ON THE DETERMINATION OF ELECTRON DENSITY IN NON-THERMAL PLASMAS USING BALMER SERIES HYDROGEN LINES

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Abstract. A new Optical Emission Spectroscopy method for measuring of electron density of non-thermal plasmas, based on the difference of Lorentzian broadenings of *H*□ and *H*□, two Balmer series hydrogen lines, valid for electron densities in 10^{14} cm^{-3} order and above, is presented. For the application of this method, there is no need to know the gas temperature and the van der Waals contribution to the Lorentzian part of the line profile. This method is applied for the determination of the electron density in an argon microwave-induced plasma at atmospheric pressure. The obtained results are compared with results obtained with other diagnostic methods.

1. INTRODUCTION

Non-thermal plasmas, also called non-equilibrium or cold plasmas, are characterized by a large difference in the electron temperature relative to those of the ions and neutrals (gas temperature). For the determination of electron density (n_e) of such plasmas, sustained at atmospheric pressure (Griem, 1974), optical emission spectroscopy methods, based on the analysis of Balmer series hydrogen lines, are commonly used if the gas temperature (T_g) is low But since in such conditions van der Waals broadening, depending on T_g becomes important, contributing non-negligibly to the Lorentzian part, in order to determine the electron density, we should know the value of T_g.

We present here a method to determine electron density of such plasmas without the necessity to know the value of T_g, with the help of Lorentzian widths of H_α and H_β. This method can be applied for plasmas with electron density of the order of 10^{14} cm^{-3} or higher, namely above the so called fine structure limit (Konjević et al., 2012). It is tested here and compared with the results obtained using other diagnostic methods on an argon microwave plasma at atmospheric pressure.

2. THE METHOD

Different broadening mechanisms contribute to the shapes of spectral emitted by plasmas at pressures higher than 100 Torr. The line profiles generated by the *van der Waals broadening* (due to collisions of emitter with neutral atoms) have a Lorentzian form, while *Doppler broadening* (due to the thermal movement of emitters) and *instrumental broadening* (due to the device used for the spectrum registration) results in line shapes with a Gaussian form. *Stark broadening,* due to collisions of the emitter with charged particles, may deviate from a simple Lorentz form in the case of H_α and H_β lines, due to fine structure and quasistatic ion broadening, but for electron densities of the order of 10^{14} -10^{15} cm^{-3}, these line profiles can be approximated to a Lorentz function (Konjević et al., 2012). Consequently, their experimental profiles can be aproximated by a Voigt function resulting from the convolution of a Gaussian and Lorentzian profiles.

For an argon plasma at atmospheric pressure with a typical electron density n_e of $5\cdot 10^{14}$ (cm^{-3}) and gas temperature T_g around 2000 K, the full width at half maximum (FWHM) of the Lorentzian profile for H_α and H_β lines, w_L, could be written as

$$w_L^{H_\alpha}(T_e, n_e, T_g, \mu_r) = w_S^{H_\alpha}(T_e, n_e, \mu_r) + w_W^{H_\alpha}(T_g) \quad (1)$$

$$w_L^{H_\beta}(T_e, n_e, T_g, \mu_r) = w_S^{H_\beta}(T_e, n_e, \mu_r) + w_W^{H_\beta}(T_g) \quad (2)$$

where w_s and w_w are FWHM due to Stark and van der Waals broadening, respectively, T_e is the plasma electron temperature and μ_r a fictitious reduced mass of the pair H-pertubed atom. In order to avoid the necessity to know the value of the gas temperature needed for the subtraction of the van the Waals contribution, if we want to obtain the electron density, we propose here an alternative method which uses the fact that H_α and H_β lines have very similar values of van der Waals widths. We demonstrated in Yubero et al. (2014) that for a typical gas temperature of 1000 K, the difference between van der Waals widths of these two lines is less than 5 %. Consequently, we can assume that the difference between the H_β and H_α Lorentzian widths not depends on the van der Waals broadening, and write:

$$\begin{aligned} w_L^{H_\beta}\left(T_e, n_e, T_g, \boldsymbol{\mu}_r\right) - w_L^{H_\alpha}\left(T_e, n_e, T_g, \boldsymbol{\mu}_r\right) &= w_S^{H_\beta}\left(T_e, n_e, \boldsymbol{\mu}_r\right) - w_S^{H_\alpha}\left(T_e, n_e, \boldsymbol{\mu}_r\right) + R(T_g) \\ &\approx f\left(T_e, n_e, \boldsymbol{\mu}_r\right) \end{aligned} \quad (3)$$

Gigosos et al. (2003) proposed the Computer Simulatiom (CS) method for the calculation of Stark broadened profiles and performed the corresponding calculations for H_α and H_β lines, which enabled to us to obtain the corresponding value of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ for several values of electron density, electron temperature and fictitious reduced mass. In Yubero et al. (2014), is found that the dependence of $\left(w_S^{H_\beta} - w_S^{H_\alpha}\right)$ on T_e and fictitious reduced mass for electron densities in the range between 10^{14} and 10^{16} cm^{-3} is weak, so that for this electron density range Eq. 3 becomes:

$$w_L^{H_\beta}(T_e, n_e, T_g, \mu_r) - w_L^{H_\alpha}(T_e, n_e, T_g, \mu_r) \approx f(n_e) \quad (4)$$

Moreover, the theoretical relationship between $\left(w_L^{H_\beta} - w_L^{H_\alpha}\right)$ and n_e can be approximated with a simple expression

$$n_e(\cdot 10^{14}\,\mathrm{cm}^{-3}) \approx 185\left(w_L^{H_\beta} - w_L^{H\alpha}\right)^{3/2} \quad (5)$$

$$n_e(\cdot 10^{14}\,\mathrm{cm}^{-3}) \approx 168\left(w_L^{H_\beta} - w_L^{H\alpha}\right)^{3/2} \quad (6)$$

where w are in nm.

Equations (5) and (6) are valid for an electron temperature range between 5000-15000 K, and give possibility for an easy and quick calculatio of the electron density, without necessity to know the gas temperature.

3. ELECTRON DENSITY OF A MICROWAVE PLASMA AT ATMOSPHERIC PRESSURE

In order to test this method we used it for the determination of electron density in an argon microwave (2.45 GHz) induced plasma at atmospheric pressure generated inside a quartz tube, using a *surfaguide* device (Moisan et al., 1998). The experimental set-up and experiment is described in detail in Yubero et al. (2014).

The electron density was determined in two ways, using the proposed method (Eq. 5) and the results for Stark broadening of H_α and H_β obtained by Gigosos et al. (2003). The values of n_e obtained with both methods are quite similar. All details are given in Yubero et al. (2014).

In order to test the adequacy of the used deconvolution procedure, the Lorentzian widths of H_α and H_β line profiles were also determined by fixing the Gaussian part (for a value of $T_g = 1380 \pm 120$ K, typical in the plasmas studied) of the Voigt function as suggested in Konjevic et al. (2012), and significant differences were not found.

In Yubero et al. (2014) is shown that present results are in good agreement with those obtained using CS model for H_α and H_β lines (Garcia et al., 2004), extracting from the total Lorentzian contribution the van der Waals contribution (for $T_g = 1380 \pm 120$ K).

Aknowledgements

The authors wish to acknowledge to *Física de Plasmas: Diagnosis, Modelos y Aplicaciones (FQM 136)* research group for their funding and technical support, as well as to the support through projects 176002 and III44002 of Ministry of Education and Science of Republic of Serbia.

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