

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

CRISTINA YUBERO<sup>1</sup>, MARIA CARMEN GARCÍA<sup>1</sup>,  
MILAN S. DIMITRIJEVIC<sup>2</sup>, ANTONIO SOLA<sup>1</sup>  
and ANTONIO GAMERO<sup>1</sup>

<sup>1</sup>*Grupo de Física de Plasmas: Diagnósis, Modelos y Aplicaciones (FQM-136)  
Edificio A. Einstein (C-2), Campus de Rabanales. Universidad de Córdoba,  
14071 Córdoba, Spain*

<sup>2</sup>*Astronomical Observatory, Volgina 7, 11060 Belgrade, Serbia.  
E-mail: f62yusec@uco.es, mdimitrijevic@aob.rs*

**Abstract.** A new Optical Emission Spectroscopy method for measuring of electron density of non-thermal plasmas, based on the difference of Lorentzian broadenings of  $H_{\square}$  and  $H_{\square}$ , two Balmer series hydrogen lines, valid for electron densities in  $10^{14} \text{ cm}^{-3}$  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  $H_\alpha$  and  $H_\beta$ . This method can be applied for plasmas with electron density of the order of  $10^{14}$  cm<sup>-3</sup> 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  $H_\alpha$  and  $H_\beta$  lines, due to fine structure and quasistatic ion broadening, but for electron densities of the order of  $10^{14}$  -  $10^{15}$  cm<sup>-3</sup>, these line profiles can be approximated to a Lorentz function (Konjević *et al.*, 2012). Consequently, their experimental profiles can be approximated 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<sup>-3</sup>) and gas temperature  $T_g$  around 2000 K, the full width at half maximum (FWHM) of the Lorentzian profile for  $H_\alpha$  and  $H_\beta$  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  $\mu_r$  a fictitious reduced mass of the pair H-perturbed atom. In order to avoid the necessity to know the value of the gas temperature needed for the subtraction of the van der Waals contribution, if we want to obtain the electron density, we propose here an alternative method which uses the fact that  $H_\alpha$  and  $H_\beta$  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  $H_\beta$  and  $H_\alpha$  Lorentzian widths not depends on the van der Waals broadening, and write:

$$w_L^{H_\beta}(T_e, n_e, T_g, \mu_r) - w_L^{H_\alpha}(T_e, n_e, T_g, \mu_r) = w_S^{H_\beta}(T_e, n_e, \mu_r) - w_S^{H_\alpha}(T_e, n_e, \mu_r) + R(T_g) \approx f(T_e, n_e, \mu_r) \quad (3)$$

Gigosos *et al.* (2003) proposed the Computer Simulation (CS) method for the calculation of Stark broadened profiles and performed the corresponding

calculations for  $H_\alpha$  and  $H_\beta$  lines, which enabled to us to obtain the corresponding value of  $(w_S^{H_\beta} - w_S^{H_\alpha})$  for several values of electron density, electron temperature and fictitious reduced mass. In Yubero et al. (2014), is found that the dependence of  $(w_S^{H_\beta} - w_S^{H_\alpha})$  on  $T_e$  and fictitious reduced mass for electron densities in the range between  $10^{14}$  and  $10^{16}$   $\text{cm}^{-3}$  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  $(w_L^{H_\beta} - w_L^{H_\alpha})$  and  $n_e$  can be approximated with a simple expression

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

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

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 calculation 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  $H_\alpha$  and  $H_\beta$  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  $H_\alpha$  and  $H_\beta$  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  $H_\alpha$  and  $H_\beta$  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: Diagnósis, 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.

## References

- García, M. C., Yubero, C., Calzada, M. D., Martínez-Jiménez, M. P.: 2004, Spectroscopic characterization of two different microwave (2.45 GHz) induced argon plasmas at atmospheric pressure, *Appl. Spectrosc.*, **59**, 519-528.
- Gigosos, M. A., González, M. A., Cardeñoso, V.: 2003, Computer simulated Balmer-alpha, -beta and -gamma Stark line profiles for non-equilibrium plasmas diagnostics, *Spectrochim. Acta Part B*, **58**, 1489-1504.
- Griem, H. R.: 1974, *Spectral Line Broadening by Plasmas*, Academia Press, New York.
- Konjević, N., Ivković, M., Sakan, N.: 2012, Hydrogen Balmer lines for low electron number density plasma diagnostics, *Spectrochim. Acta B*, **76**, 16-26.
- Moisan, M., Etermandi, E., Rostaing, J. C. : 1998, Fr. Pat. Specif. 2, 762.
- Yubero, C., Garcia, M.C., Dimitrijević, M. S., Sola, A., Gamero, A.: 2015, Measuring the electron density in non-thermal plasmas from the difference of Lorentzian widths of two Balmer series hydrogen lines, *Spectrochim. Acta B*, **107**, 164-169.