UDC 52–355.3(082) YU ISSN 0373-3742

PUBLIKACIJE ASTRONOMSKE OPSERVATORIJE U BEOGRADU
PUBLICATIONS DE L'OBSERVATOIRE ASTRONOMIQUE DE BELGRADE

Sv. 50 No. 50

PROCEEDINGS OF THE FIRST YUGOSLAV CONFERENCE ON SPECTRAL LINE SHAPES

September 11–14, 1995, Krivaja, Yugoslavia

Edited by M. S. Dimitrijević and L. Č. Popović

BEOGRAD
1995

PUBL. OBS. ASTRON. BELGRADE No. 50, 1–150 BELGRADE AUGUST 1995

The First Yugoslav Conference

on Spectral Line Shapes

September 11–14, 1995, Krivaja, Yugoslavia

Scientific Organizing Committee

M. S. Dimitrijević (Chairman, Astronomical Observatory Belgrade), S. Djurović (PMF, Novi Sad), S. Djeniže (Faculty of Physics, Belgrade) R. Kobilarov (PMF, Novi Sad), N. Konjević (Faculty of Physics, Belgrade; Institute of Physics, Zemun), A. Mihajlov (Institute of Physics, Zemun), J. Purić (Faculty of Physics, Belgrade), I. Vince (Astronomical Observatory, Belgrade)

Local Organizing Committe

O. Atanacković-Vukmanović, D. Jevremović, L. Č. Popović (Chairman)

Editors of the Conference Proceedings

Milan S. Dimitrijević
Luka Č. Popović

CONTENTS

Contributed papers

FOREWORD

The story about the stars is contained in their radiation which is reaching us and one of the important methods allowing us to disclose those secrets from their radiation involves the study of the spectral line shapes. In this way we are able to determine the temperature on the stellar surfaces, their gravity and the abundance of particular chemical elements. The study of the spectral line shapes represents a multidisciplinary approach, furnishing results of importance for the modeling, diagnostics and for spectral analysis, as well as for quite a number of research fields in physics, astronomy and technology, where plasma and the need for its diagnostics, modeling and examination, come, into play.

The first papers relating to this field to appear in Yugoslavia were published in 1962 and 1964, the former by V. Vujnoviįn Zagreb and latter by M. D. Marinković in Serbia. According to three bibliographies with citation indexes issued by me, covering the period 1962-1993, the number of bibliographic units pertaining to this field, published in this country, is 869 (689 of which on the part of Serbian authors) by 128 Yugoslav authors (100 of whom are from Serbia, 26 from Croatia and 1 from Macedonia, working in Paris). Succesfully defended were 11 doctoral disserations and 20 master's theses. In 1993 for example, 69 bibliographic units were published by 20 authors – a testimony to the swing this research field has acquired in our country.

Intensive growth such as this, having led to the emergence of separate groups devoted to the researching in the spectral line profiles at the Institute of Physics in Zemun, Faculty of Physics and Astronomical Observatory in Belgrade and the Faculty of Sciences and Mathematics in Novi Sad, as well as the number of individuals engaged in this field or making use of the results achivied, fully warrant the organisation of a conference like this one. It will contribute to better mutual connections, provide opportunity for exchanging ideas and for critical evaluation and discussion of the results obtained. It is my hope that this Conference, which already has met with the notable interest by our friends from abroad, will grow into regular manifestation, thus becoming a forum, possessing critical mass, for scrutinizing and evaluating our scientific creativity, for developing and advanced training of the young as well as for getting astronomers together which stimulates the spirit of community and cooperation.

Milan S. Dimitrijević

Publ. Obs. Astron. Belgrade No. 50 (1995), 7 *Invited lecture*

SOLUTION OF THE LINE FORMATION PROBLEM BY THE USE OF ITERATION FACTORS

O. ATANACKOVIĆ-VUKMANOVIĆ[1] and E. SIMONNEAU[2]

[1]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*
E–mail oatanackovic@aob.aob.bg.ac.yu

[2]*Institut d'Astrophysique, 98 bis Boulevard Arago, 75014 Paris, France*

A new fast–convergent iterative method developed to solve non–LTE line transfer problem will be presented. The simultaneous solution of the radiative transfer and statistical equilibrium equations is performed by an efficient revision of the straight-forward Λ iteration scheme.

The improvement of the iterative procedure is achieved by means of the introduction of proper functions - so called iteration factors according to physical considerations. At each iteration step the factors are computed from the current solution and then used to get the new one. In order to warrant stable and fast convergence the iteration factors must be quasi–invariants along the run of the iterative procedure. This is achieved by defining the factors as the proper ratios of two homologous physical quantities, e.g. two radiation field intensity moments.

We will discuss the method on the well–studied instance – spectral line formation in a two–level atomic model as the key–problem for the solution of a much wider range of radiative transfer problems.

Publ. Obs. Astron. Belgrade No. 50 (1995), 9 *Invited lecture*

A PROGRAMME TO PROVIDE STARK BROADENING DATA FOR STELLAR AND LABORATORY PLASMA INVESTIGATIONS

M. S. DIMITRIJEVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia

In order to provide the needed Stark broadening parameters for investigation and modeling of stellar and laboratory plasmas, an effort to obtain the corresponding data for all transitions with the sufficiently complete set of atomic energy levels is in course. Using the semiclassical perturbation method (Sahal–Bréchot, 1969ab) extensive calculations for 79 neutral helium multiplets, 62 Na, 51 K, 61 Li, 25 Al, 24 Rb, 3 Pd, 19 Be, 270 Mg, 28 Ca II, 30 Be II, 23 Al III, 10 Sc III, 10 Ti IV, 39 Si IV, 90 C IV, 5 O IV, 19 O V, 30 N V, 30 O VI, 21 S VI, 10 F VII, 20 Ne VIII, 8 Na IX, 7 Al XI and 9 Si XII multiplets become available and additional data for Li II, Mg II, C V and P V are in preparation. Data for particular lines of F I, Ar II, Ga II, Ga III, Si II, Cl I, Br I, I I, Cu I and Hg II also exist. Our intention is to cover all radiators where a sufficiently complete set of reliable atomic data exists and where the additional effects influencing on calculations like *e.g.* relativistic effects may be neglected. When the semiclassical method is not applicable or is applicable only with smaller acuraccy due to the lack of relevant atomic data, our intention is to supply the corresponding Stark broadening data obtained by using the modified semiempirical approach (Dimitrijević and Konjević, 1980).

Here is presented a review of available semiclassical calculations of Stark broadening parameters and comparison of different semiclassical procedures is discussed, as well as the agreement with critically selected experimental data and more sophysticated, close coupling calculations. The modified semiempirical approach, usefull especially in such astrophysical problems where large scale calculations and analyses must be performed and where a good average accuracy is expected, has also been discussed as well as his applications. We discuss as well the criteria used for selection of radiator spectra for analysis and the future development of the programme.

References

Sahal–Bréchot, S. : 1969, *Astron. Astrophys.* **1**, 91.
Sahal–Bréchot, S. : 1969, *Astron. Astrophys.* **2**, 322.
Dimitrijević, M. S., Konjević, N. : 1980, *JQSRT*, **24**, 451.

Publ. Obs. Astron. Belgrade No. 50 (1995), 11 *Invited lecture*

EXPERIMENTAL DIFFICULTIES IN DETERMINATION OF THE SPECTRAL LINE SHAPES EMITTED FROM PLASMA

S. DJUROVIĆ, R. KOBILAROV and B. VUJIČIĆ
Institute of Physics, Faculty of Science, University of Novi Sad
Trg Dositeja Obradovića 4, 21000 Novi Sad, Yugoslavia

From the plasma radiation and from spectral line profiles it is possible to obtain pieces of information about the plasma conditions. These pieces of information are, for example, concentration of the neutral or charged particles, their temperatures and atomic data. Experimentaly obtained data have great importance in plasma diagnostic, theory testing and plasma applications.

During the experimental work many difficulties appear. The aim of this paper is to classify experimental problems and to offer method for their solving.

In this paper, first a rewiew of spectral line broadening causes and corresponding theories is given. The experimental technique and checking and corrections of self absorption are described also. Furthermore, procedure of spectral line halfwidth and shift determination from experimental profiles is given. Finally, the Abel inversion, important for plasma sources with cylindrical symmetry is considered. All of above mentioned techniques and procedures are followed by many experimental examples.

Publ. Obs. Astron. Belgrade No. 50 (1995), 13 *Invited lecture*

DOUBLY-EXCITED ATOMS AND THE LINE BROADENING

P. V. GRUJIĆ

Institute of Physics, P.O. Box 57, 11001 Belgrade, Yugoslavia

Atomic systems with doubly-excited electrons have been the objects of extensive studies in the last fifteen years. These autoionizing states may be longlived metastable atoms, with a number of properties peculiar to those systems where interelectron correlations play crucial role, and the independent-particle picture fails even as a zero-order approximation.

We shall expound principal mechanisms for forming such states, quote essential features of the two-electron excited states and the most common ways for their decays. Particular attention will be paid to the methods for evaluating energy spectra, especially quantum mechanical and semiclassical approaches for calculating line positions and widths. Possible modes of radiative transitions will be enumerated and a number of mechanisms of line broadening shall be discussed. Some prospective developments in the line broadening theory will be outlined.

Publ. Obs. Astron. Belgrade No. 50 (1995), 15 *Invited lecture*

QUANTUM MECHANICAL CALCULATIONS OF SELF-BROADENING IN RARE GASES

P. J. LEO[1], D. T. P. MULLAMPHY[2], G. PEACH[1] and I. B. WHITTINGHAM[3]

[1]*Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom*

[2]*Department of Mathematics and Statistics, James Cook University, Townsville, Australia, 4811*

[3]*Department of Physics, James Cook University, Townsville, Australia, 4811*

Full quantum-mechanical calculations of the self-broadening of non-resonant lines in the spectra of helium and neon will be discussed and the results compared with recent experimental data. The calculations are based on the use of accurate interatomic potentials and on the impact theory of Baranger. The Born-Oppenheimer approximation is made in setting up the quantum-mechanical scattering equations and is shown to be valid for the conditions of interest here, namely temperatures in the range 77K to 273K. The equations are then integrated numerically using an R-matrix method which has proved to be very suitable for this purpose since it has the advantage that once the R-matrices have been set up, results for a large number of different incident velocities can be obtained at little extra cost. Thus an accurate average over the Maxwell distribution can be carried out; this is very important when making detailed comparisons with experiment as the use of a single mean velocity in itself leads to significent error.

Publ. Obs. Astron. Belgrade No. 50 (1995), 17 *Invited lecture*

INFLUENCE OF ION–DYNAMICS EFFECT ON THE SHAPE OF NEUTRAL ATOM SPECTRAL LINES

Z. MIJATOVIĆ

Institute of physics, Trg Dositeja Obradovića 4, 21000 Novi Sad, Yugoslavia

Here are presented the results of experimental investigation of the influence of ion-dynamics effect on the widths and shifts of neutral atoms spectral lines. Measured values are compared with the theories which treat ions as static and dynamic perturbers.

The influence of ion-dynamics is tested on five He I and two C I spectral lines. Helium is chosen as the lightest non-hydrogenic neutral emitter, while carbon is chosen as heavier neutral emitters. It could be expected that influence of ion-dynamics is greatest on spectral lines of the lightest emitters (He), while is less in the case of heavier ones (C).

The confirmation of this effect, especially for the He I lines, could be of great importance for plasma diagnostics purposes. It is shown that with the decrease of plasma electron density the importance of this effect increases. The magnitude of this influence reaches more than 40 % in the case of shifts of certain He I lines.

Publ. Obs. Astron. Belgrade No. 50 (1995), 19 *Invited lecture*

REGULARITIES IN THE STARK BROADENING AND SHIFT PARAMETERS OF SPECTRAL LINES

J. PURIĆ

Faculty of Physics, University of Belgrade, P. O. Box 368, 1100o Belgrade, Yugoslavia

This lecture surveys some recent advances in plasma diagnostic research based on the investigation of spectral line shapes. The emphasis is on contribution to : (i) the experimental measurements and theoretical calculations of the Stark broadening parameters of large number of spectral lines originating from different neutral and ionized omitters; (ii) verification of the Stark parameters dependence on the fundamental plasma parameters such as are the electron density (N) and temperature (T); (iii) discovering and verification of Stark parameters dependence on different atomic structure parameters such as are the upper level ionization potential (χ) of a particular transition within transition array or the same type of transition (a.g. resonance's or off resonance's) of all elements in Periodic table, χ and rest core charge (Z_c) of the emitter seeing by the electron undergoing transition within isoelectronic and isonuclear sequences, (and nuclear charge number (Z) within homologous sequences; (iv) Stark parameters calculation using the established dependence on the upper level ionization potential for the spectral lines not been investigated so far experimentally or theoretically but belonging to the above mentioned similar spectra, and (v) comparison of the our experimental and theoretical data with those obtained by the other authors.

Publ. Obs. Astron. Belgrade No. 50 (1995), 21 – 26 *Invited lecture*

ON INVERSE METHODS USED AT BELGRADE OBSERVATORY FOR ANALYSIS OF SPECTRAL LINE SHAPES

I. VINCE, L. Č. POPOVIĆ, S. JANKOV, G. DJURAŠEVIĆ,
O. ATANACKOVIĆ-VUKMANOVIĆ and D. JEVREMOVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E–mail ivince@aob.aob.bg.ac.yu

Abstract. In this paper we present inverse methods used for analysis of the spectral line shapes at Belgrade Observatory. A short description of the methods and some examples of application are given.

1. INTRODUCTION

Spectral line profiles of stars and other celestial objects, and those of laboratory sources may have a very complex shape caused by emission and absorption of different parts of the source. For instance, stellar spectral line profiles may consist of intrinsic component and of a component, which is formed in the circumstellar or/and interstellar space. The intrinsic component might be perturbed by surface features (e.g., dark spots, bright spots, chemical inhomogeneities etc.).

To study the physics of these parts separately it is necessary to reconstruct their original spectral line shapes. This, in principle, can be done by using the direct or the inverse method. At our Observatory we have developed inverse methods for the reconstruction of intrinsic and interstellar spectral line profiles of cool late-type stars, for Doppler imaging of a stellar surface and for reconstruction of spectral line shapes of different surrounding regions of quasars and Seyfert galaxies.

2. THE PRINCIPLES OF INVERSE METHODS

Let us suppose that the observed profile can be presented by a model through a function $f(x, a_1, a_2, ..., a_n)$, where $a_1, a_2, ..., a_n$ are the known but undetermined parameters of the model, which depend on physical conditions in the observed object. The inverse method consists of determining these parameters so that the difference between the observed and the calculated data reaches its minimum value.

3. STELLAR LINES

3. 1. STELLAR SPECTRAL LINES WITH INTERSTELLAR ABSORPTION

When the observed stellar spectral lines show interstellar absorption, for a separation of the intrinsic line profile from the interstellar one we can use the following procedure.

We suppose that a cloud of interstellar media exists between our telescope and the observed star, and that $I^0(\lambda)$ is the intrinsic intensity of the stellar line. Then for the observed intensity $I(\lambda)$ we could write the following equation

$$I(\lambda) = I^0(\lambda)e^{-\Delta\tau_\lambda} + \int_1^2 S(t)e^{-(\tau_\lambda - t_\lambda)}dt_\lambda, \quad (1)$$

where $S(t)$ is the source function of the absorption interstellar media and τ is the optical depth. If we suppose that in the interstellar cloud there are no emission sources, i.e., $S(t) = 0$, and $\Delta\tau << 1$, equation (1) may be rewritten as

$$I(\lambda) = I^0(\lambda)(1 - \Delta\tau). \quad (2)$$

For $\Delta\tau$ we may take

$$\Delta\tau = \overline{\varphi} \cdot T,$$

where T is the optical depth of the cloud at the core of line profile. If we take that $\overline{\varphi}T$ is a Gaussian function, then for observed intensity distribution of a line we may write

$$I(\lambda) = I^0(\lambda)(1 - a_1 e^{-((x-a_2)/a_3)^2}). \quad (3)$$

From eq. (3) we may reconstruct the intrinsic stellar line profile $I^0\lambda$ and the interstellar absorption line profile by determining the free parameters (a_i; $i = 1, 2, 3$) using the inverse method technique.

As an example of the inverse method technique the reconstruction of a high-resolution IUE spectrum of the RS CVn type star HR 7275 is presented. The observed MgII h spectral line profile shows a prominent interstellar absorption component near the core of the emission line profile. In Fig. 1 are shown the observed and the reconstructed intrinsic MgII h spectral line profile with the best fit parameters.

3. 2. IMAGE RECONSTRUCTION OF LATE-TYPE STARS FROM SPECTROSCOPIC ROTATIONAL MODULATION

A Doppler imaging method consists of using the effect of localized spots on line profiles, Doppler broadened due to the star's rotation. This method can be used to derive an image of photospheric and chromospheric features (spots and plages).

The image reconstruction can be performed using a set of the observed line profiles, which covers the star's rotation period well. This set of line profiles creates the data vector. Doppler imaging can be applied to fast rotating stars only.

Using the term image to represent the distribution of the specific intensities on the surface of the star under investigation it was shown (Jankov, 1992) that the image is related in some known way to the spectroscopic data. In addition it is showed (Jankov and Foing, 1992) that the problem of Doppler imaging can be fully linearized when the *shape* of the local spectrum does not depend on the position on a stellar surface (while allowing the local continuum intensities to vary). Under this assumption the

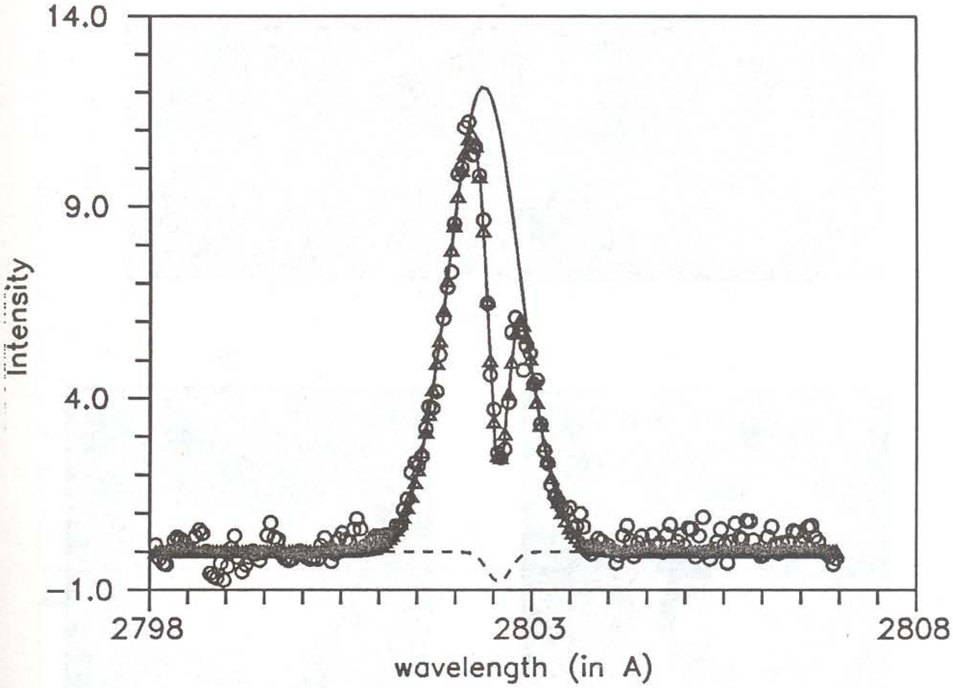

Fig. 1. The observed (circles), the best fitted (full line with triangles), the reconstructed emission (full line) and absorption (dashed line) spectral line profiles.

problem can be translated into the indirect imaging terms by considering the image-data transformation in the linear form :

$$Y_i = \sum_{j=1}^{J} R_{ij} X_j \qquad i = \overline{1, I}.$$

where the vector Y_i represents the data, the matrix R is a mapping, which takes a function in the image space into a function in the data space and X_j is the image vector. This representation, ensuring the uniqueness of the solution, leads also to significant computational savings.

Since the inverse matrix R^{-1} is badly conditioned a solution is obtained by minimizing an appropriate "regularising functional", of the image function subject to the classical constraint $\chi^2 = \chi_0^2$:

$$\sum_{i=1}^{I} \left((Y_i - \sum_{j=1}^{J} R_{ij} \hat{X}_j) / \sigma_i \right)^2 = \chi_0^2,$$

where χ_0^2 is determined by the required confidence level to data statistics χ^2, $\hat{X}_J$ is the solution, and σ_i is the standard error in the datum i. The data statistic χ^2 is

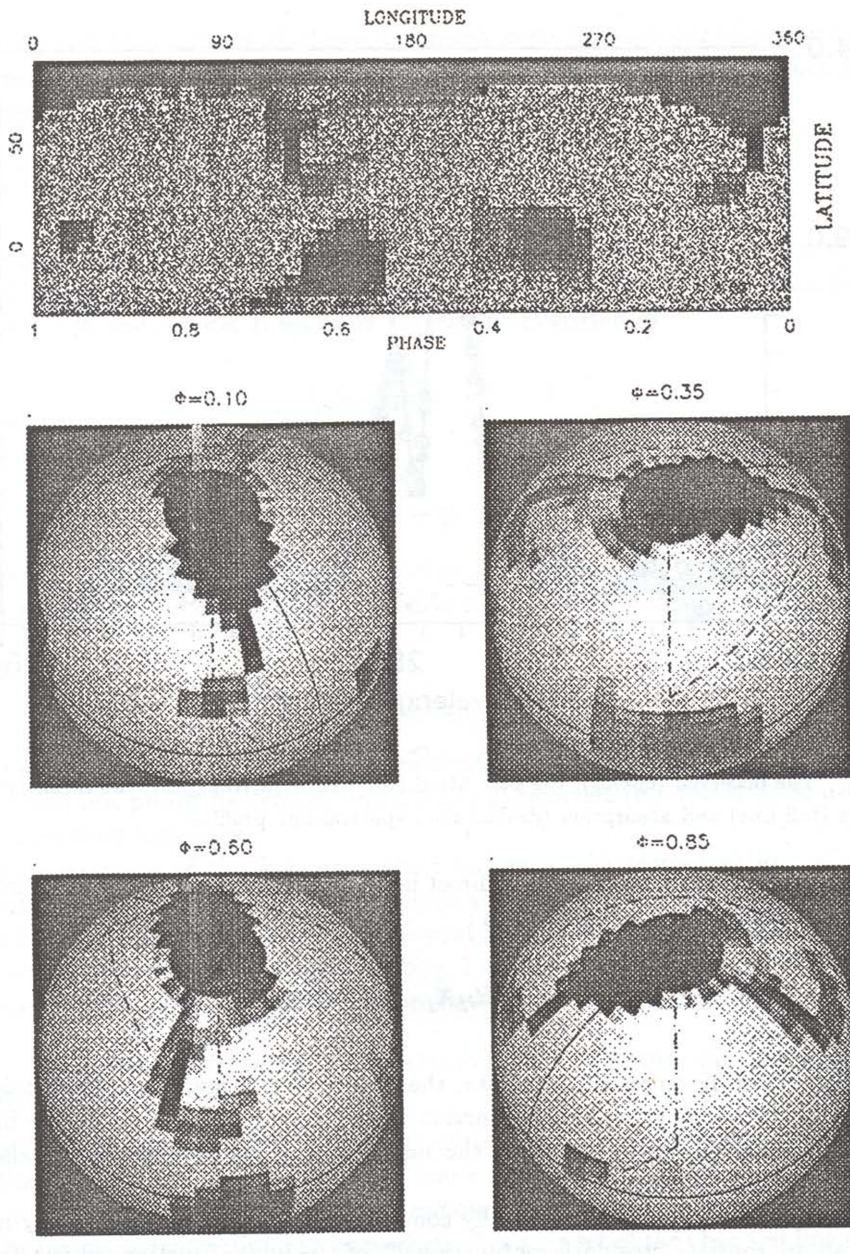

Fig. 2. The reconstructed image of HR 1099.

used to measure the discrepancy between the observed and modeled data, while the χ^2 surfaces are convex ellipsoids in J dimensional image space.

The search strategy employed for the image reconstruction consisted in minimizing χ^2 until reaching the hypersurface χ_0^2 by the constrained gradient method. The entropy is further maximized on the hypersurface $\chi^2 = \chi_0^2$ until reaching the parallelity

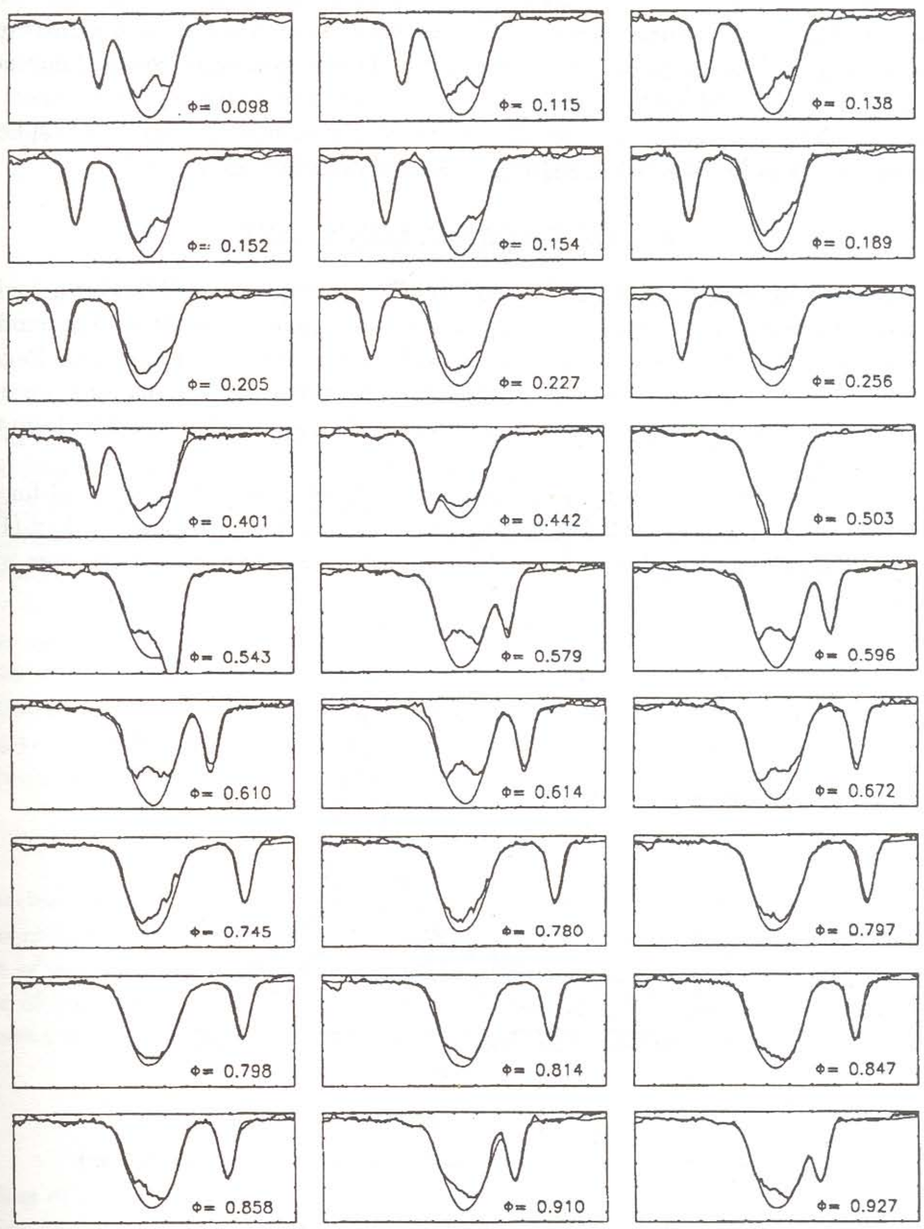

Fig. 3. The observed line profiles.

of the gradients of χ^2 and entropy, i.e., practically, until reaching the neighbourhood of the maximum entropy point defined so that the cosine of the angle between the gradients is greater than or equal to 0.99.

An example the image reconstruction of the RS CVn binary system HR 1099 is shown in Fig. 2, based on a set of high-resolution and high signal-to-noise ratio spectra (Fig. 3). The maps show cool ($T = 2500K$) extended spotted structures : one at high latitude adjacent to the rotation pole and symmetric versus longitude, two nearly equatorial spots positioned approximately symmetrically with respect to the secondary star and several smaller spots. The presence of bright photospheric faculae seems to be established slightly above the detection level.

4. THE CASE OF AGN'S LINES

The spectral lines of active galactic nuclei (AGN), i.e., quasars and Seyfert galaxies, consist of parts that originate in different regions around the nucleus. The models propose that the observed line is formed usually in two regions : Broad Line Region and Narrow Line Region (see, e.g., Nazarova, 1991). For determining the physical conditions in these regions we have to reconstruct their spectral line profiles from the observed one.

Here, as an example, we show the result of a fit of observed L_α spectral line of MKN 335 Syfert galaxy with five gaussian functions using the inverse method (Fig. 4). The emission part of the Lα line is fitted with two, and the absorptions ones with three gaussian functions.

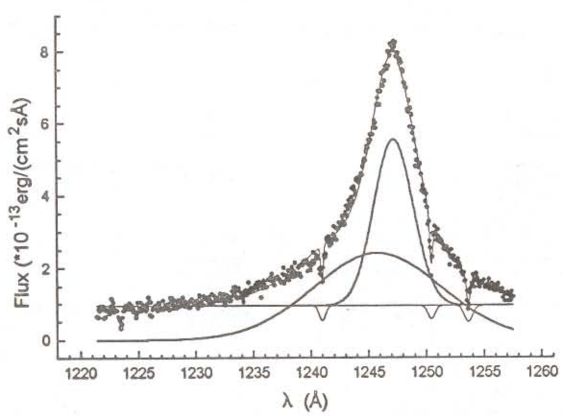

Fig. 4. The observed L_α line profile (dots) and its Gaussian fit (full line).

References

Jankov, S. : 1992, Ph.D. thesis, Paris VII, Paris
Jankov, S., Foing, B.H. : 1992, *Astron. Astrophys.* **256**, 533-550.
Nazarova L. S., 1991, *Sops. Spec. Astrophys. Obs.* **66**, 37.

Publ. Obs. Astron. Belgrade No. 50 (1995), 27 – 30

ON THE LS COUPLING ALONG THE BORON SEQUENCE

B. BLAGOJEVIĆ, M. V. POPOVIĆ and N. KONJEVIĆ
Institute of Physics, 11080 Belgrade, P.O.Box 68, Yugoslavia

1. INTRODUCTION

LS or Russell-Saunders coupling is dominant for many transitions in the spectra of light elements. The spin-orbit interaction in atomic Hamiltonian becomes more important in comparison to the electrostatic separation between levels of the same principal quantum number n but different orbital angular moments. Electrostatic separation increases as Z while the spin-orbit interaction grows as $Z^4 \cdot \alpha^2$ where α is fine structure constant, Z is nuclear charge, so the LS-coupling scheme becomes inappropriate at some point. Systematic failure of the LS-coupling approximation is expected from lower to higher elements of an isoelectronic sequence for nl-nl′ transitions. The aim of this paper is to test the validity of experimental data for the LS-coupling approximation in NIII and OIV ions (3s-3p and 3p-3d transitions) with the theory and experimental data in Glenzer *et al.* (1994).

2. THEORY

Detailed model of LS coupling for boron like ions is given in Glenzer *et al.* (1994). Theoretical values calculated from multiconfiguration Dirac-Fock (MCDF) wave function of moderate accuracy are compared with our measured intensity ratios. For the case of pure LS coupling the relative line strength within multiplet for a transition between levels J_1 and J_2 is proportional to the factor (Cowan, 1981; Appendix I)

$$D^2_{\text{line}} = (2J_1+1)(2J_2+1)\begin{Bmatrix} L_1 & S_1 & J_1 \\ J_2 & 1 & L_2 \end{Bmatrix}. \tag{1}$$

Values of the 6j symbol are given in Appendix D of (Cowan, 1981). The intensity ratio of two multiplet components is represented by Glenzer *et al.* (1994)

$$\frac{I}{I'} = \left(\frac{\lambda'}{\lambda}\right)^4 \left(\frac{D_{\text{line}}}{D'_{\text{line}}}\right)^2 e^{\frac{E'-E}{kT}} \tag{2}$$

where I,λ and I′,λ are the total intensities and wavelengths of the two components, and E and E′ are the energies of the upper levels of the two components, respectively.

3. EXPERIMENT

The light source was a low pressure pulsed arc with quartz discharge tube 10 mm internal diameter. The distance between aluminium electrodes was 161 mm and 3 mm diameter holes were located at the center of both electrodes to allow end-on plasma observations. The central part around the pulsed arc axis was imaged 1 : 1 onto the entrance slit of the 1 m monochromator by means of the concave 1 [m] focal length, focusing mirror. A 30 mm diaphragm placed in front of the focusing mirror ensures that light comes from the narrow cone about the arc axis. The entire description of measuring apparatus is given in Blagojević *et al.* (1994). The greatest care was taken to find the optimum conditions with the least line self absorption. It was found that the percentage of oxygen in the mixture was of crucial importance for the elimination of self-absorption. The ratios N_2 : He = 2 : 98 and O_2 : He = 1.4 : 98.6 were determined after a number of experiments in which N_2 and O_2 were diluted gradually until strong line intensities NIII and OIV are found proportional to the concentration of N_2 and OIV in the gas mixtures respectively. During the spectral line recording continuous flow of nitrogen-helium and oxygen-helium mixtures were maintained at a pressure of about 400 Pa.

4. PLASMA DIAGNOSTICS

For the electron-density measurements we use the width of HeII P_α 468.6 nm line. The full width at half maximum $\Delta\lambda_{FWHM}$ of this line is related to the electron density N_e using the following relationship (Pittman and Fleurier, 1982; Fleurier and Gall, 1984; Pittman and Fleurier, 1986)

$$N_e = 2.04 \cdot 10^{16}(\Delta\lambda_{\rm FWHM})^{1.21}\ [\rm cm^{-3}] \tag{3}$$

where $\Delta\lambda$ is in 0.1 [nm] units. This equation is based on the fitting of the experimental data, and in fact closely agrees with calculations by Griem and Shen (1961). Our main concern in electron-density measurements is a possible presence of self-absorption of the 468.6 nm line which may distort the line profile. This would result in erroneous reading of the line half width which, after the use of Eq.(3), introduces an error in electron-density measurements. There are several experimental methods which can be used for self-absorption check (Konjević and Wiese, 1976) but unfortunately, none of them is convenient for the HeII 468.6 nm line or for our long, pulsed plasma source. Recently, in order to determine the optical thickness of the investigated line Kobilarov *et al.* (1989) have introduced in the discharge an additional movable electrode. By positioning the movable electrode at two different positions and by recording the line profiles from two plasma lengths it is possible to determine $k_\lambda l$ where k_λ is the spectral line absorption coefficient and l is the plasma length along the direction of observation. If $k_\lambda l$ is not large ($k_\lambda l < 1$ (Wiese, 1965)) it is possible to recover the line profile (Fig.2 of Kobilarov *et al.* (1989) for the optically thin case. The same method is used here for the HeII 468.6 nm line self absorption testing. For this purpose an additional aluminum electrode (10 mm thick) is located inside the discharge tube and the profiles of 468.6 nm line are recorded with two plasma lengths.

5. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results for intensity ratios R_m from 3s-3p multiplet ($I_{1/2-3/2}/I_{1/2-1/2}$) and 3p-3d multiplet $[(I_{3/2-5/2}+I_{3/2-3/2})/I_{1/2-3/2}]$ of N III and O IV ions are given in Table 1 together with electron concentration.

Table 1

Transition array	N III 3s-(^1S)3p	N III 3p-(^1S)3d	O IV 3s-(^1S)3p	O IV 3p-(^1S)3d
Ne [10^{17} cm^{-3}]	R_m	R_m	R_m	R_m
1.38	2.08	1.99		
1.71	1.78	1.80		
2.06		2.11		
2.52	1.73			
2.64	1.69			
5.07			1.92	1.80
6.45			1.85	
5.38			1.89	
4.97			1.96	
1.04		1.88		
1.11	1.70	1.68		
0.86	1.98			

There is only one intensity ratio R for O IV 3p-3d multiplet because the intensity I is too low for all other electron concentrations. Table 2 contains the comparison between our experimental ratios R with those from Glenzer *et al.* (1994) and theoretical ratios R calculated in Glenzer *et al.* (1994) from eqs. (1) and (2). Our results for $< R >$ are systematically smaller then those from Glenzer *et al.* (1994) (see Table 2). Further investigations are in progress.

Table 2

Transition array	$< R_m >_{\text{(our data)}}$	$< R_m >_{\text{(Glenzer } et\ al.)}$	$R_{LS\text{(Glenzer } et\ al.)}$
C II 3s-(^1S)3p		2.05±0.03	2.00
C II 3s-(^1S)3p		1.97±0.04	1.99
N III 3s-(^1S)3p	1.8±0.2	1.99±0.09	2.01
N III 3p-(^1S)3d	1.8±0.2	1.97±0.12	1.99
O IV 3s-(^1S)3p	1.9±0.2	2.00±0.09	2.01
O IV 3p-(^1S)3d	1.8±0.2	1.96±0.10	1.98
F V 3s-(^1S)3p		1.97±0.22	2.02
F V 3p-(^1S)3d		2.11±0.31	1.98
Ne VI 3p-(^1S)3d		2.14±0.15	1.96

References

Blagojević, B., Popović, M. V., Konjević, N., Dimitrijević, M. S. : 1994, *Phys. Rev.* **E 50**, 2986.

Cowan, R. D. : 1981, *The Theory of Atomic Structure and Spectra*, (University of California Press, Berkeley.

Griem, H. R. and Shen, K. Y. : 1961, *Phys. Rev.* **122**, 1490.

Glenzer, S., Kunze, H. J., Musielok, J., Kim, Y. K. and Wiese, W. L. : 1994, *Phys. Rev.* **A 49**, 221.

Fleurier, C. and Gall, P. Le : 1984, *J. Phys.* **B 17**, 4311.

Konjević, N. and Wiese, W. L. : 1976, *J. Phys. Chem. Ref. Data*, **5**, 259.

Kobilarov, R., Konjević, N. and Popović, M. V. : 1989, *Phys. Rev.* **A 40**, 3871.

Pittman, T. L. and Fleurier, C. : 1982, in Proceedings of the Sixth International Conference on Spectral Line Shapes, 4 Boulder, (de Gruyter, Berlin, 1983).

Pittman, T. L. and Fleurier, C. : 1986, *Phys. Rev.* **A 33**, 1291.

Wiese, W. L. : 1965, in Plasma Diagnostic Techniques, edited by R. M. Huddleston and S. L. Leonard (Academic, New York).

Publ. Obs. Astron. Belgrade No. 50 (1995), 31 – 34

ON THE STARK BROADENING AND SHIFT OF TRIPLY IONIZED OXYGEN LINES

B. BLAGOJEVIĆ[1], M. V. POPOVIĆ[1], N. KONJEVIĆ[1] and M. S. DIMITRIJEVIĆ[2]
[1] *Institute of Physics, 11080 Belgrade, P.O.Box 68, Yugoslavia*

[2] *Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*
E–mail mdimitrijevic@aob.aob.bg.ac.yu

Abstract. Stark broadening parameters of triply ionized oxygen $3s^2S$-$3p^2P^o$ and $3p^2P^o$-$3d^2D$ transitions have been observed experimentally in the plasma of a low pressure pulsed arc, and studied theoretically within the semiclassical perturbation approach. The temperature dependence of the Stark widths and shifts and the influence of forbidden perturbing level, have been considered as well.

1. INTRODUCTION

Temperature dependence of the Stark widths and shifts of the O IV $3s^2S$-$3p^2P^o$ and $3p^2P^o$-$3d^2D$ transitions have been studied theoretically using the impact semiclassical method and experimentally observed in the plasma of a low pressure pulsed arc. Plasma electron densities were determined from the width of the He II P_α line while electron temperatures were measured from the relative line intensities. To estimate influence of different ions on the width and shift of lines, evaluation of plasma composition data was performed and in conjunction with our theoretical results the contribution of ion broadening estimated. Furthermore in our theoretical calculations we included for the first time the influence of forbidden perturbing levels on the width and shift of investigated O IV spectral lines.

2. THEORY

By using the semiclassical-perturbation formalism (Sahal-Bréchot, 1969ab) we have calculated previously (Blagojević *et al.*, 1994) electron-, proton-, and He II-impact broadening parameters for OIV $3s^2S$-$3p^2P^o$ and $3p^2P^o$-$3d^2D$. Energy levels needed for these calculations have been taken from Bashkin and Stoner (1975). Oscillator strengths were calculated by using the method of Bates and Damgaard (1949); (see also tables in Oertel and Shomo, 1968). For higher energy levels the method described in Van Regemorter *et al.* (1979) has been used. Since in the case of the considered transitions, several forbidden transitions may influence significantly, particularly shift values, new calculations with the inclusion of such transitions have been performed here. In order to assure the consistency of the data set, all oscillator strengths (and not only those for added forbidden transitions) have been taken from the TOP base (the complete package of the opacity project (OP) data with the database management system is usually refered to as TOP base) (Butler *et al.*, 1993; Cunto *et al.*, 1993). Besides electron impact line widths and shifts, Stark broadening parameters, due to all relevant ion perturbers, have been calculated as well.

3. EXPERIMENT

Experimental apparatus and procedure are described in Blagojević *et al.* (1994) so only minimum details will be given here. The light source was a low pressure pulsed arc with a quartz discharge tube 10 mm internal diameter. The distance between aluminum electrodes was 161 mm, and 3 mm diameter holes were located at the center of both electrodes to allow end-on plasma observations. All plasma observations are performed with 1-m monochromator with inverse linear dispersion 8.33 Å/mm in the first order of the diffraction grating, equipped with the photomultiplier tube and a stepping motor. The discharge was driven by a 15.2 μF low inductance capacitor charged to 6 kV, peak current I_p = 27 kA, pressure of the gas mixture p = 3 torr, continuous flow of the gas mixture, composition : 1.4% of O_2 in He. The stepping motor and oscilloscope are controlled by a personal computer, which was also used for data acquisition. Recordings of spectral line shapes were performed shot-by-shot. At each wavelength position of the monochromator time evolution and decay of the plasma radiation were recorded by the oscilloscope. Four such signals were averaged at each wavelength. To construct the line profiles these averaged signals, at different wavelengths and at various times of the plasma existence, were used to construct the line profiles. Spectral line profiles were recorded with instrumental half widths of 0.165 Å. To determine the Stark half width from the measured profile, a standard deconvolution procedure for the Lorentzian (Stark) and Gaussian (instrumental+Doppler) profiles was used. For the line-shift measurements we used line profiles at different times of the plasma existence (Purić and Konjević, 1972). For this technique of shift measurements it is necessary to know plasma parameters (electron density and temperature) at the times when both profiles are recorded. Descriptions of electron density and electron temperature measurements are given in Blagojević *et al.* (1994).

4. EXPERIMENTAL RESULTS AND DISCUSSION

The experimental results for Stark widths of O IV lines and comparisons with theoretical results are given in Fig.1 and Fig.2 for O IV $3s^2S$-$3p^2P^o$ and $3p^2P^o$-$3d^2D$ transitions, respectively. In order to evaluate contribution of ion impact widths it was necessary to compute plasma composition data for the conditions of width measurements (electron density and temperature). Measured shifts and comparison with the semiclassical theoretical shifts are given in Table 1.

The inclusion of some perturbing forbidden levels in our semiclassical calculations of O IV line widths and shifts improves the agreement between theory and experiment.

Table 1. Experimental Stark shifts d_m determined as a wavelength shift between two line profiles measured at N_{e1} , T_{e1} and N_{e2} , T_{e2} and normalized to N $=10^{17}$ cm^{-3}, compared with corresponding theoretical shift d^e_{DSB} for electron impacts.

Transition	N_{e1} (10^{17} cm^{-3})	T_1 (K)	N_e2 (10^{17} cm^{-3})	T_2 (K)	d_m (Å)	d_m/d^e_{DSB}
$3s^2S_{1/2}$–$3p^2P^o_{3/2}$	2.06	62600	5.07	93600	0.03	1.4
$3s^2S_{1/2}$–$3p^2P^o_{1/2}$	2.06	62600	5.07	93600	0.03	1.4
$3p^2$ $P^o_{1/2}$–$3d^2D_{3/2}$	2.06	62600	5.07	93600	0.03	1.5
$3p^2$ $P^o_{3/2}$–$3d^2D_{5/2}$	2.06	62600	5.07	93600	0.03	1.5

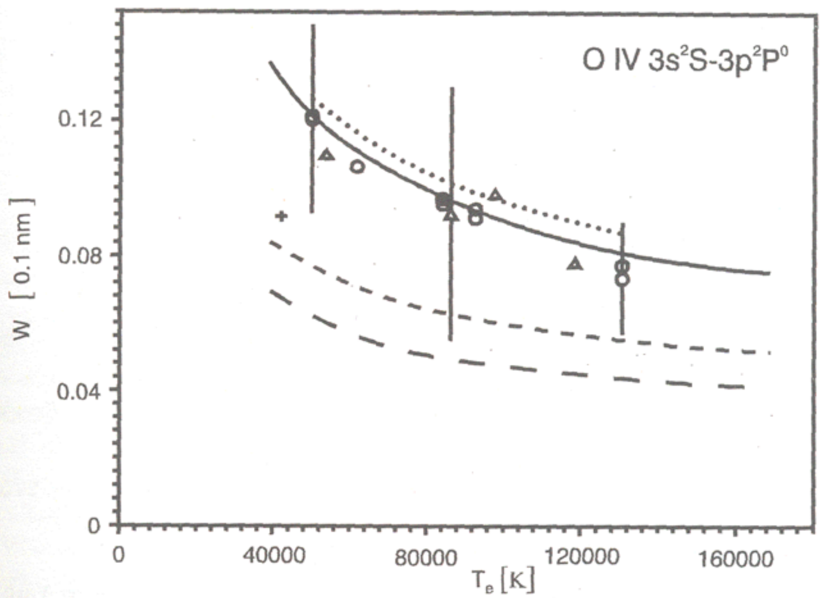

Fig. 1. Full Stark widths (normalized to an electron density of 10^{17} cm^{-3}) for the O IV $3s^2S$ - $3p^2P^o$ multiplet *vs* electron temperature. Theory : ...., semiclassical electron- + ion-impact widths, —, semiclassical, electrons only; - - -, semiclassical approximation (Eq.(526) taken from Griem, 1974); – – –, modified semiempirical formula (Dimitrijević and Konjević, 1980). Experiment : O, this work; +, Purić *et al.*, (1988); Δ, Glenzer *et al.*, (1994).

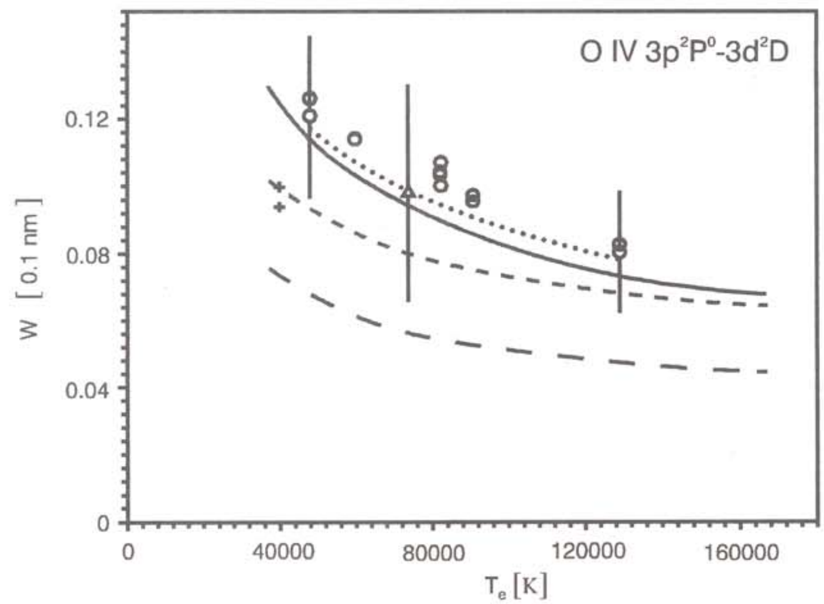

Fig. 2. Same as in Figure 2, but for O IV $3p^2P^o$-$3d^2D$ multiplet.

References

Bashkin, S., Stoner, J. O. Jr. : 1975, "Atomic Energy Levels and Grotrian Diagrams", Vol. 1, North Holland, Amsterdam.

Bates, D. R. and Damgaard, A. : 1949, *Trans. Roy. Soc. London, Ser. A* **242**, 101.

Blagojević, B., Popović, M. V., Konjević, N. and Dimitrijević, M. S. : 1994, *Phys. Rev. E* **50**, 2986.

Butler, K., Mendoza, C. and Zeippen, C. J. : 1993, *J. Phys. B* **26**, 4409.

Cunto, W., Mendoza, C., Ochsenbein, F. and Zeippen, C. J. : 1993, *Astron. Astrophys.* **275**, L5.

Dimitrijević, M. S. and Konjević, N. : 1980, *JQSRT*, **24**, 451.

Glenzer, S., Hey, J. D. and Kunze, H. J. : 1994, *J. Phys. B* **27**, 413.

Griem, H. R. : 1974, "Spectral Line Broadening by Plasmas", Academic Press, New York.

Oertel, G. K. and Shomo, L. P. : 1968, *Astrophys. J. Suppl. Series*, **16**, 175.

Purić, J., Djeniže, S., Srećković, A., Platiša, M., Labat, J. : 1988, *Phys. Rev.* A **37**, 498.

Purić, J. and Konjević, N. : 1972, *Z. Phys.* **249**, 440.

Sahal-Bréchot, S. : 1969a, *Astron. Astrophys.* **1**, 91.

Sahal-Bréchot, S. : 1969b, *Astron. Astrophys.* **2**, 322.

Van Regemorter, H., Hoang Binh Dy and Prud'homme, M. : 1979, *J. Phys. B* **12**, 1073.

Publ. Obs. Astron. Belgrade No. 50 (1995), 35 – 38

MEASURED STARK PARAMETERS OF THE NaI-D SPECTRAL LINES IN ARGON PLASMA

S. BUKVIĆ, S. DJENIŽE and A. SREĆKOVIĆ
Faculty of Physics, University of Belgrade,
P.O.B. 368, 11001 Belgrade, Serbia, Yugoslavia

Abstract. Stark widths and shifts of the NaI-D spectral lines (588.995 nm and 589.59 nm) have been measured in the argon plasma at the 38 000 K electron temperature and $3.5 \cdot 10^{23} \mathrm{m}^{-3}$ electron density. The measured widths and shifts were compared with the existing theoretical predictions.

1. INTRODUCTION

Information on Stark broadening parameters (width and shift) of the sodium spectral lines (which are found in typical stars spectra) are of great astrophysical interest because they are necessary in the opacity calculations (Dimitrijević and Sahal-Brechot, 1985) and they are also useful for the diagnostics of astrophysical and laboratory plasmas (Griem, 1974). However, to the knowledge of the authors only three experiments (Purić *et al.*, 1976; Baur and Cooper, 1977; Djeniže *et al.*, 1992) dealt with the Stark widths and only three papers : Purić *et al.* (1976), Djeniže *et al.* (1992a) and Srećković and Djeniže (1994), are devoted to the measurements of the NaI-D spectral line Stark shifts.

The aim of this work is to extend the range of the experimental data concerning Stark parameter values of the NaI-D spectral lines (588.995 nm, 589.59 nm) at 38 000 K electron temperature, and also, a comparison of these values with the existing theoretical data calculated on the basis of various approximations : Dimitrijević and Sahal-Brechot (1985), Griem (1974) and Mazure and Nollez (1978) will be presented.

2. EXPERIMENT

The linear pulsed arc, that has been used as a plasma source, has been described elsewhere (Djeniže *et al.* 1991, 1992). A pulsed discharge occured in a Pyrex discharge tube of 5 mm i. d. and had an effective plasma length of 5.8 cm. Sodium atoms have been released as impurities by sputtering from a discharge tube (the Pyrex glass contains 4.4% of Na_2O). In order to release impurity atoms from glass walls more efficiently, and obtain highest possible electron density, we have used discharge of the condenser battery of 8 μF capacity charged up to 108 J, as described in details in Djeniže *et al.* (1992). The working gas was argon at a 130 Pa filling pressure. We have determined the following electrical characteristics of the discharge from the Rogowski coil signal : circuit inductance = 2.3 μH, equivalent circuit resistance = 0.29 Ω, period = 28 μs and the peak current = 6.6 kA.

Investigated spectral lines were well isolated from other spectral lines emitted by this plasma. We have obtained a good reproducibility (>90 %) of the investigated spectral line radiation intensities. The selfabsorption of the measured sodium spectral lines was small, owing to the low concentration of the investigated emitting atomic species in the plasma due to the method by which the sodium impurity atoms have been introduced.

The spectroscopic observations were made end-on, along the axis of the discharge tube. Scanning of the spectral line profiles was done by using a shot-to -shot technique, while advencing the exit slit-photomultiplier combination in small wavelength steps (Djeniže *et al.*, 1991). The photomultiplier signal was digitized using HAMEG 205-2 oscilloscope interfaced to a computer. The measured profiles were of the Voigt type. The standard deconvolution procedure (Davies and Voughan, 1963) was computerized using the least square algoritm. The estimated error of the obtained Stark FWHM (full-width at half maximum intensity) (w) was within ±15 %.

The Stark shifts (d) were measured relative to the unshifted spectral lines emitted by the same plasma (Purić and Konjević, 1972). The Stark shifts were determined with ±8% error. In Fig. 1 eleven NaI-D spectral line profiles recorded at different time (starting from 10 μs up to 60 μs with 5 μs increment) after the beginning of the discharge are presented. The red shift of the both NaI-D lines is evident.

The electron temperature (T) decay was found from the ratios of the relative intensities of 280.94 nm Ar IV, 328.58 nm Ar III and 335.09 nm ArII spectral lines with an estimated error of ±11% assuming the existence of LTE. The electron density (N) decay was obtained using a single wavelength He-Ne laser interferometer at the 632.8 nm with an estimated error of ±6%

Atomic parameters required for the diagnostic purposes (for ArIV, ArIII and ArII spectra) have been taken from Wiese *et al.* (1969).

Table 1 Measured Stark width and shift values

λ(nm)	T	N	w_m	d_m	$\frac{w_m}{w_G}$	$\frac{w_m}{w_{MN}}$	$\frac{w_m}{w_{DSB1}}$	$\frac{w_m}{w_{DSB2}}$	$\frac{d_m}{d_G}$	$\frac{d_m}{d_{MN}}$	$\frac{d_m}{d_{DSB1}}$	$\frac{d_m}{d_{DSB2}}$
588.995	3.8	3.5	2.62	0.38	1.34	1.25	1.88	1.42	0.98	0.92	0.61	0.47
589.59	3.8	3.5	2.28	0.41	1.16	1.08	1.62	1.23	0.106	0.99	0.66	0.50

3. RESULTS

The results of the measured Stark FWHM (w_m, in Å), and shift (d_m) values (in Å) at the given T (in 10^4 K) and N (in 10^{23}m^{-3}) are presented in Table 1. Ratios of the measured w_m and d_m values to the calculated w_G, w_{MN}, w_{DSB1}, w_{DSB2}, d_G, d_{MN}, d_{DSB1} and d_{DSB2} Stark width and shift values are also given. For the evaulation of the NaI-D spectral lines Stark width and shift values, at the given electron density and temperature, we use Eq. (226) and Eq. (227), respectively from Griem (1974), based on the quasistatic ion approximation. The necessary data like electron impact half width (w_e), shift (d_e) and ion broadening parameter (α) are taken from

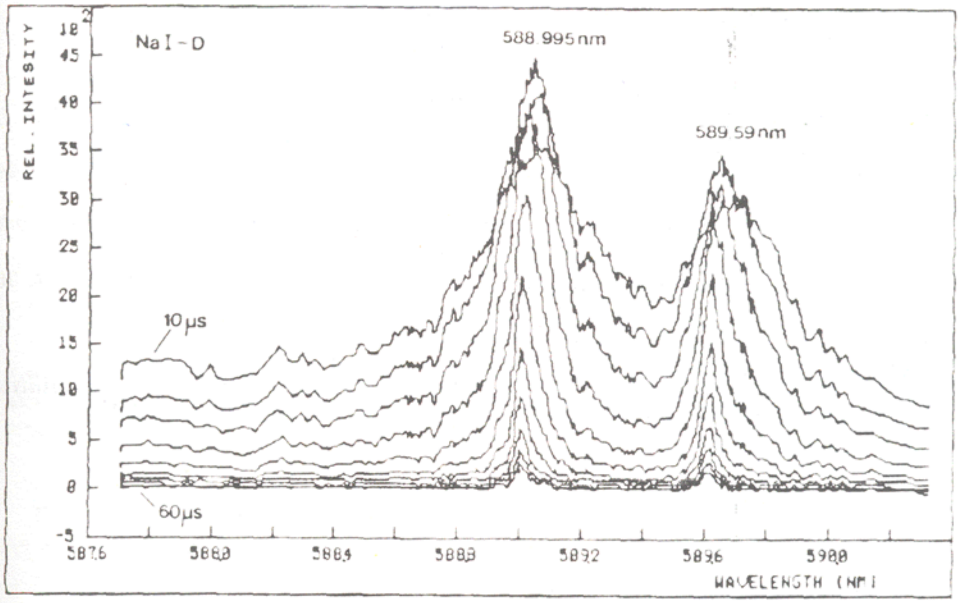

Fig. 1. Recorded spectral lines at various instants after the beginning of the discharge.

Griem (1974)-(G), and Dimitrijević and Sahal-Brechot (DSB_1). The values w_{DSB2} and d_{DSB2} are calculated width and shift data by Dimitrijević and Sahal-Brechot (1985), based on the ion impact approximation. In the case of the Model Microfield Method presented by Mazure and Nollez (MN) (1978), the total Stark width and shift values (w_{MN} and d_{MN}) were obtained using Fig. 1 in Mazure and Nollez (1978).

4. CONCLUSION

Our measured Stark shift values (d_m) are in excellent agreement with Griem's and Mazure and Nollez's predictions and are lower (about 39%) than those calculated by Dimitrijević and Sahal-Brechot on the basis of the quasistatic-ion approximation. Predicted d_{DSB2} data are higher than our d_m values up to a factor 2.1. In the case of the Stark width data there is also resonable agreement between our experimental values (w_m) and those obtained by the Model Microfield Method taking into account experimental accuracy and limited reliability of the theoretical model (the average ratio w_m/w_{MN} is 1.16).

Acknowledgements

This research was supported in part by Republic Fund for Science of the Republic Serbia.

References

Baur, J. F. and Cooper, J. : 1977, *JQSRT*, **17**, 311.
Davies, J. T. and Vaughan, J. M. : 1963, *Astrophys. J.* **137**, 1302.
Dimitrijević, M. S. and Sahal-Brechot, S. : 1985, *JQSRT*, **34** 149.
Djeniže, S., Srećković, A., Labat, J. and Platiša, M. : 1992, *Phys. Scripta*, **45**, 320.
Djeniže, S., Srećković, A. and Labat, J. : 1992a, *Proceedings the 11 ICSLS*, Carry Le Rouet, France, A 24.
Djeniže, S., Srećković, A., Labat, J., Konjević, R. and Popović, L. : 1991, *Phys. Rev.* A **44**, 410.
Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic Press, New York.
Mazure, A. and Nollez, G. : 1978, *Z. Naturforsch.* 33a, 1575.
Purić, J., Labat, J., Djeniže, S., Ćirković, Lj. and Lakićević, I. : 1976, *Phys. Lett.* A **56**, 83.
Purić, J. and Konjević, N. : 1972, *Z. Phys.* **249**, 440.
Srećković, A. and Djeniže, S. : 1994, *Proceedings the XVII SPIG*, Beograd, p. 181.
Wiese, W. L., Smith, M. W. and Miles, B. M. : 1969, *Atomic Transition Probabilities*, Vol. II NSRDS-NBS 22 (U. S. Government Printing Office, Washington, DC).

Publ. Obs. Astron. Belgrade No. 50 (1995), 39 – 42

INVESTIGATION OF SPECTRAL LINE SHAPES BY INTRACAVITY LASER SPECTROSCOPY METHODS

V. S. BURAKOV, A. P. VOITOVICH, V. V. MASHKO and S. N. RAIKOV

Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, F.Scaryna prosp. 70, 220072 Minsk, Belarus
E–mail imafbel%bas05.basnet.minsk.by@demos.su

Abstract. Intracavity laser spectroscopy investigations of absorption line profiles in gas and plasma media are presented for study of some physical processes, that cause the profile transformation.

High-sensitive intracavity laser spectroscopy (ICLS) methods are widely applied for solving varied spectroscopic tasks. The main attention was given to determination of optical density and wavelengths of absorption. This allowed to find particle concentration and to identify a medium. Lesser attention was paid to spectral line contour measurements. However, such measurements can give additional important spectroscopic information which can be used for investigation of different physical processes in gaseous media.

Some aspects of application of ICLS methods for investigation of spectral line contours are developed in this paper.

Sufficiently exact measurement of optical density or amplification of atomic gaseous medium can be performed on varied frequencies by intracavity method, utilizing narrow-band laser. A magnetic field is convenient to scan the line contour about generation frequency. A measurement procedure is following. Initially, losses g_0 of laser cavity in the absence of the medium are determined at the frequency ν_0 by inserting additional losses upsetting the generation. Then, such additional losses g are measured in the presence of a medium. A difference $g_0 - g$ of losses gives a value of optical density (amplification) on the frequency ν_0 . Supplement of longitudinal magnetic field to medium in the case of simple Zeeman effect gives a possibility of measuring optical density (amplification) on the frequency ν_0 deturned from central frequency ν_0' of the contour by value $\Delta\nu = \nu_0' - \nu_0 + \Delta_H$, where Δ_H is magnetic splitting of line. So one can investigate spectral line contour by changing magnetic field intensity H.

The method described gives the most exact results when frequencies ν_0 and ν_0' coincide with each other and magnetic field does not influence the generated frequency and population of transition levels. As estimates show, systematic errors connected with above factors may be neglected, for example, when contours of 0.63 and 1.15 μm neon lines are investigating using helium-neon laser at $H < 400$ Oe.

Contours of both absorption of pure neon and amplification of helium-neon mixture at 1.15 μm wavelength are measured at different gas pressures, discharge currents and diameters of discharge tube. The contour of pure neon has Doppler form. In the case of helium-neon mixture a line broadening is determined mainly by Doppler effect, too. However, the contour form slightly differs from Doppler one. Moreover, a width of a line is increased comparetively to those in the case of pure neon under the same pressure and power, supplied to discharge. As investigations performed show, such effects are caused by transforming a part of potential energy into kinetic energy in result of second kind impacts.

The advantages of the ICLS for spectral lines profiles study are most completely realized when broadband tunable lasers are used. Plasma formations are highly perspective for such investigations. The spectrum recording is possible for a single microsecond or nanosecond laser pulse, that excludes distortions, caused by self-radiation of an object to be studied and its parameters temporal variation. The following such objects have been chosen :

1. The ablation plume, formed under laser radiation with flux power of $10^6 - 10^{10}$ W/cm^2 on a surface of aluminium target (Burakov *et al.*, 1995).

2. High current pulsed electric discharge in noble gases, nitrogen and carbon dioxide with strong erosion of transparent quartz wall (Burakov *et al.*, 1992).

3. The gas phase of a thermal graphite atomizer with barium, cesium and thallium vapours (Burakov *et al.*, 1994).

The instantaneous laser intensity in the modes with selective absorption is expressed by the following relationship similar to the Bouger-Lambert law :

$$i(\nu,t) = i'(t)exp[-k(\nu)ct\frac{L}{L_c}], \quad (1)$$

where $i'(t)$ is the instantaneous laser intensity beyond (near) the absorption line, $k(\nu)$ – the absorption coefficient at a frequency ν , c – the velocity of light, t – the current laser duration, L – the length of an absorbent in a cavity, L_c – the cavity base.

Experimentally, most often, measured are the integral values of the laser intensities $I(\nu)$ in the modes with absorption and I' near the line. As the absorption measure the value of relative intensity is used :

$$\frac{I(\nu)}{I'} = [1 + \frac{k(\nu)c\tau L}{nL_c(\frac{\tau}{t_m})}]^{-(n+1)}, \quad (2)$$

where τ is the total duration of laser pulse, t_m is the duration of laser pulse leading front, n is the parameter, characterizing the time shape of laser pulse ($n = 1, 2$ or 3). The relation (2) has been obtained for bell- shape time profile of laser pulse :

$$f(t) \sim (t/t_m)^n exp[-n(t/t_m - 1)]. \quad (3)$$

The spectral distribution $k(\nu - \nu_0)$ of an absorption coefficient (where ν_0 is the frequency of spectral line profile centre) can be found experimentally from the intracavity absorption spectrum with known time profile of a laser pulse. For the real in our experiments time profile with parameter n=2 :

$$k(\nu - \nu_0) = \frac{(I'/I)^{1/3} - 1}{(I'/I_0)^{1/3} - 1}, \tag{4}$$

where I_0 - integral laser intensitiy in the centre of absorption line at the frequency ν_0.

In ablation plasmas the Al I ($\lambda = 394{,}4$ nm) and Ca II ($\lambda = 393{,}4$ nm) spectral lines widths as well as their profiles have been measured for different moments of plume evolution (t) and various distances from the target surface (z). The maximal values of a width and aluminium line centre shift have been equal accordingly $\Delta\lambda = 0.22$ nm and $\delta\lambda = 0.17$ nm at the initial moments of a plume expansion ($t = 1.2$ μs and z = 1 mm). Under the same conditions the calcium line has $\Delta\lambda = 0.18$ nm and $\delta\lambda = 0$. These lines parameters provide determination of electrons density ($N = 0.9 \cdot 10^{18}$ cm^{-3}) and together with the species densities, measured from the lines intensities, a calculation of plasmas temperature ($T = 2.3$ eV) as well as plume pressure ($P = 6$ atm). At the late stages of plasmas expansion, including the afterglow, the mentioned lines parameters have been observed up to $t = 80$ μs and $z = 5$ mm.

In the plasmas of electric discharge the ICLS is an efficient method for component composition study, including the precise measurements of electrons density by using the width and profile of H_α line (hydrogen is a probe impurity in a gas).

The spectral lines profiles are possible to calculate and compare with experimental ones in a gas phase of thermal atomizer, taking into account Van-der-Vaals and Doppler broadening. The experimental (and calculated) widths of barium, cesium and thallium absorption lines are the following :

Ba I, 553.55 nm – 0.065 (0.041) nm,
Cs I, 455.54 nm – 0.090 (0.057) nm,
Tl I, 535.05 nm – 0.050 (0.041) nm.

The most satisfactory conformity of calculated and experimental data has been reached for thallium with resolved superfine structure , where the ratio of intensities of separate components has been measured - 1 : 0.36 and the distance between their centres - $1.08 \cdot 10^{-2}$ nm, while the calculated ones - 1 : 0.33 and $1.12 \cdot 10^{-2}$ nm, respectively.

There are situations when it is necessary to use a high optical density medium in laser cavity when ICLS method is applied. Such situation takes place, for example, in ICLS of two-photon transitions. Wide dips in intracavity absorption spectra appear in this case. Supplying of longitudinal magnetic field to medium in presence of polarizer in the cavity leads to sufficient transforming of dips. They are broadening and display one or more pairs of narrow resonances inside themselves. Components of each pair are situated symmetrically about central frequency ν_0 of transition. Investigations carried out allow to interpret these resonances as caused by rotation of polarization plane of light, because of Faraday effect. The condition of appearance of resonances is $\phi_\nu = n\pi/2$, where ϕ_ν is Faraday rotation angle at some frequency ν of absorbing contour, n is integer. This condition gives a possibility of measuring high optical densities by ICLS method, because of relation between volume ϕ_ν and optical density k_0l at the center of nonsplitted absorption contour. Such relation is expressed by proportional dependence $\phi_\nu = k_0lF$, where F is a function of frequency deturning $\nu - \nu_0$, intensity H of magnetic field and line shape parameter $\Gamma/\Delta\nu_D$ (Γ is homogeneous width of line) (Voitovich, 1987). So, taking into account the condition of appearance of resonances, we have :

$$k_0l = n\pi/2F. \tag{5}$$

The deturning $\nu - \nu_0$ can be determined as half difference of frequencies of resonances of the same pair with number n. One can simply calculate parameter $\Gamma/\Delta\nu_D$, if the temperature of gas is known. The value of H may be experimentally determined.

Optical densities of potassium vapour up to value $\sim 2 \cdot 10^5$ have been experimentally measured by described method. It is possible to find higher optical densities. Principally measurable value of k_0l is limited by the width of generated spectrum.

The results obtained indicate an efficiency of using of ICLS methods for investigation of spectral lines contours for purposes of plasma and gaseous media diagnostics.

References

Burakov, V. S., Isaevich, A. V., Misakov, P. Ya. and Raikov, S. N. : 1994, *Microchemical Journal*, **50**, 365.

Burakov, V. S., Naumenkov, P. A., Nechaev, S. V. and Raikov, S. N. : 1992, *Journal of High Temperature Chemical Processes*, **1**, 471.

Burakov, V. S., Raikov, S. N., Savastenko, N. A. and Tarasenko, N. V. : 1995, *Journal of Molecular Structure*, **349**, 281.

Voitovich, A. P. : 1987, *Journal of Soviet Laser Research*, **8**, 551.

Publ. Obs. Astron. Belgrade No. 50 (1995), 43 – 45

STARK BROADENING OF IONIZED NICKEL LINES

M. S. DIMITRIJEVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E–mail mdimitrijevic@aob.aob.bg.ac.yu

Abstract. Stark widths and shifts for two spectral lines within the a^4F - z^4G^o multiplet have been calculated using semiclassical - perturbation approach. Obtained results have been compared with experimental data and simpler estimates.

1. INTRODUCTION

As a member of the iron-group elements, the nickel spectrum is of interest for astrophysics as well as for laboratory plasma research. Spectral lines of Ni II are often observed in stellar spectra. For example, such lines have been found in the spectra of Gamma Geminorum and 7 Sextantis (Adelman and Philip, 1992), stars of A0 V type, where the main pressure broadening mechanism is the Stark effect. Consequently, the corresponding Stark broadening parameters are needed for various astrophysical problems as *e.g.* abundance determination or modelling of stellar spectra.

The first experimental determination of Ni II Stark widths and shifts has been performed recently (Djeniže *et al.* 1994). and a surprisingly large discrepancy between experimental and theoretical values has been reported. Since the sufficiently complete set of atomic data for the considered Ni II lines exists, it is of interest to performe more sophysticated theoretical analysis within the frame of the semiclassical approach.

By using the semiclassical-perturbation formalism (Sahal-Bréchot, 1969ab), we have calculated Stark broadening parameters for two lines within Ni II a^4F - z^4G^o multiplet. Perturbers are electrons, protons and a singly charged perturber with the mass equal to 35 a.u. corresponding to the averaged mass of perturbing ions in Solar atmosphera. A summary of the formalism is given in Dimitrijević *et al.* (1991).

2. RESULTS AND DISCUSSION

Energy levels for Ni II lines have been taken from Corlis and Sugar (1981). In order to test the applicability of the Coulomb approximation for the considered case, we compared presently calculated oscillator strengths with the experimental values of Bell *et al.* (1960). For Ni II a^4F - z^4G^o, 2270.21Å and 2264.46Å lines Bell *et al.* (1960) obtained oscillator strengths equal to 0.24, while present result within the Coulomb approximation (Bates and Damgaard, 1949) is 0.32, indicating that the Coulomb approximation is applicable for the considered transitions.

Table 1 This table shows Stark broadening full half-widths (FWHM) and shifts in Å for Ni II for a perturber density of 10^{17} cm^{-3} and temperatures from 5,000 up to 150,000 K. Perturbers are electrons, protons and singly charged perturbers with the mass equal to 35 a.u. corresponding to the averaged mass of perturbing ions in Solar atmosphera. By using c [see Eq.(5) in Dimitrijević *et al.* 1991], we obtain an estimate of the maximum perturber density for which the line may be treated as isolated and tabulated data may be used.

PERTURBER DENSITY = 1xE+17cm-3

PERTURBERS ARE :		ELECTRONS		PROTONS		He III	
TRANSITION	T(K)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)
Ni II 2264.5	5000.	0.984E-01	0.706E-03	0.128E-02	-0.751E-04	0.288E- 02	-0.742E-04
2265.2 A	10000.	0.715E-01	-0.470E-03	0.243E-02	-0.166E-03	0.405E-02	-0.153E-03
C= 0.19E+21	30000.	0.432E-01	-0.493E-03	0.416E-02	-0.423E-03	0.499E-02	-0.310E-03
	50000.	0.355E-01	-0.552E-03	0.459E-02	-0.546E-03	0.537E-02	-0.383E-03
	100000.	0.291E-01	-0.617E-03	0.514E-02	-0.727E-03	0.563E-02	-0.459E-03
	150000.	0.269E-01	-0.562E-03	0.542E-02	-0.808E-03	0.575E-02	-0.511E-03
Ni II 2270.2	5000.	0.976E-01	0.518E-03	0.124E-02	-0.862E-04	0.281E-02	-0.850E-04
2270.9 A	10000.	0.710E-01	-0.557E-03	0.236E-02	-0.190E-03	0.396E-02	-0.173E-03
C= 0.20E+21	30000.	0.428E-01	-0.615E-03	0.408E-02	-0.476E-03	0.490E-02	-0.346E-03
	50000.	0.351E-01	-0.665E-03	0.450E-02	-0.613E-03	0.527E-02	-0.423E-03
	100000.	0.287E-01	-0.751E-03	0.505E-02	-0.800E-03	0.553E-02	-0.506E-03
	150000.	0.264E-01	-0.690E-03	0.533E-02	-0.890E-03	0.564E-02	-0.561E-03

In addition to electron-impact full halfwidths and shifts, Stark-broadening parameters due to proton-impacts, and to impacts with a singly charged perturber with the mass equal to 35 a.u. corresponding to the averaged mass of perturbing ions in Solar atmosphera, have been calculated. Our results for two lines within the Ni II a^4F - z^4G^o multiplet are shown in Table 1, for a perturber density of $10^{17}cm^{-3}$ and temperatures T = 5,000 - 150,000K. We also specify a parameter *c* (Dimitrijević *et al.* 1991), which gives an estimate of the maximum perturber density for which the line may be treated as isolated when it is divided by the corresponding electron-impact full width at half maximum.

In Djeniže *et al.* (1994), the results of their calculations by using the simplified version (SMSE-Dimitrijević and Konjević, 1987) of the modified semiempirical method (MSE-Dimitrijević and Konjević, 1980) have been presented and the ratios of measured and calculated Stark widths equal to 4.4 for 2264.5 Å line and 3.9 for 2270.2 Å line have been reported. However, the calculations of Djeniže *et al.* (1994) have been performed by using atomic energy levels from Moore (1958). Since the more recent and accurate atomic energy levels exist (Corlis and Sugar, 1981) permitting the use of more sophisticated approaches as well, their calculations were repeated here. The ion broadening contribution has also been neglected as well in Djeniže *et al.* (1994). As a working gas they used a mixture of 72% Ar and 28% He. Since there is more Ar and it has lower ionization potential than He, a reasonable assumption is that Ar II-impact broadening parameters may be used to estimate the ion broadening contribution. With more accurate atomic data and with the ion broadening contribution included, we obtain 3.2 and 3.0 as ratios of measured and calculated values for Ni II 2264.5 Å and 2270.2 Å lines instead of 4.4 and 3.9 obtained by Djeniže *et al.* (1994). With the use of the non simplified version of the MSE approach, the corresponding ratios are 2.7 and 2.4, and for the full semiclassical calculations 1.7 and 1.5, which is much better but still not satisfying.

The ratio of the semiclassical and the MSE values is also too large, equal to 1.7 for both lines. If one performs an analysis of the contributions of different types of collisions, for Ni II 2264.5 Å line (T = 20000 K and the electron density $10^{17}cm^{-3}$), the inelastic collision contribution is 0.875 $10^{10}s^{-1}$ for the upper and 0.802 $10^{10}s^{-1}$ for the lower level. The elastic collision contribution is 0.948 $10^{10}s^{-1}$. Moreover, the strong collision contribution to elastic and inelastic part is 0.597 $10^{10}s^{-1}$. The elastic collisions contribution consists of contributions due to strong collisions, the polarization and the quadrupole potentials. For the considered line the contribution due to the polarization potential is only 0.241 $10^{9}s^{-1}$. Consequently, for the considered line, elastic collisions, strong collisions and higher order interactions, taken as corrections implicitly in the modified semiempirical approach or neglected, play an important role.

Our results for the shift have a different sign from experimental ones. Since the considered lines are 4s-4p transition with a far 4d perturbing level with smaller influence, it is logical that the shift is around zero or negative. In spite of the fact that the agreement between the theory and experiment is better if one uses the more sophisticated semiclassical - perturbation approach, the differences are still such that a new experiment is of interest.

References

Adelman, S. J., Philip, A. G. D. : 1992, *PASP*, **104**, 316.

Bates, D.R., Damgaard, A. : 1949, *Trans. Roy. Soc.* London, Ser. A **242**, 101

Bell, G. D., Paquet, D. R., Wiese, W. L. : 1960, *Astrophys. J.* **143**, 559.

Corlis, L., Sugar, J. : 1981, *J. Phys. Chem. Ref. Data*, **10**, 197.

Dimitrijević, M. S., Sahal-Bréchot, S., and Bommier, V. : 1991, *Astron. Astrophys. Suppl. Series*, **89**, 581.

Dimitrijević, M. S. and Konjević, N. : 1980, *JQSRT*, **24**, 451.

Dimitrijević, M. S. and Konjević, N. : 1987, *Astron. Astrophys.* **q72**, 34.

Djeniže, S., Skuljan, Lj., Labat, J., Bukvić, S., Konjević, R. : 1994, *Astron. Astrophys. Suppl. Series*, **105**, 115.

Moore, C. E. : 1958, *Atomic Energy Levels*, NSRDS-NBS 467, Vol.III (Washington).

Sahal-Bréchot, S. : 1969a, *Astron.Astrophys.* **1**, 91.

Sahal-Bréchot, S. : 1969b, *Astron.Astrophys.* **2**, 322.

Publ. Obs. Astron. Belgrade No. 50 (1995), 47 – 50

STARK BROADENING OF S III AND S IV SPECTRAL LINES

M. S. DIMITRIJEVIĆ[1], S. DJENIŽE[2], A. SREĆKOVIĆ[2] and M. PLATIŠA[2]
[1]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Serbia, Yugoslavia*
E–mail mdimitrijevic@aob.aob.bg.ac.yu

[2]*Faculty of Physics, University of Belgrade, P.O.Box 550, Serbia, Yugoslavia*

Abstract. Stark widths of three S III spectral lines belonging to 4p - 5s transitions have been measured and calculated. Measurements have been performed in the low pressure linear pulsed arc at 2.1 10^{23} m^{-3} electron density and 40 000 K electron temperature. Calculations for S III lines were performed by using the modified semiempirical approach. For S IV $4s^2S$ - $4p^2P^o$ multiplet, calculations were performed within the semiclassical perturbation formalism. The obtained results were compared with the other theoretical and experimental data.

1. INTRODUCTION

The experimental study of the Stark broadening of spectral lines within S III 4p - 5s transitions has been performed The experimental results will be compared with the theoretical results calculated by using the modified semiempirical approach (Dimitrijević and Konjević, 1980), the approximate semiclassical approach (Griem, 1974, Eq. 526) and its modification (Dimitrijević and Konjević, 1980). Since for S IV, the new atomic energy level data enabling the ful semiclassical perturbation calculation (Sahal - Bréchot, 1969ab) become available, the S IV lines will be considered here as well.

2. APPARATUS AND PROCEDURE

Details of the experimental apparatus were described elsewhere (Djeniže *et al.* 1990). A pulsed discharge occured in a Pyrex discharge tube of 5 mm i.d. and had an effective plasma length of 7.4 cm. The tube had end on quartz windows. The working gas was SO_2 at an initial filling pressure of 400 Pa. A capacitor of 0.3μF was charged up to 14.6 kV and supplied discharge currents up to 6.0 kA. The discharge period was 3.7 μs.

Spectroscopic observations of isolated spectral lines were made end-on along the axis of the discharge tube. Great care was taken to minimize the influence of the selfabsorption on Stark FWHM (fullwidth at half intensity maximum) determination. In order to find existence of selfabsorption of lines, one has to check wheather the ratio of their intensities (I) is the same as the ratio of products of spontaneous transition

Table 1. Stark full widths of S III spectral lines for an electron density of 2.1 10^{17} cm^{-3} and T = 40,000 K. With W_m is denoted experimental width. Present theoretical results : W_{MSE} - by using the modified semiempirical approach [4]; W_{GM} - by using the modified version [4] of the symplified semiclassical approach [12, eq. 526]; W_G - by using the Griem's symplified semiclassical approach [12, eq. 526].

	Transition	$\lambda[\AA]$	$W_m[\AA]$	$W_{MSE}[\AA]$	$W_{GM}[\AA]$	$W_G[\AA]$
S III	$4p^3D$-$5s^3P^o$	2508.15	0.402	0.483	0.466	0.623
	(17 UV)	2499.08	0.360	0.483	0.466	0.623
S III	$4p^3S$-$5s^3P^o$	2785.49	0.380	0.569	0.552	0.752
	(20 UV)					

probabilities (A) and statistical weights (g) of their upper level, *i.e.* : $I_1 : I_2 = A_1g_1 : A_2g_2$. In the case of the spectral lines from the 17UV multiplet this ratio were found to be the same within the experimental error, proving that no significant selfabsorption exists.

The spectral line profiles were recorded by the step by step method, described elsewhere (Djeniže *et al.* 1990), using spectrograph - photomultiplier combination. The electron density was measured using a single wavelength He - Ne laser interferometer for the visible 6328. Å transition with an estimated error of : ±7%. Peak electron density was found to be 2.4 10^{23} m^{-3}. The electron temperature was deduced from the relative intensity ratios of 4333.7 Å S III and S II 5646.9 Å lines, assuming the existence of the LTE. It was found to be 40 000 K ±14% at 5μs after the begining of the discharge and decayed slowly during the first 20 μs.

3. RESULTS AND DISCUSSION

In Dimitrijević and Konjević (1980) it is emphasized that "for S III, data on the 4f and 5p levels are unavailable which may affect the results for the multiplets 15 UV - 18 UV". This statement concerns as well to the multiplet 19 UV (Dimitrijević, 1988). In spite of the fact that a new comprehensive investigation of S III spectrum (Johansson *et al.* 1992) exists, as well as a new review of critically selected atomic energy level data (Martin *et al.* 1990), the reliable data on 4f and 5p energy level positions are still missing. Since the experimental results obtained here for S III 17 UV multiplet are (in average) around 3 times larger than calculated (Dimitrijević, 1988), we recalculated them with the inclusion of the new energy values for 4d levels (Johansson *et al.* 1992) and of the estimated (Breger, 1980) positions of $5p^3P$ level (220419 cm^{-1}) and of $5p^3D$ level (219184 cm^{-1}). The present experimental results for line widths within S III $4p^3D$ - $5s^3P^o$ (17 UV) and $4p^3S$ - $5s^3P^o$ (20 UV) multiplets are compared in Table 1 with the present calculations by using the modified semiempirical approach (Dimitrijević and Konjević, 1980), the symplified semiclassical approach (Griem 1974, eq. 526) and its modification (Dimitrijević and Konjević, 1980). One can see that the results obtained by using the modification (Dimitrijević and Konjević, 1980) of the symplified semiclassical approach (Griem, 1974, eq. 526) and the modified semiempirical approach (Dimitrijević and Konjević, 1980), agree better with the present experimental results than with the symplified semiclassical approach (Griem, 1974, eq. 526). If one takes into account that the error bars of the approximate approaches are within 50 per cents (Griem, 1974) and that the positions of 5p levels are approximate, the agreement with experiment is within the error bars of theoretical uncertainties.

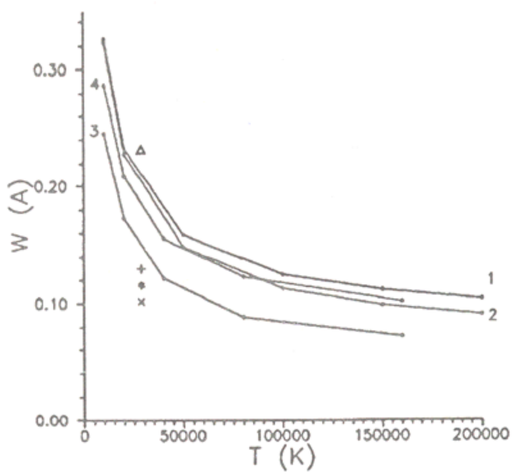

Fig. 1. Full Stark widths for S IV $4s^2S$ - $4p^2P^o$ multiplet as a function of temperature for an electron density of 10^{17} cm^{-3} Experiment : * - Platiša *et al.* (1979). Theory : 1 - present semiclassical results with the ion broadening contribution included; 2 - present semiclassical results, electrons broadening only; 3 - modified semiempirical formula (Dimitrijević and Konjević, 1980); 4 - calculations of Dimitrijević and Konjević (1980) by using the semiclassical approximation (Eq.(526) taken from Griem, 1974); x - Hey and Breger (1980), the method I; + - Hey and Breger (1980), the method II; Δ - semiclassical calculations of Dimitrijević and Konjević (1982).

Needed energy levels for S IV have been taken from Martin *et al.* (1980). In Fig. 1, our results for S IV $4s^2S$ - $4p^2P^o$ multiplet Stark broadening parameters, are compared with experimental results (Platiša *et al.* 1979) and other theoretical calculations, *i.e.* with results obtained by using the modified semiempirical formula (Dimitrijević and Konjević, 1980); calculations of Dimitrijević and Konjević (1980) by using the semiclassical approximation (Eq.(526) taken from Griem, 1974); approximate approaches of Hey and Breger (1980) and with the semiclassical calculations of Dimitrijević and Konjević (1982). Experimental results (Platiša *et al.* 1979) compare better with the approximate approaches of Hey and Breger (1980) and Dimitrijević and Konjević (1980) than with more sophysticated semiclassical calculations. More experimental data will be of use for a better investigation of these discrepancies.

References

Breger, P. : 1980, *M.Sc. Thesis*, University of Cape Town.
Dimitrijević, M. S. : 1988, *Astron. Astrohys. Suppl. Series*, **76**, 53.
Dimitrijević, M. S. and Konjević, N. : 1980, *JQSRT*, **24**, 451.
Dimitrijević, M. S. and Konjević, N. : 1982, *JQSRT*, **27**, 203.
Djeniže, S., Srećković, A., Platiša, M., Konjević, R., Labat, J. and Purić, J. : 1990,*Phys. Rev. A* **42**, 2379.
Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic Press, New York.
Hey, J. D. and Breger, P. : 1980, *JQSRT*, **24**, 427.
Johansson, L., Magnusson, C. E., Joelsson, I. and Zetterberg, P. O. : 1992, *Physica Scripta*, **46**, 221.
Martin, W. C., Zalubas, R. and Musgrove, A. : 1990, *J.Phys. Chem. Ref. Data*, **19**, 821.
Platiša, M., Popović, M., Dimitrijević, M. and Konjević, N. : 1979, *JQSRT*, **22**, 333.
Sahal – Bréchot, S. : 1969a, *Astron. Astrophys.* **1**, 91.
Sahal – Bréchot, S. : 1969b, *Astron. Astrophys.* **2**, 322.

Publ. Obs. Astron. Belgrade No. 50 (1995), 51 – 54

STARK BROADENING OF P V LINES

M. S. DIMITRIJEVIĆ[1] and S. SAHAL-BRÉCHOT[2]
[1]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*
E–mail mdimitrijevic@aob.aob.bg.ac.yu

[2]*Observatore de Paris, 92195 Meudon Cedex, France*
E–mail sahal@obspm.fr

Abstract. Using a semiclassical approach, we have calculated electron-, proton-, and He III-impact line widths and shifts for 51 P V multiplets.

1. INTRODUCTION

Investigation of Stark broadening parameters of P V lines is the continuation of our effort to provide needed data for the analysis of laboratory and astrophysical plasmas (see Dimitrijević and Sahal-Bréchot 1995a and references therein). Stark widths and shifts of P V spectral lines are of interest for the plasma diagnostic as well as for the research of regularities and systematic trends. Recently e.g., estimates of the Stark widths for P V 4s-4p and 4p-4d transitions have been performed within a study on Stark broadening regularities within successive ionization stages of phosphorus (Srećković *et al*. 1990).

By using the semiclassical-perturbation formalism (Sahal-Bréchot, 1969ab), we have calculated electron-, proton-, and He III-impact line widths and shifts for 51 P V multiplets, in order to continue our research of multiply charged ion line Stark broadening parameters. A summary of the formalism is given in Dimitrijević *et al*. (1991).

2. RESULTS AND DISCUSSION

Energy levels for P V lines have been taken from Bashkin and Stoner (1975). Oscillator strengths have been calculated by using the method of Bates and Damgaard (1949) and the tables of Oertel and Shomo (1968). For higher levels, the method described by Van Regemorter *et al*. (1979) has been used. In addition to electron-impact full halfwidths and shifts, Stark-broadening parameters due to proton-, and He III-impacts have been calculated. Our results for 51 P V multiplets, for perturber densities 10^{17} - 10^{22} cm^{-3} and temperatures T = 50,000 - 1,000,000K will be published in Dimitrijević and Sahal-Bréchot (1995b,c).

Here, in Table 1, we present only a sample of results obtained. We also specify a parameter c (Dimitrijević and Sahal-Bréchot, 1984), which gives an estimate for the

Table 1
This table shows electron-, proton-, and He III-impact broadening full half-widths (FWHM) and shifts for P V for a perturber density of 10^{17} cm^{-3} and temperatures from 50,000 up to 500,000 K. By deviding c with the full linewidth, we obtain an estimate for the maximum perturber density for which the line may be treated as isolated and tabulated data may be used.

PERTURBER DENSITY = 1xE+17cm-3

PERTURBERS ARE :		ELECTRONS		PROTONS		He III	
TRANSITION	T(K)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)
P V 3S 3P	50000.	0.626E-02	-0.594E-04	0.633E-04	-0.266E-04	0.122E-03	-0.519E-04
1121.8 A	100000.	0.447E-02	-0.762E-04	0.136E-03	-0.516E-04	0.266E-03	-0.103E-03
C= 0.11E+21	150000.	0.371E-02	-0.584E-04	0.190E-03	-0.713E-04	0.373E-03	-0.143E-03
	200000.	0.328E-02	-0.729E-04	0.224E-03	-0.875E-04	0.443E-03	-0.176E-03
	300000.	0.278E-02	-0.871E-04	0.278E-03	-0.108E-03	0.550E-03	-0.219E-03
	500000.	0.232E-02	-0.764E-04	0.329E-03	-0.139E-03	0.657E-03	-0.280E-03
P V 3S 4P	50000.	0.139E-02	0.178E-04	0.619E-04	0.890E-05	0.121E-03	0.174E-04
328.6 A	100000.	0.103E-02	0.166E-04	0.923E-04	0.156E-04	0.182E-03	0.310E-04
C= 0.34E+19	150000.	0.877E-03	0.202E-04	0.110E-03	0.201E-04	0.218E-03	0.406E-04
	200000.	0.792E-03	0.224E-04	0.117E-03	0.228E-04	0.233E-03	0.460E-04
	300000.	0.693E-03	0.220E-04	0.127E-03	0.277E-04	0.252E-03	0.561E-04
	500000.	0.598E-03	0.206E-04	0.138E-03	0.321E-04	0.275E-03	0.649E-04
P V 3S 5P	50000.	0.175E-02	0.497E-04	0.158E-03	0.299E-04	0.310E-03	0.583E-04
255.6 A	100000.	0.140E-02	0.570E-04	0.200E-03	0.439E-04	0.399E-03	0.875E-04
C= 0.95E+18	150000.	0.125E-02	0.646E-04	0.217E-03	0.529E-04	0.432E-03	0.107E-03
	200000.	0.116E-02	0.584E-04	0.228E-03	0.574E-04	0.453E-03	0.116E-03
	300000.	0.105E-02	0.566E-04	0.243E-03	0.638E-04	0.484E-03	0.130E-03
	500000.	0.934E-03	0.528E-04	0.258E-03	0.728E-04	0.514E-03	0.148E-03
P V 3S 6P	50000.	0.282E-02	0.104E-03	0.356E-03	0.694E-04	0.705E- 03	0.135E-03
229.8 A	100000.	0.238E-02	0.137E-03	0.404E-03	0.961E-04	0.804E- 03	0.192E-03
C= 0.42E+18	150000.	0.217E-02	0.124E-03	0.433E-03	0.107E-03	0.863E- 03	0.216E-03
	200000.	0.204E-02	0.122E-03	0.452E-03	0.115E-03	0.902E-03	0.234E-03
	300000.	0.187E-02	0.117E-03	0.471E-03	0.128E-03	0.938E-03	0.259E-03
	500000.	0.170E-02	0.114E-03	0.492E-03	0.145E-03	0.974E-03	0.293E-03
P V 4S 4P	50000.	0.170	-0.412E-02	0.600E-02	-0.260E-02	0.117E-01	-0.508E-02
3185.6 A	100000.	0.127	-0.405E-02	0.908E-02	-0.405E-02	0.179E-01	-0.812E-02
C= 0.32E+21	150000.	0.110	-0.481E-02	0.109E-01	-0.493E-02	0.217E-01	-0.996E-02
	200000.	0.997E-01	-0.485E-02	0.117E-01	-0.558E-02	0.233E-01	-0.113E-01
	300000.	0.882E-01	-0.432E-02	0.128E-01	-0.619E-02	0.255E-01	-0.125E-01
	500000.	0.767E-01	-0.423E-02	0.142E-01	-0.714E-02	0.283E-01	- 0.144E-01

Table 1 continued

PERTURBER DENSITY = 1xE+17cm-3

PERTURBERS ARE :		ELECTRONS		PROTONS		He III	
TRANSITION	T(K)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)	WIDTH(Å)	SHIFT(Å)
P V 4S 5P	50000.	0.217E-01	0.112E-03	0.172E-02	0.122E-03	0.337E-02	0.238E-03
845.8 A	100000.	0.174E-01	0.218E-03	0.218E-02	0.200E-03	0.433E-02	0.400E-03
C= 0.10E+20	150000.	0.156E-01	0.228E-03	0.235E-02	0.242E-03	0.468E-02	0.487E-03
	200000.	0.144E-01	0.142E-03	0.246E-02	0.279E-03	0.491E-02	0.562E-03
	300000.	0.131E-01	0.164E-03	0.262E-02	0.320E-03	0.523E-02	0.650E-03
	500000.	0.117E-01	0.142E-03	0.278E-02	0.367E-03	0.553E-02	0.740E-03
P V 4S 6P	50000.	0.218E-01	0.471E-03	0.256E-02	0.428E-03	0.506E- 02	0.833E-03
616.8 A	100000.	0.183E-01	0.753E-03	0.290E-02	0.597E-03	0.577E- 02	0.119E-02
C= 0.30E+19	150000.	0.166E-01	0.617E-03	0.310E-02	0.662E-03	0.618E-02	0.134E-02
	200000.	0.156E-01	0.605E-03	0.324E-02	0.718E-03	0.646E-02	0.145E-02
	300000.	0.144E-01	0.591E-03	0.337E-02	0.796E-03	0.671E-02	0.162E-02
	500000.	0.130E-01	0.586E-03	0.349E-02	0.906E-03	0.694E-02	0.182E-02
P V 5S 5P	50000.	1.88	-0.715E-01	0.121	-0.588E-01	0.238	-0.114
6872.7 A	100000.	1.53	-0.866E-01	0.156	-0.817E-01	0.311	-0.163
C= 0.69E+21	150000.	1.38	-0.805E-01	0.171	-0.906E-01	0.343	-0.183
	200000.	1.28	-0.819E-01	0.182	-0.983E-01	0.365	-0.199
	300000.	1.16	-0.783E-01	0.199	-0.109	0.398	-0.221
	500000.	1.04	-0.767E-01	0.215	-0.123	0.431	-0.251
P V 5S 6P	50000.	0.193	-0.123E-02	0.196E-01	-0.105E-02	0.388E-01	-0.204E-02
1710.8 A	100000.	0.163	-0.425E-03	0.222E-01	-0.157E-02	0.441E-01	-0.313E-02
C= 0.23E+20	150000.	0.149	-0.116E-02	0.237E-01	-0.192E-02	0.472E-01	-0.387E-02
	200000.	0.140	-0.995E-03	0.247E-01	-0.212E-02	0.492E-01	-0.429E-02
	300000.	0.129	-0.968E-03	0.257E-01	-0.236E-02	0.511E-01	-0.477E-02
	500000.	0.116	-0.815E-03	0.266E-01	-0.269E-02	0.527E-01	-0.546E-02
P V 6S 6P	50000.	13.5	-0.860	1.18	-0.629	2.34	-1.21
12638.2 A	100000.	11.6	-0.803	1.38	-0.780	2.76	-1.54
C= 0.13E+22	150000.	10.6	-0.804	1.51	-0.869	3.01	- 1.75
	200000.	10.0	-0.771	1.60	-0.933	3.22	-1.89
	300000.	9.25	-0.751	1.69	-1.02	3.38	-2.06
	500000.	8.34	-0.669	1.84	-1.13	3.63	-2.31
P V 3P 4S	50000.	0.276E-02	0.194E-03	0.441E-04	0.100E-03	0.869E-04	0.195E-03
544.0 A	100000.	0.203E-02	0.187E-03	0.103E-03	[illegible]	0.301E-03	
C= 0.93E+19	150000.	0.173E-02	0.213E-03	0.142E-03	0.184E-03	0.284E-03	0.371E-03
	200000.	0.155E-02	0.223E-03	0.182E-03	0.205E-03	0.363E-03	0.415E-03
	300000.	0.136E-02	0.209E-03	0.219E-03	0.228E-03	0.440E-03	0.461E-03
	500000.	0.116E-02	0.199E-03	0.263E-03	0.259E-03	0.536E-03	0.526E-03

maximum perturber density for which the line may be treated as isolated when it is divided by the corresponding electron-impact full width at half maximum. For each value given in Table 1, the collision volume (V) multiplied by the perturber density (N) is much less than one and the impact approximation is valid (Sahal- Bréchot, 1969ab). When the impact approximation is not valid, the ion broadening contribution may be estimated by using quasistatic estimations (Sahal-Bréchot, 1991 and Griem, 1974). The accuracy of the results obtained decreases when broadening by ion interactions becomes important.

Estimates of the Stark widths for P V 4s-4p transitions obtained by using regularities within successive ionization stages (Srećković *et al.* 1990), give for full width a value of 0.14Å for T=40000 K and an electron density of 10^{17} cm^{-3}. We obtain a full width of 0.17Å at T = 50000 K, an excellent agreement encouraging the use of regularities and systematic trends for predictions and interpolations of Stark broadening parameters.

References

Bashkin, S., Stoner, J. O. Jr. : 1975, "Atomic Energy Levels and Grotrian Diagrams", Vol. 1, North Holland, Amsterdam.

Bates, D. R. and Damgaard, A. : 1949, *Trans. Roy. Soc. London, Ser. A* **242**, 101.

Dimitrijević, M. S. and Sahal-Bréchot, S. : 1984, *JQSRT*, **31**, 301.

Dimitrijević, M. S. and Sahal-Bréchot, S. : 1995a, *Astron. Astrophys. Suppl. Series*, **109**, 551.

Dimitrijević, M. S. and Sahal-Bréchot, S. : 1995b, *Astron. Astrophys. Suppl. Series* submitted.

Dimitrijević, M. S. and Sahal-Bréchot, S. : 1995c, *Bull. Astron. Belgrade*, **152**, in press.

Dimitrijević, M. S., Sahal-Bréchot, S. and Bommier, V. : 1991, *Astron. Astrophys. Suppl. Series*, **89**, 581.

Griem, H. R. : 1974, "Spectral Line Broadening by Plasmas", Academic Press, New York.

Oertel, G. K. and Shomo, L. P. : 1968, *Astrophys. J. Suppl. Series*, **16**, 175.

Sahal-Bréchot, S. : 1969a, *Astron. Astrophys.* **1**, 91.

Sahal-Bréchot, S. : 1969b, *Astron. Astrophys.* **2**, 322.

Sahal-Bréchot, S. : 1991, *Astron. Astrophys.* **245**, 322.

Srećković, A., Djeniže, S., Labat, J., Platiša, M., Purić, J. : 1990, *Fizika*, **22**, 583.

Van Regemorter, H., Hoang Binh Dy, and Prud'homme, M. : 1979, *J. Phys. B* **12**, 1073.

Publ. Obs. Astron. Belgrade No. 50 (1995), 55 – 60

THE ANALYSIS OF THE SIMPLIFIED FORMULA FOR THE STARK BROADENING OF NEUTRAL ATOM LINES

M. S. DIMITRIJEVIĆ and N. K. TODOROVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E–mail mdimitrijevic@aob.aob.bg.ac.yu

Abstract. The approximate semiclassical formula of Dimitrijević and Konjević for isolated neutral atom spectral lines has been applied to neutral helium lines. The desagreements with the more sophisticated full semiclassical calculations of Griem are within 20 per cents. It is demonstrated as well how one can introduce simple corrections in order to achieve even better agreement. With such corrections the largest desagreement is 2 percents.

1. INTRODUCTION

Starting from the semiclassical approach for Stark broadening parameters of neutral atom lines, in the version adapted for practical calculations by Griem, Jones and Benett (see *e.g.* Griem, 1974), Freundenstein and Cooper (1978) developed a simple approximate method for line width (w) calculation. This method has been improved and adapted as well for the shift (d) by Dimitrijević and Konjević (1986). Our objective here is to analyse the applicability of this method. Since the method has been derrived from the more sophisticated Griem's semiclassical approach, we will compare results obtained by both methods in order to see desagreements due to the additional simplifications introduced in the approach of Dimitrijević and Konjević (1986). The neutral helium lines have been choosen first of all since Stark broadening of neutral helium lines is well described within the semiclassical theory (Griem, 1974), and a comprehensive set of theoretical data checked by numerous experiments exists (see *e.g.* Griem, 1974)

2. RESULTS AND DISCUSSION

By using the methods of Freundenstein and Cooper (1978) (FC) and Dimitrijević and Konjević (1986) (DK), Stark broadening widths (w_{FC}, w_{DK}) and shifts (d_{DK}) for 12 neutral helium multiplets have been calculated at an electron density $N_e = 10^{16}$ cm^{-3} and temperatures 5000 - 40000 K.The ratios of obtained results and Griem's (1974) values (w_G, d_G) are shown in Table 1 for the width and in Table 2 for the shift. The corresponding averaged values denoted as $(...)_{av}$ are shown as well One can see in Tables 1 and 2 that the desagreements with the more sophisticated full semiclassical calculations of Griem are within 20 per cents. Since the error bars of the semiclassical method are estimated on 30 per cents (Griem, 1974), the corresponding error bars of the approach of Dimitrijević and Konjević (1986) may be estimated as 50 percents which is in accordance with the estimated error bars for the semiempirical method (see *e.g.* Griem, 1974).

TABLE 1

Ratios w_{DK}/w_G and w_{FC}/w_G for neutral helium spectral line widths (w) for an electron density of $N_e = 10^{16}$ cm^{-3}. DK - present calculations by using the method of Dimitrijević and Konjević (1986); FC - present calculations by using the method of Freundenstein and Cooper (1978); G - Griem (1974)

SINGLETS			
	T [K]	w_{DK}/w_G	w_{FC}/w_G
2s - 3p, $\lambda = 501,7$ nm	5000	1,248	2,103
	10000	1,278	1,947
	20000	1,275	1,808
	40000	1,242	1,624
2s - 4p, $\lambda = 396,5$ nm	5000	1,184	1,720
	10000	1,190	1,590
	20000	1,163	1,500
	40000	1,118	1,390
2p - 4s, $\lambda = 504,8$ nm	5000	1,038	1,000
	10000	1,148	1,110
	20000	1,178	1,140
	40000	1,121	1,090
2p - 5s, $\lambda = 443,8$ nm	5000	1,056	1,030
	10000	1,152	1,130
	20000	1,145	1,130
	40000	1,080	1,070
2p - 3d, $\lambda = 667,8$ nm	5000	1,156	2,430
	10000	1,199	2,320
	20000	1,232	2,200
	40000	1,252	1,980
2p - 4d, $\lambda = 492,2$ nm	5000	1,060	1,660
	10000	1,045	1,770
	20000	1,042	1,570
	40000	1,029	1,480
2p - 5d, $\lambda = 438,8$ nm	5000	0,996	1,400
	10000	0,984	1,330
	20000	0,976	1,280
	40000	0,965	1,220

Table 1 (continued)

TRIPLETS			
	T [K]	w_{DK}/w_G	w_{FC}/w_G
2s - 3p $\lambda = 388,9$ nm	5000 10000 20000 40000	1,529 1,526 1,470 1,384	1,910 1,930 1,790 1,640
2s - 4p $\lambda = 318,8$ nm	5000 10000 20000 40000	1,438 1,402 1,326 1,246	1,690 1,670 1,530 1,390
2s - 5p $\lambda = 294,5$ nm	5000 10000 20000 40000	1,398 1,354 1,260 1,177	
2p - 4s $\lambda = 471,3$ nm	5000 10000 20000 40000	1,000 1,009 1,185 1,165	
2p - 5s $\lambda = 412,1$ nm	5000 10000 20000 40000	1,029 1,137 1,189 1,138	

T [K]	$(w_{DK}/w_G)_{av}$	$(w_{FC}/w_G)_{av}$
5000	$1,178 \pm 0,177$	$1,660 \pm 0,664$
10000	$1,210 \pm 0,148$	$1,644 \pm 0,380$
20000	$1,204 \pm 0,122$	$1,550 \pm 0,330$
40000	$1,160 \pm 0,107$	$1,430 \pm 0,280$

TABLE 2

Ratios d_{DK}/d_G for neutral helium spectral line shifts (d) for an electron density of $N_e = 10^{16}$ cm^{-3}. DK - present calculations by using the method of Dimitrijević and Konjević (1986); G - Griem (1974)

λ (nm)	d_{DK}/d_G 5000 K	10000 K	20000 K	40000 K
501,7	0,892	0,830	0,763	0,720
396,5	1,178	0,786	0,732	0,722
504,8	1,222	1,112	0,972	0,849
443,8	1,172	1,063	0,919	0,823
667,8	0,992	0,969	0,913	0,851
492,2	0,885	0,877	0,856	0,818
438,8	0,845	0,834	0,818	0,794
388,9	1,040	0,912	0,823	0,772
318,8	1,032	0,920	0,858	0,826
294,5	0,988	0,888	0,839	0,818
471,3	1,231	1,129	1,023	0,892
412,1	1,170	1,082	0,968	0,854

$(d_{DK}/d_G)_{av}$			
5000 K	10000 K	20000 K	40000 K
1,054 ± 0,132	0,950 ± 0,114	0,873 ± 0,084	0,812 ± 0,049

The accuracy of an approximate method may be improved if we have a set of theoretical or experimental data of higher accuracy, like the Griem's (1974) semiclassical calculations in the considered case. We will take into account that the ratios of corrected values w_c, d_c and the corresponding Griem's values must be close to unity, and we will search correction functions $f_w(n,T)$ and $f_d(n,T)$ such that $w_c = f_w(n,T)w_{DK}$ and $d_c = f_d(n,T)d_{DK}$, where the principal quantum number is denoted with n The obtained corrected width is

$$w_c = \frac{aT^m + C_1 \ln T + C_2}{(w_{DK}/w_G)_m} \cdot w_{DK} \quad .$$

Since $aT^m + C_1 \ln T + C_2 \approx 1$ one can also use the approximation $f_w(n,T) \approx \frac{1}{(w_{DK}/w_G)_m}$, so we have $w_c \approx \frac{w_{DK}}{(w_{DK}/w_G)_m}$. Here $(w_{DK}/w_G)_m$ is the mean value formed by grouping results for similar transitions on the same temperature. For the shift one obtains the completely analogous expression. For width we obtain $a = 1.407$, $m =$ -0.039, $C_1 = 0.038$, and $C_2 =$ -0.330 and for shift $a = 3.88$, $m =$ -0.139, $C_1 = 0.145$ and $C_2 =$ -1.419.

TABLE 3
Ratio of our corrected (w_c) and Griem's (w_G) width values at different temperatures for He I spectral lines ($N_e = 10^{16}$ cm^{-3}).

λ	w_c/w_G			
(nm)	5000 K	10000 K	20000 K	40000 K
501,7	1,042	1,078	1,057	1,029
396,5	0,990	1,004	0,964	0,928
504,8	1,008	0,969	0,978	0,930
443,8	1,026	0,973	0,950	1,054
667,8	0,967	1,010	1,020	1,038
492,2	1,030	1,005	1,032	1,000
438,8	0,967	0,946	0,966	0,942
388,9	1,049	1,063	1,042	1,145
318,8	0,987	0,979	0,947	1,033
294,5	0,960	0,945	1,046	0,976
471,3	0,971	1,056	0,982	0,967
412,1	1,000	0,958	0,987	0,944

$(w_c/w_G)_{av}$			
5000 K	10000 K	20000 K	40000 K
0,999 ± 0,103	0,999 ± 0,040	0,998 ± 0,038	0,999 ± 0,060

TABLE 4
Ratio of our corrected (d_c) and Griem's (d_G) shift values at different temperatures for He I spectral lines ($N_e = 10^{16}$ cm^{-3}).

λ (nm)	d_c/d_G 5000 K	10000 K	20000 K	40000 K
501,7	1,024	0,980	0,868	0,892
396,5	0,712	0,926	0,834	0,902
504,8	1,026	0,986	1,108	1,052
443,8	0,984	1,068	1,047	1,020
667,8	0,982	0,974	1,041	1,049
492,2	1,020	1,035	0,976	1,014
438,8	0,968	0,984	0,933	0,984
388,9	1,027	0,916	0,935	0,970
318,8	1,018	0,926	0,977	1,029
294,5	0,979	1,048	0,958	1,012
471,3	1,035	1,002	1,164	1,104
412,1	0,983	1,087	1,103	1,058

$(d_c/d_G)_{av}$ 5000 K	10000 K	20000 K	40000 K
0,980 ± 0,084	0,994 ± 0,053	1,000 ± 0,100	1,007 ± 0,060

In tables 3 and 4, ratios of corrected values for widths and shifts and the corresponding Griem's values are shown, as well as the averaged values. One can see that the largest desagreement now is 2 per cents.

References

Dimitrijević, M. S., Konjević, N. : 1986, *Astron. Astrophys.* **163**, 297.
Freundenstein, S. A., Cooper, J. : 1978, *Astrophys. J.* **224**, 1079.
Griem, H. R. : 1974, Spectral Line Broadenintg by Plasmas, Academic Press, New York.

Publ. Obs. Astron. Belgrade No. 50 (1995), 61 – 64

STARK WIDTHS OF ArIII SPECTRAL LINES FROM 4s' – 4p' TRANSITION

S. DJENIŽE, S. BUKVIĆ, A. SREĆKOVIĆ and M. PLATIŠA
Faculty of Physics, University of Belgrade,
P.O.B.368 11001 Belgrade, Serbia, Yugoslavia

Abstract. Stark widths of three ArIII spectral lines that belong to $4s' - 4p'$ transition have been measured at the electron density of $3.5 \cdot 10^{23} m^{-3}$ and electron temperature of 38 000 K in a pulsed linear arc discharge in argon plasma . The measured values were compared to existing theoretical data calculated on the basis of various approaches.

1. INTRODUCTION

Knowledge of the Ar III spectral line charecteristics is important for the determination of chemical abundances of elements and for the estimation of the radiative transfer through the stellar plasmas as well as for opacity calculalations (Iglesias *et al.*, 1990). A number of experimental and theoretical papers have dealt with Stark broadening of ArIII spectral lines (Fuhr and Lesage, 1993). However, only 16 spectral lines from five multiplets (Platiša *et al.*, 1975; Konjević and Pittman, 1987; Purić *et al.*, 1988; Kobilarov and Konjević, 1990) and 6 lines from 1(UV) multiplet (Baker and Burgess, 1979) have been investigated. Only two papers (Platiša *et al.*, 1975; Konjević and Pittman, 1987) are devoted to the experimental investigation of the ArIII spectral lines from the $4s' - 4p'$ ($^3D^0 -^3 F$) transition.In both of them Stark widths were measured in plasma with electron temperature up to 26 000 K.

In this work we present measured Stark FWHM (full width at half maximum intensity) (w) values of three Ar III spectral lines originating from $4s' - 4p'$ transition (Mult.No.3) at 38 000 K electron temperature. The measured values of Stark widths were compared with existing theoretical predictions based on various theoretical approximations calculated by Dimitrijević and Konjević (1981).

2. EXPERIMENT

The linear pulsed arc,that was used as a plasma source,has been described in detail in our previous publication (Djeniže *et al.*, 1991), so only a few details will be given here. A pulsed discharge occured in a Pyrex discharge tube of 5 mm i.d. and had an effective plasma length of 5.8 cm. The tube had quartz windows. The working gas was argon-helium mixture (Ar72+He28%) at 130 Pa filling pressure in flowing regime. Spectroscopic observation of isolated spectral lines were made end-on along the axis of the discharge tube. A capacitor of 8.0 μF was charged up to 5.2 kV and supplied discharge current up to 6.6 kA. From the coil Rogovski signal follows that the discharge duration is 30 μs. The line profiles were recorded by a shot-by-shot technique using photomultiplier(EMI 9789 QB)-spectrograph (Zeiss PGS-2, inverse linear dispersion 0.73 nm/mm in the first order) combination. The exit slit of the spectrograph with the calibrated photomultiplier was micrometrically traversed along the spectral plane in small (0.0073 nm) wavelength steps. The photomultiplier signal was digitized using HAMEG 205-2 digital scope interfaced to a computer.A sample output, as an example, is shown in Fig.1.

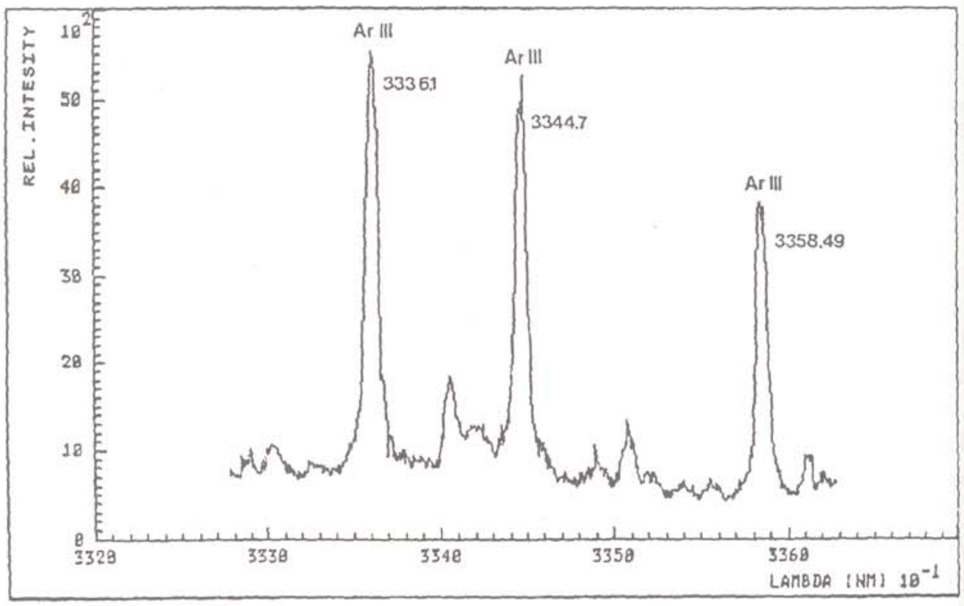

Fig. 1. The recorded spectrum at 15 μs after the beginning of the discharge with the investigated ArIII spectral lines.

Plasma reproducibility was monitored by the ArIII line radiation and also by the discharge current (it was found to be within $\pm 6\%$). The measured profiles were of the Voigt type due to the convolution of the Lorentzian Stark and Gaussian profiles caused by Doppler and instrumental broadening. Van der Waals and resonance broadening are estimated to be smaller by more than an order of magnitude in comparison to Stark,Doppler and instrumental broadening. A standard deconvolution procedure (Davies and Vaughan, 1963) was used. The deconvolution procedure was computerized using the least square algoritm . Great care was taken to minimize the influence of self-absorption on Stark width determination. The opacity has been checked by measuring line - intensity ratios within multiplets (No.3). The values obtained were compared with calculated ratios of the products of the spontaneous emission probabilities and the corresponding statistical weigths of the upper levels of the lines (Wiese *et al.*, 1969). These ratios were found to differ by less than $\pm 12\%$. The Stark width data were determined with an error of ±15% The plasma parameters were determined using standard diagnostic methods. So, the electron temperature (T) decay was determined from the Boltzmann slope of nine ArIII lines (330.2, 328.6, 349. 97, 350.4, 348.6, 335.8, 334.5, 333.6, 302.4 nm with a corresponding upper level energy interval of 4.8 eV), with an estimated error of ±13%. All the atomic parameters that were necessary were taken from Wiese *et al.* (1969). Electron density (N) decay was measured using a single wavelength He-Ne laser interferometer (Aschby *et al.*, 1965) for the 632.8 nm transition with an estimated error of ±6%.

3. RESULTS AND DISCUSSION

The measured Stark FWHM (w_m) values are presented in Table 1 at given electron temperature (T in 10^4 K) and density (N in $10^{23}\mathrm{m}^{-3}$). In the same Table we give, also, values w_m/w_{th}, where w_{th} are the Stark FWHM values calculated on the basis of various theoretical calculations performed by Dimitrijević and Konjević (1981). w_{SE} and w_{SEM} denote semiempirical and modified semiempirical results,respectively and w_G and w_{GM} denote values obtained on the basis of the semiclassical (Griem, 1974) approximation.

Table 1 Measured Stark FWHM values

λ (Å)	Transition	T	N	w_m (Å)	$\frac{w_m}{w_G}$	$\frac{w_m}{w_{GM}}$	$\frac{w_m}{w_{SE}}$	$\frac{w_m}{w_{SEM}}$
3336.1	4s' - 4p'	3.8	3.5	0.56	0.99	1.31	2.35	1.44
3344.7	4s' - 4p'	3.8	3.5	0.54	0.95	1.26	2.27	1.39
3358.5	4s' - 4p'	3.8	3.5	0.46	0.81	1.07	1.93	1.18

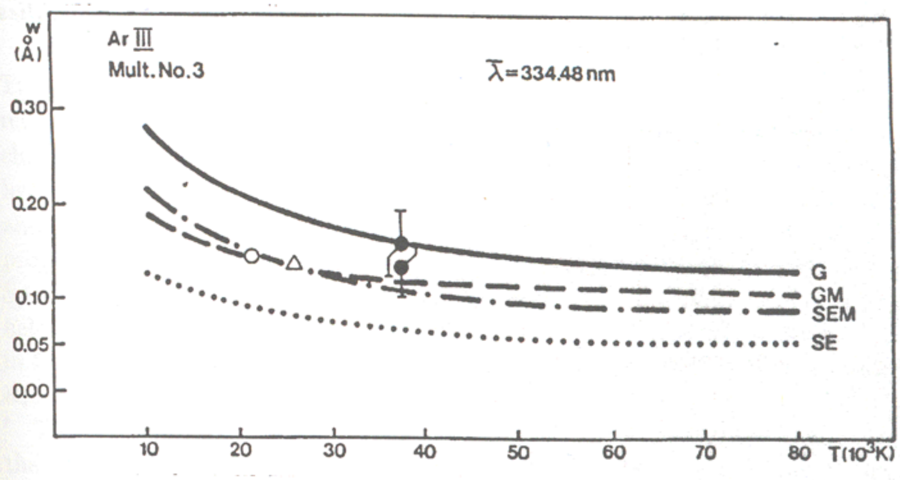

Fig. 2. Stark FWHM dependence on the electron temperature.

The theoretical Stark FWHM (w_{th}) dependence on the electron temperature together with the values of other authors (∘, Platiša *et al.*, 1975; Δ, Konjević and Pittman, 1987) and our experimental results (•) at the electron density $N = 1 \cdot 10^{23} m^{-3}$ are presented graphically in Fig.2. $\overline{\lambda}$ is the average wavelength in the multiplet. The error bars include the uncertainties of the width and electron density measurements.

We can conclude that our experimental w_m values well agree, within experimental accuracy, with theoretical predictions (w_G and w_{GM}) based on the semiclassical approximation. The average ratio w_m/w_{SEM}=1.34 (three measurements) shows, also, acceptably agreement between w_m and w_{SEM} values at 38 000 K electron temperature while w_{SE} values are lower than our w_m data up to the factor 2.2 .

References

Aschby, D. E. T. F., Jephcott, D. F., Malein, A. and Ragnev, F. A. : 1965, *Appl. Phys.* **36**, 29.

Baker, E. A. M. and Burgess, D. D. : 1979, *J. Phys.* B **12**, 2097.

Davies, J. T. and Vaughan, J. M. : 1963, *Astrophys. J.* **137**, 1302.

Dimitrijević, M. S. and Konjević, N. : 1981, *Spectral Line Shapes* ed B.Wende (Berlin, de Gruyter) p. 211.

Djeniže, S., Srećković, A., Labat, J., Konjević, R. and Popović, L. : 1991, *Phys. Rev.* A **44**, 410.

Fuhr, J. R. and Lesage, A. : 1993, *Bibliography on Atomic Line Shapes and Shifts* (July 1978 through March 1992) NIST Special Publication 366 Supplement 4 US : DC National Institute of Standards and Technology.

Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, (New York : Academic Press).

Iglesias, C. A., Rogers, F. J. and Wilson, B. G. : 1990, *Astrophys. J.* **360**, 221.

Kobilarov, R. and Konjević, N. : 1990, *Phys. Rev.* A **41**, 6023.

Konjević, N. and Pittman, T. L. : 1987, *J. Quant Spectrosc. Radiat. Transfer*, **37**, 311.

Platiša, M., Popović, M., Dimitrijević, M. and Konjević, N. : 1975, *Z. Naturf.* **30A**, 212.

Purić, J., Djeniže, S., Srećković, A., Labat, J. and Platiša, M. : 1988, *Z. Phys.* D **8** 343.

Wiese, W. L., Smith, M. W. and Miles, B. M. : 1969, *Atomic Transition Probabilities*, NSRDS-NBS22 vol 2 (Washington, DC : US Govt Printing Office).

Publ. Obs. Astron. Belgrade No. 50 (1995), 65 – 68

THE H_β ASYMMETRY IN THE PRESENCE OF A DC MAGNETIC FIELD

S. DJUROVIĆ, Z. MIJATOVIĆ, M. PAVLOV, B. VUJIČIĆ,
R. KOBILAROV and D. NIKOLIĆ
*Institute of Physics, Faculty of Science, University of Novi Sad,
Trg Dositeja Obradovića 4, 21000 Novi Sad, Yugoslavia*

1. INTRODUCTION

It is well known that H_β spectral line emited from plasmas is asymmetric and red shifted. Theoretical calculations of hydrogen line profiles (Keple and Griem, 1968; Vidal *et al.*, 1973) give symmetrical and unshifted profiles. However, many experiments have shown that H_β line has asymmetrical profile, especially in the intensity difference between blue and red peaks (Helbig and Nick, 1981; Mijatović *et al.*, 1987, Halenka, 1988). The asymmetry results from inhomogeneities of the ion produced electric field (ion - atom quadrupole interactions) and from non-negligible second order alterations arising from the homogeneous term of the ionic field (Halenka *et al.*, 1989).

Here we present experimental results of the H_β asymmetry in presence of the low DC magnetic field. The results are compared with our measurements obtained in absence of the magnetic field.

2. EXPERIMENT

The plasma source was a small magnetically driven shock tube of T-shape with a reflector. The tube was energized by a $1\mu F$ capacitor bank. The capacitor bank was charged to 20 kV. The discharge circuit was critically damped. The filling gas was hydrogen at a pressure of 300 Pa. Magnetic field was produced by an electromagnet and was perpendicular to the T-tube axis that is to the direction of the shock front propagation. The magnetic line density between poles measured in a free air was 0.5 T. Spectroscopic plasma observations were made by 1m monochromator along magnetic field through a hole in an electromagnet pole. The point of observation was 15 mm in front of the reflector. The photomultiplier signals were recorded by an oscilloscope equipped with a 35 mm camera.

The H_β profiles were scanned at close intervals by using successive discharges over the wavelength range $\pm$ 30 nm from the line center. Electron densities in range from $2 \times 10^{23} m^{-3}$ to $8 \times 10^{23} m^{-3}$ were determined from the H_β line halfwidth (Vidal *et al.*, 1973). Electron temperatures in range from 19000 K to 27000 K were determined from the line-to-continuum intensity ratios of the H_β line (Griem, 1964).

3. RESULTS AND CONCLUSIONS

In this paper we analized asymmetry of the whole H_β profile in such a way as is illustrated in Fig. 1. We measured the center of the line on 0.8, 0.6, 0.5, 0.4, 0.2 and 0.1 of the maximum H_β profile (I/I_{max}). Line drawn through obtained central points is not straight line. This line illustrates the asymmetry of the H_β profile.

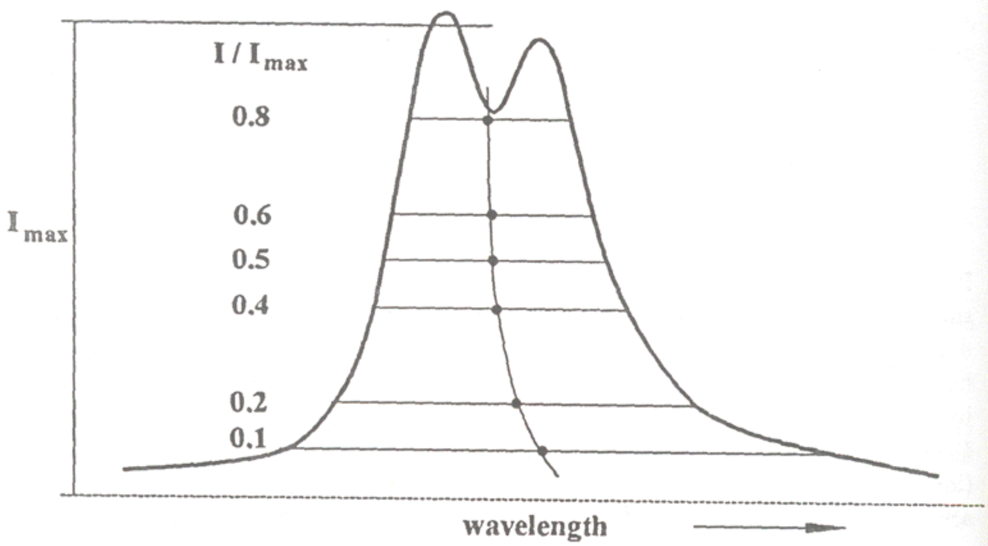

Fig. 1.

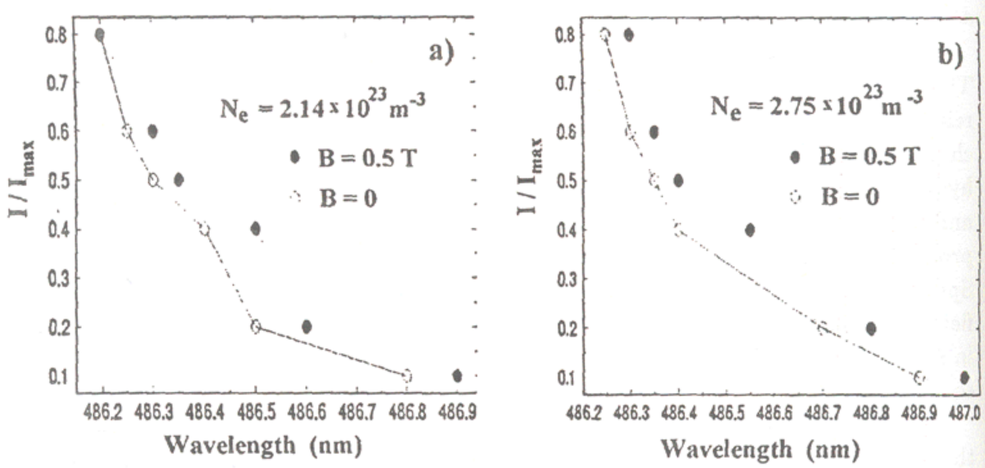

Fig. 2.

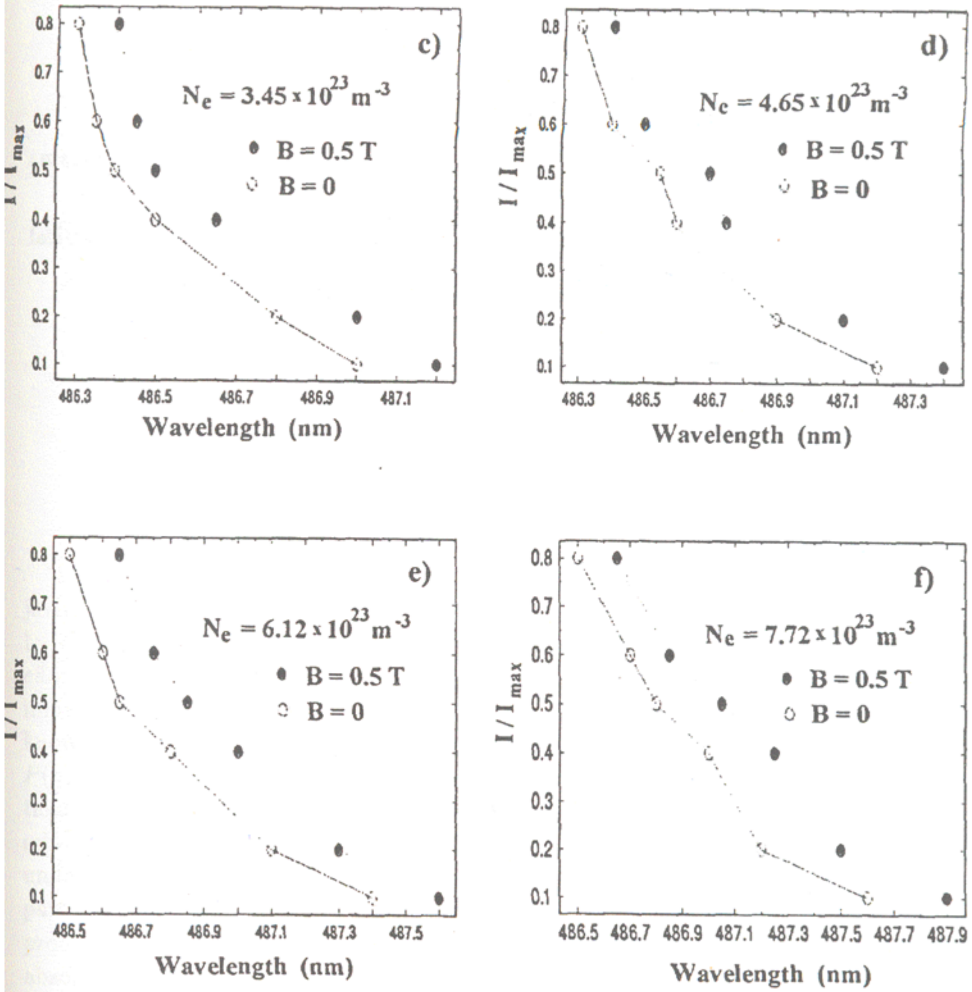

Fig. 2. continued.

The H_β spectral line asymmetry obtained by above described procedure in the presence and in the absence of a magnetic field are shown in Fig. 2(a-f). The open circles represent asymmetry in the absence of a magnetic field, while full circles represent asymmetry in the presence of a magnetic field.

One can notice that the line asymmetries with and without magnetic field behave in the same manner, so one can conclude that the presence of the low DC magnetic field has no influence on asymmetry of the H_β profile. The magnetic field causes only a small additional red shift of the whole H_β profile as much as the asymmetry lines with and without magnetic field are shifted one relative to the other. It is in agreement with our previous results (Pavlov *et al.*, 1988; Mijatović *et al.*, 1995) where we found small additional shift of H_β profile, in the presence of a magnetic field, measured in halfwidth position.

References

Griem, H. R. : 1964, *Plasma Spectroscopy*, McGraw-Hill, New York.
Halenka, J. : 1988, *J. Q. S. R. T.* **39**, 347.
Halenka, J., Vujičić, B., Djurović, S. : 1989, *J. Q. S. R. T.* **42**, 571.
Helbig, V., Nick, K. P. : 1981, *J. Phys.* B **14**, 3573.
Keple, P., Griem, H. R. : 1968, *Phys. Rev.* **173**, 317.
Mijatović, Z., Djurović, S., Pavlov, M., Kobilarov, R., Vujičić, B. T. : 1995, *Contrib. Plasma Phys. Spec. Iss.* (in press).
Mijatović, Z., Pavlov, M., Djurović, S. : 1987, *J. Q. S. R. T.* **38**, 209.
Pavlov, M., Mijatović, Z., Djurović, S. : 1988, *Contributed papers of SPIG'88*, Electrical Engineering Faculty, Sarajevo, p. 337.
Vidal, C. R., Cooper, J., Smith, E. W. : 1973, *Astrophys. J. Suppl. Ser.* **25**, 37.

Publ. Obs. Astron. Belgrade No. 50 (1995), 69 – 71

THE INTERDEPENDENCE BETWEEN THE PARAMETERS OF STARK BROADENING AND ASYMMETRY OF SELF-REVERSED SPECTRAL LINES WITH THE QUADRATIC STARK EFFECT

I. S. FISHMAN, G. G. IL'IN, O. A. KONOVALOVA,
E. V. SARANDAEV and M. Kh. SALAKHOV
Department of Physics, Kazan State University Kazan 420008, Tatarstan, Russia

There is ample literature (see for example Griem, 1964; Griem, 1974; Dimitrijević, 1991) on the theoretical and experimental investigations of Stark broadening by charged particles (electrons and ions) of spectral lines with the quadratic Stark effect. The important parameters are here the electron impact half-width d, electron impact shift h or shift parameter $t = h/d$ and ionic broadening parameter A. The knowledge of these parameters gives the possibility to construct the broadening profile $P(v)$ normalized to unit area over a frequency scale v. The experimental investigations of $P(v)$ profiles are carried out ordinarily by using spectral lines free from the self-absorption. It is often difficult to get spectral lines free from the self-absorption under the conditions of dense plasmas with the predominant broadening by charged particles (the plasmas of pulsing discharges, exploding wires, sparks, plasma jets, laser produced plasmas etc.). The atom resonace spectral lines tend particularly to the self-absorption. The self-absorption causes here usually the formation of strongly asymmetric self-reversed spectral lines. The theoretical and experimental investigations of asymmetric self-reversed lines carried out by us (Fishman *et al.*, 1981; Salakhov *et al.*, 1981; Fishman *et al.*, 1991) show that the interesting information about Stark broadening parameters may be received by the parameters of self-reversed lines.

The theoretical analysis of self-reversed profiles has been carried out on the basis of computer calculation of an emission transfer equation for different lines of sight of strongly inhomogeneous axially symmetric plasma described in Il'in *et al.* (1976). The source function $f(r)$ (r is the geometric coordinate) characterizing the relative distribution of emission atoms concentration relative to distribution of absorption atoms concentration was set at $0 < r < D$ (D is radius of emission zone) as

$$f(r) = f(0)[1 - F(r)]$$

where $F(r)$ is r/D to power m (m is the inhomogeneity parameter) and $f(r) = 0$ at $r > D$. The radial concentration variation of absorption atoms $n(r)$ on the lower level of spectral transition was set as

$$n(r) = n(0)[1 + agG(r)]\exp(-gG(r))$$

where $G(r)$ is r/D to power 2 (a and g are the parameters). The local broadening profile $P(v,r)$ was represented in terms of Stark profile $j(x, A(r), R)$ (Griem, 1974) (x is related with v; R is the Debay shielding parameter) with the electron impact half-width

$$d(r) = d(0)\exp(-bG(r))$$

at $0 < r < D$ and

$$d(r) = d(0)\exp(-b)$$

at $r > D$ (b is the parameter) and electron impact shift $h(r) = td(r)$. For the computer calculation of emission transfer equation the central part of the profile $j(x, A(r), R)$ given in tabulated form in Griem (1974) was represented in accordance with Preobrazhenskii (1971) in form of two Student distributions with different parameters dependent on the local ionic broadening parameter

$$A(r) = A(0)q(r)$$

where $q(r)$ is $d(r)/d(0)$ to power 1/4 as a first approximation. For the wings of the profile $j(x, A(r), R)$ the asymptotic formulae (Griem, 1974) are used. The procedure of $P(v)$ construction is described in detail in Il'in and Konovalova (1995).

The calculated data have permitted to investigate in detail the influence of the parameters m, a, g, b, t, $A(0)$, R and the value of absorption (through the absorption parameter p) on the principal parameters of asymmetry of self-reversed lines - the ratio of intensity I_1/I_2 (I_1 is the maximal intensity of big intensity peak; I_2 is the maximal intensity of small intensity peak) and the wings asymmetry parameter

$$w = \frac{u_1 - u_2}{d(0)}$$

(u_1 and u_2 are the wing extents at a certain intensity height calculated from the unperturbed frequency V in the direction of big and small intensity peaks respectively). With the increase of p the ratio I_1/I_2 for the central line of sight in the plasma cross-section passes through the maximum (for the comparison of experimental and calculated data the graphs of dependence I_1/I_2 on $2s = M/d(0)$ are very useful where M is the distance between maxima of intensity). The main influence on I_1/I_2 the parameters t, a and g give : At $t = 1$, $a = 2$ and $g = 0.83$ (the main part of absorption atoms placed in the emission zone) $I_1/I_2 = 1.5 - 2.0$. At $t = 1$, $a = 30$ and g=0.1 (the main part of absorption atoms placed out of the emission zone) I_1/I_2=3.0-4.0. The parameter w is sensible mainly to the Stark broadening paramerters t and $A(0)$ and may be calculated by the equation $w = 1.55|t| + 6.4 \cdot A(0)$ (Fishman *et al.*, 1991) as a first approximation. This circumstance gives the possibility simple enough to determine $d(0)$ and then the plasma electron concentration by the measured u_1 and u_2.

For the comparison of experimental and calculated data the *Al I* 394.4 nm and *Al I* 396.1 nm resonance lines for which the Stark broadening parameters are given in Griem (1974) are convenient. In accordance with Griem (1974) for these lines we have t=-(1.0-1.2) in the frequency scale and $A(0)$=0.1 under the conditions of low-voltage pulse discharges (Fishman *et al.*, 1981; Sarandaev *et al.*, 1988). For the experimental self-reversed profiles I_1/I_2=3.5-4.0, $u_1 - u_2$=(0.14-0.2) nm in the wavelength scale. These values of $u_1 - u_2$ give the electron concentration values differing by no more than (10-15) % of the electron concentration values obtained by the H_α line of hydrogen. The large experimental values of I_1/I_2, on the one hand, show on the big a and small g for aluminium atoms (such $n(r)$ distribution is confirmed by absorption spectra (Fishman *et al.*, 1991)) and, on the other hand, show on the large value of t of the order of 1. These results confirme for the given resonance aluminium lines the theoretical values of t, A and d (Griem, 1974).

The interesting results have been obtained for the *Cu* I 324.7 nm and *Cu* I 327.4 nm resonance self-reversed lines. For these lines there are no data in literature about the shift parameter t. The small values of $u_1 - u_2$= (0.02-0.04) nm under the conditions of low-voltage pulse discharge (Sarandaev *et al.*, 1988) show that the *Cu* I 324.7 nm and *Cu* I 327.4 nm lines have a small Stark shift (t no more than 0.1-0.2). The small shift of copper resonance lines is well in accord with the small theoretical Stark shift of *Cu* I 510.5 nm, *Cu* I 570 nm and *Cu* I 578.2 nm lines (Konjević and Konjević, 1986).

These examples show that the asymmetry of self-reversed spectral lines may be used both for the test of theoretical Stark broadening parameters and for the estimation of Stark shift of spectral lines for which there are no data in literature.

References

Dimitrijević, M. S. : 1991, *Publ. Obs. Astron. Belgrade*, **41**, pp. 1-129.

Griem, H. R. : 1964, *Plasma Spectroscopy*, Mc Graw-Hill, New York.

Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic Press, New York and London.

Fishman, I. S., Salakhov, M. Kh., Sarandaev, E. V. and Semin, P. S. : 1981, *Opt. Spectrosc.* **51**, 785.

Fishman, I. S., Il'in, G. G. and Salakhov, M. Kh. : 1991, *XX ICPIG*, Piza, Italy, Contr. Papers 3, 809.

Il'in, G. G. and Konovalova, O. A. : 1995, *Dep. VINITI*, N 804-B95.

Il'in, G. G., Salakhov, M. Kh. and Fishman, I. S. : 1976, *Z. Prikl. Spectrosc.* **24**, 201.

Konjević, R. and Konjević, N. : 1986, *Fizika*, **18**, 327.

Preobrazhenskii, N. G. : 1971, *Spectroscopy of an Optically Thick Plasma*, Nauka, Novosibirsk.

Salakhov, M. Kh., Fishman, I. S., Semin, P. S. and Sarandaev, E. V. : 1981, *Izvestija Vuzov Fiz.* **7**, 11.

Sarandaev, E. V., Salakhov, M. Kh., Fishman, I. S. : 1988, *Z. Prikl. Spectrosc.* **48**, 513.

Publ. Obs. Astron. Belgrade No. 50 (1995), 73 – 74

REGULARITIES IN THE STARK PARAMETERS OF SPECTRAL LINES OF SINGLY IONIZED ALUMINUM

I. S. FISHMAN, M. Kh. SALAKHOV, and E. V. SARANDAEV
Department of Physics, Kazan State University, 420008 Kazan, Tatarstan, RUSSIA

In a series of experimental and theoretical papers (Konjević and Wiese, 1976; Konjević *et al.*, 1984; Konjević and Wiese 1990) the Stark parameters of spectral lines of singly ionized aluminum were studied. Experimental data for some lines obtained by different authors differ considerably from each other. Determination of regularities in the behaviour of the Stark parameters of spectral lines is one of the ways to estimate the reliability of experimental and theoretical data.

In this paper based on the approach we proposed for finding these regularities (Sarandaev *et al.*, 1991; Salakhov *et al.*, 1991), the dependencies allowing one to analyze experimental and theoretical data for Al II and to estimate Stark widths and shifts of the Al II lines, which are neither calculated theoretically nor measured experimentally, are obtained.

The main point of the proposed approach is based on determining regularities for energy levels rather than for lines assuming that the following relations hold with the accuracy to the interference terms :

$$w = dE(q_2) - dE(q_1) \tag{1}$$

$$d = dd(q_2) - dd(q_1), \tag{2}$$

where w and d are the line width and shift, respectively, $dE(q_2)$, $dE(q_1)$, $dd(q_2)$ and $dd(q_1)$ are the widths and shifts of the upper and lower levels, respectively, in frequency units. These dependencies were approximated as follows :

$$\lg(dE) = a \cdot \lg(n) + \lg(A) \tag{3}$$

$$\lg(dd) = b \cdot \lg(n) + \lg(B) \tag{4}$$

where n is the effective principal quantum number of the level. A, a, B and b are constants independent of n.

These dependencies as well as those established for other atoms and ions are obtained based on semiclassical calculations of (Griem, 1974), where the widths and shifts of 15 Al II spectral lines are given. The dependence obtained for the widths of levels was approximated by the relation :

$$\lg(dE) = 4.68 \cdot \lg(n) + 9.11 \quad (5)$$

The values of the widths of levels are well described by a straight line : the correlation coefficient is not less than 0.99. The comparison of the line widths obtained using (1) and (5) with the values of the initial semiclassical calculations (Griem, 1974) shows that the discrepancy does not exceed 30%.

We have also compared our estimates with the literature experimental data on the Al II line widths. For example, for three lines Al II 390 nm, Al II 263.1 nm and Al II 559.3 nm our estimates agree with experiment (Colon *et al.*, 1993). For other lines the experimental values are 2-3 times higher than our estimates. We give possible reason for this discrepancy.

The dependence obtained for the shifts of levels was approximated by the relation :

$$\lg(dd) = 4.13 \cdot \lg(n) + 9.53 \quad (6)$$

The values of the shifts of levels are well described by a straight line : $R = 0.986$. The comparison of the line shifts obtained using (2) and (6) with the values of the initial semiclassical calculations (Griem, 1974) shows that the discrepancy does not exceed 25%.

References

Colon, C., Hatem, G., Verdugo, E., Ruiz, P. and Campos, J. : 1993, *J. Appl. Phys.* **73**, 4752.

Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic Press, New york and London, p. 491.

Konjević, N., Dimitrijević, M. S. and Wiese, W. L. : 1984, *J. Phys. Chem. Ref. Data.* **13**, 649.

Konjević, N. and Wiese, W. L. : 1976, *J. Phys. Chem. Ref. Data.* **5**, 259.

Konjević, N. and Wiese, W. L. : 1990, *J. Phys. Chem. Ref. Data.* **19**, 1307.

Salakhov, M. Kh., Sarandaev, E. V., Fishman, I. S. : 1991, *Opt. Spectr.* **71**, 882.

Sarandaev, E. V., Fishman, I. S. and Salakhov, M. Kh. : 1991, *XX Inter. Conf. Phenom. Ion. Gases. Piza*, Italy, P. 115.

Publ. Obs. Astron. Belgrade No. 50 (1995), 75 – 80

FOURIER ANALYSIS OF ROTATIONALLY BROADENED STELLAR SPECTRA

SLOBODAN JANKOV

Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E–mail sjankov@aob.aob.bg.ac.yu

Abstract. A complex combination of physical processes affecting mainly the *shape* of a spectral line formed in stellar atmosphere can be better distinguished at low Fourier frequiencies than in the profile itself. Considering the analysis of stellar rotationally broadened line as a typical example of those astrophysical problems where it is more advantageous to use the Fourier transform of the profile, we present a method for determination of stellar projected rotational velocity and limb-darkening coefficient.

1. INTRODUCTION

In the past the use of the Fourier transform for spectral line shape analysis has centered around several active areas as microturbulence and macroturbulence in stellar atmospheres, stellar rotation, the detection of Zeeman splitting and global velocity fields in stellar atmospheres (Smith and Gray, 1976).

Many types of line broadening functions involving different kinds of processes, especially those occuring on a macroscopic scale due to collective motions, are quite different from one another. These differences may be greately smoothed when convolution is performed. A theoretical profile may appear to reproduce an observed profile fairly well, when in fact, there are small but systematic differences extending over the profile. Often only subtle variations in the shape of the core and far wings of the broadened profile can give clues to the mechanism. The power of the Fourier technique rests on the fact that subtle but systematic variations of the line profile show up as significant and easily identifiable signatures in the amplitudes of certain Fourier components. The Fourier analysis provides a sensitive way to use all of the information contained in the shape of a line profile to estimate the contributions of various types of velocity fields.

The Fourier transform analysis is most effective when broadening mechanisms in the stellar atmosphere affect the detailed *shape* of the observed flux profile. However it is not such a powerful tool for analysis of physical processes related to *global* parameters of the profile as it is, for example, the relation of chemical composition to the equivalent width of the profile.

2. ROTATIONAL BROADENING

Rotation is the dominate line broadening mechanism in a large number of stars. Let us consider the star rotating with the equatorial velocity V_e, inclined by the angle i. Under the condition that the shape of intrinsic spectrum does not depend significantly on the position on a stellar surface, the observed normalized profile is given by the relation (Gray, 1976) :

$$R(t) = \int_{-1}^{1} H(t-y)G(y)\mathrm{d}y, \tag{1}$$

where $H(\lambda)$ is the normalized intrinsic spectrum as it would be observed on the apparent disc of the star,

$$y = \frac{\lambda - \lambda_0}{\Delta\lambda_\mathrm{D}} \qquad ; \qquad \Delta\lambda_\mathrm{D} = \frac{\lambda_0}{c} V_\mathrm{e} \sin i,$$

and the rotational profile $G(y)$ is defined by

$$G(y) = \frac{\int\limits_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} I_\mathrm{c}'(M, \lambda_0)\mathrm{d}z}{\int\limits_{-1}^{1} \mathrm{d}y \int\limits_{-\sqrt{1-y^2}}^{\sqrt{1-y^2}} I_\mathrm{c}'(M, \lambda_0)\mathrm{d}z},$$

with the axis y, chosen to be oriented in the direction of the spectrum dispersion and axis z chosen to be oriented in the direction of the projection of stellar rotational axis on to the tangent plane. The emergent intensity in the continuum $I_\mathrm{c}'(M, \lambda_0)$ corresponds to the area defined by angle Θ between the line of sight and the outward normal at the point M.

By assuming a limb darkening law for the continuum intensity distribution on the apparent disc of the star in form of :

$$I_\mathrm{c}'(M, \lambda_0) = I_\mathrm{c}(\lambda_0)[1 - \varepsilon + \varepsilon \cos\Theta],$$

for the star with uniform surface intensity distribution $I_\mathrm{c}(\lambda_0) = \mathrm{const.}$, the observed spectrum of the rotating star can be represented as a convolution of the intrinsic spectrum of a nonrotating star and the rotational profile defined as :

$$G(y) = \begin{cases} \frac{2(1-\varepsilon)}{\pi(1-\varepsilon/3)}\sqrt{1-y^2} + \frac{\varepsilon}{2(1-\varepsilon/3)}(1-y^2) & y < 1 \\ 0 & y \geq 1 \end{cases}, \tag{2}$$

where limb darkening coefficient ε, as a slowly varying function of λ is considered constant over the line profile.

3. FOURIER ANALYSIS

The mathematical treatment of the problem can be simplified by introducing for a given distribution $F(\lambda)$ of the space coordinate λ its Fourier transform $f(\omega)$ of spatial frequency (radians/length) ω defined as :

$$f(\omega) = N^{-1} \sum_{\lambda} F(\lambda) \exp\left(-\imath \omega \lambda \frac{2\pi}{N}\right)$$

where $\imath$ denotes the imaginary unity and N is the number of measurements.

For the Fourier transform pairs $R(\lambda), r(\omega)$; $H(\lambda), h(\omega)$ and $G(\lambda), g(\omega)$ the relation (1) can be expressed in the Fourier domain :

$$r(\omega) = h(\omega) \cdot g(\omega)$$

This conversion of convolutions of functions in the wavelength domain to their products in the Fourier domain is the most obvious reason for the choice of Fourier domain for analysis of stellar spectra, since in many cases the broadening of a spectral line can be adequately represented by some unbroadened intrinsic profile convolved with a function which depends on a geometry of the motions involved.

Further, the Fourier transform of an absolutely integrable function is known to tend to zero as $\omega \to \infty$ and the smoother the function $R(\lambda)$ the faster its Fourier transform falls. The convolution itself acts as a low-pass filter that eliminates all frequencies beyond some truncation frequency. It means that the essential information about the shape of the spectral line is described by the components at lower frequencies. In contrast, noise is distributed over all Fourier frequencies providing that the low frequency Fourier components are less affected by the noise than data in original domain.

As a consequence, many physical functions have characteristic signatures in their transforms showing up as rather large amplitude differences in Fourier domain comparing with shape differences that are often difficult to detect in original domain.

The finite extension of the rotational profile (2) implies that $g(\omega)$ has zero amplitude at certain Fourier frequencies ω_i. Table I list the positions of the first (s_1), second (s_2) and third (s_3) zero of the rotational profile, where $s_i = \Delta\lambda_D \omega_i$. Important property is that the multiplication of $g(\omega)$ by the transform of $H(\lambda)$ will not change the positions of zeros s_1, s_2, ..., so the method is applicable for all stars where the dominant broadening mechanisms act as a convolution with the rotational velocity field.

Since $G(\lambda)$ scales with $V_e \sin i$ (through y) and ε, it is assumed that only two parameters need to be measured. In fact one needs to determine only the positions of two zeros of the Fourier transform of the roational profile in order to determine the projected rotational velocity and limb-darkening coefficient. However the position of the third zero should be also used to estimate the error bars on two parameters, providing the information if the real star under investigation, conforms to our model. This is true for all broadening mechamisms at microscopic level, microturbulence and the isotropic macroturbulence that is usually assumed to take the form of convolution with a Gaussian broadening function.

TABLE I
Zeros of Fourier amplitude of rotation profile in function of limb darkening coefficient

ε	s_1	s_2	s_3
0.0	0.609	1.116	1.618
0.1	0.616	1.121	1.623
0.2	0.623	1.127	1.628
0.3	0.631	1.134	1.634
0.4	0.640	1.142	1.642
0.5	0.649	1.151	1.650
0.6	0.660	1.162	1.661
0.7	0.672	1.175	1.674
0.8	0.685	1.190	1.690
0.9	0.700	1.208	1.711
1.0	0.716	1.230	1.736

Note that the microturbulence can produce a sidelobe structure as well as a characteristic structure of rotation, however the additional zeros of the Fourier transform introduced by microturbulence does not affect the position of zeros of the rotational profile.

Concerning the accuracy of resulting estimates for $V_e \sin i$ and ε, in addition to limb angle dependence of line profile and departures from linear model, one should also be concerned with the existence of global velocity fields. The relevance of these problems to rotating line profiles has been investigated in Jankov, Unruh, Collier-Cameron (1995).

Center-to-limb variation of the intrinsic profile has been analysed calculating specific intensity profiles for different limb angles on the stellar disc. Figure 1. shows the resulting profiles with and without limb angle dependence of the intinsic profile and resulting estimates for a star with $V_e \sin i = 91\text{kms}^{-1}$ and $\varepsilon = 0.65$.

In spite of the fact that the deviation of the observed profile from the calculated profile are rather small, and that the estimate $V_e \sin i = 90.9\text{kms}^{-1}$ is correct the determination of ε (=0.75) is overestimated by neglecting these second order effects.

As other example we use a more general formulation of the macroturbulence including an arbitrary velocity distribution that, in general, cannot be represented by a convolution. Most of all stars have a macroturbulent velocity distribution which is not the often assumed isotropic Gaussian. The macroturbulence allowed to move only in radial and tangential streams (i.e. anisotropically) with a Gaussian distribution of velocity amplitudes is often called the radial-tangential macroturbulence.

Figure 2. shows the profile calculated performing disk integrations and using the model of radial-tangential macroturbulence. This effect do not seem to have a major influence on the profiles in the wavelength domain, however it can be clearly seen in the Fourier domain. One can notice overestimated value of $V_e \sin i = 92.4\text{kms}^{-1}$ but also a significant interaction between the two parameters (velocity field and limb-darkening coefficient) leading to overestimated $\varepsilon(= 0.73)$.

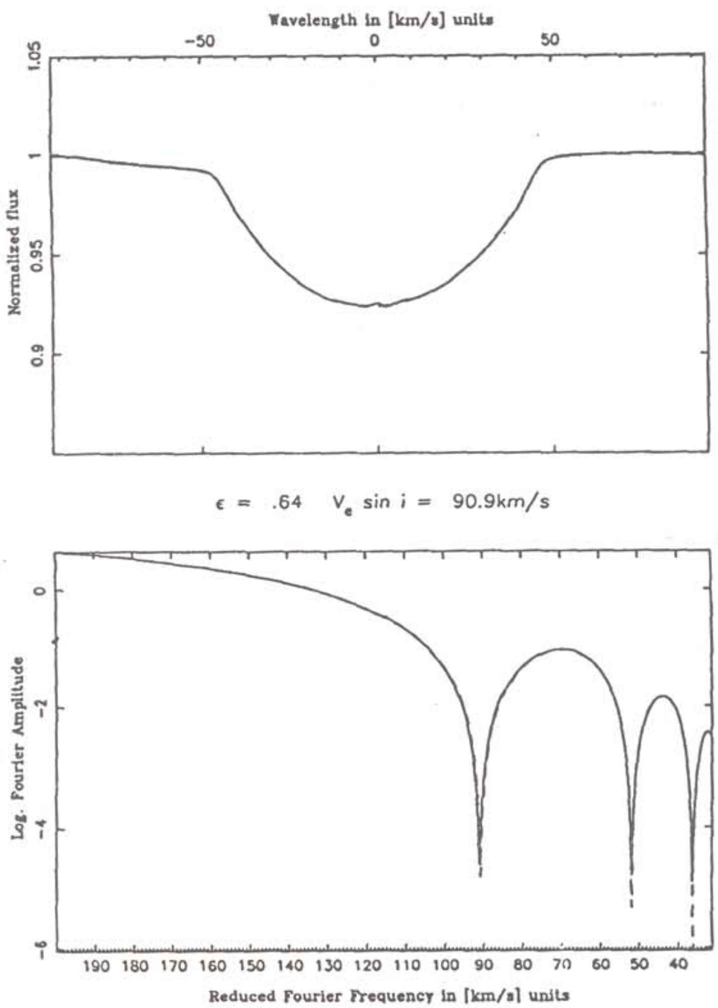

Fig. 1. **Top.** Full line represents the profile calculated using the equations (1) and (2) with $V_e \sin i = 91\mathrm{kms}^{-1}$ and $\varepsilon = 0.65$, under the presumption that the shape of intrinsic spectrum does not depend on the position on a stellar surface. Dashed line represents the profile calculated performing disk integrations where a model photosphere for a K0 IV star is used to generate $H(\lambda)$. **Bottom.** Fourier transforms of corresponding profiles are shown. Note that the abscisa is reduced to velocity kms^{-1} units.

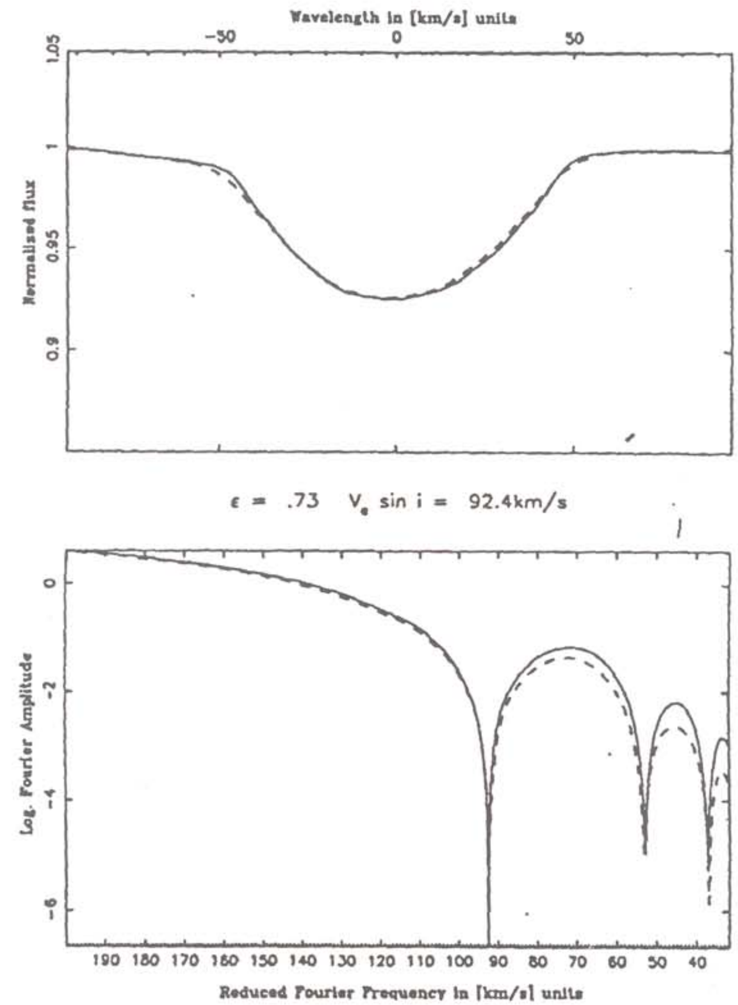

Fig. 2. **Top.** Full line represents the profile calculated under same conditions as on the Fig. 1. Dashed line shows the profile calculated performing disk integrations and using the model of radial-tangential macroturbulence of 5 kms^{-1}. **Bottom.** Fourier transforms of corresponding profiles are shown. Note that high Fourier frequencies of the profile represented by the dashed line are filtered by the macroturbulence.

References

Gray, D. : 1976, *The Observations and Analysis of Stellar Photospheres,* John Wiley & Sons, Inc.

Jankov, S., Unruh, Y., Collier-Cameron, A. : 1995, *Determination of limb darkening and projected equatorial velocity using first zeros of Fourier transform of stellar rotation profile,* in preparation.

Smith, M. A., Gray, D. F. : 1976, *Fourier Analysis of Spectral line profiles : a new tool for an old art,* PASP, **88**, 526.

Publ. Obs. Astron. Belgrade No. 50 (1995), 81 – 85

ELECTRON DENSITY MEASUREMENTS IN A LASER INITIATED Nd PLASMA PULSE DISCHARGE

S. JOVIĆEVIĆ, M. IVKOVIĆ and N. KONJEVIĆ
Institute of Physics, 11 080 Zemun, Pregrevica 118, Yugoslavia

Abstract. In this paper we present the preliminary results of diagnostics of laser initiated rare earth's plasma pulse discharge. The time dependence of the change of electron concentration was determinated from the shape of the He I 447 nm spectral line.

1. INTRODUCTION

The investigation of the radiation properties of the rare earth's plasmas are very significant for astrophysical research, in particular for understanding the physical processes in some stars atmosphere. These investigations are also of importance for laser emission studies from rare earth's plasmas in gas phase (Cahuzac, 1968; Bohan and Egorov, 1984; Bohan and Zakrevski, 1991). The main difficulties in these studies are the technical problems related to the high temperatures required for rare earth's evaporation and achievement of high enough concentrations of analyzed elements in plasma without other impurities. In this experiment the problem was solved by pulsed Nd-YAG laser evaporation of the Nd_2O_3.

2. EXPERIMENT

Block diagram of the experimental set-up is presented in Fig.1. The discharge tube, equipped with the quartz windows, has two hollow Al electrodes 13 cm apart. Pressure of the helium inside the discharge tube was 12 mbar. Radiation from the Nd -YAG laser, Molectron MY 34, with pulse duration of 15 ns, was focused by the lens f = 80mm focal length on the surface of the Nd_2O_3 pill, settled inside the discharge tube. Creation of plasma during the interaction of laser radiation with energy of 90 mJ with neodymium oxide pill initiate a pulse discharge energized by capacitor previously charged at voltage U = 980 V. Radiation from the discharge tube was focused on 10μm wide entrance slit of 0.5m Ebert type spectrograph/spectrometer (Jarrell Ash 82-025) with inverse dispersion 1.6 nm/mm.

In the first phase of the experiment the spectral lines in the wavelength region from 210 to 750 nm are recorded on film (Fomapan 400). The analysis of the recorded spectra was performed by the photodensitometer (Joyce Loeble).

In the second phase, spectra analysis was done by the use of photomultiplier EMI 9659QB mounted on the exit slit of the spectrometer. Photomultiplier was supplied

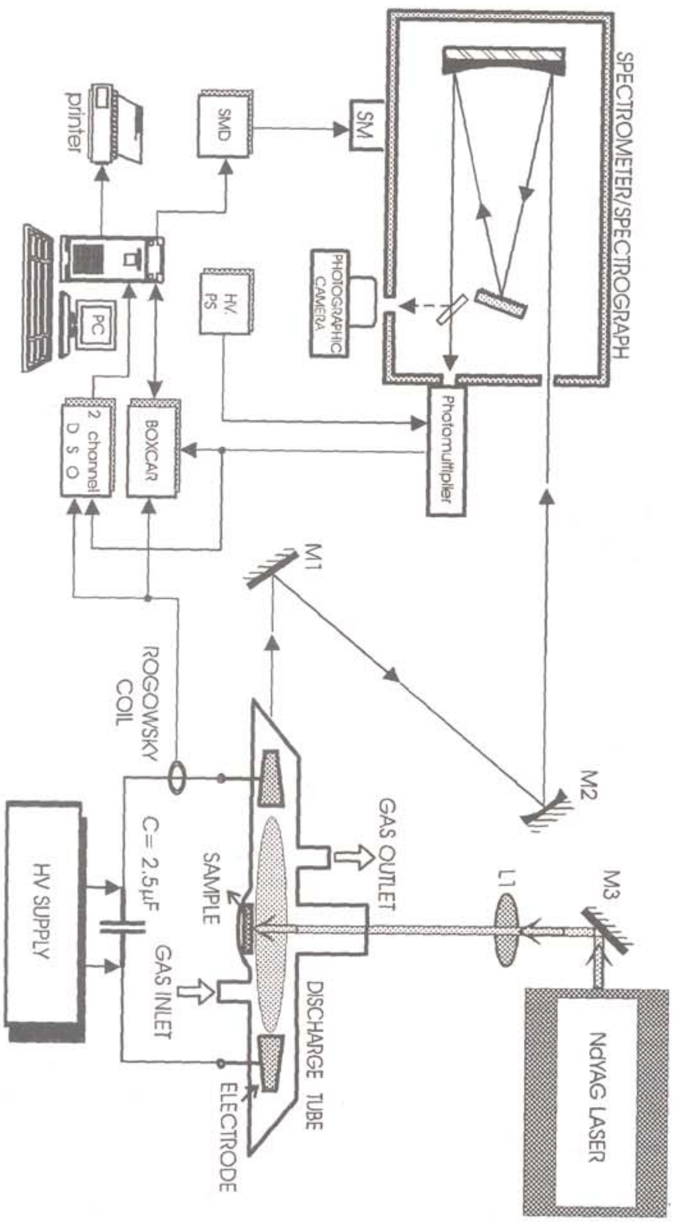

Fig. 1. Block diagram of the experimental set-up.

by the Keithley 244 High Voltage Power Supply. The wavelength scanning is performed by the step motor and step motor drive (Isert ID 3304) controlled with PC AT computer. Spectral line shapes are recorded by box-car averager (Stanford Research Systems SR 250) and the same computer. Triggering of the box-car averager was done with the signal from the Rogowsky coil. For enhancement of the signal to noise ratio, averaging of 10 samples with gate width of 30 ns was performed at each step of the motor. Time dependence of the current pulse, measured with Rogowsky coil (0.01 A/V) and intensities of spectral lines He I 447.1 nm and Nd II 401.27 nm are measured with the photomultiplier and recorded by two-channel digital storage oscilloscope (Gould 4050).

The copper target instead of the Nd_2O_3 pill is also used, for the investigation of influence of neodymium vapor on electron concentration.

3. RESULTS AND DISCUSSION

The qualitative analysis of the spectra of the discharge in pure helium (without pill) and discharge initiated by interaction of the Nd-YAG laser radiation with Nd_2O_3 pill are performed. Besides the helium and aluminum lines observed in both cases, a lot of Nd II spectral lines in laser initiated discharge are identified. The three lines of neutral neodymium, some oxygen and silicon lines are also identified. The most pronounced neodymium lines are obtained in spectral region from 385 to 435 nm, see Figure 2. Wavelengths, energy levels and transition of the strongest Nd II lines in this region are given in Table 1. (Martin *et al.*, 1978; Kuzuya *et al.*, 1993).

Table 1. Wavelengths, energy levels and transition of Nd II spectral lines in the region 385 nm - 435 nm

Wavelength λ [nm]	Energy levels [cm^{-1}]	Transition
410,946	20586-26913	$4f^4(^5I)6s(^6I) - 4f^4(^5I)6p(^4I^0)$
401,225	5086-30002	$4f^4(^5I)6s(^6I) - 4f^4(^5I)6p(^6K^0)$
406,109	3802-28419	$4f^4(^5I)6s(^6I) - 4f^4(^5I)6p(^6K^0)$
397,330	5086-38741	$4f^4(^5I)6s(^6I) - 4f^4(^5I)6p(^6I^0)$
395,745	13479-38741	$4f^3(^4I^0)5d^2(^3F)? - 4f^3(^4I^0)5d(^5L^0)6p(^6M)$
392,096	3066-28563	$4f^4(^5I)6s(^6I) - 4f^4(^5I)6p(^4K^0)$

The time dependence of the discharge current and intensities of He I 447.1 nm and strongest Nd II (401.22 nm) spectral lines recorded by oscilloscope are presented in Figure 3. The recording is a result of averaging eight successive pulses. From Fig. 3 we can see that current pulse duration is around 12 μs and that He I line starts increasing at least 5 μs from the beginning of the current pulse and lasts more than 40 μs. We can also see that Nd II 401.22 nm line appears a few microseconds before the beginning of the current pulse and lasts around 5 μs with a 30 μs long tail. Peak current I_{max} is around 800 A.

Shapes of the He I 447.1 nm at different times from the beginning of the discharge (10, 15, 20, 25, 30, 35 and 40 μs) are recorded. From these line shape recordings the electron density Ne is determined by empirical using formula (Czernichowski and Chapelle, 1985).

$$\log Ne = 23.056 + 1.586 \log (S - 0.156) + [\log (S - 0.156)]^2$$

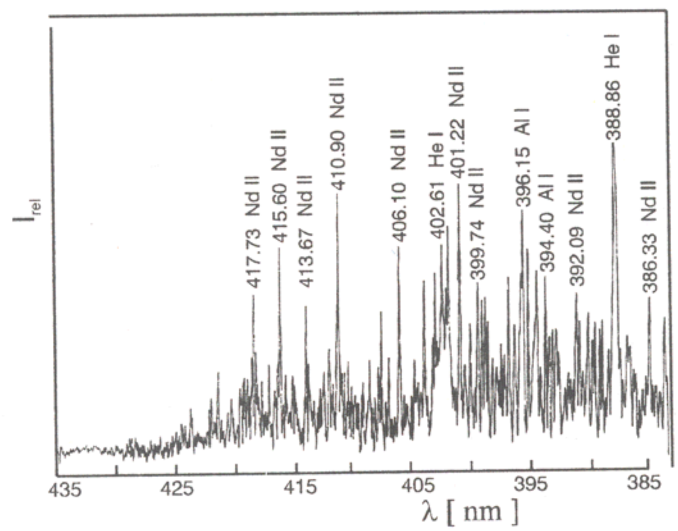

Fig. 2. Spectrum of the discharge in wavelength region 385 - 435 nm with laser interaction with Nd_2O_3 pill.

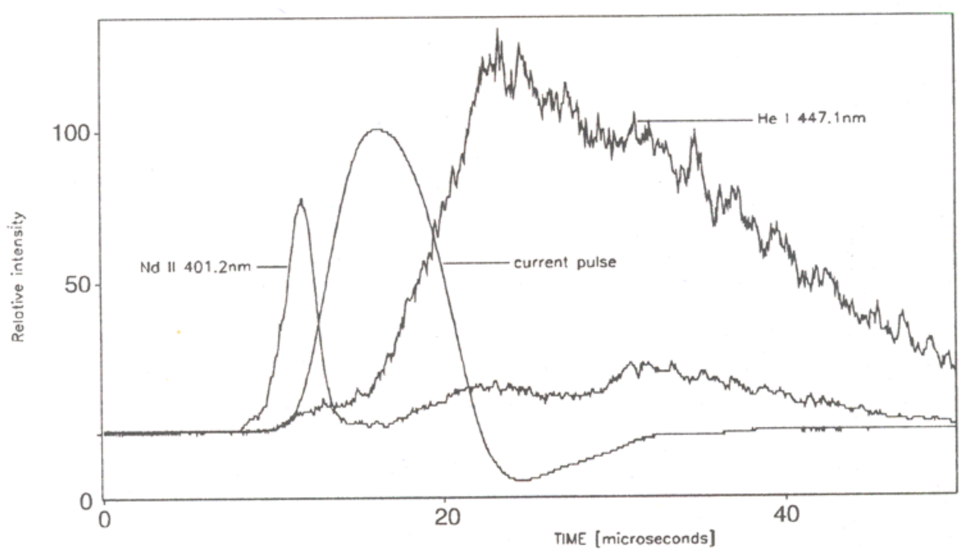

Fig. 3. Time dependence of current (1), and maximum intensities of He I 447.1 nm (2) and Nd II 401.22 nm spectral line.

Separation S between forbidden and allowed component of this line is used for electron density diagnostics to overcome difficulties caused by line selfabsorption. The obtained results with Nd_2O_3 and Cu target are presented in Figure 4.

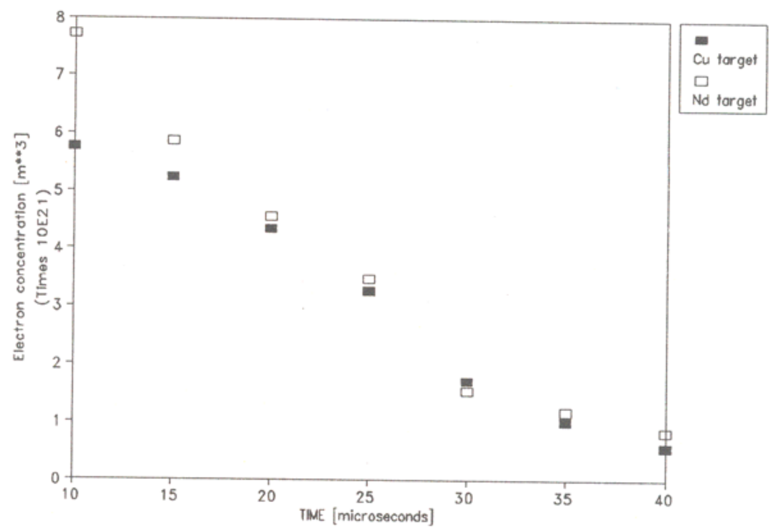

Fig. 4. Decay of the electron density Ne in time for two target materials.

4. CONCLUSION

On the basis of the obtained results, we conclude that, Nd evaporation can be achieved by means of Nd-YAG pulsed laser. Furthermore it was proven that He I 447.1 nm line can be used for electron density diagnostics in our experiment. In further investigations independent triggering of the pulse discharge and rare earth's evaporation by laser pulse after variable delay will be provided. Also, reproducibility of the Nd lines will be enhanced by laser evaporation only from previously non-irradiated part of the pill.

References

Bohan, P. A., Egorov, L. E. : 1984, *Kvant. Elektronika*, **11**, 1683.

Bohan, P. A., Zakrevski, D. E. : 1991, *Pisma ŽTF*, **12**, 89.

Cahuzac, Ph. : 1968, *Phys. Letters*, **27A**, 473.

Czernichowski, A. and Chapelle, J. : 1985, JQSRT, **33**, 427.

Kuzuya, M., Mastsumoto, H., Takechi, H. and Mikami, O. : 1993, *Appl. Spectroscopy*, **47**, 1659.

Martin, W. C., Romuald Zalubas and Lucy Hagan : 1978, *Atomic Energy Levels - The Rare-Earth Elements*, NBS Washington, D.C.

Publ. Obs. Astron. Belgrade No. 50 (1995), 87 – 90

TESTING OF SIMPLE FORMULAE FOR EVALUATION OF STARK WIDTHS

R. KONJEVIĆ
Institute of Physics, 11080 Belgrade, Pregrevica 118, Yugoslavia

1. INTRODUCTION

For evaluation of Stark broadening parameters one can use the so-called semiclassical approach or a fully quantum mechanical theoretical approach (see e.g. Griem, 1974 and references therein), which require elaborate calculations even for a single line. For large-scale calculations, when high accuracy for each particular line is not required, simple approximations with good average accuracy are very useful. Furthermore, these simple formulae do not require complete set of atomic data which are sometimes missing, in particular for some multiply ionized atoms and in this case sophisticated calculations of the Stark broadening parameter are not feasible.

The aim of this paper is to test two popular simple approaches for evaluation of Stark widths, simple semiclassical formula derived by Griem (1974, Eq. 526) and modified semiempirical formula by Dimitrijević and Konjević (1980). Estimated Stark widths will be compared with most comprehensive experimental results for doubly ionized inert gases (Konjević and Pittman, 1980). In order to determine eventual systematic discrepancies along homologous ions only analogous transitions are selected for comparison.

2. RESULTS AND DISCUSSION

Both approximate formulae, simplified semiclassical and modified semiempirical are described in detail elsewhere (Griem, 1974; Dimitrijević and Konjević, 1980). Atomic data for evaluation of Stark widths are taken from : Bashkin and Stonner (1975) and (1978), Persson *et al.* (1991) for NeIII, Bashkin and Stonner (1975) and (1978), Hansen and Persson (1987) for ArIII, Sugar and Musgrove (1991) for KrIII and Persson *et al.* (1988), Tauheed and Joshi (1993) for XeIII. The results of the comparison with experimental results w_m (Konjević and Pittman, 1980) are given in Tables 1 and 2 in the form of ratios w_m/w_G and w_m/w_{DK} where w_G and w_{DK} are theoretical results obtained from Griem's simplified semiclassical formula (Griem, 1974) and the modified semiempirical formula (Dimitrijević and Konjević, 1980), respectively. Experimental results in these tables are given normalized to the electron density Ne $=10^{17}$ cm^{-3}.

TABLE 1. Comparison of experimental w_m (Konjević and Pittman, 1980) and theoretical Stark widths evaluated from simplified semiclassical formula w_G (Griem, 1974, Eq. 526) and modified semiempirical formula w_{DK} (Dimitrijević and Konjević, 1980). Experimental results w_m are given normalized to the electron density 10^{17} cm $^{-3}$.

ION	Transition array	Multiplet	Wavelength [Å]	Temperature [K]	w_m[Å]	w_m/w_G	w_m/w_{DK}
Ne III	$2p^33s - 2p^3(^4S^0)3p$	$^5S^0 - ^5P$	2593.60	34000	0.050	0.84	1.04
			2595.68	34000	0.050	0.84	1.05
		$^3S^0 - ^3P$	2677.90	34000	0.065	0.92	1.21
			2678.64	34000	0.065	0.92	1.21
Ar III	$3p^34s - 3p^3(^4S^0)4p$	$^5S^0 - ^5P$	3285.85	26000	0.144	0.82	1.07
			3311.25	26000	0.144	0.81	1.05
		$^3S^0 - ^3P$	3514.18	27500	0.148	0.71	0.95
			3509.33	27500	0.160	0.77	1.03
Kr III	$4p^35s - 4p^3(^4S^0)5p$	$^5S^0 - ^5P$	3351.93	25000	0.163	0.86	1.11
			3325.75	25000	0.163	0.87	1.12
		$^3S^0 - ^3P$	3564.23	25000	0.167	0.72	0.95
Xe III	$5p^36s - 5p^3(^4S^0)6p$	$^5S^0 - ^5P$	3950.59	27000	0.239	0.69	0.94
			3624.08	27000	0.223	0.84	1.04
		$^3S^0 - ^3P$	3781.02	27000	0.240	0.71	0.98

TABLE 2. Same as for Table 1.

ION	Transition array	Multiplet	Wavelength [Å]	Temperature [K]	w_m[Å]	w_m/w_G	w_m/w_{DK}
Ne III	$2p^3 3s' - 2p^3(^2D^0)3p'$	$^3D^0 - ^3D$	2777.65	34000	0.054	0.78	1.03
		$^3D^0 - ^3F$	2613.41	34000	0.047	0.75	1.00
			2615.84	34000	0.047	0.76	1.00
Ar III	$3p^3 4s' - 3p^3(^2D^0)4p'$	$^3D^0 - ^3D$	3503.58	27500	0.148	0.77	1.02
			3499.67	27500	0.142	0.74	0.98
		$^3D^0 - ^3F$	3336.13	26000	0.143	0.78	1.02
			3344.72	26000	0.142	0.77	1.00
Kr III	$4p^3 5s' - 4p^3(^2D^0)5p'$	$^3D^0 - ^3D$	3474.65	25000	0.157	0.78	1.03
			3439.46	25000	0.157	0.80	1.05
		$^3D^0 - ^3F$	3191.21	25000	0.165	0.98	1.29
Xe III	$5p^3 6s' - 5p^3(^2D^0)6p'$	$^3D^0 - ^3F$	3583.65	27000	0.184	0.63	0.87
			3579.70	27000	0.191	0.66	0.91

Theoretical results for w_{DK} for KrIII lines in Tables 1 and 2 are taken from Konjević and Konjević (1994).

From the comparison of the experimental and theoretical results in Tables 1 and 2 one may conclude that both sets of theoretical results agree rather well (within estimated uncertainties of the experiment and theories) with experimental ones. However, the agreement with the modified semiempirical formula is better (with the average ratio $w_m/w_{DK} = 1.04$) than the semiclassical formula ($w_m/w_G = 0.79$). No systematic trend (increase or decrease of the ratio experiment/theory) along analogous transitions of the homologous sequence of doubly ionized inert gases can be detected.

References

Bashkin, S. and Stonner, J. O. : 1975 and 1978, Jr., *Atomic Energy Levels and Grotrian Diagrams*, (North-Holland, Amsterdam) Vol.1 and 2.
Dimitrijević, M. S. and Konjević, N. : 1980, *JQSRT*, **24**, 451.
Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, (Academic, New York).
Hansen, J. I. and Persson, W. : 1987, *J. Phys.*B **20**, 693.
Konjević, N. and Pittman, T. L. : 1980, *JQSRT*, **37**, 311.
Konjević, R. and Konjević, N. : 1994, 17th SPIG, Belgrade, Contributed papers, p. 194.
Persson, W., Wahlstrom, C. G. and Jonsson, L. : 1991, *Phys. Rev.* A **43**, 4791.
Persson, W., Wahlstrom, C. G., Bertuccelli, G., Di Rocco, H. O., Almandos, J. G. R. and Gallardo, M. : 1988, *Phys. Scripta*, **38**, 347.
Sugar, J. and Musgrove, A. : 1991, *J. Phys. Chem. Ref. Data*, **20**, 859.
Tauheed, A. and Joshi, Y. N. : 1993, *Phys. Scripta*, **47**, 555.

Publ. Obs. Astron. Belgrade No. 50 (1995), 91 – 94

STARK WIDTH AND SHIFT OF C I 538.0 nm SPECTRAL LINE

Z. MIJATOVIĆ[1], N. KONJEVIĆ[2], R. KOBILAROV[1] and S. DJUROVIĆ[1]
[1]*Institute of physics, Trg Dositeja Obradovića 4, 21000 Novi Sad, Yugoslavia*

[2]*Institute of phsics, P.O. Box 57, 11001 Beograd, Yugoslavia*

1. INTRODUCTION

The shape of asymmetrical Stark broadened spectral line profiles of neutral emitters, are well theoretically described by $j_{A,R}(x)$ function (Griem, 1974). The Stark broadening parameters - electron impact half-halfwidth w_e, electron impact shift d_e and ion broadening parameter A for C I spectral lines are theoretically calculated only in Griem (1974). The width and shift (at the halfwidth), including the ion broadening, of spectral lines of neutral emitters are given as Griem (1974) :

$$w_{th} = 2w_e(1 + gA_N)N_e 10^{-16}$$

$$d_{th} = (d_e \pm 3.20 A_N g_1 w_e)N_e 10^{-16}$$

where $g = 1.75(1.75 - 0.75R)$, $g_1 = g/1.75$, $A_N = AN_e^{1/4}10^{-4}$ and Debye shielding parameter $R = 0.090N_e^{1/6}T^{-1/2}$. w_e, d_e and A are calculated (Griem, 1974) for $N_e = 10^{16}$ cm^{-3}.

There are only a few experimental papers (Nubbemeyer and Wende, 1969; Miller and Bengston, 1970; Goly *et al.*, 1983; Jones and Wiese, 1984) which are dealing with the Stark broadening of C I 538.0 nm, and only one (Miller and Bengston, 1970) reports on the shift of this line.

In this paper we report on the widths and shifts of C I 538.0 nm spectral line emitted from the plasma of a wall-stabilized arc at two electron densities. Obtained results are compared with the theoretical (Griem, 1974) and other experimental results (Nubbemeyer and Wende, 1969; Miller and Bengston, 1970; Goly *et al.*, 1983; Jones and Wiese, 1984).

2. EXPERIMENT

A detailed description of experiment and spectroscopic measurements one can find elsewhere (Mijatović *et al.*, 1995ab). The main characteristics of this experiment and line shape measurements are :

- the wall-stabilized arc operated in argon under atmospheric pressure was used as a plasma source.
- The spectroscopic measurements are performed end-on. Due to the arc geometry and the way of introducing and exhausting gas mixture (64 % Ar, 32 % CO_2 and 4 % H_2), the near-electrode cold layer effects on the observed lines were minimized.
- As a reference light source for the shift measurements the hollow-cathode discharge lamp operated in pure hydrogen was used. The shift of C I 538.03 nm line was measured from the unshifted H_2 537.84 nm line.
- 1-m monochromator, photomultiplier and computer-controlled digital oscilloscope were used for spectroscopic measurements. The photomultiplier signals averaging technique was applied which considerably increased signal-to-noise ratio.
- Self-absorption of spectral lines was checked and found to be negligible.
- The electron densities were measured from the Stark width of hydrogen H_β line (Vidal *et al.*, 1973).
- The plasma temperatures were determined from plasma composition data evaluated following procedure described in White *et al.*, (1958).
- The deconvolution procedure (Mijatović *et al.*, 1993) for Stark broadened asymmetrical $j_{A,R}(x)$ profile and Gaussian, caused by Doppler and instrumental broadening, was applied. In this way only the Stark widths of measured profiles were obtained.
- In order to determine position of unshifted H_2 537.84 nm line, the profiles measured from reference source were fitted to Gaussian. In Fig. 1 is given an example of measured profile of C I 538.034 nm spectral line together with the reference line.

3. RESULTS AND DISCUSSION

In Table 1 the results of measured plasma parameters (N_e, T) and Stark parameters - line widths w and shifts d are given together with the results of the other experiments (Nubbemeyer and Wende, 1969; Miller and Bengston, 1970; Goly *et al.*, 1983; Jones and Wiese, 1984). The experimental results are compared to the theoretical ones (Griem, 1974). It could be seen from the Table that the agreement between experimental results of measured widths is (inside 10 %) good with the exception of the results obtained by Nubbemeyer *et al.* (1969) whose measured values are about 30 - 40 % lower then the others. The comparison with the theory shows that theory predicts slightly smaller widths than were obtained in the experiments.

Measured shifts of C I 538.0 nm line in this work are rather small (see Table). The estimated error in the shift determination is about 0.003 nm. It could be seen from the comparison with the theory that the agreement with the another experimental result (Miller and Bengston, 1970) is good, but both of them are with large error in the shift determination (30 % and more), so certain quantitative conclusion about the agreement with the theory could not be drawn.

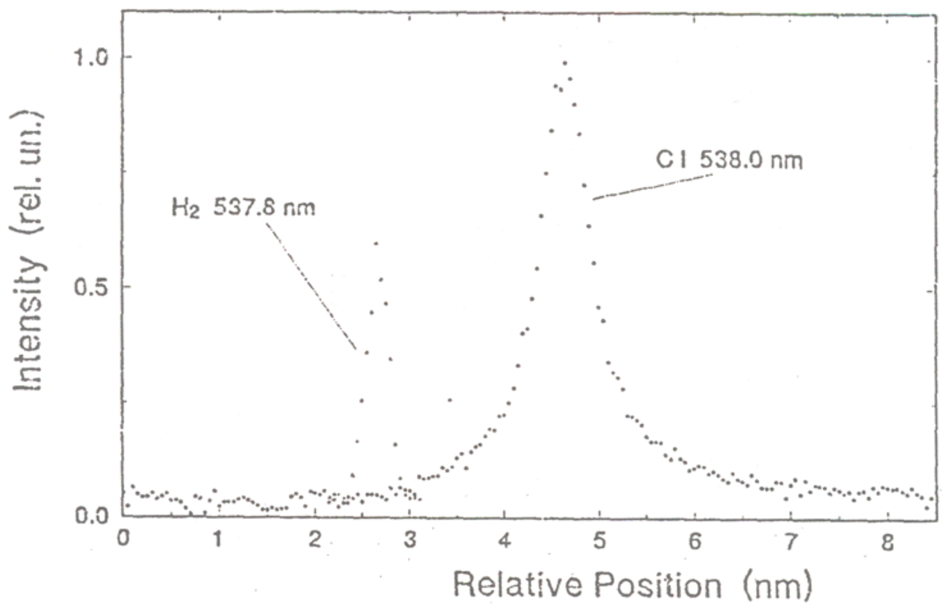

Fig. 1. An example o measured C I 538.0 nm line from the arc, and H_2 537.8 nm line from the reference source.

Table 1 Experimental widths w and shifts d for C I 538.0 nm line : I – Nubbemeyer & Wende 1969, II – Miller & Bengston 1970, III – Goly *et al.* 1983, IV – Jones & Wiese 1984. Ratios of measured and theoretical widths w_{th} and shifts d_{th} are given.

N_e [10^{22} m^{-3}]	T [K]	w [nm]	w/w_{th}	d [nm]	d/d_{th}	Acc.*	Ref.
2.20	9900	0.058	1.03	0.0092	0.69		This
2.85	10300	0.077	1.04	0.0081	0.61		work
1.2 - 1.7	9000 - 11750	0.022 - 0.148	0.78 - 0.73			C	I
10	11000	0.3	1.09	0.03	0.62	C	II
0.91 - 5.96	9000 - 11600	0.025 0.150	1.10 - 0.91			B	III
7.39	11600	0.229	1.06			A	IV

* Accuracy is taken from critical reviews (Konjević and Roberts, 1976; Konjević and Wiese, 1990).

Acknowledgements

The authors gratefully acknowledge Dr. Ivanka Holclajtner-Antunović for the evaluation of plasma composition data.

References

Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic, New York.
Goly, A., Rakotoarijimi, D. and Weniger S. : 1983, *J.Q.S.R.T.* **30**, 417.
Jones, D. W. and Wiese, W. L. : 1984, *Phys. Rev.* **A30**, 2602.
Konjević, N. and Roberts, J. R. : 1976, *J. Phys. Chem. Ref. Data*, **5**, 209.
Konjević, N. and Wiese, W. L. : 1990, *J. Phys. Chem. Ref. Data*, **19**, 1307.
Mijatović, Z., Kobilarov, R., Djurović, S., Konjević, N. and Savić, I. : 1995b *IX Kongres fizičara Jugoslavije*, Petrovac, p. 717.
Mijatović, Z., Kobilarov, R., Vujičić, B. T., Nikolić, D. and Konjević, N. : 1993, *J.Q.S.R.T.* **50**, 339.
Mijatović, Z., Konjević, N., Kobilarov, R. and Djurovic, S. : 1995a, *Phys. Rev.* **E51**, 613.
Miller, M. H. and Bengston, R. D. : 1970, *Phys. Rev.* **A1**, 983.
Nubbemeyer, H. and Wende, B. : 1969, *Z. Phys.* **225**, 69.
Vidal, C. R., Cooper, J. and Smith, E. W. : 1973, *Astrophys. J. Suppl. Ser.* **25**, 37.
White, W. B., Jonson, S. M. and Dantzig, G. B. : 1958, *J. Chem. Phys.* **28**, 751.

Publ. Obs. Astron. Belgrade No. 50 (1995), 95 – 98

STARK WIDTHS AND SHIFTS OF NIII SPECTRAL LINES OF 2p3p-2p3d TRANSITION

V. MILOSAVLJEVIĆ, S. DJENIŽE and J. LABAT
Faculty of Physics, University of Belgrade,
P.O.B. 368 11001 Belgrade, Serbia, Yugoslavia

Abstract. Stark parameters (width and shift) of four doubly ionized nitrogen spectral lines have been measured in the linear pulsed low pressure arc discharge in the nitrogen plasma at 53 000 K electron temperature and $2.8 \cdot 10^{23} m^{-3}$ electron density. The measured values were compared to the existing experimental and calculated data.

1. INTRODUCTION

A number of experimental and theoretical papers have dealt with Stark broadening and shift of NIII spectral lines (Fuhr and Lesage, 1993 and references therein). However,only three papers (Källne *et al.*, 1979; Purcell and Barnard, 1984; Purić *et al.*, 1987) dealt with the experimental investigation of the Stark widths of seven NIII spectral lines that belong to 2s2p3p-2s2p3d transition and only one contribution (Purić *et al.*, 1988) was devoted to the Stark shift measurements of four spectral lines from this transition. The relative small electron density ($1.78 \cdot 10^{23} m^{-3}$) in the latter work makes the measured shift values obtained unreliable,especially in the case of the multiplet No.9 .

The aim of this work is to present Stark shift and width values of the NIII spectral lines belonging to 2p3p-2p3d transition at $2.8 \cdot 10^{23} m^{-3}$ electron density and 53 000 K electron temperature. Stark shift of 486.72 nm spectral line from multiplet No.9 has not been measured before and the Stark shift of the 298.36 nm spectral line is the first data for the multiplet No.25uv in NIII spectra.

The measured values of Stark widths were compared with existing theoretical predictions based on the various approximations.

2. APPARATUS AND PROCEDURE

The linear pulsed arc,that has been used as a plasma source,has been described elsewhere (Djeniže *et al.*, 1990; Djeniže *et al.*, 1991). A pulsed discharge occured in a Pyrex discharge tube of 5 mm i.d. and had an effective plasma length of 5.8 cm.In order to obtain highest possible electron density,we have used discharge of the condenser battery of 14 μF capacity charged up to 63 J energy. The working gas was nitrogen at a 70 Pa filling pressure in flowing regime. We have determined the following electrical characteristics of the discharge from the Rogowski coil signal : circuit inductance = 1.7 μH, equivalent circuit resistance = 0.2 Ω, period = 32 μs and the peak current =7.7 kA.

We have obtained a good reproducibility (>90 %) of the investigated spectral line radiation intensities.Great care was taken to minimize the influence of selfabsorption on Stark width determination. The opacity has been checked by measuring line intensity ratios within multiplets (No.9). The values obtained were compared with calculated ratios of the products of the spontaneous emission probabilities and the corresponding statistical weigths of the upper levels of the lines (Wiese *et al.*, 1966). These ratios were found to differ by less than ±10%.

The spectroscopic observations were made end-on,along the axis of the discharge tube.Scanning of the spectral line profiles was done by using a shot-to -shot technique,while advencing the exit slit-photomultiplier combination in small wavelength steps (Djeniže *et al.*, 1991). The photomultiplier signal was digitized using HAMEG 205-2 digital scope interfaced to a computer. The standard deconvolution procedure (Davies and Vaughan, 1963) was computerized using the least square algoritm. The measured profiles were of Voigt type due to the convolution of the Lorentzian Stark and Gaussian profiles caused by Doppler and instrumental broadening. Van der Waals and resonance broadening are estimated to be smaller by more than an order of magnitude in comparison to Stark, Doppler and instrumental broadening. The estimated error of the measured Stark FWHM (full-width at half intensity maximum) (w_m) was within ±13 %.

The Stark shifts (d_m) were measured relative to the unshifted spectral lines emitted by the same plasma (Purić and Konjević, 1972). The Stark shifts were determined with ±15 % error.

The plasma parameters were determined using standard diagnostic methods. The electron temperature (T) decay was found from the ratios of the relative intensities of 347.45 nm NIV and 375.47 nm NIII spectral lines with an estimated error of ±11% assuming the existence of LTE. The electron density (N) decay was obtained using a single wavelength He-Ne laser interferometer at the 632.8 nm with an estimated error of ±7%. Atomic parameters required for the diagnostic purposes (for NIV and NIII spectra) have been taken from Wiese et al. (1966).

3. RESULTS

Table 1 Measured w_m and d_m values

multiplet	λ (nm)	w_m	d_m
$^2P - ^2P^0$	298.358	0.40	0.01
(25uv)			
$^4D - ^4F^0$	486.715	0.62	0.04
(9)	486.133	0.59	0.02
$^4S - ^4P^0$	454.636	0.51	-0.05
(13)			

The results of measured Stark FWHM (w_m in $\AA$) and shift (d_m in $\AA$) values at 53 000 K electron temperature and $2.8 \cdot 10^{-23}m^{-3}$ electron density are presented in Table 1. The positive shift is toward the red.

4. DISCUSSION

To the knowledge of the authors only one paper (Dimitrijević and Konjević, 1981) contains calculated values of the Stark width for the 2p3p-2p3d transition.In Fig.1 we have presented Stark FWHM as a function of electron temperature for multiplet No.9 predicted by theoretical calculations at $1 \cdot 10^{23}m^{-3}$ electron density. G and GM denote Stark FWHM values calculated on the basis of the semiclassical and modified semiclassical formulae,respectively (Griem, 1974), both SC and SEM denote values calculated on the basis of the semiclassical theory and modified semiempirical formulae, respectively,performed by Dimitrijević and Konjević (1981). The existing experimental data were also given : Δ, Purcell and Barnard (1984); $\circ$, Purić *et al.* (1987); $\square$, Källne *et al.* (1979) and $\bullet$, our results. $\overline{\lambda}$ is the average wavelength in the multiplet No.9. The error bars include the uncertainties of the width and electron density measurements. We can conclude that in the case of the multiplet No.9 our measured w_m values agree well (within 10%) with predictions of the modified semiclassical theory. The agreement with SEM theoretical values is also acceptable (within 26%), while the theoretical G and SC values are higher than our results up to factors 1.30 and 1.56, respecively. Our experimental data agree well with those from Purić *et al.* (1987).

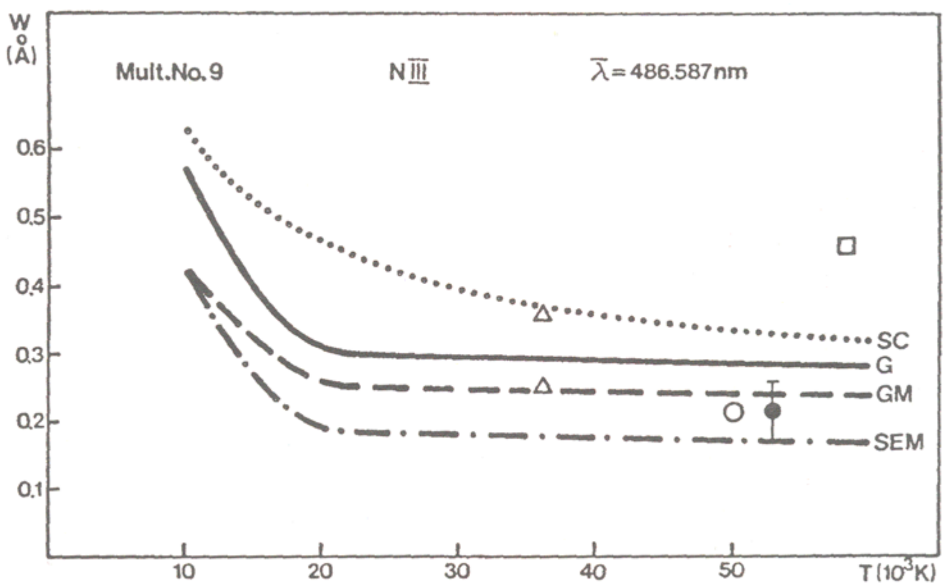

Fig. 1. Calculated Stark FWHM dependence on the electron temperature for the multiplet No.9.

For the Stark shift sign. we confirm earlier obtained conclusion made by Purić *et al.* (1988) for the multiplet No.13, both in the case of the multiplet No.9, we found positive shift.

Acknowledgements

This research was supported by Ministry for Science and Technology of the Republic of Serbia.

References

Aschby, D. E. T. F., Jephcott, D. F., Malein, A. and Ragnev, F. A. : 1965, *Appl. Phys.* **36**, 29.

Davies, J. T. and Vaughan, J. M. : 1963, *Astrophys. J.* **137**, 1302.

Dimitrijević, M. S. and Konjević, N. : 1981, *JQSRT*, **25**, 387.

Djeniže, S., Srećković, A., Labat J., Konjević R. and Popović L. : 1991, *Phys. Rev.* A **44**, 410.

Djeniže, S., Srećković, A., Platiša, M., Konjević, R., Labat, J. and Purić, J. : 1990, *Phys. Rev.* A **42**, 2379.

Fuhr, J. R. and Lesage, A. : 1993, *Bibliography on Atomic Line Shapes and Shifts* (July 1978 through March 1992) NIST Special Publication 366 Supplement 4 US : DC National Institute of Standards and Technology.

Griem, H. R. : 1974, *Spectral Line Broadening by Plasmas* (New York : Academic Press).

Källne, E., Jones, L. A., Barnard, A. J. : 1979, *JQSRT*, **22**, 589.

Purcell, T. and Barnard, A. J. : 1984, *JQSRT*, **32**, 205.

Purić, J. and Konjević, N. : 1972, *Z. Phys.* **249**, 440.

Purić, J., Srećković, A., Djeniže, S. and Platiša, M. : 1987, *Phys. Rev.* A **36**, 3957.

Purić, J., Djeniže, S., Srećković, A., Milosavljević, M., Platiša, M. and Labat, J. : 1988, *Proceedings of XIV SPIG* (eds. Konjević N., Tanević L., Tanević N.), Sarajevo, p.345.

Wiese, W. L., Smith, M. W. and Glennon, B. M. : 1966, *Atomic Transition Probabilities*, NSRDS NBS 4 Vol.2 (Washington, DC : US Govt Printing Office).

Publ. Obs. Astron. Belgrade No. 50 (1995), 99 – 101

SPECTROSCOPIC DIAGNOSTICS OF PULSED PLASMA FLOWS USING SPECTRAL LINE BROADENING

L. Ya. MIN'KO, V. B. AVRAMENKO, G. I. BAKANOVICH and A. N. CHUMAKOV
Institute of Molecular and Atomic Physics
Academy of Sciences of Belarus, Fr. Skaryna Avenue 70,
Minsk 220072, Belarus

To apply adequately methods of plasma diagnostics based on atom and ion spectral lines broadening, further improvements in the broadening parameters data bank, as well as experimental checking of particular methods under conditions of real plasma sources, are to be made.

In the laboratory of nonequilibrium processes (presently the laboratory of radiative plasma dynamics) of the IMAF a long-standing experience concerning activities in the above mentioned directions is gained. Development and investigations of various pulsed plasma sources, both electric-discharge and laser ones, have called for conducting spectroscopic diagnostics of plasma under conditions of spatial and temporal nonuniformity inherent in generated pulse plasma flows (Min'ko, 1970; Elashevich *et al.*, 1972; Bakanovich *et al.*, 1978; Bakanovich *et al.*, 1979; Ananin *et al.*, 1990; Astashinsky *et al.*, 1991; Min'ko *et al.*, 1994). On the other hand, created and studied sources of plasma flows provide a means of modeling the rather wide range of conditions characteristic of the laboratory and astrophysical plasmas.

It is well known that available numerous data on Stark broadening of spectral lines (Griem, 1974; SLS 1981, 1985) are often contradictory and remain up to now incomplete, therefore the need for calculations and careful studies of line profiles is still of great importance.

Such studies were conducted in the NBS (e.g., Kelleher, 1981). Broadening parameters of spectral lines for great number of atoms and ions accounting for influence of electrons, ions, and protons, are being effectively calculated in the Yugoslav School (Dimitrijević, 1993; Konjević, 1989; Dimitrijević, 1991; Dimitrijević, 1994). Analysis of calculated profiles of spectral lines broadened by both Stark and Doppler effects, including those with consideration for forbidden components is contained in our papers as well (e.g., Min'ko, 1974). Systematic spectroscopic studies of various electric-discharge and laser plasma formations have shown that sufficiently accurate measurements of electron concentrations in plasma based on the line broadening are possible over the specific and relatively narrow Ne range only, and that checking the appropriate methods for their applicability is the necessary condition of their correct employment. Use of sets of spectral lines with variety of the above mentioned Ne range limits allows coverage of great area of parameters wherein sufficiently accurate measurements of charged particles concentrations based on broadening of lines with differing broadening parameters and excitement potentials are possible.

To further extend the capabilities of spectroscopic diagnostics, we also used the procedure of intentional introduction of the admixtures of atoms and ions of the elements with reliable data on broadening parameters for their spectral lines into plasma (Astashinsky *et al.*, 1991).

Due to nonstationary character and spatial nonuniformity of pulsed plasma flows the spectral diagnostics was conducted, for the most part, by the methods of high-speed cine-spectrography and spectrochronography, enabling spatial-temporal distribution of the plasma parameters to be obtained (Min'ko, 1970; Elashevich *et al.*, 1972; Bakanovich *et al.*, 1978; Bakanovich *et al.*, 1979; Ananin *et al.*, 1990; Astashinsky *et al.*, 1991; Min'ko *et al.*, 1994). The results of electron concentration measurements based on broadening of lines recorded on both frames and streak photographs of spectra, could be compared with those derived from spectral brightness of emission in continuum (Bakanovich *et al.*, 1978; Min'ko *et al.*, 1994), as well as obtained by interferometric and holographic methods (Ananin *et al.*, 1990; Avramenko *et al.*, 1973). For example, investigations of emitting compression plasma flows using high-speed spectroscopic methods and interferometric ones (by means of laser interferometer with photoelectric recording and two-mirror autocollimation interferometer with the field visualization) yielded practically coinciding values of electron concentrations (Ananin *et al.*, 1990).

Spectroscopic studies of the effect of laser radiation on different absorptive materials might give us information only in case we use the methods providing for both space- and rather high time resolution (Bakanovich *et al.*, 1979). This is attainable by high-speed frame-wise spectrum recording which enables the diagnostics of plasma clusters corresponding to separate laser spikes to be performed. Intensive continuum and spectral lines of atoms and ions of target materials elements have been used for measurements of the main plasma parameters. The electron densities have been found both by measured space-time resolved spectral brightness of plasma and by spectral lines broadening due to the quadratic Stark effect. We succeeded in obtaining the electron distribution along the plasma formation due to used technique.

Experimental studies of electric-discharge and laser plasma sources were accompanied by numerical simulations of plasma parameters (Ananin *et al.*, 1990; Eliyashevich *et al.*, 1985). Close correspondence of electron concentrations and temperatures obtained by spectroscopic methods to the results of numerical simulations shows the efficiency in integrated approach to diagnostics of complex plasma formations in modern plasma sources.

References

Ananin, S. I., Astashinsky, V. M., Bakanovich, G. I. : 1990, *Fisika Plasmy*, **16**, N 2, 186.

Astashinsky, V. M., Bakanovich, G. I., Bukova, N. A., Kuzmitsky, A. M., Man'kovsky, A. A., Min'ko, L. Ya. : 1991, *Zh. Prikl. Spektroskop.* **55**, N2, 337.

Avramenko, V. B., Burmakov, A. P., Labuda, A. A., Min'ko, L. Ya. : 1973, *Proc. II All-Union Conf. on Plasma Acselerators*, Minsk. p. 325.

Bakanovich, G. I., Min'ko, L. Ya., Tyunina, E. S., Chumakov, A. N. : 1978, *Spectroscopic Diagnostics of Erosive Laser Plasma. Preprint N149*, Institute of Physics, Academy of Sciences of BSSR, Minsk.

Bakanovich, G. I., Min'ko, L. Ya. and Chumakov, A. N. : 1979, *Journal de Physique*, **40**, coll. C7, suppl. au N7, 761.

Dimitrijević, M. S. : 1991, Line Shapes Investigations in Yugoslavia II (1985-1989), Beograd, 1991; Line Shapes Investigation in Yugoslavia and Serbia III (1989-1993), Beograd, 1994.

Dimitrijević, M. S. : 1993a, *Astron. Astrophys. Suppl. Ser.* **100**, 237.

Dimitrijević, M. S. : 1993b, *Astron. Astrophys. Suppl. Ser.* **100**, 593.

Griem H. R. : 1974, *Spectral Line Broadening by Plasmas*, Academic Press, Inc.

Eliyashevich, M. A., Avramenko, V. B., Bakanovich, G. I., Min'ko, L. Ya. : 1972, *Zh. Prikl. Spektroskop.* **16**, N3, 422.

Eliyashevich, M. A., Min'ko, L. Ya., Romanov, G. S. : 1985, *Izv. Akad. Nauk SSSR*, **49**, 1132.

Kelleher, D. E. : 1981, *JQSRT* **25**, 190.

Konjević, N. : 1989, *Proc. XIX ICPIG. Invited Papers. Belgrade*, 382.

Min'ko, L. Ya. : 1970, Obtaining and investigations of pulsed plasma flows. "Nauka i Tekhnika", Minsk.

Min'ko, L. Ya., Chumakov, A. N., Bakanovich, G. I. : 1994, *Zh. Prikl. Spektroskop.* **61**, N 5-6, 476.

SLS, 1981, 1985, *Spectral Line Shapes*, Proc. Internnational Conference, ed. B. Weude, W. de Gruyter P. C. Berlin.

Publ. Obs. Astron. Belgrade No. 50 (1995), 103 – 104

THE INTENSITY PROFILE IN THE MODEL OF "FRACTIONAL" OSCILLATOR

R. R. NIGMATULLIN, M. Kh. SALAKHOV and O. N. MAKSIMOV
Department of Physics, Kazan State University, 420008, Kazan, Tatarstan, Russia

In Nigmatullin (1992) it has been shown that partial summation of the temporal "Cantor fingers" convoluted with a smooth function $f(t)$ can be substituted in the limit $N \to \infty$ by temporal fractional integral (TFI) taken from the smooth function. The importance of this general approach to physical understanding of TFI has been stressed recently in the review Olemsky and Flat (1993). The main result of Nigmatullin (1992) can be expressed in the form

$$< J(t) >= \lim_{N\to\infty} J_N(t) = \lim_{N\to\infty} \frac{1}{2^N} \sum_{m=1}^{2^N} f(t - t_m^{(N)}) =$$

$$= B(\nu)T^{-\nu} \frac{1}{\Gamma(\nu)} \int_0^t (t-\tau)^{\nu-1} f(\tau) d\tau = B(\nu)T^{-\nu} D^{-\nu}[f(t)] \tag{1}$$

For $0 < t/T < 1$, $\nu = \ln 2/\ln(1/\xi)$, $0 < \xi < 1/2$. Here $t_m^{(N)}$ is the N-th generation of the points of the Cantor set, [0,T] is an initial interval of the location of the Cantor set, ξ is an initial length of the Cantor column, $\nu = \ln n 2/\ln(1/\xi)$ is the fractal dimension of the Cantor set,

$$B(\nu) = (1-\xi)^{-\nu} 2^{-\frac{1+\nu}{2}}$$

is the constant, depending on ν, $D^{-\nu}[f(t)]$ is the symbol of TFI determinated from (1). This result can be applied to consideration of selfsimilar collisions which can be generated by random collision force.

Based on this relationship (1) it is easy to outline the new approaches to consideration of collision motion.

Let us suppose that the process of interaction of the physical system considered with external surroundings is described by means of random and collisional force. In this case the Newton's equation assums the form.

$$\frac{m}{T^2} \frac{\mathrm{d}^{1+\nu}(\Delta\bar{r})}{\mathrm{d}u^{1+\nu}} = B(\nu)\overline{F}(\bar{r}, \bar{v}, t), \quad 0 < \nu < 1,\ 0 < u = t/T < 1 \tag{2}$$

The equation (2) can be used for description of the collision and brownian processes where irreversibility due to interactions (the processes of "remnant" memory (Nigmatullin, 1992; Olemsky and Flat, 1993)), is taken into account "automatically". If the force $\overline{F}(\overline{r}, \overline{v})$ coincides with additive sum of elastic and friction force (for simplicity we consider onedimensional case)

$$\overline{F}(\overline{r}, \overline{v}) = -\gamma \Delta \overline{v} - k \Delta x \tag{3}$$

then equation (2) is reduced to the equation of "fractional" oscillator with losses describing the movement of a system in a medium with selfsimilar collisions

$$\frac{d^{1+\nu}x}{du^{1+\nu}} + B(\nu)(2\lambda T \frac{dx}{du} + \omega_0^2 T^2 x) = 0, \qquad 0 < \nu < 1, \; u = t/T \tag{4}$$

Irreversibility and collisions are taken into account by the exponent ν. At $\nu = 0$. we obtain solution for amplitude which leads to the Lorentz profile for intensity. At $\lambda = 0$ it is possibble to obtain the solution for $x(t)$ in the form

$$\frac{x(t)}{x(0)} = E_{1+\nu}(-\tau^{1+\nu}) \tag{5}$$

where $\tau = \omega_p t$, $\omega_p = [B(\nu)(\omega_0 T)^2]^{1/(1+\nu)}/T$ is the natural frequency of "fractional" oscillator, $E_\alpha(z) = \sum_{n=0}^{\infty}(z^n/(\Gamma(\alpha n + 1)))$ is Mittag-Lefleur function.

The Fourier transformation of $x(t)$ gives the amplitude $a(\omega)$ which leads to the profile of intensity $P(\omega) = a^*(\omega)a(\omega)$.

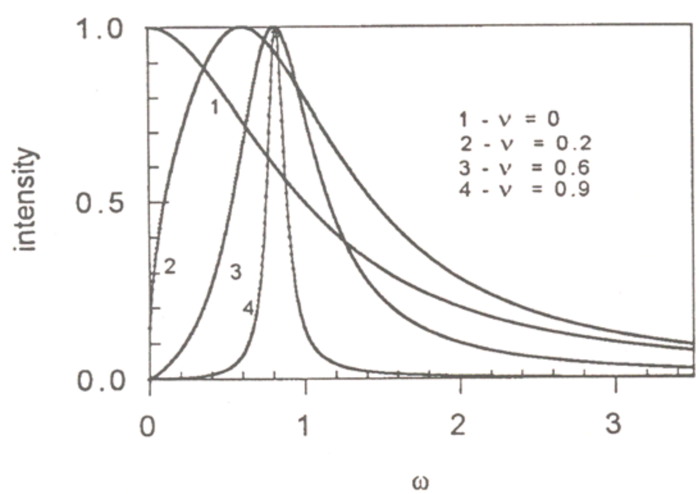

Fig. 1.

In the Figure the distribution of intensity vs frequency ω in arbitrary untis for various ν is shown.

Thus the conception of TFI and its generalizations can find wide application for description of dynamical processes in physics having fractal grounds in their origin. This model of fractional oscillator can serve as the ground for consideration of line broadening in plasma.

References

Nigmatullin, R. R. : 1992, *Theor. Math. Phys.* **90**, 242.
Olemsky, A. I. and Flat, A. Ya. : 1993, *Physics-Uspekhi* **36**, 1.

Publ. Obs. Astron. Belgrade No. 50 (1995), 105 – 106

STARK BROADENING OF DOUBLE IONIZED ATOMS : As III AND Se III

L. Č. POPOVIĆ and M. S. DIMITRIJEVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E-mail lpopovic@aob.aob.bg.ac.yu

1. INTRODUCTION

Stark broadening data for multple ionized atom spectral lines are needed for astrophysical modeling of stellar and laboratory plasma. Stark broadening mechanism is the main pressure broadening mechanism in hot stars with $T_{eff} \gtrapprox$10000 K. Sometimes Stark broadening mechanism may be important for cooler stars, e.g. for lines originating from energy levels with large principle quantum numbers. Consequently providing of Stark broadening parameters for a large number of transitons for many atoms and ions is of interest. Here we present our calculation for Stark widths of double ionized As and Se spectral lines.

2. RESULTS

For calculation, the modified semi-empirical approach developed by Dimitrijević and Konjević (1980) has been used. Energy level data needed for calculation have been taken from Moore's tables (1971) and oscillator strengths taken from Migdalek (1976). In Table 1 we present results of our calculations of Stark widths for four As III and three Se III spectral lines. For these ions there are no experimental Stark broadening data for comparison.

Table 1 Stark full width (FWHM) of As III and Se III spectral lines. The electron density is 10^{23}m^{-3}. The avaraged wavelength of the multiplet is denoted by $\overline{\lambda}$.

Transition	T (K)	W (nm)
As III	5000.	.216E-02
$\overline{\lambda} = 95.5$ nm	10000.	.151E-02
$4p^2P^0 - 5s^2S$	20000.	.106E-02
	30000.	.865E-03
	40000.	.753E-03
	50000.	.681E-03

Table 1, continued

Transition	T (K)	W (nm)
As III $\overline{\lambda} = 86.4$ nm $4p^2P^0 - 4d^2D$	5000.	.608E-03
	10000.	.423E-03
	20000.	.291E-03
	30000.	.235E-03
	40000.	.203E-03
	50000.	.183E-03
As III $\overline{\lambda} = 396.1$ nm $5s^2S - 5p^2P^0$	5000.	.573E-01
	10000.	.401E-01
	20000.	.280E-01
	30000.	.228E-01
	40000.	.200E-01
	50000.	.182E-01
As III $\overline{\lambda} = 702.5$ nm $4d^2D - 5p^2P^0$	5000.	.128
	10000.	.893E-01
	20000.	.621E-01
	30000.	.505E-01
	40000.	.441E-01
	50000.	.401E-01
Se III $\overline{\lambda}= 381.5$ nm $6s^3P - 6p^3D$	5000.	.170E-01
	10000.	.119E-01
	20000.	.823E-02
	30000.	.667E-02
	40000.	.580E-02
	50000.	.526E-02
Se III $\overline{\lambda}= 353.4$ nm $6s^3P - 6p^3P$	5000.	.155E-01
	10000.	.108E-01
	20000.	.754E-02
	30000.	.624E-02
	40000.	.555E-02
	50000.	.513E-02
Se III $\overline{\lambda}= 327.1$ nm $6s^3P - 6p^3S$	5000.	.134E-01
	10000.	.935E-02
	20000.	.659E-02
	30000.	.550E-02
	40000.	.493E-02
	50000.	.459E-02

References

Dimitrijević, M. S. and Konjević, N. : 1980, *JQSRT*, **24**, 451.
Migdalek, J. : 1997, *JQRST*, **16**, 385.
Moore, C. E. : 1971, *Atomic Energy Levels*, NSRDS-NBS, Vol. **2**, Washington D.C.

Publ. Obs. Astron. Belgrade No. 50 (1995), 107 – 110

L_α LINE IN THE MKN335 SEYFERT 1 GALAXY

L. Č. POPOVIĆ[1], D. JEVREMOVIĆ[1], I. VINCE[1] and T. MILOVANOV[2]
[1]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*
E–mail lpopovic@aob.aob.bg.ac.yu

[2]*People's Observatory, Gornji grad 16, Kalemegdan, 11000 Belgrade, Yugoslavia*

Abstract. The analysis of the L_α emission line profile of MKN 335 Seyfert 1 galaxy is presented. The line profile shows a prominent blue asymmetry (A=-0 18) For description of this asymmetry a model with outflow emission gas and gravitational redshift effect in Broad Line Region (BLR) are applied.

1. INTRODUCTION

The MKN 335 is a variable Seyfert 1 galaxy. The variability is noted in the continuum in the line fluxes (see, e.g., Shuder, 1981; Osterbrock and Shuder, 1982; Levshakov *et al.*, 1989) and in the x-ray flux, too (Lee *et al.*, 1987). But the shape of its emission spectral line profiles (H_β, H_α...) seems to remain constant, showing a blue asymmetry (Popov and Khachikyan, 1980; Osterbrock and Shuder, 1982; Crenshaw, 1986; Van Groningen, 1987). The line widths of MKN 335 are narrower than those of other Seyfert 1 galaxies.

Using IUE observations Wu *et al.* (1980) have measured the flux of L_α line of MKN 335, and found that it is about seven times larger than the H_β flux. But, as we know, detailed study of the L_α shape has not been done yet. There is an interest in L_α shape investigation in Seyfert 1 nuclei, because this line is originated close to the nuclei and the influence of the disk on its shape (especially on the wings (Nazarova, 1991; Van Groningen, 1987)) could be significant.

Using a set of Huble Space Telescope high resolution spectral observations of MKN 335 we analyze the shape of the L_α spectral line. We apply a model of MKN 335 that takes into account the outflow velocity of emission gas. The gravitational redshift effect, which has been noticed in BLR (Popović *et al.*, 1995), is taken into account, too. In this paper the preliminary results of our investigation are presented.

2. ANALYSIS AND RESULTS

2. 1. THE L_α LINE SHAPE

Similarly as with Balmer lines (see Osterbrock and Shuder, 1982; Crenshaw, 1986) a blue asymmetry of the L_α line profile of MKN 335 is noticed (see Fig. 1). We have found that the asymmetry

$$A = \frac{(HWHM)_{red} - (HWHM)_{blue}}{(HWHM)_{red} + (HWHM)_{blue}}$$

at half maximum is -0.18 (HWHM is half width at half maximum). The full width at half maximum (FWHM) is 1380 km/s. In the L_α profile there are three absorption lines : λ_1 = 1240.95 Å, λ_2 = 1250.47 Å and λ_3 = 1253.7 with FWHM w_1 = 0.4 Å, w_2 = 0.2 Å and w_3 = 0.2 Å. The last two lines are probably orginated in the interstellar matter of our Galaxy and their wavelengths are near SiII ($\lambda\lambda$1250.43 Å), S II ($\lambda\lambda$1250.5 Å) and Li II or S II ($\lambda\lambda$1253.8 Å). Moreover, one should notice that the absorption lines may be originated from the galaxy.

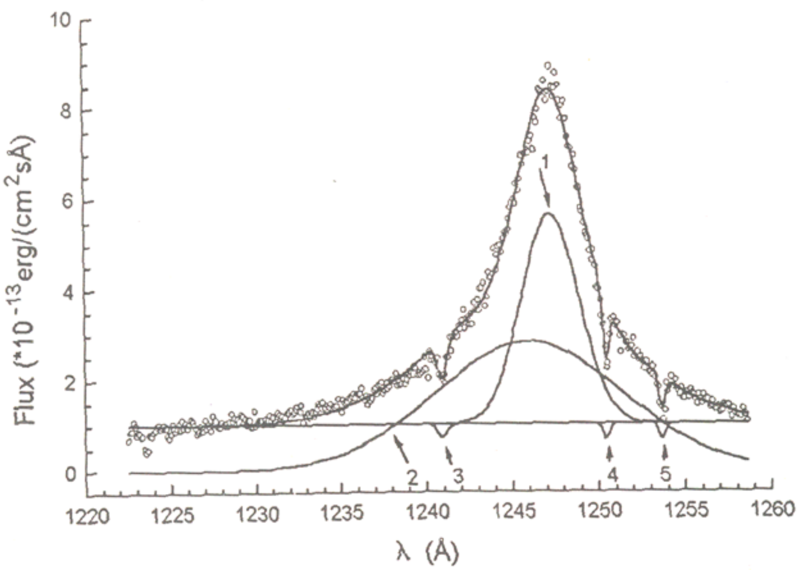

Fig. 1. The shape of observed L_α line (dots) and its Gaussian decomposition (full line).

2. 2. THE TWO-GAUSS-FIT APPROXIMATION

For more detailed analysis of the L_α line shape we use the method described in Vince *et al.* (1995).

In order to separate the Broad Line Component (BLC) from the Narrow Line Component (NLC) of the line, taking into account the consideration given by Corbin (1995), we fit the profile with two Gaussian components where the intensity, width and position of Gaussian components were free parameters. The best fit gives a separation of V_{em}=320 km/s between two Gaussian functions; the BLC is shifted toward blue. The blueshift of the BLC compared with NLC could be explained by Doppler effect of the outflow of emission gas. The turbulence velocity of the emission gas ($v_t = FWHM$ of Gaussian component/1.67) is about 350 km/s in the NLR and 1130 km/s in BLR.

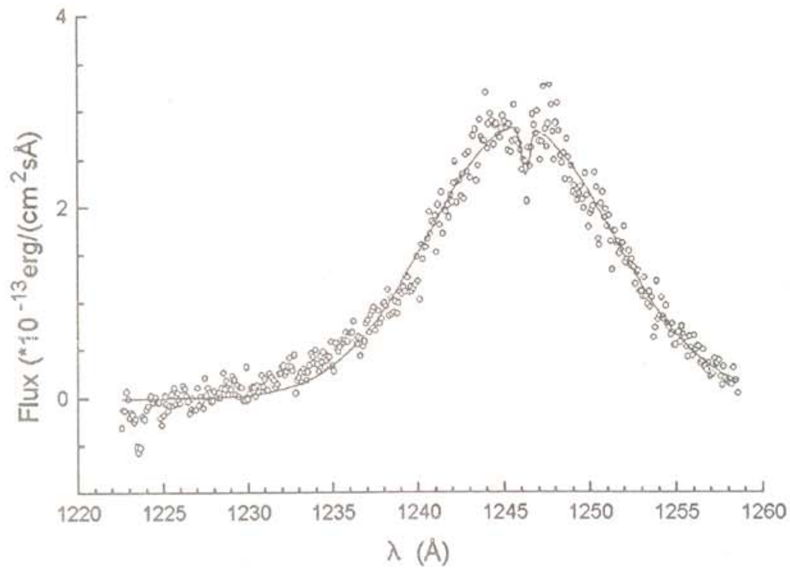

Fig. 2. BLC of the L_α line : dots are observed, full line is the synthetic profile where the outflow of matter and the effect of gravitational redshift were taken into account.

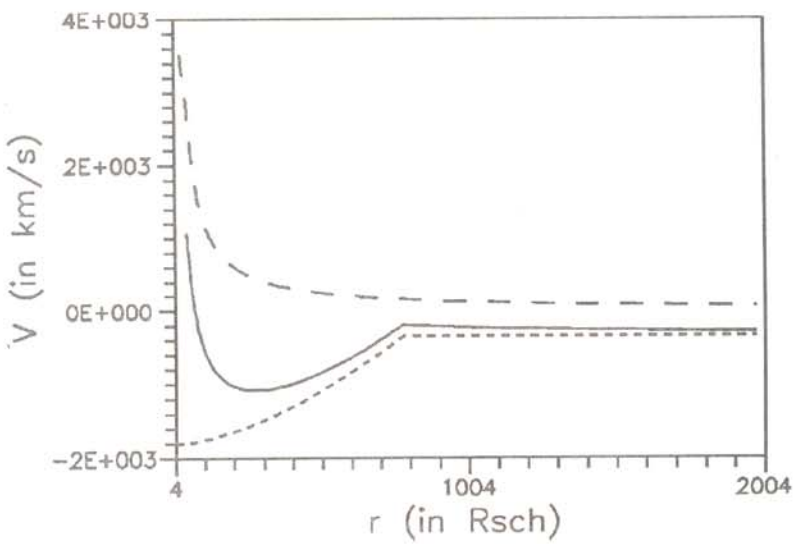

Fig. 3. The outflow gas radial velocity (- - -), the gravitational redshift (— —), and the resulting velocity distribution (——) with distance.

2. 3. A MODEL OF THE BLR

We suppose that the NLR is transparent for BLC, the NLC is symmetrical and that the BLR for L_α is optically thin. We suppose that the density of emitters in the whole BLR is constant. We decompose the NLC from BLC (Fig. 2) of the L_α line.

For BLR we use a simple model where the outflow of emission gas and gravitational redshift effect are taken into account. By using this model and fitting the L_α profile, we found that the BLR was located between 2.5 R_{Sch} (Schwarzschild's radius) and 2000 R_{Sch} far from center of the galaxy. We determine the emission gas ejection velocity distribution, too (Fig. 3).

3. CONCLUSION

Using the simple model of BLR in MKN 335, which takes into account the outflow of emission gas and the gravitational redshift effect we found that the BLR is located between 2.5 and 2000 R_{Sch}. The outflow velocity decreases very fast between 2.5 and 780 R_{Sch}. The redshift effect is dominant between 2.5 and 150 R_{Sch}.

For more accurate study of BLR model of MKN 335 one has to take into account the selfabsorption effect that was noted in the central core of the BLC of L_α line.

References

Corbin, M. R. : 1995, *Astrophys. J.* in press.
Crenshaw, D. M. : 1986, *Astrophys. J.* **62**, 821.
Lee, M. G., Balick, B., Halpern, J., Heckman, T. : 1987, *Bull. Am. Astron. Soc.* **19**, 733.
Levshakov, S. A., Mikhailov, V. P., Afanas'ev, V. L : 1989, *Soob. Byuarkan Spets. Astrofiz. Obs.* **61**, 84.
Nazarova, L. S. : 1991, *Sops. Spec. Astrophys. Obs.* **66**, 37.
Osterbrock, D. E. and Shuder J. M. : 1982, *Astrophys. J. Suppl. Series*, **49**, 149.
Popov, V. N. and Khachikyan, E. E. : 1980, *Astrofizika*, **16**, 207.
Popović, L. Č., Atanacković–Vukmanović, O., Vince, I., Kubičela, A. : 1995, *Astron. Astrophys.* **293**, 309.
Shuder, J. M. : 1981, *Astrophys. J.* **86**, 1599.
Vince, I., Popović, L. Č., Jankov, S., Djurašević, G., Atanacković-Vukmanović, O., Jevremović, D. : 1995, *Publ. Astron. Obs.* **50**, 21.
Van Groningen, E. : 1987, *Astron. Astrophys.* **186**, 103.
Wu, C. C., Boggess, A., Gull, T. R. : 1980, *Astrophys. J.* **266**, 28.

Publ. Obs. Astron. Belgrade No. 50 (1995), 111 – 114

ANALYSIS OF THE MgII h SPECTRAL LINE SHAPES IN HR7275 AND IM Peg

L. Č. POPOVIĆ, I. VINCE, S. JANKOV, G. DJURAŠEVIĆ,
O. ATANACKOVIĆ-VUKMANOVIĆ and D. JEVREMOVIĆ
Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia
E-mail lpopovic@aob.aob.bg.ac.yu

Abstract. The analysis of high-resolution IUE spectra of the RS CVn type stars HR 7275 and IM Peg is presented. The inverse method technique was applied to the MgII h chromospheric emission line, that shows the presence of interstellar absorption, in order to recover the intrinsic stellar line profile parameters.

1. INTRODUCTION

The RS CVn type stars are chromospherically active stars consisting of a binary, one of whose components is a G-K sub-giant or giant. This component shows strong MgII k and h emission. It is established that the variations in the optical light curves of the RS CVn variables can be interpreted in terms of cool surface spots analogous to sunspots, but covering a large fraction of the RS CVn active component (Jankov, 1992). Associated with the modulation of optical light are variations in the strengths of chromospheric and transition region lines, which are generally in antiphase with the optical light curve (Rodono *et al.* 1986, 1987). So, the chromospheric MgII h spectral line shape reconstruction is very important for diagnostics of this region.

2. DATA AND ANALYSES

In this paper an inverse technique method, described by Vince *et al.* (1995), was used to reconstruct the MgII h spectral line shapes of HR 7275 and IM Peg stars from UV spectra observed by IUE.

2. 1. THE HR 7275 STAR

It is known from the catalogue of chromospherically active binary stars (Strassmeier *et al.*, 1988) that the HR 7275 (HD 179094) star ($m_v = 5.8$) is a member of the RS CVn class with K1IV-III spectral type. It is an object with X-ray and chromospheric emission in CaII H & K (class B) and MgII h & k, and H_α filled-in absorption. Radio emission was not detected. The star possesses a moderate projected rotational velocity $v \sin i = 15$ km/s.

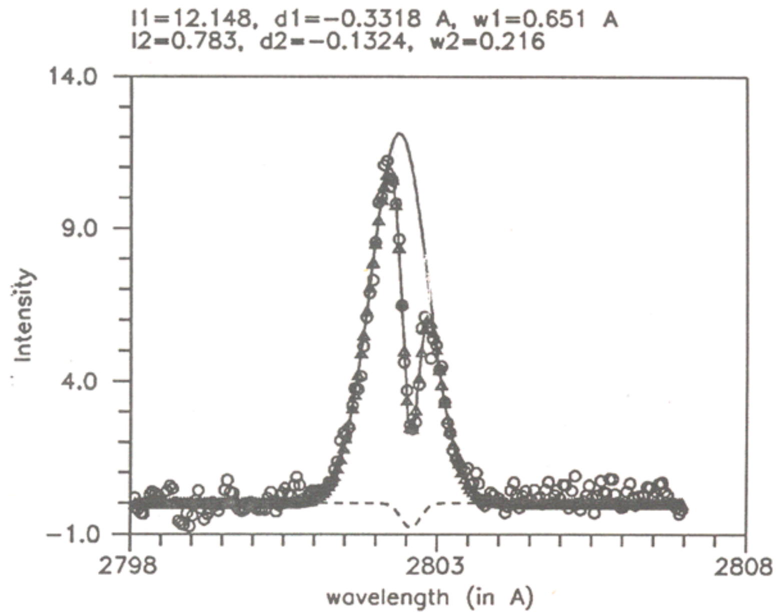

Fig. 1. The observed (circles), the best fitted (full line with triangles), the reconstructed emission (full line) and absorption (dashed line) spectral line profiles. I_1 is the intensity, d_1 is the shift and w_1 is the width of the emission line profile; I_2, d_2, and w_2 are the same parameters for the absorption line profile; exp. time=23 min

The two high-dispersion long wavelength IUE spectra were obtained with the LWR camera (image number LWR 10317, exposure time : 23 min) on 9th April 1981 and with the LWP camera (image number LWP 13852, exposure time : 30 min) 15th August 1988.

The observed MgII h spectral line profiles show a prominent interstellar absorption component near the core of the emission line profile (Figs. 1 and 2.).

The reconstructed MgII h spectral line profiles with the best fit parameters are given in Figs. 1 and 2.

2. 2. THE IM PEG STAR

The catalogue of chromospherically active binary stars (Strassmeier *et al.*, 1988) contains the following data on IM Peg (HD 216489). It is classified as a RS CVn K2III-II spectral type star (m_v = 5.60) with radio, X-ray and chromospheric emission in CaII H & K (class A) and MgII h & k, and H_α filled-in absorption. The star has an enhanced projected rotational velocity $v \sin i = 24$ km/s.

The two high-dispersion long wavelength IUE spectra were obtained with the LWR camera on 10th January 1981 (image number LWR 9680, exposure time : 15 min and image number LWR 9681, exposure time : 30 min).

The observed MgII h spectral line profiles show a prominent interstellar absorption component near the core (blue side) of the emission line profile (Figs. 3 and 4.).

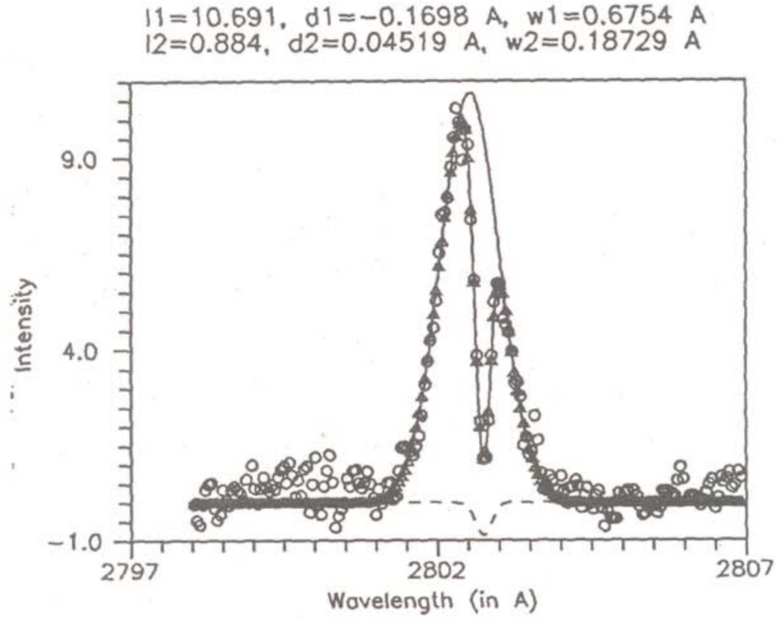

Fig. 2. The same as in Fig. 1; exp. time= 30 min

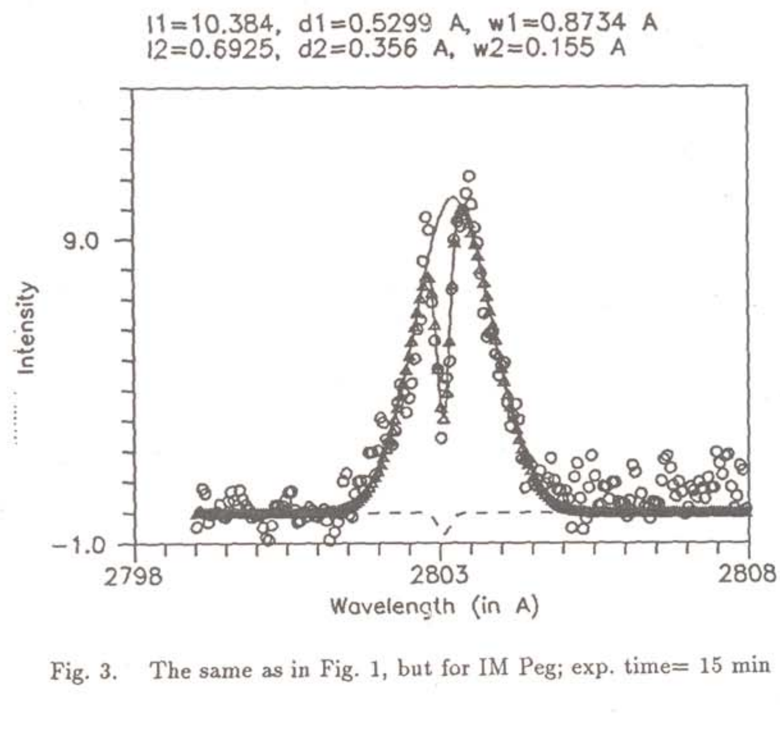

Fig. 3. The same as in Fig. 1, but for IM Peg; exp. time= 15 min

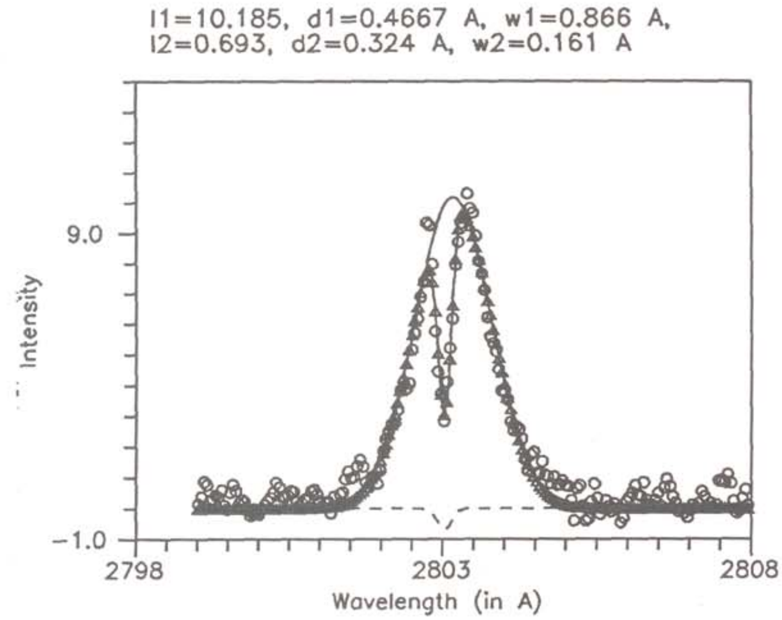

Fig. 4. The same as in Fig. 1, but for IM Peg; exp. time=30 min

The reconstructed MgII h spectral line profiles with the best fit parameters are given in Figs. 3 and 4.

References

Jankov, S., Foing, B. H. : 1992, *Astron. Astrophys.* **256**, 533-550.

Rodonò, M., Cutispoto, G., Pazzani, V., Catalano, S., Byrne, P. B., Doyle, J. G., Butler, C. J., Andrews, A. D., Blanco, C., Marilli, E., Linsky, J. L., Scaltriti, F., Busso, M., Cellino, A., Hopkins, J. L., Okazaki, A., Hayashi, S. S., Zeilik, M., Helston, R., Henson, G., Smith, P., Simon, T. : 1986, *Astron. Astrophys.* **165**, 135.

Rodonò, M., Byrne, P. B., Neff, J. E., Linsky, J. L., Simon, T., Butler, C. J., Catalano, S., Cutispoto, G., Doyle, J. G., Andrews, A. D., Gibson, D. M. : 1987, *Astron. Astrophys.* **176**, 267.

Strassmeier, K. G., Hall, D. S., Zeilik, M., Nelson, E., Eker, Z., Fekel, F. C. : 1988, *Astron. Astrophys. Supplement* **72**, 291.

Vince I., Popović, L. Č., Jankov, S., Djurašević, G., Atanacković-Vukmanović, O., Jevremović, D. : 1995, *Publ. Astron. Obs. Belgrade* **50**, 21.

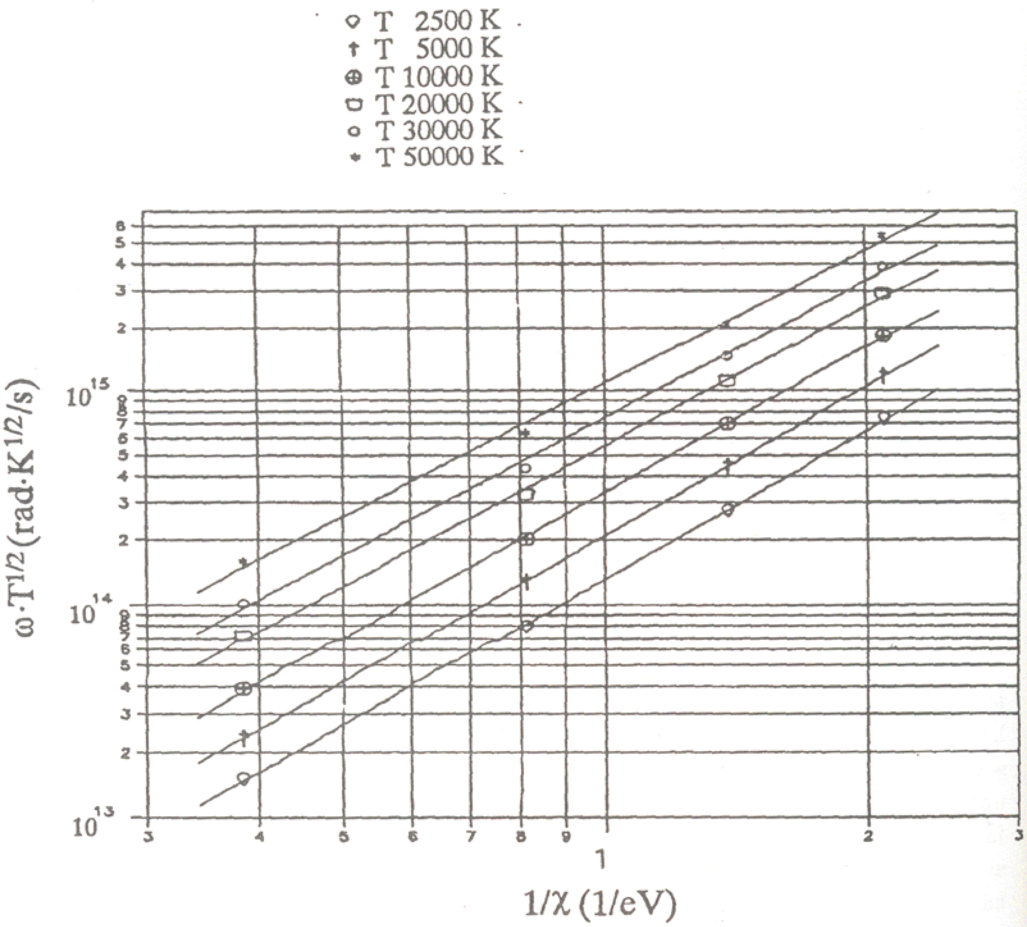

Fig. 1. a)

a) electron-impact width (w_e) of Rb I 4d - np and b) electron-impact width (w_e) of Li I 2s - np spectral lines as the functions of the inverse value of the upper level ionization potential χ. By a comparison of the regularities found here and those presented elsewhere (Figures 1 - 7) (Dimitrijević and Sahal-Bréchot, 1992) one can conclude that the method used here differs in the choice of the variable conveying atomic structure information. Prior work (Dimitrijević and Sahal-Bréchot, 1992) was based on the hydrogenic model. Consequently, it used integer principal quantum numbers instead of the upper level ionization potential. Although both parameters take into account the density of states perturbing the emitting state, the advantages of the present method are : (i) $\chi-$ based trend analyses achieve better fits; (ii) χ values of the lowering of the ionization potential (Inglis and Teller, 1939) are taken into account, predicting merging with continuum when the plasma environment causes a line's upper state

Table 1.

T (K)	electron				proton				Ar II			
	width		shift		width		shift		width		shift	
	A*	b	A*	b	A*	b	A*	b	A*	b	A*	b
2500	5,28	2,29	2,50	2,7	1,62	2,20	0,738	2,6	1,31	1,97	0,556	3,04
5000	4,21	2,31	2,57	2,7	1,19	2,23	0,614	2,7	0,957	2,01	0,465	3,09
10000	3,37	2,27	1,83	2,7	0,886	2,27	0,501	2,7	0,741	2,12	0,306	2,81
20000	2,76	2,18	1,17	2,6	0,660	2,30	0,405	2,7	0,539	2,14	0,249	2,84
30000	2,49	2,14	0,826	2,6	0,557	2,32	0,356	2,7	0,448	2,16	0,220	2,84
50000	2,17	2,07	0,523	2,5	0,452	2,35	0,300	2,7	0,356	2,18	0,188	2,85

a)

T (K)	electron				proton				He II			
	width		shift		width		shift		width		shift	
	A*	b	A*	b	A*	b	A*	b	A*	b	A*	b
2500	10,28	2,8	5,16	3,0	3,16	2,7	1,84	3,3	2,92	2,6	1,85	3,6
5000	7,65	2,8	3,328	2,9	2,432	2,7	1,50	3,4	2,15	2,6	1,24	3,4
10000	5,71	2,8	1,90	2,7	1,88	2,7	1,21	3,4	1,65	2,7	1,01	3,4
20000	4,21	2,7	0,990	2,5	1,40	2,7	0,884	3,2	1,227	2,7	0,806	3,4
30000	3,54	2,7	0,635	2,4	1,20	2,7	0,774	3,2	1,09	2,7	0,681	3,2
40000	3,112	2,6	4,91	2,3	1,25	2,8	0,840	3,2	1,09	2,7	0,681	3,2

b)

*A is given in $10^{10} \times \left[\frac{\text{rad}}{\text{s}}\right]$

the members where not available so far. The electron-, proton- and ionized helium-, and ionized argon-impact widths and shifts predicted by intraseries regressions analyses are of the same accuracy as the results used in the course of the calculation of coefficients A and b that are used in Eq.(1) to generate widths and shifts for higher series members. This method is computationally simple, involving each line' s upper level ionization potential and one multiplicative and one exponential fitting parameter per spectral series and emitter temperature and electron density. Such method is conductive to the method' s incorporation into mathematical simulations of stellar atmosphere opacities.

References

Dimitrijević, M. S., and Sahal-Bréchot, S. : 1991, *Bull. Obs. Astron.* Belgrade, **143**, 29.
Dimitrijević, M. S., and Sahal-Bréchot, S. : 1992, *Astron. Astrophys.*, **93**, 359.
Dimitrijević, M. S., and Sahal-Bréchot, S. : 1994, *Physica Scripta*, **49**, 661.
Inglis, D. R., Teller, E. : 1939, *Astrophys. J*, **90**, 439.
Purić, J. : 1993, XXI ICPIG, Invited Papers, Bochum.
Purić, J., Ćuk, M., Dimitrijević, M. S., Lesage, A. : 1991, *Astrophys. J.*, **382**, 353.
Purić, J., Miller, M. H., Lesage, A. : 1993, *Astrophys. J.* **416**, 825.

Publ. Obs. Astron. Belgrade No. 50 (1995), 121 – 125

A NOTE ON THE NEUTRINO DECAY LINE AND THE POSSIBILITIES OF ITS DETECTION

S. SAMUROVIĆ[1] and V. ČELEBONOVIĆ[2]

[1] *People's Observatory, Gornji grad 16, Kalemegdan, 11000 Belgrade, Yugoslavia*
E-mail srdjanss@mrsys1.mr-net.co.yu

[2] *Institute of Physics, Pregrevica 118, 11080 Zemun–Belgrade, Yugoslavia*
E-mail vladanc@mrsys1.mr-net.co.yu

When talking about spectral line shapes and intensities, one usually envisages some plasma similar to those produced in a laboratory, or existing in a natural environement. It is more than often completely disregarded that spectral lines can occur in a seemingly non-plasmatic part of physics – elementary particle physics.

The purpose of this contribution is to propose and discuss some mathematically simple but physically important results concerning the neutrino line and the possibilities of its detection. The cosmological importance of neutrinos stems from the fact that massive neutrinos may be the solution to the dark matter problem in the Universe (discussed in Frampton and Vogel, 1982; Sciama, 1993; Gelmini and Roulet, 1994, and numerous other publications). Outside cosmology, neutrinos are useful as probes of solar and stellar internal structure (for example, Hirata *et al.*, 1987; Burrows, 1990; Bahcall, 1994; Petcov, 1995) and stellar evolution (Castellani and Degl'Innocenti, 1993). Various kinds of interactions in which neutrinos participate can give rise to different spectral lines. The predicted wavelengths depend on the supposed neutrino masses.

The modern particle physics theory allows that neutrinos could have rest masses different from zero (Zeldovich and Hlopov, 1981). There are three neutrino types : ν_e, ν_μ and ν_τ, i.e. the number of types is equal to : $N_\nu = 3.00 \pm 0.04$ (Ting, 1993). The upper limit for their masses based upon earth based experiments are :

$$m_{\nu_e} < o(10\,\mathrm{eV}),$$

$$m_{\nu_\mu} < 160\,\mathrm{KeV}$$

and

$$m_{\nu_\tau} < 31\,\mathrm{MeV}.$$

(Gelmini and Roulet, 1994).

The hot big-bang cosmology sets the upper limit to the total neutrino mass (Klinkhamer and Norman, 1981) :

$$\sum_i m_{\nu_i} < 100\,\mathrm{eV}.$$

Neutrino mass plays the central role in the Sciama's (1993) decaying dark matter (DDM) model as well as in cold + hot dark matter (Cν^2DM) model created by Primack, Holtzman, Klypin and Caldwell (1995).

Neutrinos were relativistic at the decoupling and their present density for each neutrino type is :

$$n_\nu = 112\,\mathrm{cm}^{-3}$$

(Sciama, 1993).

The value of the neutrino mass for the type x, where $x = \nu, \mu, \tau$ can be expressed in the following form (see for example Schaeffer, 1994 and Samurović, 1995) :

$$m_{\nu_x} \sim 94 h^2\, \Omega_{\nu_x}\,\mathrm{eV} \tag{1}$$

where Ω_{ν_x} is the density parameter for the universe, and the estimations for its value are different in the different models. Hubble parameter, $h \equiv \frac{H_0}{100\frac{\mathrm{km/s}}{\mathrm{MPc}}}$ varies between 0.5 and 1, but it is possible that it is close to 0.5 in order not to get too small a value of the age of the universe.

Thus DDM model predicts $\Omega_{\nu_x} \sim 1$ and

$$m_{\nu_x} \sim 30\,\mathrm{eV}$$

(Sciama, 1993). Here ν_x denotes most probably tau neutrino, ν_τ. Sciama (1993) found a lower limit for m_ν for the Milky Way :

$$m_\nu = 27.6 \pm 1\,\mathrm{eV}.$$

Because of the fact that different neutrino types have different rest masses it is possible that the heavier neutrino decays into a lighter one. This process is followed by the emission of photons which produces observable ionization effects. Neutrino decay can be represented in the following form :

$$\nu_1 \rightarrow \nu_2 + \gamma.$$

We shall take that the more massive tau neutrino, ν_τ, decays into a photon and a muonic neutrino, ν_μ, where $m_{\nu_\tau} \gg m_{\nu_\mu}$:

$$\nu_\tau \rightarrow \nu_\mu + \gamma, \quad E_\gamma = \frac{1}{2} E_{\nu_\tau} = \frac{1}{2} m_{\nu_\tau}. \tag{2}$$

DDM theory (Sciama, 1993) gives the folowing value of this ratio $\frac{m_{\nu_\mu}}{m_{\nu_\tau}} \lesssim 0.2$. If we take that $E_{\nu_\tau} = 28\,\mathrm{eV}$ we shall get the flux of 14 eV photons – this value exceeds a little the Lyman limit of 13.6 eV for the hydrogen ionizing energy. However, these emitted photons will be redshifted by cosmological expansion and, therefore, will be able to ionize hydrogen near their point of origin. Also, self-absorption of the decay photons by the neutrinos can be ignored, because their energy will be below the one needed to initiate "the reverse action" of the type $\nu_\mu + \gamma \to \nu_\tau$ (OWB).

Due to the similarity of their ionization potentials, wherever hydrogen is ionized, nitrogen is also ionized. It can be shown (Sciama, 1993a) that :

$$14.53 < E_\gamma < 14.68\,\mathrm{eV}.$$

The upper limit for the value of the decaying photon energy follows from the requirement that these photons are the solution of the C^0/CO ratio problem.

Thus one obtains that

$$E_\gamma = 14.605 \pm 0.075\,\mathrm{eV}$$

(Sciama, 1993a). This would give, accordong to equation (2) the following value for the tau neutrino mass :

$$m_{\nu_\tau} = 29.21 \pm 0.15\,\mathrm{eV}$$

(Sciama, 1993a).

Under the assumption that the dark halo of the Galaxy consists mainly of massive neutrinos, Melott and Sciama (1981) and Sciama (1993) found that the neutrino decay will give the following limit for the neutrino lifetime :

$$\tau \geq 10^{23}\left(\frac{T}{10^4}\right)^{\frac{3}{2}}\left(\frac{0.6\,\mathrm{cm}^{-3}}{n_e}\right)^2\left(\frac{1\,\mathrm{kpc}}{d}\right)\left(\frac{0.05\,\mathrm{rad}}{\varphi}\right)\left(\frac{30\,\mathrm{eV}}{m_\nu}\right)N$$

where τ is expressed in seconds. T is the cloud temperature, n_e its electron density, d its distance, φ its angular radius and N is the average number of ionizations caused by a given photon. From this equation one can see that lifetime τ ranges from 10^{23} to 10^{24} s.

One can establish an equation that connects the lifetime τ and transition magnetic moment μ_{12} under the assumption $\frac{m_{\nu_\mu}}{m_{\nu_\tau}} \ll 1$ (Sciama, 1993) :

$$\tau = 10^{23}\left(\frac{30\,\mathrm{eV}}{m_1}\right)^3\left(\frac{10^{-14}\mu_B}{\mu_{12}}\right)^2 \mathrm{s}$$

where the Bohr magneton $\mu_B = \frac{eh}{2m_e c}$. For $m_1 = m_{\nu_\tau} \sim 30$ eV and $\mu_{12} \sim 10^{-14}\mu_B$ one would obtain the lifetime $\tau \sim 10^{23}$ s. Castellani and Degl'Innocenti (1993) considered the effect of a nonvanishing neutrino magnetic moment on the stellar evolution and obtained the upper limit $\mu_{12} < 10^{-12}\mu_B$ which points out that the estimated value for the neutrino lifetime τ is possible.

Although Hopkins Ultraviolet Telescope during its observations of the cluster A655 did not detect the line of the decay photon with energy E_γ that ranges between 14.5 and 15 eV (Sciama, 1993) it is quite possible that the dark matter in the center of this cluster is partly baryonic (Ashman, 1992). In this case the strength of the neutrino decay line is less than the one predicted by the fact that *all* the dark matter in the cluster is made of decaying neutrinos (Ashman, 1992). In this cluster there could be significant amounts of neutrinos (Sciama, 1993).

However, Reimers and Vogel (1993) detected HeI resonance lines in four high-redshift Lyman limit systems of the QSO HS 1700+6416 (z=2.72). They found neutral hydrogen to neutral helium column density ratios $\frac{N_{\rm HI}}{N_{\rm HeI}} \approx 30$. According to their analysis HeI column densities are ~ 5 times greater than column densities obtained by their model calculations. The fact that effective hydrogen ionizing flux is ~ 8 times greater than helium ionizing flux may be the consequence of the feature of the DDM theory, according to which decay photons can ionize hydrogen but not helium (Sciama, 1994).

According to Cν^2DM theory proposed by Primack, Holtzman, Klypin and Caldwell (1995) that uses cold + hot dark matter (CHDM) requirement that a total neutrino mass ~ 5 eV, suggests that masses of mu and tau neutrinos are approximately equal i.e. $m_{\nu_\mu} \approx m_{\nu_\tau} \approx 2.4$ eV. It is worth noting that this value is obtained from equation (1), but the density parameter is taken to be $\Omega_\nu \sim 0.3$ and the Hubble parameter is again $h \sim 0.5$.

We discuss the simple case of the radiative decay of these light neutrinos. The obvious relation :

$$m_\nu c^2 = h\frac{c}{\lambda}$$

gives

$$\lambda = \frac{h}{m_\nu c}$$

for the wavelength of the spectral line emitted in the process. When we insert the appropriate numerical values, we obtain :

$$\lambda_{\rm nm} = \frac{1239.85}{m_{\nu[\rm eV]}}.$$

For $m_\nu = 2.4$ eV, we obtain $\lambda = 516.6$ nm.

Another spectroscopically interesting question is the shape of this line. As cross sections for neutrino interactions with matter are very low, it can safely be assumed that the line is very nearly monochromatic, i.e., that it only has the natural width. Its value can be simply estimated from the uncertainty principle as :

$$\Delta\lambda = \frac{\lambda^2}{2\pi c\tau}$$

which tends to 0 due to huge values of τ.

The order of magnitude estimates of the neutrino decay line wavelength and its natural width are presented in the Table 1.

Table 1

Neutrino type	m_ν	λ [nm]
e	10 eV	123.985
μ	150 KeV	0.0083
τ	30 MeV	4.1×10^{-5}

It can be concluded that the line is monochromatic. As for the wavelenghts, the only one which could be experimentally detected is the line originating in the radiative decay of ν_e. The precise value of the wavelength depends (obviously) on the mass; if $m_\nu \approx 2.4$ eV, as in the Cν^2DM theory, $\lambda = 516.6$ nm. The line intensity is a function of the concentration of the decaying neutrinos; the precise form of this dependence remains a problem for further study. It has very recently been shown (Vassilevskaya, Gvozdev and Mikheev, 1995) that the probability of a radiative decay of a massive neutrino can greatly increase in strong electromagnetic fields. Under certain conditions, the increase can be as large as 10^{33} times! This renders the detection of the neutrino decay line much easier in the case of astronomical objects in whose vicinity exist strong electromagnetic fields.

A word about cosmological neutrinos. A neutrino decaying in an astronomical object having redshift z would give a line with

$$\lambda = \frac{h}{m_\nu c}(1+z)$$

which could be important in case of QSOs, for example.

1. CONCLUSION

The object of this note is the spectral line due to the radiative decay of a massive neutrino. We have calculated the wavelength and the natural width of the line as a function of the mass and lifetime of the neutrino having $m_\nu \lesssim 10$ eV. Several observational consequences of this process were discussed. The newly discovered enhacement of the decay rate in strong electromagnetic fields renders the analysis of the neutrino decay line important even for observational astronomers.

References

Ashman, K. M. 1992, *Pub A.S.P.*, **104**, 1109.
Bahcall, J. N. : 1994, *Phys. Lett.*; **B338**, 276.
Burrows, A. : 1990, *Annu. Rev. Nucl. Part. Sci.*, **40**, 181.
Hirata, K., Kajita, T., Koshiba, M. *et al.* : 1987, *Phys. Rev. Lett.*, **58**, 11490.
Castellani, V. and Degl'Innocenti, S. : 1993, *Ap. J.*, **402**, 574.
Frampton, P. H. and Vogel, P. : 1982, *Phys. Rep.*, **82**, 339.
Gelmini, G. and Roulet, E. : 1994, preprint CERN-TH 7541/94.
Melott, A. L. and Sciama, D. W. : 1981, *Phys. Rev. Lett.*, **46**, 1369.
Overduin, J. M., Wesson, P. S. and Bowyer, S. (OWB) : 1993, *Ap. J.*, **404**, 460.
Petcov, S. T. : 1995, preprint SISSA 12/95/EP.
Primack, J. R., Holtzman, J., Klypin, A. and Caldwell, D. O. : 1995, *Phys. Rev. Lett.*, **74**, 2160.
Samurović, S. : 1995, unpublished work.
Schaeffer, R. : 1994, *Cosmologie*, Saclay preprint, T94/025.
Sciama, D. W. : 1993, *Modern Cosmology and the Dark Matter Problem*, Cambridge University Press.
Sciama, D. W. : 1993a, *Ap. J.*, **415**, L31.
Sciama, D. W. : 1994, *Ap. J.*, **422**, L49.
Ting, S. C. C. : 1993, preprint CERN - PPE/93-34.
Vassilevskaya, L. A., Gvozdev, A. A. and Mikheev, N. V. : 1995, *Jadernaja fizika*, **58**, 712.
Zeldovich, Y. B. and Hlopov, M. Y. : 1981, *U.F.N.*, **135**, 45.

Publ. Obs. Astron. Belgrade No. 50 (1995), 127 – 129

MEASURED STARK WIDTH OF THE 324.75 nm Cu I RESONANCE SPECTRAL LINE

LJ. SKULJAN[1], S. BUKVIĆ[2] and S. DJENIŽE[2]
[1]*Astronomical Observatory, Volgina 7, 11050 Belgrade, Yugoslavia*

[2]*Faculty of Physics, University of Belgrade, P.O.B. 368 11001 Belgrade, Serbia, Yugoslavia*

Abstract. Stark width of the 324.75 nm CuI resonance spectral line have been measured in a linear pulsed arc plasma, superimposed to the glow discharge positive column plasma in argon-helium mixture. Copper atoms have been released as impurities by sputtering from a glow discharge copper electrode separated from the optical axis.

1. INTRODUCTION

CuI resonance spectral lines belong to the group of most intensive lines (Zaidel *et al.*, 1977). Because of that a knowledge of their characteristics is important for diagnostics of astrophysical and various plasmas created in laboratory in which copper exists as impurity. To the knowledge of the authors (Fuhr and Lesage, 1993) no experimental Stark widths data exist for the CuI resonance lines. In this work we present measured Stark FWHM (full-width at half maximum intensity) (w_m) values of the 324.75 nm CuI resonance spectral line at 17 000 K electron temperature in the argon-helium plasma.

2. PLASMA SOURCE AND PROCEDURE

A reliable plasma source has been constructed with a repetitive discharge superimposed to the continuous glow discharge. The Pyrex discharge tube is shown shematically in Fig. 1 in Djeniže *et al.* (1995). The glow discharge was driven between water-cooled copper electrodes on 50 mA circuit current in argon-helium mixture at 130 Pa filling pressure in flowing regime. Copper atoms have been released as impurities by sputtering from a copper electrode. The homogenous positive-column plasma was located in the linear part of the discharge tube (i. d 5 mm). This part was sealed with quartz windows. Two auxiliary ring-shaped electrodes were positioned along the optical axis of the glow discharge positive column plasma, 80 mm apart from each other. They were used to drive the pulsed discharge from condenser of 80 μF charged up to 1.2 kV. Investigated CuI spectral line was well isolated from other spectral lines emitted by this plasma. The spectroscopic observations were made end-on, along the

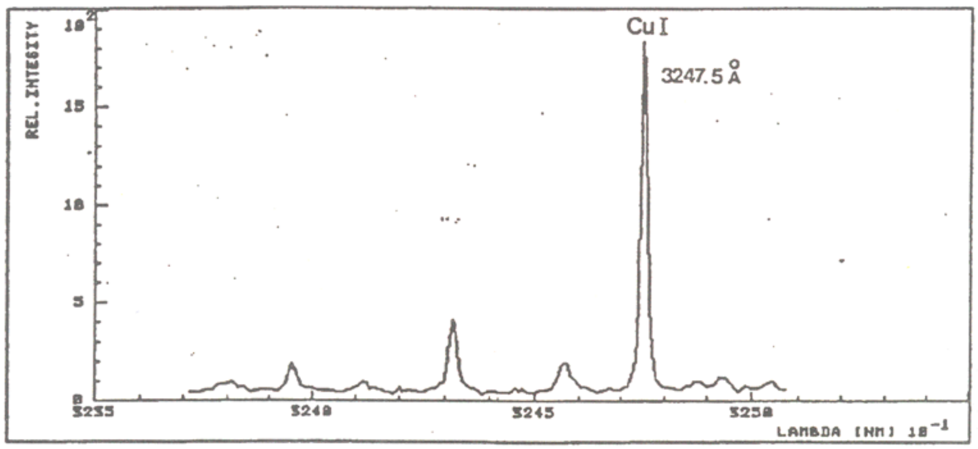

Fig. 1. The recorded spectrum with the CuI resonance spectral line.

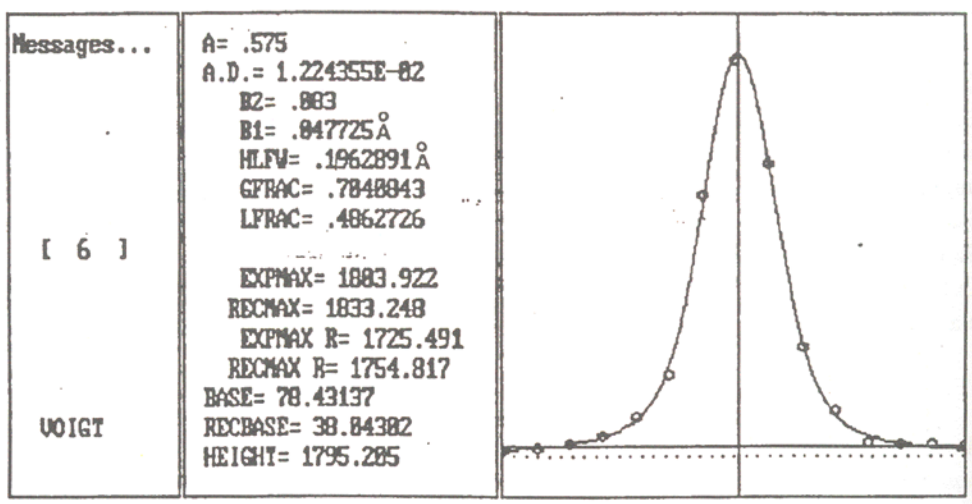

Fig. 2. CuI line profile, o-experimental points and (—) fitted Voigt profile.

axis of the discharge tube. Scanning of the spectral line profile was done using a shot-to-shot technique described elsewhere (Djeniže *et al.*, 1991).

The photomultiplier signal was digitized using digital scope interfaced to a computer. A sample output, as example, is shown in Fig. 1. The measured profil was of a Voigt type. The standard deconvolution procedure (Davies and Vaughan, 1963) was computerized using the least square algoritm. A sample output is shown in Fig. 2. The estimated error of the obtained Stark FWHM was within ±22% caused dominantly by the relatively small contribution of the Lorentz fraction to the Voigt profile.

Parameters of the pulsed plasma were determined by a standard diagnostic method. Electron temperature (T) of 17 000 K was found from the ratio of relative intensities of ArII 500.9 nm and ArI 696.5 nm spectral lines assuming the existence of the LTE within ±15% accuracy. The necessary atomic parameters were taken from Wiese *et al.* (1969). The electron density (N) decay was found by a single wavelength laser interferometry (Ashby *et al.*, 1965) using 632.8 nm He-Ne laser line. The maximal electron density on $6.6 \cdot 10^{22} \mathrm{m}^{-3}$ was obtained within ±8% accuracy.

3. RESULTS

The measured w_m value at electron temperature of 17 000 K and electron density of $6.6 \cdot 10^{22} \mathrm{m}^{-3}$ was 0.0095 nm.

Acknowledgements

This research was supported by Republic Fund for Science of the Republic Serbia.

References

Ashby, D. E. T. F., Jephcott, D. F., Malein, A., Ragnev, F. A. : 1965, *Appl. Phys.* **36**, 29.

Davies, J. T., Vaughan, J. M. : 1963, *Astroph. J.* **137**, 1302.

Djeniže, S., Skuljan, Lj., Konjević, R. : 1995, *JQSRT* (in press)

Djeniže, S., Srećković, A., Labat, J., Konjević, R., Popović L. : 1991, *Phys. Rev.* A **44**, 410.

Fuhr, J. R., Leasge, A. : 1993, *Bibliography on Atomic Line Shapes and Shifts* (July 1978 through March 1992) NIST Special Publication 366 Supplement 4 US : DC National Institute of Standards and Technology.

Wiese, W. L., Smith, M. W., Miles B. M. : 1969, *Atomic Transition Probabilities*, NSRDS-NBS 22 (U. S. GPO, Washington, D. C.) Vol. II.

Zaidel, A. N., Prokofev, V. K., Raisky, S. M. : 1977, *Tablitsy Spectralnyih Linii* (in Russian) Nauka, Moscow.

Publ. Obs. Astron. Belgrade No. 50 (1995), 131 – 134

LIGHT SOURCE FOR THE STUDY OF NEUTRAL GAS PRESSURE BROADENING

N. ŠIŠOVIĆ[1], I. VIDENOVIĆ[1], M. KURAICA[1], V. MILJEVIĆ[2] and N. KONJEVIĆ[1]
[1] *University of Belgrade, Faculty of Physics, P.O.Box 368, 11001 Belgrade, Yugoslavia*

[2] *Atomic Physics Laboratory, Institute "Vinča", P.O.Box 552, 11001 Belgrade, Yugoslavia*

Abstract. A discharge formed in a cylindrical coaxial diode with a cylindrical mesh cathode (CMCD) as new light source for the study of neutral gas pressure broadening is investigated. The pressure broadened profiles of two neon spectral lines emitted from low pressure CMCD glow dischrage have been studied using a Fabry-Perot interferometer.

1. INTRODUCTION

Spectroscopic study of neutral gas pressure broadened spectral lines at low pressures meets certain experimental problems related to the basic features of commonly used light sources. Standard sources for these studies are water-cooled capillary glow discharges (see e.g. Bielski and Wolnikowski, 1978) with relatively high current densities even in low discharge current regime. In this paper we describe new light source with transversal excitation and much lower current density. The results of the line shape studies of two neon spectral lines λ = 585.25 nm, λ = 692.95 nm in low pressure regime are reported.

2. EXPERIMENTAL

Our CMCD is shown in Fig 1. This type of glow discharge is first reported by Miljević in 1982 and used at lower pressures as magnetron light source. It consists of two coaxial electrodes : a cylindrical anode - CA (ID 18 mm × 80 mm), and a cylindrical mesh cathode - CMC (ID 5.5 mm, OD 7.5 mm × 110 mm). The mesh is manufactured of stainless steel wire (dia 0.4 mm), and has a transparency of about 60%. The diode is placed in a glass tube (Pyrex, dia 5 cm, long 50 cm). Quartz windows are mounted on ends of the tube to allow end-on glow discharge observations along optical axis. The countinous flow of the working gas - neon was sustained at pressure in the region $p = 266 - 931$ Pa by means of a needle valve and two stage mechanical vacuum pump. To run discharge a stabilized dc voltage power supply (0 – 2 kV, 0 – 100 mA) was used. Ballast resistor $R = 10$ kΩ was placed in series with the discharge and power

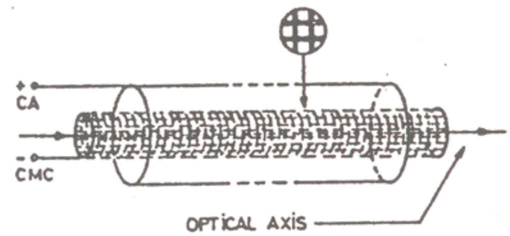

Fig. 1. Schematic diagram illustrating the CMCD.

supply. All measurements were performed at the discharge current $I = 20$ mA and voltage $U = 210$ V.

The light from CMDC was focused by achromatic lens (focal length $f = 15$ cm) onto front mirror of piezoelectrically-scanned Fabry-Perot interferometer (distance between mirrors $d = 12$ mm, $R = 0.875 - 0.980$, free spectral range $\Delta\lambda_S = 0.014 - 0.020$ nm), combined with 0.25 m grating monochromator-photomultiplier detection system. The signals from detection system were A/D converted, collected and processed by PC.

3. RESULTS AND DISCUSSION

Typical recorded line shape of neon spectral line $\lambda = 585.25$ nm is given in Fig.2. In the analysis of the profile, we have made assumption that the overall profile is convo-

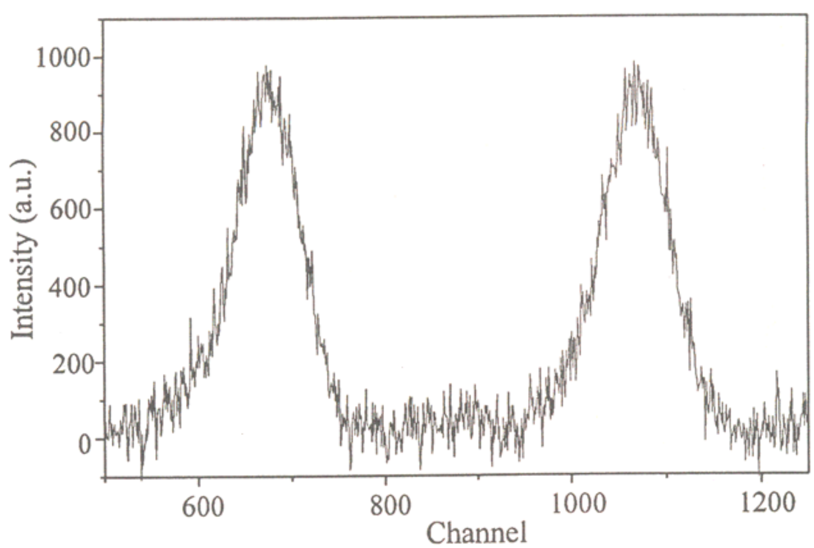

Fig. 2. Typical Fabry-Perot interferogram of NeI λ=585.25 nm at the pressure p=266 Pa.

lution of Airy's, apparatus function of Fabry-Perot interferometer, and Voigt profile. The Gaussian part of the Voigt profile gives the information about gas kinetic temperature of the discharge, while the Lorentzian fraction describes the pressure broadening of the spectral line. In the deconvolution procedure, we have followed the method of graphic deconvolution, described by Platiša *et al.* (1983). The results of such analysis are given in Figures 3. and 4.

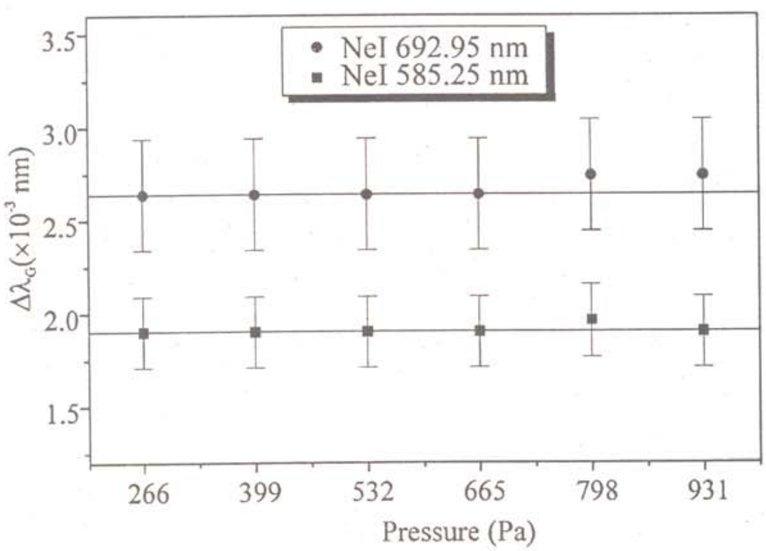

Fig. 3. Dependence of Gaussian half-width $\Delta\lambda_G$ vs. neon pressure.

As can be seen the Gauusian half-width is independent of the neon pressure. Gas temperatures derived from Gaussian part of line profiles are $T_G = (400 \pm 40)$K.

The half-widths of Lorentzian component of both spectral line profiles show the predicted linear dependence upon the neon pressure (Fig.4.).

For the line λ = 585.25 nm, we have obtained the simmilar value of pressure broadening coefficient, β = 4.04, in comparsion with that measured by Bielski and Wolnikowski (1978) (β = 3.72). Unfortunately, the half-widths of Lorentzian part are three times larger. At this moment we can not trace the cause for this large discrepancy.

Further experimental work is in progress and results will be reported at the Conference.

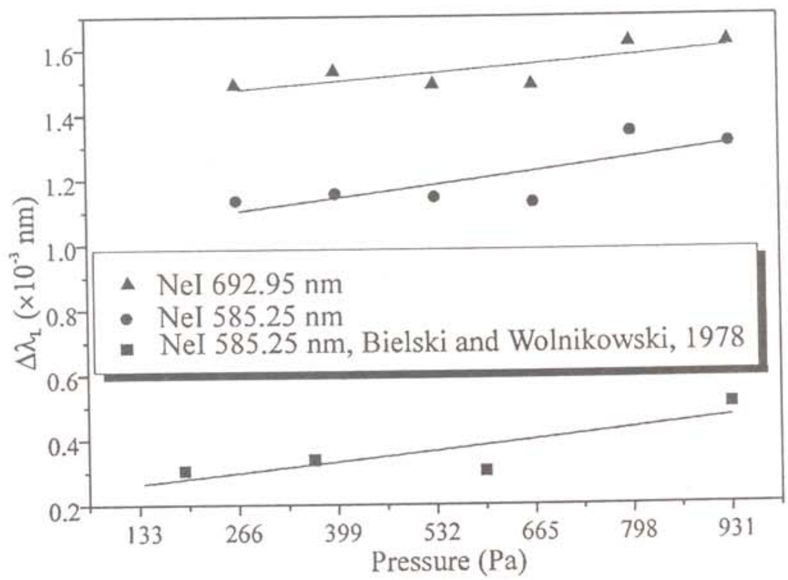

Fig. 4. Dependence of Lorentzian half-width $\Delta\lambda_L$ vs. neon pressure.

References

Bielski, A. and Wolnikowski, J. : 1978, *Acta Phys. Pol.*, **A 54**, 601.
Miljević, V. : 1982, *Phys. Lett.*, **92 A**, 439.
Platiša, M. *et al.* : 1983, *Opt. Las. Tech.*, **9**, 209.

Publ. Obs. Astron. Belgrade No. 50 (1995), 135 – 138

A SIMPLE CORRECTION OF LOW N BALMER LINE INTENSITIES FOR BOUNDARY LAYER INFLUENCE IN SMALL T–TUBE PLASMAS

M. TERZIĆ and M. PAVLOV

University of Novi Sad, Faculty of Science & Mathematics, Trg Dositeja Obradovića 4, 21000 Novi Sad, Yugoslavia

1. INTRODUCTION

It has been generally accepted (Kolb, 1957; Pavlov and Prasad, 1968) that plasmas produced in small electromagnetic T–shaped shock tubes are quite homogeneous radially and also axially behind the reflected shock front. Thereafter these plasmas appear as very attractive for spectroscopic observations of their radiation, since no, say Abel inversion is required. Apart from small-scale turbulence, the only inhomogeneities encountered occur in the boundary layers between the inner plasma and the cold glass tube walls. The thickness of these boundary layers reaches approx. 1 mm within a few microseconds after the reflected shock front has passed the point of observation (Pavlov and Prasad, 1968; Pavlov and Djurović, 1982). Because these boundary layers are thin compared to typical tube diameters of 25 mm, it has been assumed that they do not introduce noticeable changes in spectral intensities (Meins and Weiss, 1976; Hay and Griem, 1975). Influence of simplified boundary layer model on line profiles (Pavlov and Terzić, 1987) showed that this need not be true. Emitted spectral intensities (per unit wavelength) in the cited paper (Pavlov and Terzić, 1987) were calculated by numerical integration of the equation for radiative transfer (Griem, 1964).

2. LINE INTENSITIES EMITTED BY T–TUBE PLASMAS

Total line intensities $J_{\rm b}$ influenced by boundary layers, for H_α, H_β and H_γ were calculated by numerical integration of spectral intensities (per unit wavelenght) of the lines. So were calculated total line intensities $J_{\rm h}$ when T–tube is filled from wall-to-wall with homogeneous plasmas. It turned out that the ratios $J_{\rm b}/J_{\rm h}$ are linear functions of boundary layer thickness δ as illustrated in Fig. 1. for H_β line. It means that the ratio $J_{\rm b}/J_{\rm h}$ can be presented as

$$\frac{J_{\rm b}}{J_{\rm h}} = 1 + A \cdot \delta \quad . \qquad (1)$$

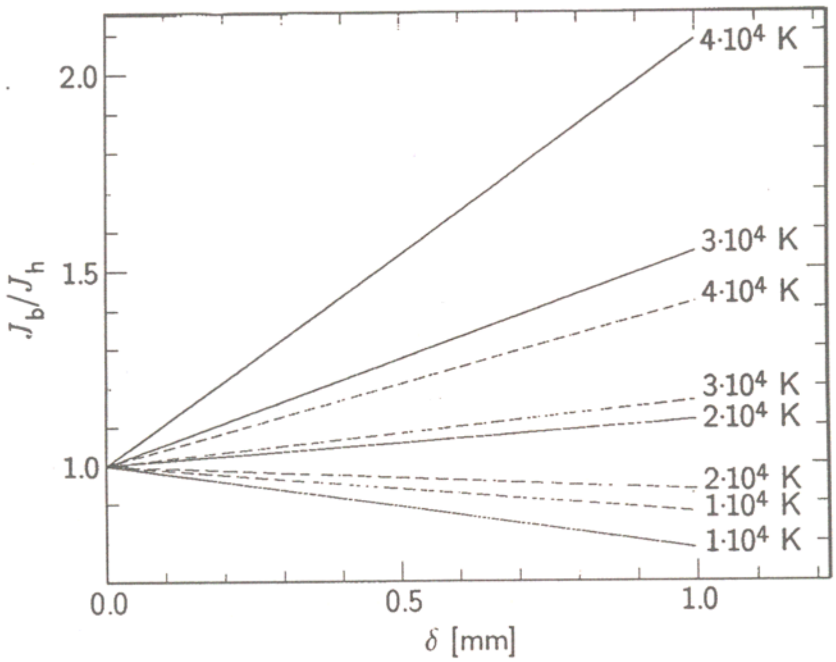

Fig. 1. Ratio of total line intensities influenced by boundary layers J_b / homogeneous plasma J_h, as function of the boundary layer thickness for electron concentration of $N_e = 1 \cdot 10^{22}$ m^{-3} (solid lines) and $N_e = 5 \cdot 10^{23}$ m^{-3} (dashed lines).

Correction factor $A \cdot \delta$ can be calculated using Tables 1, 2 and 3 for relevant values of A, as well as independently determined (or at least estimated) thickness δ of the boundary layer (Pavlov and Prasad, 1957; Pavlov and Djurović, 1982). The intensity J_h, without influence of boundary layers can then be calculated from the above-adduced equation after J_b is measured say by shot-to-shot scanning technique.

Table 1.
Coefficient A of Eq. 1. (in mm^{-1}) for H_α line

N_e [m^{-3}]	T [K]			
	$1 \cdot 10^4$	$2 \cdot 10^4$	$3 \cdot 10^4$	$4 \cdot 10^4$
$1 \cdot 10^{22}$	-0.183	0.159	0.697	1.413
$2 \cdot 10^{22}$	-0.162	0.117	0.581	1.203
$5 \cdot 10^{22}$	-0.141	0.048	0.435	0.934
$1 \cdot 10^{23}$	-0.135	0.002	0.326	0.754
$2 \cdot 10^{23}$		0.044	0.203	0.560
$5 \cdot 10^{23}$		0.082	0.047	0.313
$1 \cdot 10^{24}$		0.099	-0.052	0.093

Table 2.
Coefficient A of Eq. 1. (in mm^{-1}) for H_β line

N_e [m^{-3}]	T [K]			
	$1 \cdot 10^4$	$2 \cdot 10^4$	$3 \cdot 10^4$	$4 \cdot 10^4$
$1 \cdot 10^{22}$	-0.217	0.130	0.545	1.080
$2 \cdot 10^{22}$	-0.215	0.095	0.466	0.936
$5 \cdot 10^{22}$	-0.207	0.042	0.372	0.767
$1 \cdot 10^{23}$	-0.192	0.007	0.297	0.657
$2 \cdot 10^{23}$	-0.164	-0.025	0.243	0.547
$5 \cdot 10^{23}$	-0.124	-0.067	0.137	0.415
$1 \cdot 10^{24}$	-0.102	-0.087	0.103	0.309

Table 3.
Coefficient A of Eq. 1. (in mm^{-1}) for H_γ line

N_e [m^{-3}]	T [K]			
	$1 \cdot 10^4$	$2 \cdot 10^4$	$3 \cdot 10^4$	$4 \cdot 10^4$
$1 \cdot 10^{22}$	-0.221	0.099	0.480	0.950
$2 \cdot 10^{22}$	-0.221	0.075	0.449	0.827
$5 \cdot 10^{22}$	-0.218	0.037	0.424	0.695
$1 \cdot 10^{23}$	-0.215	0.001	0.302	0.585

3. DISCUSSION

For the purpose of say inner plasma electron temperature T determination from line to continuum intensity ratio (Griem, 1964), it is necessary to use J_h as well as J_{hc} (continuum intensity for homogeneous plasma). Influence of the boundary layers on continuum intensity is descused elsewhere (Pavlov and Radujkov, 1985; Radujkov and Pavlov, 1986).

Inspecting the Tables 1, 2 and 3 for H_α, H_β and H_γ one can see that for small values of electron temperature and densities of inner part of plasma, the ratio J_b/J_h can considerably differ from unity having in mind that δ is typically a fraction of a millimetre.

The ratio J_b/J_h, that is the value of correction factor $1+A\cdot\delta$, for a given δ is the largest at the high temperature and low density part od the Table 1, 2, and 3. Luckily, the T–tube plasmas decay starts typically at the high density and temperature corner of the Tables 1, 2 and 3 terminating at the opposite corner, that is at low density and temperature of the plasma. One can see that along the Tables diagonals the values of A are very small. That means, the correcting factor $1+A\cdot\delta$ is close to 1 particularly at the beginning of the plasma decay where the boundary layer thickness δ is also small, typically 0.1 mm during the first 2 μs (Pavlov and Radujkov, 1985; Radujkov and Pavlov, 1986).

References

Griem, H. R. : 1964, *Plasma Spectroscopy*, McGraw-Hill, New York.
Hay, J. D. and Griem H. R. : 1975, *Phys. Rev.* **A12**, 169.
Kolb, A. C. : 1957, *Phys. Rev.* **107**, 345.
Meins, D. and Weiss, W. : 1976, *JQSRT*, **16**, 273.
Pavlov, M. and Prasad, A. N. : 1968, *Z. Phys.* **212**, 266.
Pavlov, M. and Djurović, S. : 1982, *Rev. Res. Fac. Sci. Univ. Novi Sad* **14**, 43.
Pavlov, M. and Terzić, M. : 1987, *JQSRT* **37**, 373.
Pavlov, M. and Radujkov, V. : 1985, *JQSRT*, **33**, 475.
Radujkov, V. and Pavlov, M. : 1986, *JQSRT*, **35**, 479.

Publ. Obs. Astron. Belgrade No. 50 (1995), 139 – 143

THE USE OF ATOMIC HYDROGEN LINE SHAPES FOR ABNORMAL GLOW DISCHARGE DIAGNOSTICS

I. VIDENOVIĆ, M. KURAICA and N. KONJEVIĆ
University of Belgrade, Faculty of Physics, P.O.Box 368, 11001 Belgrade, Yugoslavia

Abstract. The measurements of the shape of Balmer H_β line in the cathode fall and negative glow regions of the abnormal glow discharge in pure hydrogen are reported. The electric field intensity distribution is obtained using polarization-dependent Stark splitting of hydrogen lines. Two groups of excited neutrals with significantly different velocities have been detected.

1. INTRODUCTION

Recent spectroscopic measurements (Barbeau and Jolly, 1991; Ganguly and Garscadden, 1991) of the electric field intensity distribution, performed in conventional parallel – plates discharge structures, confirm that almost whole voltage drop takes part in the cathode fall region of glow discharges. On the other hand, studies of shapes of atomic-hydrogen lines (Benesch and Li, 1984; Petrović *et al.*, 1992; Kuraica and Konjević, 1992) in the negative glow region of hollow and plane-cathode glow discharges have shown hydrogen line shapes with extraordinary broad wings, which indicate the presence of excited hydrogen atoms with high velocities.

Both of these effects we have been faced whithin our experiment. As a light source we have used the plane cathode, cylindrical hollow anode abnormal glow discharge of the Grimm type (1967, 1968). This lamp is extensively used in atomic emission spectroscopy.

2. EXPERIMENT

Our discharge is laboratory made and fully described elsewhere (Kuraica *et al.*, 1992). Here we should mention only a few important details. The exchangeable hollow anode 30 mm long with inner and outside diameters 8 and 13 mm, has a longitudinal (15 mm long, 1.5 mm wide) slot for plasma observations. The water-cooled cathode holder has an exchangeable iron electrode 18 mm long and 7.60 mm in diameter which screws tightly onto its holder to ensure good cooling. Spectra recordings were performed side-on (see Fig.1.), in 1/8 mm steps along the discharge axis. The gas flow through the discharge of about 500 cm^3/min STP was sustained at a pressure of 150 Pa by means of a needle valve and two-stage mechanical vacuum pump. To run the discharge a 0-2 kV, 0-100 mA dc voltage stabilized power supply was used. In series with the discharge and power supply a ballast resistor of 10 kΩ was placed. The measurements were performed at 20 mA discharge current and 640 V applied to the electrodes.

After polarization (Glan Thompson prism), the light from the plasma source was focused with unity magnification (maximum solid angle 6°) onto the entrance slit of scanning monochromator-photomultiplier system (2 m focal length with 600 g/mm reflection grating and reciprocal dispersion 0.74 nm/mm). The measured instrumental half-width with 15 mm slits was 0.014 nm. The signals from detection system were A/D converted, collected and processed by PC.

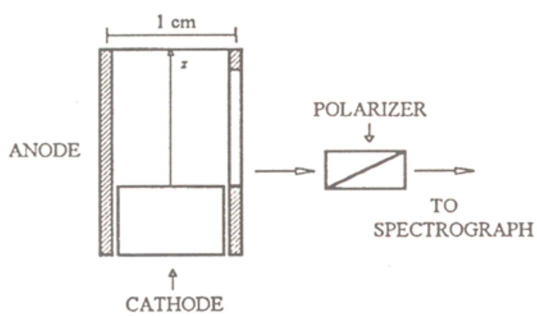

Fig. 1. Schematic diagram illustrating the discharge and polarizing prism.

3. RESULTS AND DISCUSSION

Spectra recordings along the discharge axis from the cathode surface enables us to observe continuously both cathode fall and negative glow region of the discharge.

Cathode fall region. Typical profiles measured in the vicinity of the cathode are shown in Fig.2. Two distinctive maximums of H_β profiles, recorded with polarizer axis parallel (Fig.2.a.) and perpendicular (Fig.2.b.) to the discharge axis, indicate that the presence of external electric field predominantly determines the line shapes in this part of the discharge. Following the theory of the linear Stark effect (Condon and Shortley, 1977) we assumed that overall profile of both components (linearly polarized, parallel to the electric field (**E**), i.e. $\pi-$component, and circularly polarized one in the plane perpendicular to **E** - $\sigma-$component) of H_β line consists of ten sub-components. The distance between these sub-components is equal to the integer multiple of (Ryde, 1976) :

$$\Delta\lambda_0(\text{nm}) = 1.51 \times 10^{-3} \times E\ (\text{kV/cm}).$$

To the each sub-component we have assigned the Gauss function which takes into account the Doppler and instrumental broadening. Considering overall profile as the sum of Gaussians, we have fitted the experimental data with the resulting function, taking the electric field intensity and temperature of H-atoms as variables. The fitted functions are represented by dashed lines in Fig.2. Knowing the electric field intensity from the first fit, we have performed additional fitting of the far wings of the profiles with smaller amplitude and higher temperature. The results of those calculations are represented by short dashed lines, while overall profiles (sum of both fitting procedures) are shown by solid lines in Fig.2.

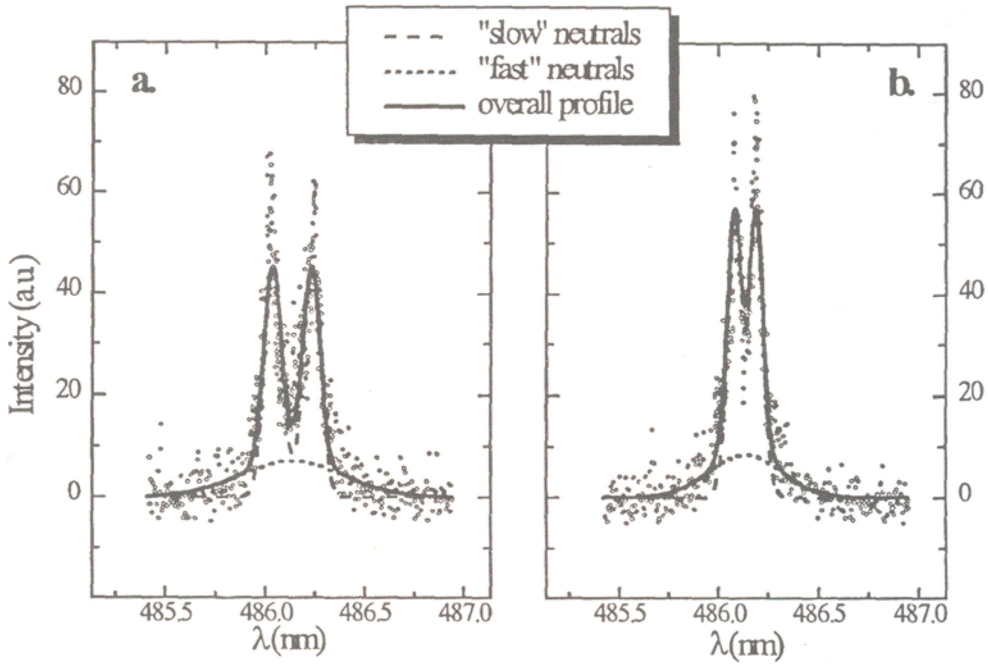

Fig. 2. Typical H_β profiles recorded at 0.12 mm from the cathode : a. π−component, b. σ−component. Discharge conditions : 150 Pa, 20 mA, 640 V.

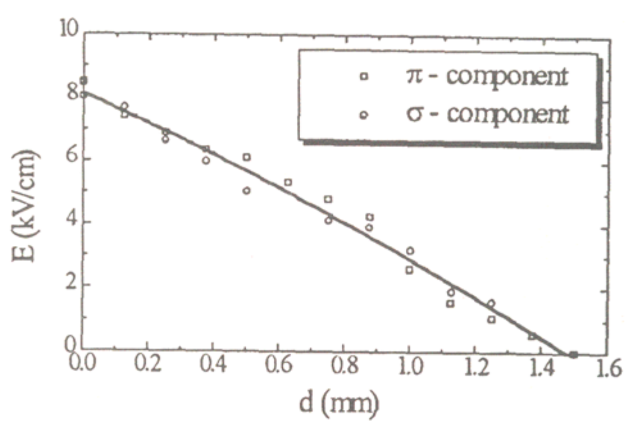

Fig. 3. Electric field intensity vs. distance from the cathode.

Applying this procedure at each recorded position, the decrease of the electric field intensity along the cathode fall region has been obtained (see Fig.3). The integral under the electric field curve is equal 633 V (±5%), which is very close to the applied voltage (640 V) to the electrodes of the discharge. So, we may conclude that in Grimm's type glow discharge the whole voltage drop takes part in cathode fall region. The large difference between temperatures calculated from higher and lower part of the profiles suggest that two groups ("slow" and "fast") of excited H-atoms exist. Their average temperatures, T_s and T_f respectively, as well as their relative concentrations in the cathode fall region are given in Table 1.

Table 1. Average temperatures and relative concentrations of slow (index s) and fast (index f) neutrals in the investigated regions of abnormal glow discharge.

REGION	T_s (eV)	$(\%)_s$	T_f (eV)	$(\%)_f$
cathode fall	4.7	63.4	121.4	36.6
negative glow	8.4	49.5	120.3	14.4

Negative glow region. In this region, the difference between π and $\sigma-$component of H_β profile disappears and the central narrow peak induced by Stark and Doppler broadening in the plasma appears. The profile recorded at 1.62 mm distance from the cathode is shown in Fig.4. Applying the same algorithm as above, with condition E=0, two groups of excited H-atoms are detected again. Contribution of slow neutrals is marked by dashed line, and the one of the fast neutrals by short dashed line in Fig.4.

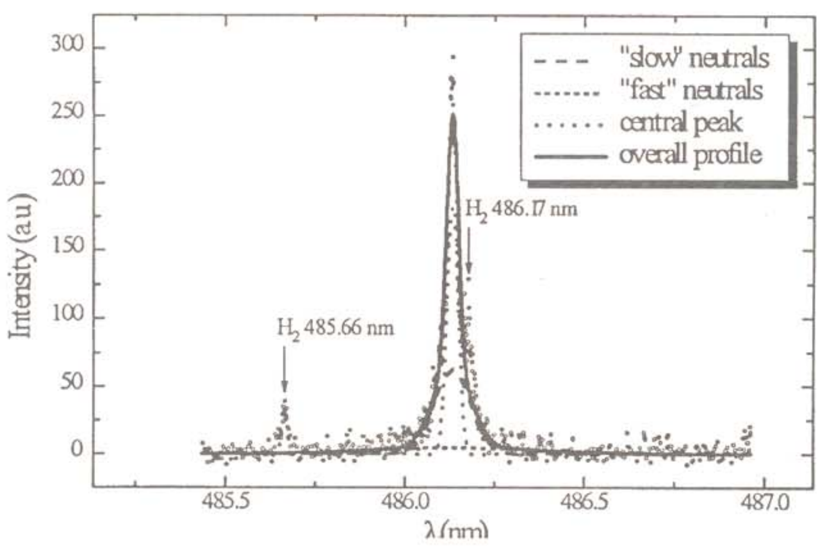

Fig. 4. H_β profile recorded at 1.62 mm from the cathode. Discharge conditions same as above.

In the same figure the central narrow peak (dotted line) is shown, but is already considered by Kuraica and Konjević (1992). Average temperatures and relative concentrations of slow and fast neutrals in the negative glow region are also given in Table 1.

4. CONCLUSIONS

Measurements of the line shapes in the cathode fall and negative glow region of the plane-cathode abnormal glow discharge indicate the presence of two effects responsible for broadening of hydrogen lines : linear Stark effect from external electric field in cathode fall region only, and Doppler broadening from two groups of excited H-atoms with considerably different velocities - in both regions. The origin of slow and fast neutrals is the subject of our further investigations.

References

Barbeau, C. and Jolly, J. : 1991, *Appl. Phys. Lett.*, **58**, 237.
Benesch, W. and Li, E. : 1984, *Opt. Lett.* **9**, 338.
Condon, E. U. and Shortley, G. H. : 1977, *The theory of atomic spectra,* University Press, Cambridge.
Ganguly, B. N. and Garscadden, A. : 1991, *J. Appl. Phys.*, **70**, 621.
Grimm, W. : 1967, *Naturwissenschaften*, **54**, 586.
Grimm, W. : 1968, *Spectrochim. Acta*, **23B**, 443.
Kuraica, M. and Konjević, N. : 1992, *Phys. Rev.*, **A46**, 4429.
Kuraica, M., Konjević, N., Platiša, M. and Pantelić, D. : 1992, *Spectrochim. Acta*, **47B**, 1173.
Petrović, Z. Lj., Jelenković, B. M. and Phelps, A. V. : 1992, *Phys. Rev. Lett.* **68**, 325.
Ryde, N. : 1976, *Atoms and molecules in electric fields*, Almqvist & Wiksell International, Stockholm.

AUTHOR INDEX

PROGRAMME

1st Yugoslav Conference on Spectral Line Shapes

Conference site: Hotel Visoravan, Krivaja (Bačka Topola)

Monday, September 11, 1995

9:00 Bus departure from Astronomical Observatory

11:00 Visit to the old city of Sremski Karlovci

14:00 Lunch

18:00 Arrival in Krivaja and registration at Hotel Visoravan

19:30 Opening ceremony

Tuesday, September 12, 1995

10:00 Atanacković-Vukmanović O. and Simonneau E.: Solution of the line formation problem by the use of iteration factors

10:50 Leo P. J., Mullamphy D. T. P., Peach G. and Whittingham I. B.: Quantum mechanical calculations of self-broadening in rare gases

11:40 Coffee break

12:00 Grujić P. V.: Doubly-excited atoms and the line broadening

13:00 Lunch

14:30 - 16:00 Poster session

16:00 Visit to Zobnatica

20:00 Conference dinner

Wednesday, September 13, 1995

10:00 Dimitrijević M. S.: A programme to provide Stark broadening data for stellar and laboratory plasma investigatopns

10:50 Purić J.:Regularities in the Stark broadening and shift parameters of spectral lines

11:40 Coffee break

12:00 Mijatović Z.: Influence of ion–dynamics effect on the shape of neutral atom spectral lines

13:00 Lunch

14:30 - 16:00 Poster session

16:00 Visit to The Fantast Castle

Thursday, September 14, 1995

9:00 Djurović S., Kobilarov R. and Vujičić B.: Experimental difficulties in determination of the spectral line shapes emitted from plasma

9:50 Vince I., Popović L. Č., Jankov S., Djurašević G., Atanacković-Vukmanović O. and Jevremović D.: On inverse methods used at Belgrade observatory for analysis of spectral line shapes

10:40 Coffee break

11:00–12:00 Round–table discussion

12:00 End of the Conference

LIST OF PARTICIPANTS

Arsenijević J., Astronomical Observatory, Belgrade, Yugoslavia

Atanacković-Vukmanović O., Astronomical Observatory, Belgrade, Yugoslavia

Avramenko V. B., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Bakanovich G. I., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Blagojević B., Institute of Physics, Belgrade – Zemun, Yugoslavia

Bukvić S., Faculty of Physics, University of Belgrade, Yugoslavia

Burakov V. S., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Chumakov A. N., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Ćuk M., Faculty of Physics, University of Belgrade, Yugoslavia

Čelebonović V., Institute of Physics, Belgrade – Zemun, Yugoslavia

Dimitrijević M. S., Astronomical Observatory, Belgrade, Yugoslavia

Djurašević G., Astronomical Observatory, Belgrade, Yugoslavia

Djurović S., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Djeniže S., Faculty of Physics, University of Belgrade, Yugoslavia

Fishman I. S., Department of Physics, Kazan State University, Tatarstan, Russia

Grujić P. V., Institute of Physics, Belgrade – Zemun, Yugoslavia

Il'in G. G., Department of Physics, Kazan State University, Tatarstan, Russia

Ivković M., Institute of Physics, Belgrade – Zemun, Yugoslavia

Jankov S., Astronomical Observatory, Belgrade, Yugoslavia

Jevremović D., Astronomical Observatory, Belgrade, Yugoslavia

Jovićević S., Institute of Physics, Belgrade – Zemun, Yugoslavia

Kobilarov R., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Konjević N., Faculty of Physics, University of Belgrade, Yugoslavia

Konjević R., Institute of Physics, Belgrade – Zemun, Yugoslavia

Konovalova O. A., Department of Physics, Kazan State University, Tatarstan, Russia

Kuraica M., Faculty of Physics, University of Belgrade, Yugoslavia

Labat J., Faculty of Physics, University of Belgrade, Yugoslavia

Leo P. J., Department of Physics and Astronomy, University College London, United Kingdom

Maksimov O. N., Department of Physics, Kazan State University, Tatarstan, Russia

Mashko V. V., Institute of Molecular and tomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Mijatović Z., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Miljević V., Atomic Physics Laboratory, Institute "Vinča", Belgrade, Yugoslavia

Milosavljević V., Faculty of Physics, University of Belgrade, Yugoslavia

Milovanov T., People's Observatory, Gornji grad 16, Kalemegdan, 11000 Belgrade, Yugoslavia

Min'ko L. Ya., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Mullamphy D. T. P., Department of Mathematics and Statistics, James Cook University, Townsville, Australia

Nigmatullin R. R., Department of Physics, Kazan State University, Tatarstan, Russia

Nikolić D., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Pavlov M., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Peach G., Department of Physics and Astronomy, University College London, United Kingdom

Platiša M., Faculty of Physics, University of Belgrade, Yugoslavia

Popović L. Č., Astronomical Observatory, Belgrade, Yugoslavia

Popović M. V., Institute of Physics, Belgrade – Zemun, Yugoslavia

Purić J., Faculty of Physics, University of Belgrade, Yugoslavia

Raikov S. N., Institute of Molecular and Atomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Sahal-Bréchot S., Observatore de Paris, Meudon Cedex, France

Salakhov M. Kh., Department of Physics, Kazan State University, Tatarstan, Russia

Samurović S., People's Observatory, Gornji grad 16, Kalemegdan, 11000 Belgrade, Yugoslavia

Sarandaev E. V., Department of Physics, Kazan State University, Tatarstan, Russia

Simonneau E., Institut d'Astrophysique, Paris, France

Skuljan Lj., Astronomical Observatory, Belgrade, Yugoslavia

Srećković A., Faculty of Physics, University of Belgrade, Yugoslavia

Šišović N., Faculty of Physics, University of Belgrade, Yugoslavia

Terzić M., University of Novi Sad, Faculty of Science & Mathematics, Yugoslavia

Todorović N. K., Astronomical Observatory, Belgrade, Yugoslavia

Videnović I., Faculty of Physics, University of Belgrade, Yugoslavia

Vince I., Astronomical Observatory, Belgrade, Yugoslavia

Voitovich A. P., Institute of Molecular and tomic Physics, Academy of Sciences of Belarus, Minsk, Belarus

Vujičić B., Institute of Physics, Faculty of Science, University of Novi Sad, Yugoslavia

Whittingham I. B., Department of Physics, James Cook University, Townsville, Australia