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Examples of line profiles from laboratory plasma similar to profiles from astrophysical plasmas

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Abstract. In this paper several examples of line spectra from four different laboratory plasma sources are presented. Polarization Stark spectroscopy using hydrogen and helium lines is used for measuring electric filed strength in the discharges. Doppler shifted and excessively broadened profiles are obtained showing presence of atoms with velocities close to those in the narrow line region of AGN. Radiation from a high energy, high density plasma source features very broad profiles used for determination of plasma density. Systematic interpretation of spectra is needed in the conditions where several effects are present simultaneously: electric and magnetic field, Doppler effect and plasma inhomogeneity. Examples of line of sight influence on line profile are also presented. Similarity between laboratory and astrophysical profiles open a possible field for experimental simulation of astrophysical plasmas. To that aim an experiment was devoted to the investigation of hydrogen lines absorption by inhomogeneous plasma

Key words. Plasma spectroscopy, Laboratory plasma, Experiment, Doppler shift

1. Introduction

Analyzing the line profiles and general spectra is a common tool in astrophysics for retrieving information about various astrophysical objects. Line profiles from different atoms and ions are fitted with different types of functions supposing that these components come from corresponding physical causes. After the overall profile is decomposed into components, information about astrophysical plasma is obtained from line width of the components or their relative intensity; see for instance (Sulentic et al. 2000). Typical use is the application of Doppler shift for determination of velocity of emitters (see e.g. La Mura et al. 2009).

Astrophysical plasmas are present in the wide range of plasma parameters i.e. plasma density, temperature and macroscopic velocity. Strong magnetic and electric fields may also be present. All these influences are seen through line profiles and line intensity of spectra. On the other hand, laboratory plasmas can also have a wide range of parameters depending on the discharge source. Some of these plasmas can reach certain parameters that are close to parameters in astrophysical plasma (Griem 1964). Important exceptions are very high magnetic fields in various objects and high velocities in the broad line region of ac-

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tive galactic nuclei. The idea of this paper is to present several examples of spectra from laboratory plasma obtained within our group that have similar characteristic with astrophysical spectra sometimes even coming from plasma with similar characteristics as space objects. Interpretation of this line profiles in laboratory plasma is in many cases very different.

We will present several methods of Stark spectroscopy for determination of electric field and Doppler spectroscopy for determination of velocities of atoms. These profiles come from several different types of electrical discharges. Interpretation of these spectra may be very complicated and it is not always possible to use the standard line functions commonly used in spectroscopy. The advantage of laboratory plasma spectroscopy is the possibility to change the plasma parameters and ways of observations. This enables examining in detail different line effects and sometimes eliminating some causes. Use of Monte Carlo simulations for obtaining the velocity distribution for line fitting will also be shown.

2. Laboratory plasma sources

We will present spectra from four different discharges from our laboratory. Working gases used in this paper are pure hydrogen, pure helium and hydrogen helium mixture. excessive Doppler broadening.

Grimm type discharge (Grimm 1968) is an abnormal DC glow discharge commonly used in the analytical spectroscopy due to its high level of excitation of atomic spectra and high signal to noise ratio. This device consists of a flat, water cooled, cathode and a cylindrical anode. For over a decade we are using a modification of this discharge which enables measurements along the discharge axis i.e. orthogonal to electric field in various working gases. Ionized gas in this discharge is not in thermodynamic equilibrium and in some parts not electrically neutral. When working with mentioned gases, electron temperatures are around 5000 K, while gas temperatures are around 400 K. Plasma density is in the range of 10^{10}-10^{11} cm^{-3}. All these parameters vary in the discharge volume. Due to its geometry and

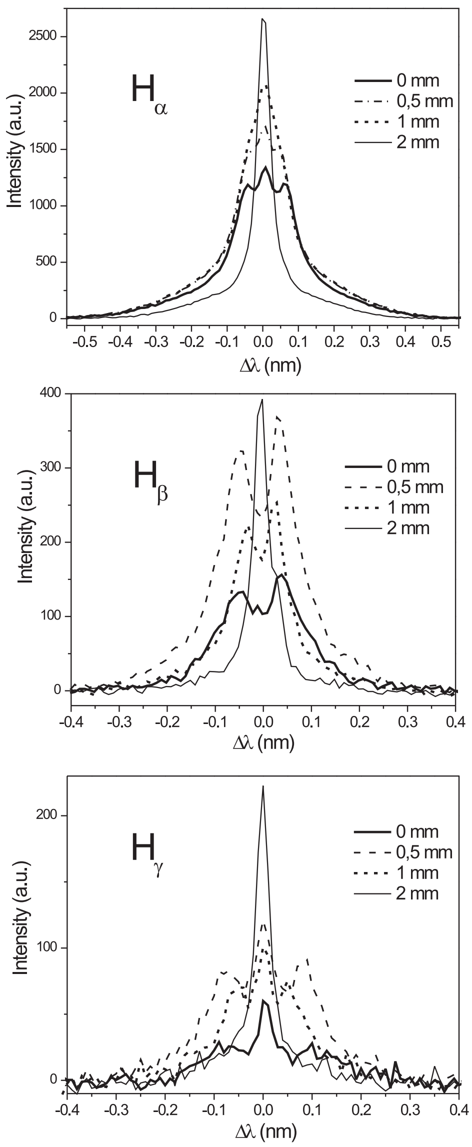

Fig. 1. Profiles of hydrogen Balmer series lines recorded at different distances from the cathode of Grimm type glow discharge. Operating conditions: voltage-900 V, pressure-3.8 mbar, (Kuraica et al. 2009).

low operational pressure this discharge is characterized with high voltage (~1kV) and relatively short cathode fall region (~2 mm). These

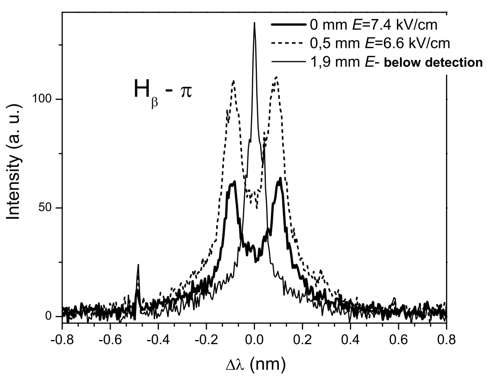

Fig. 2. π components of Hβ line recorded with a polarizer at different distances from the cathode of Grimm type glow discharge. Measured electric field strengths are listed, (Kuraica et al. 2009).

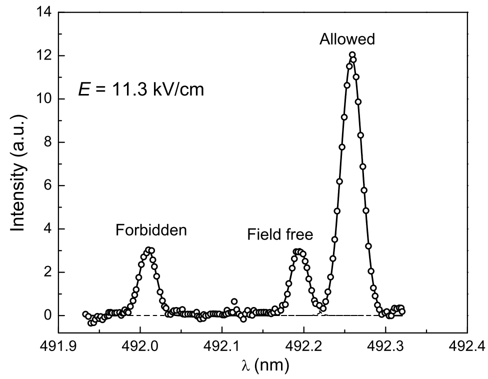

Fig. 3. HeI 447.1 nm line with its forbidden component recorded in the high field region of Grimm type glow discharge with He at pressure of 4 mbar (Kuraica et al. 2009).

features create a region of high electric field strength ($\sim$10 kV/cm) and enables ions to reach high velocities, up to 500 km/s. Experimental setup for observation can be seen elsewhere (Cvetanović et al. 2005) and is used here with some slight modifications.

Hollow cathode discharge is a type of glow discharge which is usually characterized with low electron densities up to 10^{12} cm^{-3}, producing very narrow spectral lines commonly below the instrumental width; Our cathode discharge consists of a cylindrical cathode and a round wire anode set further from the cathode cylinder. Also, our tube has two anodes enabling the formation of the discharge on both sides of the cathode. The cathode sheath is usually confined to a narrow layer between the cathode cylinder and the slightly smaller plasma cylinder. At pressures bellow 1 mbar plasma comes out of the cathode and moves close to the anode. The electric field of cathode fall is thus directed from the anode center and along the center axes of cathode cylinder. Here we operated at low pressure (0.4 mbar) and voltage up to 2 kV in order to obtain high velocity atoms. Electrostatic confinement is a system with concentric spherical anode and cathode, where cathode is a spherical grid. Hydrogen ions are accelerated in the high field region between the anode and cathode reaching the grid cathode with high velocity. Virtual anode is then formed within the cathode grid producing high line intensity within this low density, low field region. For experimental setup see (Obradović et al. 2002).

Magneto plasma compressor (MPC), (Dojcinović et al. 2007) is a high energy plasma source operating with voltages of several kilovolts with pressures of the order of milibars. Geometrically it consists of anode in the shape of a cylindrical grid and a specially shaped conical cathode. Due to its high current and special shape of the electrode system, plasma is compressed and accelerated with its own magnetic field. Plasma density is of the order of 10^{16} cm^{-3}, while gas and electron temperatures are close to 20000 K. This plasma is in a state close to thermodynamic equilibrium. Parameters of this plasma may be close to outer regions of stars.

3. Stark spectroscopy

Stark polarization is a tool used for measuring static electric fields in gas discharges. Over the years we have been using Stark splitting and shifting of hydrogen and helium lines to this purpose. Polarizer was used in order to distinguish the p and s components i.e. polarization along and orthogonal to electric field in the discharge.

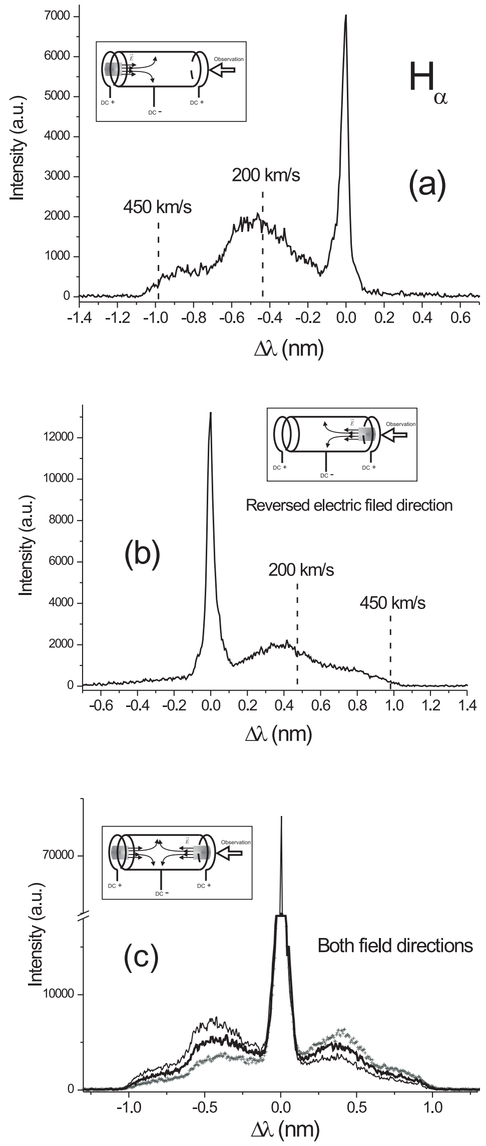

Fig. 4. Hydrogen Balmer alpha line with high Doppler shift recorded in hollow cathode discharge: a) Electric field along the line of sight, b) Reversed direction of electric field, c) Electric field present at both directions. Voltage-1.45 kV; pressure-0.4 mbar, (Kuraica et al. 2009).

Examples of line profiles of Balmer series lines are presented in Fig.1 taken from our paper (Kuraica et al. 2009) at different positions in the cathode fall of Grimm discharge. These line profiles are recorded without the polarizer. Stark broadening is evident, while Stark components may be distinguished in the high field region, near the cathode. Apart from Stark broadening and splitting, far wings of the profiles are also present coming from excessive Doppler broadening.

The H_β is the best choice when measuring electric field due to its sufficient intensity and large Stark splitting. Polarized light, namely π components of this line are shown in Fig.2 (Kuraica et al. 2009). This evolution of components was then used for measuring the electric field distribution using the method by Videnović et al. (1996). Three Helium lines and their forbidden components are sensitive to electric field strength through Stark shifting and intensity ratio of forbidden and allowed components: HeI 402.6 nm (2p3P0 - 5d3D0), HeI 447.1 nm (2p3P0 - 4d3D0), HeI 492.1 nm (2p1P0 - 4d1D0) (Kuraica et al. 1997). Example of spectra in the high field region of Grimm discharge is presented in Fig. 3. Between the HeI line and its forbidden component a non-shifted line coming from low field region can be seen. Wavelength displacement between line components was then used to obtain the electric field distribution in the cathode fall of Grimm discharge with helium and helium-hydrogen mixture.

Similar high field regions to those shown here are created in the double layer formed in various space and laboratory plasma. Double layers are high field regions created by charge separation in various astrophysical objects such as solar flares, planetary atmospheres and neutron stars. This opens a possible field of application of Stark spectroscopy for examining such phenomena in astrophysics.

4. Doppler spectroscopy

High energy hydrogen atoms, up to 1 keV, can be created in various types of discharges. This is explained by presence of fast ions accelerated in the sheath of the discharge. These ions then undergo charge exchange collision therefore creating fast hydrogen atoms, (see for instance Cvetanović et al. 2009 and references

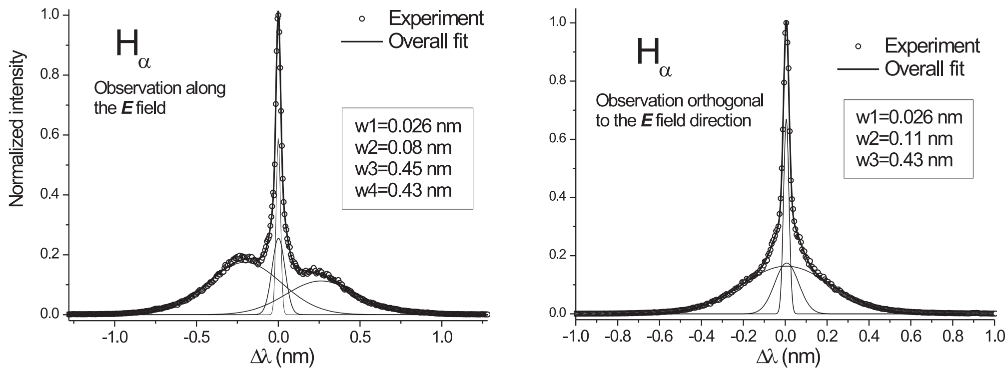

Fig. 5. H_α line from Grimm type glow discharge recorded along the direction of electric field (left) and orthogonally to the electric field (right). Voltage-2 kV, pressure-2 mbar.

therein). These atoms are then exited mostly by collisions with bulk gas particles. Lines of H atom spectra are seen excessively broadened or Doppler shifted due to their high velocity 100-500 km/s.

For demonstration of this effect we have used a hollow cathode discharge with the ability of changing the electric field direction by turning on one, or the other anode. Example of H_α line is shown in Fig.4a. As can be seen, large Doppler shift is present with atoms reaching velocities up to 450 km/s. This spectrum is similar to those obtained in some hot stars and NLR of AGN (Netzer, 2008). While the velocities are to low for BLR of AGN, Doppler mechanism is essentially the same (Sulentic 2000). However, the origin of these fast atoms is characteristic for laboratory plasma and is also present in tokamaks.

When the direction of electric field is reversed the ion motion is reversed leading to the red shift instead of the blue shift, Fig. 4b. With both directions of field on, there are two groups of ions moving in opposite directions and creating fast exited atoms as seen in Fig. 4c. In this graph both wings of the line are present. However it is interesting to point out that the intensity ratio of the left and blue wing depends on the line of sight and the focusing of two regions of ion motion. Namely, two regions of the discharge are positioned along the observation axis and consequently, their respective images are projected along the monochromator entrance slit, focused differently, and recorded on the two-dimensional ICCD. This effect is a good demonstration of possible misinterpreting the spectra from astrophysical objects when the direction of observation is not taken into account.

In the Grimm type discharge high velocity hydrogen atoms (400 km/s) create excessively Doppler broadened profiles with both wings present. As can be seen in Fig. 5, line profiles are very different depending on the direction of observation. Profile recorded along the electric field direction is asymmetric with two wings slightly separated from the central profile, while the profile recorded orthogonally to the electric field direction is symmetric. This comes from the two groups of fast H atoms, one moving towards the cathode and the other moving in the opposite direction after reflection of ions from the cathode. Similar wide two-peaked profiles may be seen in the AGN caused by radial motion of emitters (Strateva et al. 2003). In our earlier paper we have fitted the symmetric profile, obtained when viewing orthogonally to the electric field, with three Gaussians coming from three different groups of hydrogen atoms (Cvetanović et al. 2005). Namely the narrow Gaussian comes from electron atom excitation of thermalized atoms created in dissociation, while the middle width component comes from dissociation where products have a substantial kinetic energy. However, the shape of the wide compo-

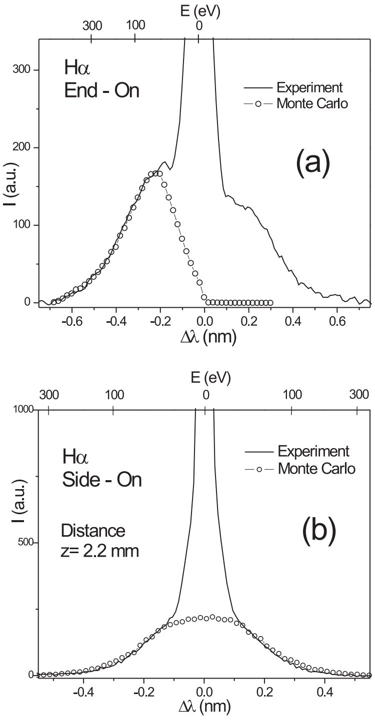

Fig. 6. Results of Monte Carlo simulation for obtaining the blue wing of the H_α profile recorded along the E field and far wings of the profile recorded orthogonally to the E filed, (Cvetanović et al. 2009).

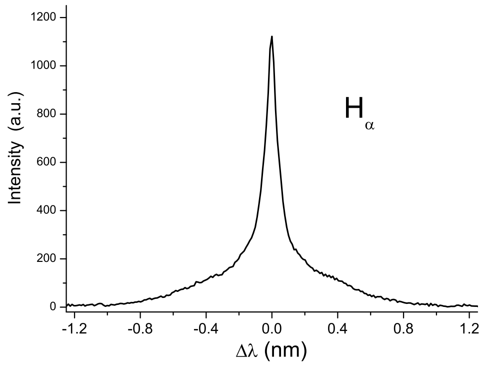

Fig. 7. H_α line from electrostatically confined plasma. Voltage-18 kV, pressure-0.8 mbar.

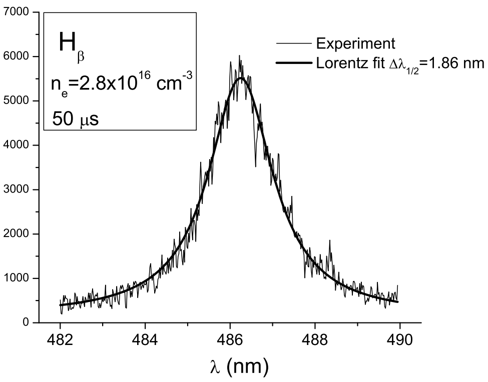

Fig. 8. H_β recorded at the time of high plasma density of MPC device.

nent is only taken to be Gaussian for estimation of line component integral while it had no theoretical, physical justification. The profile recorded along the electric field can be well fitted with four Gauss components coming from four causes, similar to the previous profile but with two high energy components moving along and opposite to the viewing direction. Analyzing these used fitting profiles one can observe that the two wide Gauss components cross the line of zero velocity and overlap each other. This implies a large number of atoms reversing their direction while moving which is highly improbable concerning the model of atom motion in the discharge. This is a good example of standard fitting function not satisfying the need for line fitting with good physical grounding. In order to find a more realistic profiles contributing to the overall profile, Monte Carlo simulation was developed for H atom transport of reflected atoms i.e. blue wing of the profile. This gave us the shape of asymmetric profiles for fitting far wings see Fig. 6 taken from reference (Cvetanović et al. 2009). Similar to these, symmetric profiles are also obtained in the electrostatic confinement discharge Fig. 7.

5. Profiles from high energy plasma source- mixed effects

Magneto plasma compressor produces plasma with parameters very different from the previously mentioned plasma sources. Since it is a pulse discharge, high current and high plasma

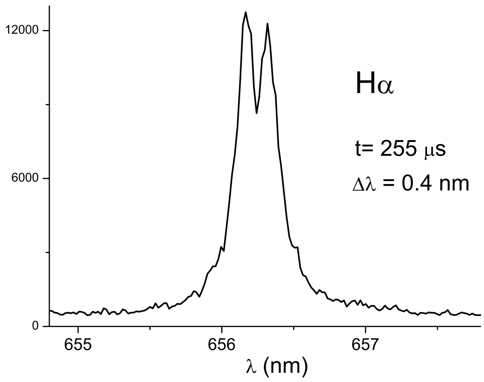

Fig. 9. Two-peaked H_α line recorded long after the termination of MPC discharge, at very low plasma density. Example of inhomogeneous gas absorption.

density exist for a period between 10 μs and 50 μs from the ignition. After that, the discharge extinguishes itself reaching zero current and very low charge density after about 100 μs. In the high current interval, plasma progresses with velocity close to 100 km/s (Dojcinović et al. 2007). In order to analyze this evolution of plasma parameters, time-resolved spectroscopy using ICCD camera was performed. Initial investigations were made with a gas mixture of 95 % He and 5 % H_2, (Kuraica et al. 2009), but here we used a gas mixture of 10 % He and 90 % H_2 in order to have a gas composition closer to the one in stellar atmospheres.

Since H_β line is sensitive to the Stark broadening, it was fitted with Lorentzian and used for determination of electron density (Hutchinson 2002), see Fig. 8. As this plasma is created in only a small fraction of chamber volume, during the cooling of the plasma a significant inhomogeneity i.e. gradient of gas temperature is created. Two-peaked Balmer alpha line is taken in this late stage, at 255 μs (Fig. 9). Line radiation transferred through optically thick inhomogeneous plasma creates a self-reversed line profile with a pronounced minimum at the line center (Griem 1964, Fujimoto 2004). This comes from absorption of the central part of the Doppler broadened line in the colder gas. Line is Doppler broadened due to transfer of directional energy of plasma into thermalized motion. This inhomogeneous absorption may be used for laboratory simulation of absorption from independent density layers in hot emission stars (Danezis et al. 2003).

6. Conclusions

Examples of line spectra from different types of laboratory plasma are presented. Broad profiles due to Stark splitting in high field regions are used to determine the electric field strength through the use of polarization spectroscopy. Doppler broadened and shifted hydrogen Balmer lines coming from atoms with velocity up to 450 km/s are also obtained in the laboratory. These profiles show similarity to profiles coming from some astrophysical objects. Interpretation of spectra with influences of electric field, micro electric field, Doppler broadening and optical transfer through inhomogeneous gas is demonstrated.

Similarities between laboratory and astrophysical profiles and to some extent closeness of plasma parameters open a possible field for experimental simulation of astrophysical plasmas. Absorption in inhomogeneous gas may be used for simulating effects that exist in spectra of hot emission stars.

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