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HIGH RESOLUTION SPECTROPOLARIMETRY: FROM ASTROPHYSICS TO ECR PLASMAS

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Abstract

Electron Cyclotron Resonance (ECR) plasmas with high density and high temperature are required by the injectors for the Accelerators and by interdisciplinary studies in Astrophysics and Nuclear Astrophysics. The magnetic traps need a very fine analysis of plasma conditions in terms of density, temperature and ionization state, not allowed by the present diagnostic methods (imaging, low resolution spectroscopy not spatially resolved).

We here describe the results routinely obtained in Astrophysics with high resolution spectroscopy, largely used to analyze astrophysical plasma in the visible range, which allows to determine physical parameters of stars as effective temperature, surface gravity, chemical abundances. In addition, we show that polarimetry is the only technique to derive the morphology of stellar magnetic fields, whose knowledge is necessary for a correct interpretation of spectra from magnetized plasmas. An application of these non-invasive methods to B-min ECR plasma concerning optical emission is discussed in view of a better comprehension of the plasma structure, magnetic confinement properties and heating processes.

INTRODUCTION

Intense beams of multiply charged ions are going to be a critical requirement for experiments in Nuclear Physics, Plasma Physics and Nuclear-Astrophysics. Most of ion sources are plasma-based, where the average charge state ($<q>$) and the current intensity (I_q) of the extracted beam depend on the electron density (n_e) and the ion confinement time (τ_q) as $<q> \propto n_e \tau_q$ and $I_q \propto \frac{n_e}{\tau_q}$. Among the sources that ensure a good compromise between charge state and current intensity there are the Electron Cyclotron Resonance Ion Sources (ECRIS, [1]) where the gas injected in a chamber is ionised by microwaves and confined by a Magneto-Hydro-Dynamic (MHD) stable B-min configuration. The ionization efficiency of these systems, producing high density ($n_e \sim 10^{10}$-10^{13} cm^{-3}) and high temperature ($T_e \sim$ 0.1-100 keV) plasma, depends on a not yet fully understood large number of parameters, and semi-empirical relations are adopted to optimize the extracted beam. According to the Geller's scaling laws [2] and the so-called "High-B mode" condition for the MHD stability [3], in order to improve the ECRIS performances we have to increase the magnetic field intensity and the microwave frequency. This trend is now limited by the rising costs and feasibility of magnets and RF generators, and a better comprehension of plasma formation and heating is therefore needed, to be performed by means of new diagnostic tools.

Present non-invasive techniques developed for plasma diagnostic range from X-ray to near infrared and are routinely based on imaging and spectroscopy. Anyway these methods are able to characterize plasma electrons, as for the X spectral range (see, e.g., [4,5]).

Not so much information is instead available concerning the ions. In addition, the ion confinement optimization, affected by the still not fully explained gas-mixing effect [6], requires a complete control of cold electrons displacement which is inaccessible by X-ray diagnostics. As to the visible spectral range, low resolution (an arbitrary boundary could be placed at $R = \lambda/\Delta\lambda < 40000$) Optical Emission Spectroscopy (OES) is commonly carried out with the aim to determine electron temperatures and densities as well as to obtain information about atomic and molecular populations by means of the line-ratio method (see e.g. [7]).

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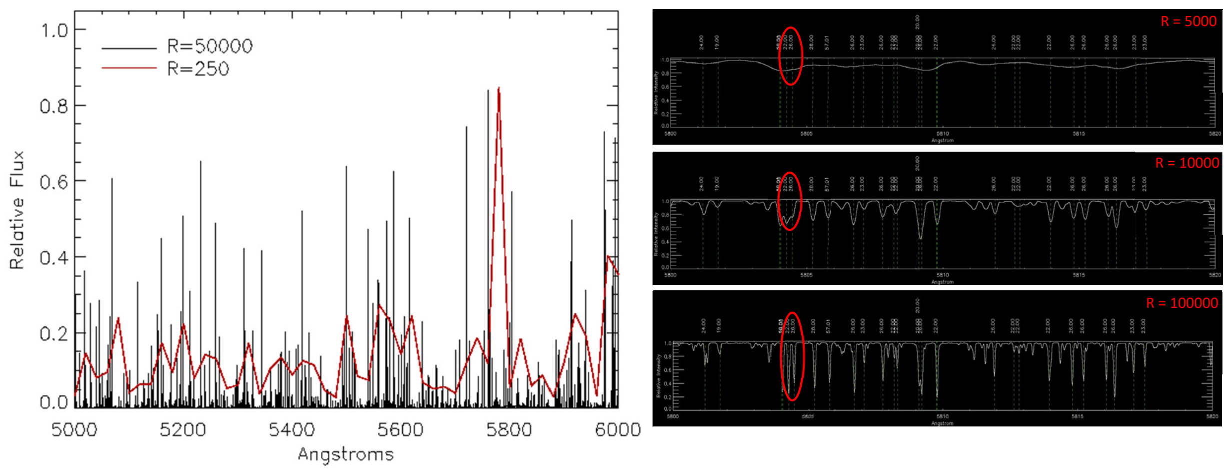

Figure 1: Left panel: small portion of the spectrum from a ThAr hallow cathode lamp as recorded at high (R = 50000, black spectrum) and low (R = 250, red spectrum) resolution. Spectra have been normalised to their maximum for an easy comparison. Right panel: synthetic solar spectra computed in the same wavelength range with different resolution as indicated on each one.

However, present OES is characterized by the absence of spatial resolution. An example is shown in [8] where the presence of lines from both atomic and molecular transitions in hydrogen spectra testifies the limits in spatially separating hot and cold plasma regions. The spectra were obtained with R = 250, which means that it is not possible to identify lines separated less than 2 nm at 500 nm. Low spectral resolution represents a further limit of plasma OES: already in [9] it is discussed the crucial role of spectral resolution for a correct measurement of profiles and wavelength shifts of spectral lines. Therefore, there is a wide room for improvements in ECRIS plasmas diagnostics, particularly in the optical range, for a number of issues; a) measurements of ion temperature; b) determination of in-plasma micro and macro turbulence; c) on-line and non intrusive determination of the inner-plasma charge state distribution; d) investigation of gas mixing dynamics and isotopic effect. All these challenges require R > 40000 and, as we will see in the following, the simultaneous implementation of polarimetry. A specific experimental program has been started at INFN in synergy with the Italian Institute for Astrophysics (INAF), under the grant MAPS_3D (MAgnetised Plasma Spectropolarimetry 3D): the projects merges backgrounds, methods and instruments routinely adopted in observational Astrophysics to be implemented in laboratory-plasmas.

STELLAR PLASMA DIAGNOSTIC

We here present the results obtained in Astrophysics by means of high resolution ($R \geq 50000$) spectropolarimetry. This technique, routinely applied to magnetized plasmas in the visible range (e.g. the atmospheres of stars), allows to determine stellar parameters and surface chemical composition, as well as the magnetic field geometry whose knowledge is necessary for reliable estimations of plasma temperature and density.

High Resolution Spectropolarimetry

We start pointing out the advantage in using high resolution spectroscopy to analyze light from stars. First, for spectral line identification, as clearly shown in Fig. 1: on the left panel a small portion of the spectrum from a ThAr hallow cathode lamp is reported, as recorded by us at R = 250 and R = 50000 with the Catania Astrophysical Observatory Spectropolarimeter (CAOS@OACT, [10]). It clearly appears that most of the lines are wasted at low resolution because of blending, and so can not be detected. A further example is given on the right panel showing synthetic solar spectra computed in the same wavelength range with different R values. Only through high resolution it is possible to distinguish between near lines of different elements, and then correctly determine stellar metallicity, especially for chemically peculiar stars (see e.g. [11,12,13,14]).

High resolution spectroscopy also allows to detect the presence of isotopes in stellar atmospheres [15] by measuring the isotopic shift of spectral lines. This shift is typically smaller than 0.01 nm, so that R > 50000 is required at wavelength 500 nm.

The measurement of velocity fields, that can be estimated only through high resolution spectroscopy on the basis of the Doppler effect, is fundamental to probe stellar plasmas. If a star moves away from us (toward us) with velocity v, its spectrum will be redshifted (blueshifted) of $\Delta\lambda_D = \lambda\, v/c$ with respect to the synthetic one. In general, the many chaotic or ordered mass flows (e.g. microturbulence, macroturbulence, oscillations or winds) present in

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cosmic objects can be disentangled by analyzing the spectral line profile, if the instrumental spectral resolution is sufficient [16]. As an example the rotational velocity of a star can be measured only if the corresponding line profile is larger than the instrumental profile $\Delta\lambda = \lambda/R$. As a consequence the minimum measurable velocity field is of the order of $v = c\ \lambda/\Delta\lambda = c/R$, i.e. v = 1200 km s^{-1} at R = 250 and 3 km s^{-1} at R = 100000. Equally is the role of spectral resolution in the determination of the gravity of stars on the basis of the collisional line broadening, that is due to the modification of atomic energy levels due to the interaction between emitters and electrons, ions or neutrals.

If the examined star has a magnetic field, atomic energy levels split in sublevels so that spectral lines also split in a series of Zeeman components. These are called π if Δm = 0, σ_b (blueshifted with respect the nominal wavelength) if Δm = +1, and σ_r (redshifted) if Δm = -1, being m the magnetic quantum number. The average separation in wavelengths among σ_b- and σ_r-components, $\Delta\lambda_\sigma$, is proportional to the modulus of the field, |**B**|:

$$\Delta\lambda_\sigma = 2 \cdot 4{,}67 \cdot 10^{-13}\ \lambda^2\ g_{eff}\ |\mathbf{B}|$$

with λ expressed in Å, **B** in G, and being g_{eff} the effective Landé factor. Then, in order to measure stellar magnetic field intensity the resolution has to be high enough that $\Delta\lambda \leq \Delta\lambda_\sigma$: the minimum field modulus ($\Delta\lambda = \Delta\lambda_\sigma$) at λ = 500 nm and for g_{eff} = 1 is 85 T with R = 250 and 0.21 T with R = 100000. With the exception of pulsars and magnetars, the field modulus of magnetic stars ranges from few Gauss [17] up to ~ 3 Tesla [18]. Sometimes π- and σ-components are superimposed and appear as a single broadened line rather than a multiplet. In this case high resolution is mandatory for a correct interpretation of the line profile, in order to avoid misunderstanding which could lead to attribute to the star wrong chemical abundances as well as temperature and surface gravity.

Anyway, high resolution spectroscopy is not enough to study magnetic stars. Spectra from magnetized plasma should be not correctly interpreted if we neglect the field geometry: in presence of a magnetic field, emission is not isotropic [19], with the most extreme case of no emission of the Zeeman π-components along the field direction (see Fig. 2). Without information on the field strength and orientation, these weaker spectral lines could be ascribed to a lower density, or assigned to a wrong temperature. In addition, [20] have shown how the magnetic intensification of spectral lines can mimic a larger chemical abundance under the hypothesis of Local Thermodynamic

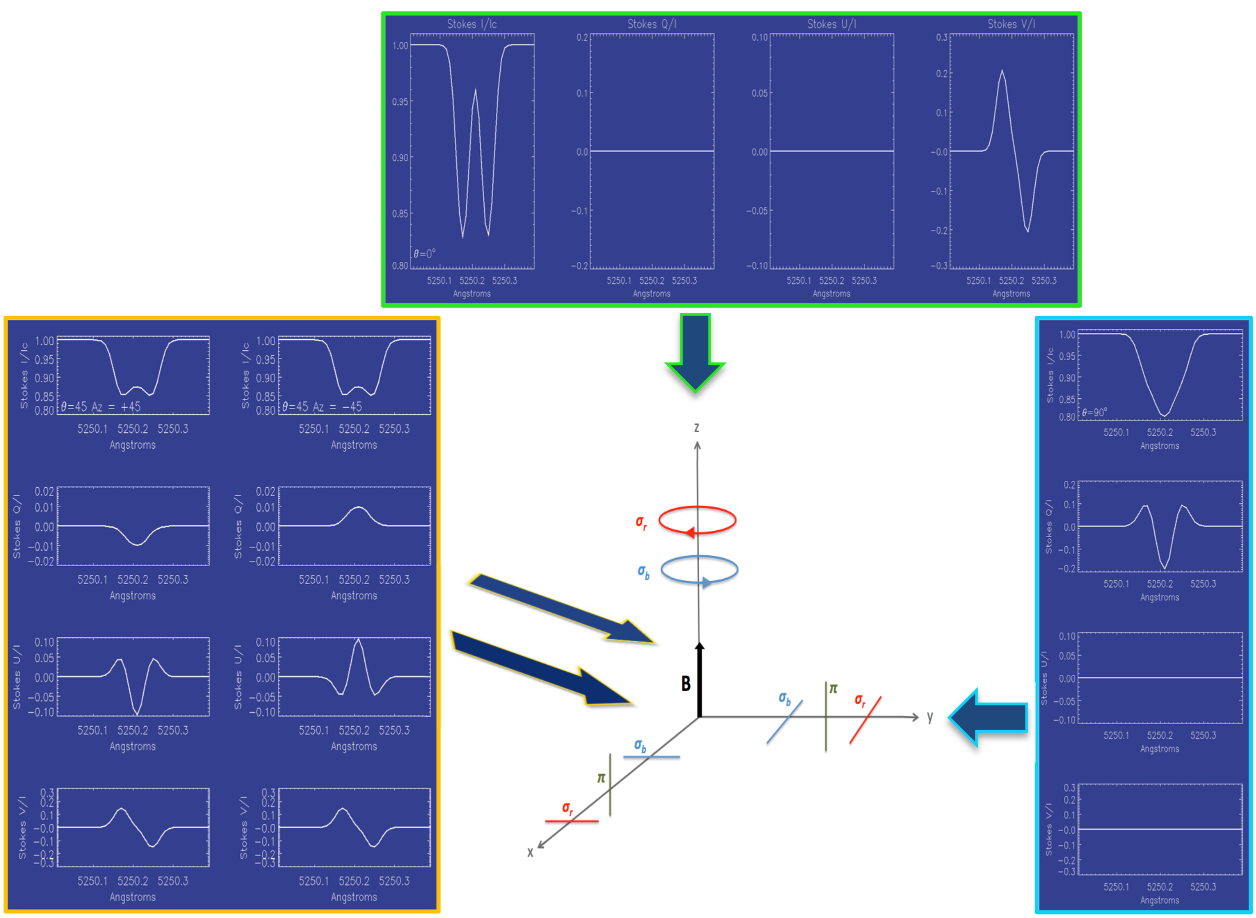

Figure 2: Synthetic Stokes profiles as observed along and transversally to the magnetic field **B** (z axis and y axis respectively), and at angle 45° respect to the field direction with Azimuth +45 and -45.

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Equilibrium regime.

It is then necessary to simultaneously determine magnetic field modulus and geometry to avoid wrong results. Polarimetry is the only non-invasive technique able to recover the magnetic field configuration. By describing the polarization through Stokes parameters, the magnetic field morphology can be derived from the corresponding profiles observed by means of a polarimeter (Fig. 2). Solar and stellar magnetic fields are commonly reconstructed on the basis of high resolution spectropolarimetry [21] by taking advantage from stellar rotation to determine the 3D geometry. Despite the great potentiality, high resolution spectropolarimetry is a not yet widely adopted technique for in-laboratory plasma diagnostics. One of the few papers on plasma polarization spectroscopy at resolution R = 44000 by [22] shows the huge potential of this technique able to disentangle the line-of-sight plasma properties of the TRIAM-1M tokamak.

FROM STARS TO ECR PLASMAS

In view of a better comprehension of the ECR plasma structure, magnetic confinement properties and heating processes, we planned to apply the above discussed methodology of optical diagnostics for astrophysical plasmas to ECR plasmas. As already mentioned, it will be done at Istituto Nazionale di Fisica Nucleare-Laboratori Nazionali del Sud (INFN-LNS) of Catania, within the INFN project MAPS_3D.

High resolution spectroscopy will be carried out with the spectrograph SARG (Spettrografo Alta Risoluzione Galileo, [23]) working in the visible range (from 370 to 1000 nm in a single shot) at resolution R = 164000. It was at Telescopio Nazionale Galileo (La Palma, Canary Island) and it is now at LNS after a Memorandum of Understanding between INFN-LNS and INAF-OACT undersigned in August 2017.

The test-bench for plasma analysis will be the Flexible Plasma Trap [24] where the plasma will be created. It is called *Flexible* because of the possibility to change the magnetic field configuration (simple mirror, magnetic beach, quasi-flat) and the direction of microwaves injection with respect to the magnetic field orientation. Plasma emission will be simultaneously recorded from three directions at 90° from each other through three polarimetric units (now under construction) fiber-linked to SARG.

This equipment, together with the development of a new radiative transfer theory, will allow a 3D spectropolarimetric characterization of plasma and magnetic field as generated within the FPT. With the SARG resolution, in fact, it is possible to identify spectral lines separated up to 0.003 nm at λ = 500 nm, and then also measure isotopic shift. This should be fundamental for the gas-mixing characterization of ECR plasmas, as well as to perform broadening measurements which represent an estimation of plasma turbulence. Finally, the magnetic field inside the FPT is $|\mathbf{B}| \leq 0.3$ T. With R = 164000 the minimum field modulus measurable is at least 0.125 T at λ = 500 nm, thus confirming that an advanced characterization of the so-called magnetoplasma is potentially possible.

First experimental data are expected to be collected within 2019.

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