Laboratory Astrophysics: from Observations to Interpretation
Proceedings IAU Symposium No. 350, 2019
F. Salama & H. Linnartz, eds.
doi:10.1017/S1743921320000058

Laboratory plasmas for high-energy astrophysics: A method to measure effective Landé *g*-factors

Marina Giarrusso†

Istituto Nazionale di Fisica Nucleare, Laboratori Nazionali del Sud,
Via S. Sofia 62, I-95123 Catania, Italy
email: marina.giarrusso@lns.infn.it

Abstract. Effective Landé g-factors (g_{eff}) are fundamental quantities in order to derive stellar magnetic field intensities. The determination of g_{eff} involves both total angular momenta and Landé g-factors of the transition levels. Theoretical g-factors are generally adopted, and the corresponding g_{eff}, often quite different from the one obtained in laboratory, affects the accuracy on magnetic field strength measurements. In this work we discuss a method to experimentally determine g_{eff} for highly ionised species, based on high resolution spectropolarimetry applied to Electron Cyclotron Resonance laboratory plasmas.

Keywords. atomic data, atomic processes, line: profiles, magnetic fields, plasmas, instrumentation: spectrographs, instrumentation: polarimeters, methods: laboratory, techniques: spectroscopic, techniques: polarimetric

1. Introduction

High resolution spectropolarimetry represents a powerful technique used in observational astrophysics to study stellar environments. It allows to derive temperature, surface gravity, chemical composition of stars, as well as magnetic field strength and morphology by comparing observed spectra with synthetic ones. Synthetic spectra are obtained on the basis of atomic databases, recording quantities univocally related to each spectral line: wavelength, element responsible for the transition, total angular momenta (J) and Landé g-factors (g) of the transition levels, and so on. Mathys (1990) pointed out the importance of experimental g values to derive magnetic field strengths of stars. In this regard, we recall that the presence of a magnetic field removes the degeneracy of energy levels. As a consequence, spectral lines usually split in a series of Zeeman components called π when refer to transitions for $\Delta m = 0$ (being m the magnetic quantum number), σ_b (blue-shifted) for $\Delta m = +1$ and σ_r (red-shifted) for $\Delta m = -1$. The mean wavelength distance between σ_b and σ_r components allows to determine stellar magnetic field strengths, if the effective Landé g-factor (g_{eff}) is known. This quantity is generally obtained from calculations involving theoretical g values. Mathys showed that the accuracy on magnetic field strength can be worst if derived through g_{eff} from theoretical g-factors rather than from experimental ones.

Indeed, for neutral and weakly ionised species all these atomic parameters are, or can be, known from the laboratory (Kupka *et al.* 1999), while experimental databases for highly ionised species are poorly developed and have to rely on theoretical calculations (Bruhweiler 1992). The lack of experimental atomic data necessary for the study of

---

† The author acknowledges the 5th Nat. Comm. of INFN supporting the grant MAPS_3D.

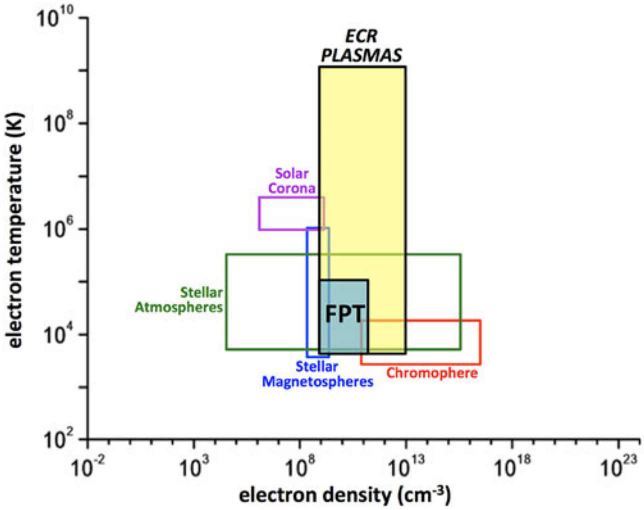

Figure 1. Boxes show electron temperatures and densities characterising different astrophysical environments. References: Leto *et al.* 2006 (Stellar Magnetospheres), Byrne 2012 and reference therein (Chromosphere and Solar Corona), Kurucz 2005 (Stellar Atmospheres). Ranges typical of Electron Cyclotron Resonance (ECR) plasmas as well as of plasmas generated inside the Flexible Plasma Trap (FPT) are also shown (see references in the text).

high-energy environments is historically due to the difficulty in reproducing stable high temperature conditions in laboratory.

In this paper we present an experimental set-up to determine $g_{\rm eff}$ for highly ionised species, necessary to establish the presence and the strength of magnetic fields in astrophysical high-energy conditions. It is based on high resolution spectropolarimetry applied to Electron Cyclotron Resonance laboratory plasmas, able to reproduce different astrophysical environments (Fig. 1).

2. Laboratory measurements of effective Landé *g*-factors

In presence of a magnetic field, by definition, the effective Landé g-factor represents a measure of the wavelength distance between the baricenter of the Zeeman σ components (weighted by their intensities) and the nominal wavelength λ of the unsplitted line. It is defined through the total angular momenta J_1, J_2 and the Landé g-factors g_1, g_2 of the two levels responsible for the transition:

$$g_{\rm eff} = \frac{1}{2}(g_1 + g_2) + \frac{1}{4}(g_1 - g_2)[J_1(J_1 + 1) - J_2(J_2 + 1)] \tag{2.1}$$

However, g values are not experimentally measured for all the transitions. Indeed g_1 and g_2 are generally calculated under the assumption of L-S coupling approximation, and the resulting $g_{\rm eff}$ can be quite different from the one obtained through experimental g values (Landi Degl'Innocenti 1982).

The quantity $g_{\rm eff}$ plays a crucial role in deriving the magnetic field strength $|\mathbf{B}|$ of a star. In weak field approximation (Landi Degl'Innocenti & Landolfi 2004) it holds the relation (see e.g. Leone *et al.* 2017):

$$|\mathbf{B}| = \frac{\Delta\lambda_\sigma}{2 \cdot 4.67 \cdot 10^{-13} \lambda^2 g_{\rm eff}} \tag{2.2}$$

where $|\mathbf{B}|$ is expressed in G, λ (in Å) is the nominal wavelength of the unsplitted line, and $\Delta\lambda_\sigma$ is the mean wavelength distance between σ_b and σ_r components.

The method proposed here to experimentally determine the effective Landé g-factor is based on the inversion of Eq. (2.2). The first step is to reproduce the high-energy astrophysical environments in laboratory, for a chosen element and by fixing the magnetic field strength. Then, by acquiring spectra of emitted radiation and by measuring the mean wavelength distance between σ_b and σ_r components for each line at nominal wavelength λ, it will be possible to obtain the corresponding $g_{\rm eff}$ value.

Anyway, in order to measure $\Delta\lambda_\sigma$, the instrumental profile width $\Delta\lambda = \lambda/R$ (being R the spectral resolution) has to be smaller than $\Delta\lambda_\sigma$ itself. That is, for a magnetic field intensity of 0.5 T, $\lambda = 500$ nm and $g_{\rm eff} = 1$, it results $\Delta\lambda_\sigma \sim 0.012$ nm, which can be detected only with $R \geqslant 43000$. If σ_b and σ_r components are blended, it will be possible to determine their central wavelengths through polarimetric observations, recording the corresponding Stokes V profiles (see e.g. Leone *et al.* 2017). For this reason, we suggest to apply high resolution spectropolarimetry in the visible range to laboratory plasma emission.

3. Reproducing astrophysical environments: ECR plasmas

Electron Cyclotron Resonance (ECR) plasmas (Geller 1996) are laboratory plasmas created in magnetic traps. In these devices microwaves at the Larmor frequency are injected in a chamber filled with the gas to study and surrounded by magnets. The few free electrons present in the gas are then accelerated and spiral around the magnetic field lines, ionising the atoms through inelastic collisions. As a result, a high electron density (up to $\sim 10^{13}$ cm^{-3}) and temperature (up to $\sim$100 keV) plasma is created and magnetically confined inside the chamber, lasting for several days. These devices, producing highly ionised plasmas (e.g. Ar^{14+} or Xe^{34+}, Nakagawa 2014), are employed in Nuclear Physics as ion sources feeding particle accelerators. In these traps many charge states simultaneously exist, from the neutral atoms close to the chamber walls to the highest possible ionisation state according to the maximum value of the temperature. Plasma emission from X-ray to radio frequencies can in principle be detected (e.g. Mascali *et al.* 2017).

Since ECR plasmas reproduce different high-energy astrophysical environments (Fig. 1), they can be used as a test-bench for astrophysical studies. This will be done under the project MAPS_3D (MAgnetised Plasma Spectropolarimetry 3D, Giarrusso *et al.* 2018; Giarrusso 2019) of the Italian National Institute for Nuclear Physics (INFN).

Although the main challenge of MAPS_3D is to improve the ECR plasma diagnostics through high resolution spectropolarimetry in the visible range, the results of the aimed plasma characterisation will also be of astrophysical interest.

4. Experimental set-up

As to MAPS_3D, ECR plasmas will be created at INFN-Laboratori Nazionali del Sud (LNS) inside of the Flexible Plasma Trap (FPT, Gammino *et al.* 2017), a cylindrical chamber surrounded by three coils for longitudinal plasma confinement through a simple mirror magnetic configuration ($|\mathbf{B}|_{max} \approx 0.5$ T), and equipped with three guides, orthogonal to each other, for microwave radio frequency launching parallel and perpendicular to the field direction.

High resolution spectroscopy will be carried out through the Spettrografo Alta Risoluzione Galileo (SARG, Gratton *et al.* 2001), previously mounted at Telescopio Nazionale Galileo (TNG, La Palma, Canary Islands) and now at LNS after a Memorandum of Understanding signed in August 2017 between INFN-LNS and Catania Astrophysical Observatory (OACT) of the National Institute for Astrophysics. SARG allows to obtain spectra in the wavelength range 370–1000 nm in a single shot with constant resolution $R = 164000$, e.g. at 500 nm it is possible to distinguish lines separated up to 0.003 nm. SARG at TNG was equipped with a polarimetric unit implemented by OACT researchers (Leone *et al.* 2003).

The tridimensional spectropolarimetric analysis will be done by means of three polarimeters coupled to FPT at the microwave launching entrances and fiber-linked to SARG. It will be possible to point-by-point map the plasma, with spatial resolution up to 1 mm^3, by varying the focus of each polarimeter.

First results about plasma characterisation and $g_{\rm eff}$ measurements are expected at the end of 2019.

References

Bruhweiler, F. C. 1992, *Highlights of Astronomy*, 9, 553

Byrne, J. P. 2012, *eprint* arXiv:1202.4005

Gammino, S., Celona, L., Mascali, D., Castro, G., Torrisi, G., Neri, L., Mazzaglia, M., Sorbello, G., Leonardi, O., Allegra, L., Calabrese, G., Chines, F., Gallo, G., & Passerello, S. 2017, *J. Instrum.*, 12, P07027

Geller, R. 1996, *Electron cyclotron resonance ion sources and ECR plasmas, Bristol: Inst. of Phys.Publ.*

Giarrusso, M., Avila, G., Del Zanna, G., Leone, F., Munari, M., Castro, G., Celona, L., Gammino, S., Mascali, D., Mazzaglia, M., & Naselli, E. 2018, *J. Instrum.*, 13, C11020

Giarrusso, M. 2019, *Il Nuovo Cimento C*, 42, 227

Gratton, R. G., Bonanno, G., Bruno, P., Calí, A., Claudi, R. U., Cosentino, R., Desidera, S., Farisato, G., Martorana, G., Rebeschini, M., Scuderi, S., & Timpanaro, M. C. 2001, *Exp. Astron.*, 12, 107

Kupka, F., Piskunov, N., Ryabchikova, T. A., Stempels, H. C., & Weiss, W. W. 1999, *A&AS*, 138, 119

Kurucz, R. L. 2005, *MSAIS* 8, 14

Landi Degl'Innocenti, E. 1982, *Solar Physics*, 77, 285

Landi Degl'Innocenti, E. & Landolfi, M. 2004, *Polarization in Spectral Lines, Astrophysics and Space Science Library, Kluwer Academic Publishers, Dordrecht*, 307

Leone, F., Bruno, P., Cali, A., Claudi, R., Cosentino, R., Gentile, G., Gratton, R., & Scuderi, S. 2003, *SPIE*, 4843, 465

Leone, F., Scalia, C., Gangi, M., Giarrusso, M., Munari, M., Scuderi, S., Trigilio, C., & Stift, M. J. 2017, *ApJ*, 848, 107

Leto, P., Trigilio, C., Buemi, C. S., Umana, G., & Leone, F. 2006, *A&A*, 458, 831

Mascali, D., Castro, G., Altana, C., Caliri, C., Mazzaglia, M., Romano, F. P., Leone, F., Musumarra, A., Naselli, E., Reitano, R., Torrisi, G., Celona, L., Cosentino, L. G., Giarrusso, M., & Gammino, S. 2017, *J. Instrum.*, 12, C12047

Mathys, G. 1990, *A&A*, 236, 527

Nakagawa, T. 2014, *Rev. Sci. Instrum.*, 85, 02A935