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Citation: Phillips, M. E., Keenan, Francis, Rose, Steven, Botha, Gert, Foord, Mark, Heeter, Robert and Ferland, Gary (2001) Photoionized plasma calculations using laboratory and astrophysical models. In: Spectroscopic Challenges of Photoionized Plasmas. ASP Conference Series, 247 (247). Astronomical Society of the Pacific, San Francisco, pp. 123-126. ISBN 978-1-58381-583-0

Published by: Astronomical Society of the Pacific

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## Photoionized Plasma Calculations using Laboratory and Astrophysical Models

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**Abstract.** We present numerical simulations from the code GALAXY, frequently employed to model the distribution of excitation and ionization, and the spectral emission from laboratory plasma experiments. In particular, preliminary calculations relevant to the Lawrence Livermore National Laboratory photoionization collaboration are presented, along with results which compare GALAXY with results from the astrophysical code CLOUDY.

### 1. Introduction

High resolution spectroscopy is of major importance in many areas of plasma physics and astrophysics. In particular, X-ray spectra can provide information on a diverse range of high temperature plasmas, including magnetically-confined tokamak, laser-produced plasmas, and astrophysical sources such as active galactic nuclei. The analysis of X-ray spectra is performed using spectral modelling codes.

However, although the results of such models have been extensively tested against experiment for collisionally-dominated plasmas, this is not the case for plasmas in which the excitation and ionization are dominated by the ambient radiation field, particularly for plasmas in a steady-state. For a plasma to be

radiation-dominated (sometimes called photoionization-dominated), the radiation field has to be intense for the photoexcitation and ionization rates to be high, and the electron density must be low for the electron collisional excitation and ionization rates to be low. Under these conditions the radiation field can dominate the excitation and ionization processes. By comparing the distribution of ionization as predicted by a computer model with the measured results, an assessment may be made of the accuracy of the model.

The distribution of ionization in steady-state radiation-dominated plasmas at low density is characterised by a single, so-called photoionization parameter

$$\xi = 4\pi F/n_e$$

where  $F$  is the flux incident on the plasma (in  $\text{erg cm}^{-2} \text{s}^{-1}$ ) and  $n_e$  is the electron number density (in  $\text{cm}^{-3}$ ).

### 1.1. The GALAXY Code

The computer code GALAXY (Rose 1998) was designed to calculate the distribution of excitation and ionization of laboratory (such as high-power laser-produced) plasmas. Given parameters such as electron density, and electron and ion temperatures, GALAXY calculates the distribution of ionization within the plasma and line emission. It can include the effects of a radiation field whether incident on the plasma or generated internally through the optical depth of the lines.

The code generates internally the atomic data required. Collisional and radiative excitation and ionization rates, together with autoionization and dielectronic recombination rates which link those levels, are generated using simple (in general, scaled hydrogenic) energy levels and rate (both collisional and radiative) coefficients. Within the average-of-configuration approximation, GALAXY allows not just K-shell (H- and He-like) ions but also more complex open L- and M-shell ions to be considered. It can also simulate mixtures of materials. GALAXY solves the coupled rate equations in the steady-state approximation.

### 1.2. Input and output of GALAXY

In order to perform a calculation GALAXY requires electron and ion temperatures, a density (either number or mass), the number fractions of each element considered and the electronic configurations for each element.

If an incident radiation field is included then the model requires a specification of the field. For the calculations performed here a radiation field of blackbody spectral shape is employed (characterised by a radiation temperature  $T_r$ ) and the radiation field reduced uniformly across the spectrum to model a geometric dilution factor. Although GALAXY is a zero-dimensional model, two lengths may also be included for the calculation of radiation transfer: an escape distance (the average distance that photons travel to escape) and emission distance (the length of the plasma along a line-of-sight for which a calculation of the emergent intensity in a spectral line is required). The escape distance is used to calculate line escape factors which are not employed in the current calculations.

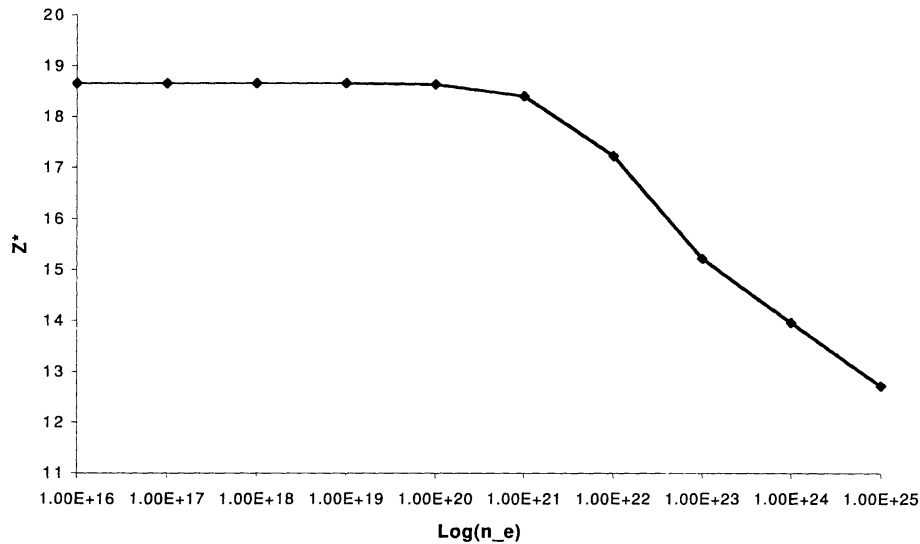


Figure 1. Average ionization of Fe with varying number density  $n_e$  (in  $\text{cm}^{-3}$ ).  $T_e = 100\text{eV}$ ,  $T_r = 200\text{eV}$ ,  $\log(\xi) = 1.0$

## 2. Applications of GALAXY

Figure 1 shows an example of the results produced by the GALAXY model for an iron plasma with an incident radiation field from one side. The radiation field is characterised by  $T_r = 200\text{eV}$ , with a dilution factor determined by  $\log(\xi) = 1$ . The electron temperature  $T_e$  is  $100\text{eV}$ . It shows that the average ionization remains constant for densities lower than approximately  $10^{19}\text{cm}^{-3}$  (low density limit) above which point 3-body effects become important, and the ionization begins to drop with increasing  $n_e$ . Figures 2 and 3 show how the ionization distribution varies with  $\log(\xi)$  and electron temperature at the low density limit.

The final plot, Figure 4, displays the ionization distribution for an iron plasma with  $T_e = 33.6\text{eV}$ ,  $T_r = 200\text{eV}$  and  $\log(\xi) = 2$ . These conditions are thought to be close to those created in recent experiments undertaken at the Z-machine at the Sandia National Laboratory, USA, which are designed to create, in the laboratory, a steady-state photoionization-dominated plasma. In comparison with GALAXY results from the code CLOUDY (Ferland et al. 1998) which is extensively used by the astrophysical community, are shown. The good agreement between GALAXY and CLOUDY is encouraging considering the considerable differences between the models used in each code.

## References

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 Ferland, G. J., Korista, K. T., Verner, D. A., Ferguson, J. W., Kingdon, J. B., & Verner, E. M. 1998, *PASP*, 110, 761-778

**Acknowledgments.** MEP acknowledges financial support from the Department of Higher and Further Education, Training and Employment and the Rutherford Appleton Laboratory.

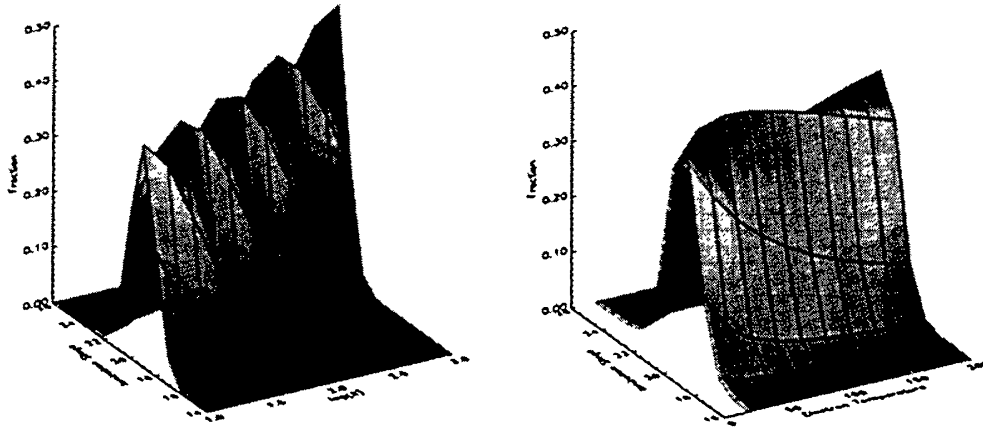


Figure 2. (Above left.) Variation in the distribution of ionization with varying  $\log(\xi)$  ( $\log(X)$  in plot).  $T_e = 100\text{eV}$ ,  $T_r = 200\text{eV}$ ,  $n_e = \text{low density limit}$

Figure 3. (Above right.) Variation in the distribution of ionization with varying  $T_e$ .  $T_r = 200\text{eV}$ ,  $\log(\xi) = 2.0$ ,  $n_e = \text{low density limit}$

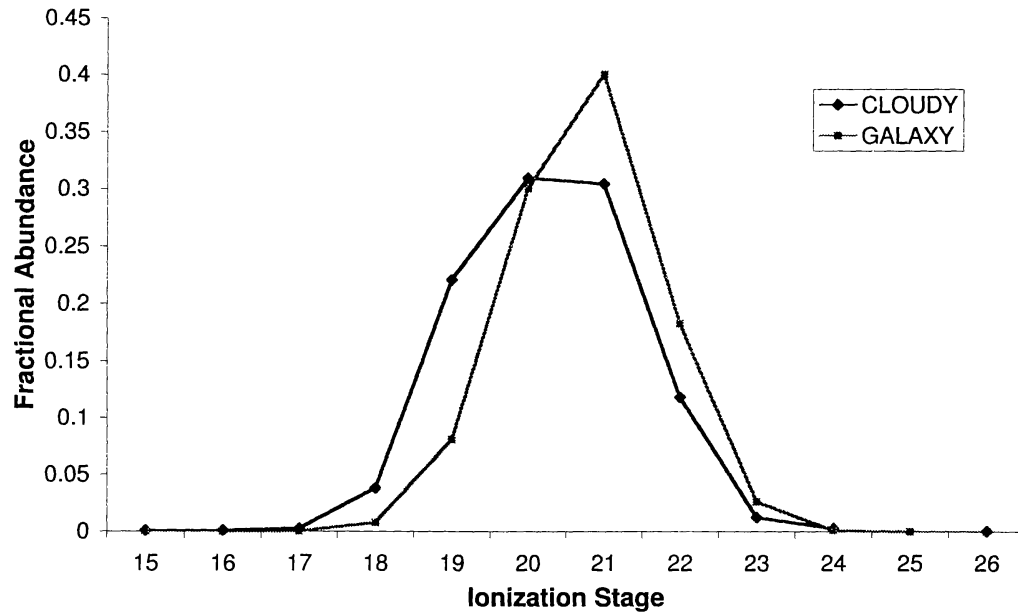


Figure 4. Distribution of ionization for Fe, predicted by CLOUDY and GALAXY for an iron plasma,  $T_e = 33.6\text{eV}$ ,  $T_r = 200\text{eV}$ ,  $\log(\xi) = 2.0$