THE AR CETRI SPECTRAL CODE FOR THIN PLASMAS

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ABSTRACT

The Arcetri Spectral Code allows to evaluate the spectrum of the radiation emitted by hot and optically thin plasmas in the spectral range 1 - 2000 Å. The Arcetri DataBase has been updated including atomic data and radiative and collisional rates to calculate level population and line emissivities for a number of ions of the Minor Elements; a critical compilation of the electron collision excitation data for these ions has been done. The present version of this program includes the CHIANTI Database (Dere et al. 1997) for the most abundant elements, the Minor Elements data, and the Fe III atomic model, collisional and radiative data.

1. Introduction

More than 25 years ago, M. Landini and B.C. Monsignori Fossi, began to develop a numerical code to evaluate optically thin plasma emissivity, for temperature larger than $10^4 K$. The computation was performed in the so called "coronal approximation" where each level population is obtained assuming collisional and radiative coupling with the ground level only. The first result of this work was the theoretical spectrum from 1 to 100 Å both in the lines and in the free-free and free-bound continuum of a few important ions (Landini and Monsignori Fossi 1970). Since then, several upgrades have been performed, including the updating of the ionization balance (Landini and Monsignori Fossi 1991), the extension of the atomic DataBase (Landini and Monsignori Fossi 1990) to include lines from 1 to 2000 Å, the computation of free-bound contribution from minor ions, the inclusion of two-photon continuum, the development of a library of numerical codes for the Differential Emission Measure evaluation.

Most recently a big upgrading of the atomic DataBase has been performed including atomic models, electron collision rates and radiative decays in order to evaluate the detailed population of each level assuming statistical balance among the excited states and decay processes. The computed spectrum has been extensively applied to the study of the solar corona and to the interpretation of the X and EUV emission of solar type stars, and a version covering the spectral interval from 70 to 700 Å has been used for data reduction of the Extreme Ultraviolet Explorer (EUV) observations.

The aim of this paper is to present the last version of the Arcetri Spectral Code and Database which now includes the whole DataBase already inserted in the CHIANTI project (Dere et al. 1997) and the line intensity of most of the ions of Minor Elements, as described in the following sections (not yet included in CHIANTI). Moreover, the Code allows the evaluation of free-free, free-bound and two-photons continuum.

2. The Line Intensity

The number of photons emitted in a spectral line $(i \rightarrow j)$ for an optically thin coronal plasma is given by:

$$I_{ij} = \int_V N_j(X^{m+}) A_{ij} dV$$

$$= \int_V G_{ij}(T, N_e) N_j^2 dV \quad \text{ph s}^{-1} \quad (1)$$

where we have defined the Contribution Function as follows:

$$G_{ij}(T, N_e) = \frac{N_j(X^{m+}) N(X^{m+})}{N(X)} \times N(X) \frac{N(H)}{N_e} \frac{A_{ij}}{N_e} \quad (2)$$

where

- $N_j(X^{m+})$ is the relative upper level population;
- $N(X^{m+})$ is the relative abundance of the ion $X^{m+}$;
- $N(X)$ is the abundance of the element $X$ relative to Hydrogen;
Figure 1. The continuum emission per unit emission measure for a thin plasma at temperature 3 \(10^4\) K and electron density 1 \(10^6\) cm\(^{-3}\) between 1 \(\AA\) and 2000 \(\AA\). Free-free (dotted line), free-bound (dashed line) and two-photon continuum (long-dashed line) are indicated.

- \(\frac{N(H)}{N_e}\) is the hydrogen abundance relative to the electron density (\(\approx 0.8\));


Level population is calculated solving the statistical equilibrium equation:

\[
N_i(N_e\Sigma C_{i,j}^e + N_p\Sigma C_{i,j}^p + \Sigma_{<j} A_{j,i}) = \Sigma_{>j} N_i N_{A_{i,j}}
\]  

(3)

where \(C_{i,j}^e\) and \(C_{i,j}^p\) the electron and proton collisional excitation rates (\(\text{cm}^3\text{s}^{-1}\)), \(C_{i,j}\) and \(C_{i,j}^p\) the electron and proton collisional de-excitation rates and \(A_{j,i}\) are radiative decay probabilities from level \(j\) to level \(i\).

The collisional excitation rate for a Maxwellian electron velocity distribution can be expressed as

\[
C_{i,j}^e = \frac{8.63 \cdot 10^{-6}}{T_e^{1/2}} \frac{\Upsilon_{i,j} (T_e)}{\omega_i} \exp\left(-\frac{\Delta E_{i,j}}{kT_e}\right)
\]  

(4)

where \(\omega_i\) is the statistical weight of level \(i\), \(k\) is the Boltzmann constant and \(\Upsilon_{i,j}\) is the thermally-averaged collision strength (effective collision strength):

\[
\Upsilon_{i,j} = \int_0^\infty \Omega_{i,j} \exp\left(-\frac{E}{kT_e}\right) d\frac{E}{kT_e}
\]  

(5)

where \(\Omega_{i,j}\) is the collision strength, related to the electron excitation cross section and \(E\) is the energy of the scattered electron relative to the final energy state of the ion. In the evaluation of the effective collision strength the scaling laws of Burgess and Tully 1992 have been adopted.

3. The DataBase

In the present update the Arcetri Spectral Code includes:

- The whole CHIANTI dataset (Dere et al. 1997) concerning the atomic models, the electron collision excitation and radiative decay rates for most of the ions of C, N, O, Ne, Mg, Al, Si, S, Ar, Ca, and Fe II and from Fe VII to Fe XXIV.

- Atomic data for the so-called Minor Elements (Na, P, Cl, K, Ti, Cr, Mn, Co and Zn) and for Al V, VI, VII, VIII not yet included in the CHIANTI DataBase. The ions of these elements may provide several observed lines, some of which weak in most spectra, which can be useful in spectral analysis and DEM studies. The Minor Elements Database includes ions belonging to the Li-like, Be-like, B-like, F-like, C-like, N-like, O-like, Na-like, Mg-like isoelectronic sequences.

For most sequences, theoretical computation available in the literature has been used; no collision data are available for the Magnesium, Oxygen and Nitrogen-like Minor Elements, so it has been necessary to interpolate the effective collision strengths and the radiative data from the isoelectronic ions which were available in the CHIANTI Database.

- Fe III atomic model, collisional and radiative dataset.
• Atomic data for the lines in the range 1-2000 Å not included neither in CHIANTI nor in the Minor Elements dataset; they have been renewed updating the transition probabilities from the literature. Line emission in this case is evaluated assuming collisional population from ground level only.

• Continuum radiation evaluation including, free-free, free-bound from all the ions in the DataBase, and two-photon continuum from H-like and He-like ions.

The program evaluates level population and Contribution Functions for temperature ranging between $10^4$ and $10^6$ K and any electron density.

An example of the continuum emission is shown in Figure 1.

4. Plasma diagnostics applications

An extended library of numerical codes has been produced during the years, to allow

• Differential Emission Measure analysis of celestial sources,

• temperature diagnostics of astrophysical plasmas,

• electron density determination

• evaluation of synthetic spectra

One example of the plasma diagnostic methods is in the Poster Temperature and density diagnostics of quiet Sun and active regions observed with CDS NIS presented at this meeting.

We show here examples of synthetic spectra computed with the Arcetri Spectral Code and comparison with the observations.

REFERENCES


Dere, K.P., Landi, E., Mason, H.E., Monsignori Fossi, B.C., Young, P.R., 1997, A&ASS, 125, 149


Figure 3. The SERTS-89 line identification. The section between 380 Å and 397 Å of the spectrum of the SERTS-89 flight (Thomas and Newpert 1994). The lines of Mn XV, Ti XI, and Cr XIV are among the new ones included in the Database.

Figure 4. NIS9 spectrum of a Solar Active Region. The Normal Incidence Spectrograph observation from SOHO of an Active Region (top) is compared with the simulated synthetic spectrum (bottom); use is made of the Arcetri Spectral Database; the electron density $2 \times 10^6$ cm$^{-3}$ is assumed. The strong line at 607 Å is the second order 305 Å of He II not included in the synthetic computation.
Figure 5. The EUVE spectrum of α Centauri. The medium wavelength section of the Extreme Ultraviolet Explorer spectrum of α Centauri: the synthetic spectrum (top) is compared with the observed one (bottom). Several prominent lines are labeled with their identifications.