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CHIANTI—AN ATOMIC DATABASE FOR EUV EMISSION LINES

Enrico Landi[1]

Max-Planck-Institut für Aeronomie, Katlenburg-Lindau, Germany

RESUMEN

CHIANTI contiene un conjunto de datos atómicos y probabilidades de transición, cuidadosamente seleccionados, para calcular el espectro de emisión de plasmas astrofísicos. Los datos contienen niveles atómicos, longitudes de onda, fuerzas de oscilador, probabilidades A de transición y tasas de excitación colisional. Se provee un conjunto de programas que usan los datos para calcular el espectro, como función de la temperatura y la densidad, en el rango de longitudes de onda deseado. Se ha desarrollado un grupo de programas para hacer diagnósticos de plasmas astrofísicos. Se describe la base de datos CHIANTI actualizada y algunos de los resultados más importantes que se han obtenido con ella.

ABSTRACT

CHIANTI consists of a critically evaluated set of atomic data and transition probabilities necessary to calculate the emission line spectrum of astrophysical plasmas. The data consist of atomic energy levels, atomic radiative data such as wavelengths, weighted oscillator strengths and A values, and electron collisional excitation rates. A set of programs that use these data to calculate the spectrum in a desired wavelength range as a function of temperature and density is also provided. A suite of programs has been developed to carry out plasma diagnostics of astrophysical plasmas. The state-of-the-art contents of the CHIANTI database will be described and some of the most important results obtained from the use of the CHIANTI database will be reviewed.

Key Words: **ATOMIC DATA — LINE:FORMATION — PLASMAS — RADIATION MECHANISMS: THERMAL — TECHNIQUES: SPECTROSCOPIC**

1. INTRODUCTION

EUV emission line intensities have been widely used in the past decades to measure the physical parameters for astrophysical plasmas, such as electron density and temperature, chemical abundances, plasma Emission Measure and Differential Emission Measure (*DEM*). However, the use of any plasma diagnostic technique involving line intensities requires the knowledge of a large amount of theoretical atomic data and transition probabilities, which are necessary to calculate theoretical line emissivities to be compared with observations (Mason & Monsignori Fossi 1994). These atomic data and transition probabilities can be found in the literature. Most of them come from theoretical calculations carried out on individual ions or isoelectronic sequences. These computations involve sophisticated atomic physics and collision codes. Only in a few cases laboratory measurements of collisional and radiative transition probabilities are available.

The aim of the CHIANTI database is to provide the astrophysical community with an extensive, updated and easy-to-use database of atomic data and transition probabilities which can be used for detailed diagnostics of astrophysical plasmas. CHIANTI also provides a suite of IDL routines which allows us to calculate theoretical intensity ratio curves for density and temperature diagnostics, generate synthetic spectra and measure the

[1]Dipartimento di Astronomia e Scienza dello Spazio, Universita' di Firenze, Firenze, Italy.

plasma *DEM* from observations. The CHIANTI database is released for wavelengths longer than 50 Å, and it includes data to account for most of the observed lines in the EUV and UV spectral range. An upper wavelength limit to CHIANTI is not easy to determine, but lies somewhere in the UV range, where lines from neutral elements (not included in CHIANTI) begin to dominate the spectrum.

Since its release in 1996 (Dere et al. 1997), the CHIANTI database has been widely used by the astrophysical community on a variety of different astrophysical sources; the comparison with observations has also enabled us to determine the completeness and accuracy of the database and to understand where the state-of-the-art atomic physics calculations need improvements. Version 2.0 of the database has been released including data for many more ions of astrophysical interest, and the continuum radiation (Landi et al. 1999a). So far, CHIANTI includes data for nearly 170 ions for the most abundant elements with $Z \leq 30$. The release of version 3.0, including data for X-ray emission, is scheduled for January 2000.

In the present paper, only a brief overview of the overall structure of the CHIANTI database will be given; more details can be found in in Dere et al. 1997 (version 1.0) and Landi et al. 1999 (version 2.0). Our attention will be focused on the most important results obtained from applications of CHIANTI to observations.

CHIANTI is an international collaboration involving Dr. K. P. Dere (Naval Research Laboratory, USA), Dr. M. Landini (Università di Firenze, Italy), Dr. E. Landi (Max Planck Institut für Aeronomie, Germany), Dr. H. E. Mason and Dr. G. Del Zanna (University of Cambridge, England) and Dr. P. R. Young (Harvard-Smithsonian Center for Astrophysics, USA).

2. THE CHIANTI DATABASE

2.1. *Radiation Processes*

The CHIANTI database allows the calculation of line and continuum emission from plasmas under two assumptions: a) the plasma is optically thin; b) the plasma is in ionization equilibrium.

Under these two assumptions, the number of photons emitted in a spectral line ($i \to j$) is given by:

$$I_{ij} = \int_V N_j(X^{+m}) A_{ji} dV = \int_V G_{ij}(T, N_e) N_e^2 dV \qquad \text{ph cm}^{-3}\ \text{s}^{-1} \tag{1}$$

.

$\mathrm{G}_{ij}(T, N_e)$ is the *Contribution Function* of the line and depends on the electron temperature (T) mainly through the ion abundance, and on the electron density (N_e), mainly through the level population.

The function $\mathrm{G}_{ij}(T, N_e)$ may be expressed as

$$G(T, \lambda_{i,j}) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} \frac{A_{ji}}{N_e} \quad , \tag{2}$$

where

1. – $\frac{N_j(X^{+m})}{N(X^{+m})}$ is the relative upper level population; this quantity is *directly calculated by CHIANTI routines using the data in the CHIANTI database*;

2. – $\frac{N(X^{+m})}{N(X)}$ is the relative abundance of the ion X^{+m}; this quantity enters as an independent input, presently taken from the literature under the assumption of ionization equilibrium;

3. – $\frac{N(X)}{N(H)}$ is the abundance of the element X relative to hydrogen; a choice of different elemental abundance datasets is given to the user;

4. – $\frac{N(H)}{N_e}$ is the hydrogen abundance relative to the electron density (≈ 0.8 for fully ionized plasmas);

5. – A_{ji} is the Einstein coefficient for spontaneous emission; CHIANTI includes A values for all possible transitions in the adopted atomic models (see later)

The relative upper level population is calculated by solving the statistical equilibrium system of equation including all the important processes involved in level excitation and de-excitation. In low density plasmas the most important populating and de-populating processes are spontaneous radiative decay and excitation and de-excitation from electron-ion collisions, since they are generally faster than ionizations and recombinations. In hot plasmas proton collision rates can also be important in determining the level population, but they have not been included in the present version of the CHIANTI database. A future release will include them.

The statistical equilibrium equations take the form

$$N_j\left(N_e \Sigma_i C^e_{j,i} + \Sigma_{i<j} A_{j,i}\right) = \Sigma_i N_i \left(N_e C^e_{i,j}\right) + \Sigma_{i>j} N_i A_{i,j} \quad , \tag{3}$$

with $C^e_{j,i}$ and $C^e_{i,j}$ the electron collisional excitation and de-excitation (cm^{3}s^{-1}), and A_{ji} (s^{-1}) are radiative decay probabilities from level j to level i. If the plasma is characterized by a Maxwellian distribution of velocities, the collisional excitation rate can be expressed as

$$C^e_{i,j} = \frac{8.63 \cdot 10^{-6}}{T_e^{1/2}} \frac{\Upsilon_{i,j}(T_e)}{\omega_i} exp\left(-\frac{\Delta E_{i,j}}{kT_e}\right) \quad , \tag{4}$$

where ω_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). $\Upsilon_{i,j}$ is given by

$$\Upsilon_{i,j} = \int_0^\infty \Omega_{i,j} exp\left(-\frac{E}{kT_e}\right) d\frac{E}{kT_e} \quad , \tag{5}$$

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. CHIANTI includes scaled $\Upsilon_{i,j}$ values as a function of electron temperature for all the possible transitions in the adopted atomic model of each included ion.

In the literature, collision strengths or effective collision strengths are provided by the authors; in case $\Omega_{i,j}$ values only are available, $\Upsilon_{i,j}$ values have been calculated using the scaling laws of Burgess & Tully (1992) and then included in CHIANTI. These scaling laws are also used to store the Υs in a compact form.

Continuum emission included in CHIANTI consists of: *Free-free*; *free-bound* and *two-photon* continuum. For the basic equations ruling these processes we refer to Landi et al. (1999a).

2.2. *Structure and Availability of the Database*

In order to calculate line emissivities, the CHIANTI database includes data for

- Ion level energies, transition wavelengths, spectroscopic information on ion levels;
- Einstein coefficients for spontaneous decay A_{ji} for all the possible transitions between the levels in the adopted atomic model;
- Collisional excitation data [$\Upsilon_{i,j}(T_e)$ values scaled according to Burgess & Tully 1992] for all the possible transitions between the levels in the adopted atomic model

Also, atomic data to calculate continuum emissivity are included in CHIANTI.

The basic unit of the CHIANTI database is the *individual ion*. For each ion, *three* different files are provided:

- the *.elvlc* file: it contains the atomic model together with theoretical and laboratory energy levels;
- the *.wgfa* file: it contains transition wavelengths, oscillator strengths and A_{ji} values;
- the *.splups* file: it contains scaled $\Upsilon_{i,j}(T_e)$ values;

The atomic data necessary for the calculation of continuum radiation are included in a single, separate file. All these files are written in *ascii* format, so that they can be read by anyone: this makes the database completely transparent.

The CHIANTI database is freely available to the astrophysical community on the web at the following addresses:

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- http://wwwsolar.nrl.navy.mil/chianti.html
- http://www.arcetri.astro.it/science/chianti/chianti.html
- http://www.damtp.cam.ac.uk/user/e2e/chianti/chianti.html

3. FUTURE CHIANTI RELEASES

Future releases of the CHIANTI database will include:

1. Data for the X-ray emission: H- and He-like sequences, innershell transitions and satellite lines; this version (CHIANTI 3.0) will be released in January 2000;
2. Proton rates;
3. Improved data for the iron ions, from the IRON PROJECT (Hummer et al. 1993);
4. Ionization and recombination rates;
5. Time dependent emissivity.

4. APPLICATIONS

The large number of ions included in CHIANTI provides a wealth of lines and line ratios which are very useful for diagnostics of plasmas under very different physical conditions. Since its release in 1996, the CHIANTI database has been mostly used by the solar community to measure the physical parameters of the solar plasma, using the wealth of spectroscopic data provided by the very recent and successful *SOHO* mission. However, CHIANTI data have been used to infer physical parameters for a few solar-type stars (e.g., Landi et al. 1997a).

4.1. *Line Identifications and Spectral Atlases*

Extensive databases such as CHIANTI can be very useful for line identification and for building spectral atlases of a variety of astrophysical sources. At the same time, such an exercise represents an excellent test for the database itself, as it allows us to check its completeness and to understand where improvements are required.

Version 1.0 of the database has been tested against all available solar observations by Dere et al. 1997, who find that CHIANTI was able to account for most of the observed lines; this has shown that, in terms of the high resolution spectral observations available at that time, CHIANTI was essentially complete.

After the release of version 1.0, the CHIANTI database has been used to build spectral atlases from the Coronal Diagnostic Spectrometer (CDS) on board the *SOHO* satellite. Details on this instrument can be found in Harrison et al. (1995): CDS is an imaging spectrometer observing the Sun in six different wavelength ranges: 151–221, 256–341, 307–379, 393–492, 513–633 and 659–785 Å. These wavelength ranges are ideal for studying the solar emission from the solar chromosphere to the corona, in very different physical conditions.

The CDS active region spectral atlas has been created by Landi et al. (2000a), using the full CDS spectral range; similar work has been carried out by Del Zanna et al. (2000a; 2000b) for quiet Sun and coronal hole conditions, and also using an off-limb spectrum.

An extensive line identification work has been carried out by Feldman et al. (2000) using the Solar Ultraviolet Measuremet of Emitted Radiation experiment (SUMER, Wilhelm et al. 1995) on board of *SOHO*. The Feldman et al. analysis consists of the study of the solar spectrum between 500 and 1610 Å emitted by flaring plasma observed off the solar disc. This study has permitted the identification of a number of forbidden lines from very highly ionized elements, many of which belong to the less abundant elements in the solar plasma; also, it has been possible to measure energies for the levels involved in some of these transitions with accuracy comparable to the accuracy achieved in previous laboratory measurements.

Young, Landi, & Thomas (1998) have used the CHIANTI database to check the solar active region spectrum observed by the 1989 flight of the rocket-borne SERTS instrument and published by Thomas & Neupert (1994). New identifications have been proposed and a few misidentifications have been corrected.

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Unfortunately, no attempt has been made to test the completeness of the database for wavelengths between 50 Å and 170 Å due to the lack of very high quality spectra in this range observed from the Sun and the stars. EUVE stellar observations could in principle help in this work, but the low signal-to-noise ratio is somewhat a limitation to such a work.

Recently, Beiersdorfer et al. (1999) found that CHIANTI, as well as the other spectral codes available in the literature, are incomplete in the 60–140 Å wavelength range, as they lack emission from Fe VII, Fe VIII, Fe IX, and Fe X lines originated by high-n levels. These lines have been observed by Beiersdorfer et al. (1999) with the Livermore electron beam ion trap (EBIT) facility and provide a quasi-continuum emission. However, it should be noted that physical conditions in laboratory plasmas might be quite different from those in solar and stellar coronae, so that the line emission observed by Beiersdorfer et al. 1999 might not necessarily play an important role in solar and stellar spectra. Further observations from the Sun and stars are required to solve this issue. Since atomic physics calculations for electron-ion collisions have never been published in the literature for the transitions observed by Beiersdorfer et al. (1999), spectral codes such as CHIANTI cannot possibly include them. For this reason further studies on electron-ion collisions for these transitions are therefore required.

Works on the solar spectral atlases have shown that the CHIANTI database is able to account for all of the strongest observed spectral lines in the 170–790 Å spectral range and for most of the weakest; moreover CHIANTI provides a large number of very useful diagnostic line pairs for density and temperature measurements. These results show that CHIANTI is essentially complete for wavelengths included in the 170–790 Å spectral range; the lack of data for neutral elements is a limitation for longer wavelengths.

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4.2. *Intensity Calibration of EUV Spectrometers*

The internal relative intensity calibration of high resolution spectrometers can be tested through the comparison of theoretical intensity ratios with observations; this method has been first used by Neupert & Kastner (1983). The large amount of data for lines from different ions included in the CHIANTI database, coupled with the spectral observation from solar plasmas carried out by high resolution spectrometers provides an unique opportunity to check the internal calibration of these instruments.

The first application of CHIANTI for calibration purposes has been performed by Young et al. (1998), who carried out a systematic check through the SERTS-89 spectrum between 171 and 440 Å (Thomas & Neupert 1994) finding that the relative intensity calibration for wavelengths greater than 400 Å required a correction up to a factor 2.

A similar study has been performed by Brosius et al. (1998a; 1998b) which determined the relative intensity calibration of the 1995 version of the SERTS instrument entirely basing their work on a comparison between CHIANTI and the uncalibrated observed spectra. They find that the resulting sensitivity curve is consistent with the design characteristics of the telescope multilayer coating and agree with the measurements carried out with SURF facility of the National Institute of Standards and Technology.

An extensive use of CHIANTI for calibration purposes has been carried out using spectra from the CDS instrument. Landi et al. (1997b) used CHIANTI to show that the CDS pre-flight intensity calibration (Bromage et al. 1996) required significant corrections in the two ranges 307–379 and 513–633 Å. Further studies (Landi et al. 1999b) determined the second order calibration for the instrument for the first time. Their results have triggered new studies on the CDS calibration, some using CHIANTI and other comparisons with data from other rocket-borne instruments. As a result a major revision in the CDS intensity calibration has been done (Lang et al. 1999). Later, Del Zanna et al. (2000c) have determined the complete CDS calibration using CHIANTI and all the lines observed in the CDS spectal range, finding that the Lang et al. (1999) results require still some more corrections.

4.3. *Calculation of Radiative Losses of Optically Thin Plasmas*

Radiative losses are a fundamental physical process in astrophysical plasmas which needs to be taken into account in any theoretical model which includes the energy balance. In the past a few computations have been published by a number of authors, who sometimes also provide analytical fits to their results for the most important temperature ranges.

Extensive databases such as CHIANTI provide a unique opportunity to re-calculate radiative losses from astrophysical plasmas since they are complete to the extent that state-of-the-art theoretical computations of transition probabilities and atomic data are.

Landi & Landini (1999) have performed such a calculation and provided analytical fits to the resulting curves for temperatures greater than 10^5 K. They also carried out detailed checks of the effects on the results of changes in the parameters necessary to the calculation of the radiative losses: electron density; excitation and de-excitation transition probabilities; ion fractions (under the assumption of ionization equilibrium); plasma chemical composition. They find that the first three parameters cause differences up to 50% in the radiative losses, while chemical abundances may change the results by a factor of 2. They conclude that the chemical composition is the most critical parameter in the calculation.

4.4. *Plasma Diagnostics*

Temperature diagnostics from CHIANTI line ratios have been carried out by Sterling et al. (1999) using *SOHO*-CDS and *Yohkoh* observations; they use their results to discuss variation with height in the thermal structure of a solar active region and its implications for the presence of loops; a similar objective has been pursued by Mason et al. 2000. Electron temperature in coronal holes and quiet Sun has been investigated by Del Zanna & Bromage (1999). Chiuderi Drago et al. (1999) used CHIANTI EUV line intensities to compare temperature measurements in coronal holes obtained from a combination of EUV and radio emission. They show that radio and EUV observation provide the same temperature values, thus removing a long-standing discrepancy existing in literature between EUV and radio temperature measurements; they find, however, large differences from *Yohkoh* results.

A number of authors have derived the electron density of solar plasma in a variety of solar conditions from CHIANTI line ratios. These densities have been used to discuss theoretical active region loop models by Aschwanden et al. (1999) and Landini et al. (1999). Measurements of the electron pressure in the solar transition region have been carried out by Griffiths et al. (1999) and Landi et al. (2000b). O'Shea, Doyle, & Keenan (1998) compare transition region electron pressure values with coronal measurements and discuss the agreement that they find in term of the absence of the unresolved fine structures proposed by Feldman (1983) and Feldman, Widing, & Warren (1999). Fletcher & DePontieu (1999) have studied the electron density of an active region on solar disk using CHIANTI to discuss the nature of the so-called "Moss" observed by TRACE. The "Moss" appears as a finely structured, low-lying and quickly changing bright emission observed in active regions in the vicinity of loops (Berger et al. 1999). Fletcher & DePontieu (1999) conclude that the "Moss" must be due to a number of small loops with elevated pressure; this can be an important issue for active region models.

A comparison between cell and network densities in quiet Sun (Del Zanna & Bromage 1999; Landi et al. 2000b) and coronal holes (Del Zanna & Bromage 1999) has shown that the two regions have similar densities. These results imply that the difference in line intensities emitted by the two regions is due to different filling factors and not to differences in electron density, as it was commonly believed.

Fludra et al. (1999) have also determined the variation of electron density and temperature as a function of the height over the photosphere in coronal holes.

A number of authors have investigated the Emission Measure (EM) and Differential Emission Measure (*DEM*) from solar observations using CHIANTI line intensities and the IDL routine for *DEM* diagnostics included in the database. This has been done in order to test the EM profiles along long-lived solar coronal loops by Lenz et al. (1999); they find that neither isothermal nor non-isothermal models fit with the observations, concluding that some physical process not included in those models is present. Griffiths et al. (1999) determine the EM distribution for the solar transition region and discuss its implication for transition region and coronal structure. Warren, Mariska, & Lean (1998) use CHIANTI to determine the solar EM distribution to calculate the solar synthetic spectrum, with the aim of building a quiet Sun irradiance spectrum in the 50–1200 Å spectral range.

The CHIANTI database has also been used to determine element abundances in the solar atmosphere, with the aim of investigating the so-called FIP effect: this consists in a difference in the chemical composition of the solar atmosphere between the photosphere and the overlying corona. This difference seems to be related to the First Ionization Potential (FIP) of the elements, in the sense that the abundance of elements with FIP $<$ 10 eV is enhanced by a factor between 3 and 4 relatively to that of elements with FIP > 10 eV (see for example Haisch, Saba, & Meyer 1996 for details). To date, no comprehensive theory has been developed which is able to account for such a behaviour of element abundances. A study of Mg (low-FIP element) to Ne (high-FIP element) relative abundance as a function of the distance from the limb using CHIANTI is reported by Dwivedi, Curdt, & Wilhelm (1999); the authors find significant variations with height. This study has been continued by Mohan et al. 2000 using other high-FIP and low-FIP ions, which find also a correlation between Mg/Ne relative abundances and active region loop structures. Young & Mason (1997) report huge variations in the relative Mg/Ne abundance in an emerging magnetic region observed with CDS; again, abundance variations are correlated with solar magnetic structures. Del Zanna & Bromage (1999) compared element abundances measured in network and cell regions and find differences both in quiet Sun and coronal holes, showing that the FIP effect seems to affect the two regions in a different way.

CHIANTI radiative data have also been used by Peter & Judge (1999) in order to calculate optical depth for Ne VIII and Mg X, finding that nonnegligible optical depths along the line of sight is present. This may have consequences on the *DEM* diagnostics involving this line.

5. CONCLUDING REMARKS

CHIANTI consists of an extensive, updated critically evaluated set of atomic data and transition probabilities necessary to calculate the emission line spectrum of astrophysical plasmas. This database includes data necessary for the evaluation of continuum emission and theoretical emissivities of lines from nearly 170 ions. The CHIANTI database is continuously updated and expanded, and a future release (version 3.0) is scheduled for January 2000, which includes data for calculating the X-ray emission.

Applications of the CHIANTI database to solar emission have shown the great potential of the database, when its use is combined with the spectroscopic capabilities of the most modern instruments observing the Sun and the stars in the EUV and UV spectral range. So far, use of the database has been made not only with the aim of diagnosing the physical parameters of the emitting plasma (the first goal of the database), but also for determining the intensity calibration of rocket and satellite-borne spectroscopes, for calculating the radiative losses of astrophysical plasmas, testing theoretical loop models, studying the density and thermal structure of the solar plasma, developing spectral altases for different solar conditions, and measuring energies for ion levels with accuracy comparable to laboratory measurements.

All these applications have also permitted us to assess the accuracy and completeness of the CHIANTI database; results have shown that CHIANTI is able to account for the vast majority of spectral features between 170 Å and 790 Å, and to provide several precious diagnostic tools in the UV wavelength range, where, however, CHIANTI is not able to account for the neutral atoms' emission. Greater caution is required in the 50–170 Å spectral range, where the presence of Fe VII to Fe X high-n transitions, suggested by Jordan (1996) and Beiersdorfer et al. (1999), could possibly play an important role in spectra from astrophysical plasmas. To our knowledge, no transition probabilities have been published in the literature for such transitions. This is a clear example to show that much work still needs to be done in order to build a really complete database.

The CHIANTI database has been (and hopefully will continue to be) of great help to the astrophysical community in the analysis of spectra from astrophysical plasmas; all these applications, and more which will be coming from future experiments, will be of great help for our understanding of the basic processes ruling astrophysical plasmas.

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Enrico Landi: Max-Planck-Institut für Aeronomie Max-Planck Strasse 2, 37191 Katlenburg-Lindau, Germany (enricol@arcetri.astro.it).