CHIANTI
A Package for Astrophysical Emission Line Spectroscopy

SOFTWARE NOTE – Version 1.0 – 10 November 2000

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Preliminary note to Version 1.0

This document describes the general characteristics of the CHIANTI database and then details the IDL procedures that can be used in conjunction with the Version 3.01 of the database, and that are available under SolarSoft in the CHIANTI package. These IDL procedures contain:

1-The basic CHIANTI v. 3.01 procedures, as can also be found on the WWW. These routines are autonomous, in the sense that do not require any other routines outside this package.

2-A set of routines that was originally written for the SOHO/CDS software. These routines have now been updated in order to make them compatible with Version 3.01 of the database. A number of new features have also been added. Please note that most of these routines use other SolarSoft procedures, that are in the $SSW/gen and $SSW/soho packages. Backward compatibility has been assured for a number of cases.

A set of routines written by Peter Young has also been included. These are described by the *cds_swnote_52.ps* document.

This document replaces the original CDS software notes, and represents the first draft user guide to the CHIANTI database and IDL routines.

In the near future, new software will be added and this Software note updated.

Written by Giulio Del Zanna, November 10 2000.

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1 Introduction

Plasma emission codes have long been used to study UV and X-ray spectral lines from the solar atmosphere. A comparison of the theoretical line intensities with the observed intensities allows a determination of the physical parameters for the plasma (cf Mason and Monsignori Fossi, 1994). If the theoretical intensities are processed using relevant instrument parameters, it also allows one to identify complications with the observational analyses, such as line blends. A comparison and critique of available plasma emission codes developed by different groups is presented in Brickhouse *et al* (1995) and Mason (1995). These codes require the input of a large amount of atomic data. Following Mewe (1972), most codes used a type of semi-classical ($\bar{g}$) approximation to represent the electron excitation rates. This type of parameterisation / approximation has severe limitations. It is very important, now that high accuracy atomic data are available, to improve the quality of the electron excitation rates in the plasma codes.

CHIANTI, developed by Dere, Landi, Mason, Monsignori Fossi and Young provides a database of atomic energy levels, wavelengths, radiative transition probabilities and electron excitation data for a large number of ions of astrophysical interest. It also includes a suite of Interactive Data Language (IDL) programs to calculate optically thin synthetic spectra and to perform spectral analysis and plasma diagnostics. This database allows the calculation of theoretical line emissivities necessary for the analysis of optically thin emission line spectra. The first version (1.01) of the CHIANTI database was released in 1996 and is described in Dere et al., (Paper I, 1997).

Sadly, during the course of this work, our collaborator and colleague, Brunella Monsignori Fossi died suddenly and prematurely. Her enthusiasm, support and friendship is a great loss not only to us but to the whole of the astronomical community.

In Paper II, Young et al. (1998) used the CHIANTI database for a detailed comparison with observed EUV solar spectra to assess the diagnostic accuracy of the two data sets.

The second version was released in 1999 (Paper III: Landi et al. 1999). It mainly included continuum emission and data for the minor ions (Na, P, Cl, K, Ti, Cr, Mn, Co, and Zn).

Both versions of the CHIANTI database have been used extensively by the astrophysical and solar communities to analyse emission line spectra from astrophysical sources.

The third version of the CHIANTI database was released in 2000 (Paper IV: Dere et al., 2000). In this version the database has been extended to wavelengths shorter than 50Å by including atomic data for the hydrogen and helium isoelectronic sequences, inner-shell transitions and satellite lines and several other ions. In addition, some of the ions already present in the database have been updated and extended with new atomic data from published calculations. The inclusion of the satellites has required a significant modification to the manner in which the spectra have been calculated with CHIANTI. Consequently, a new version 3 of the IDL package, has been produced.

The latest CHIANTI database and associated IDL procedures, are freely available at one of the CHIANTI homepages:

- NRL, USA:
  http://wwwsolar.nrl.navy.mil/chianti.html

- DAMTP, UK:
  http://www.damtp.cam.ac.uk/user/astro/chianti/chianti.html

- Arcetri Astrophysical Observatory, Italy:
  http://www.arcetri.astro.it/science/chianti/chianti.html

We maintain an e-mail list, that is used to distribute information about any developments of the CHIANTI database and programs. To get on the CHIANTI e-mailing list, send an email to Ken Dere.

2 The data

2.1 The atomic data

The best atomic data as they become available have been used.

It is anticipated that the atomic data will continue to be updated regularly as new data are calculated or measured in the laboratory.

It is intended that these atomic data can be accessed and transfered into users own analysis programs, for more sophisticated applications.

The database has a tree structure, with the top directory designated with the IDL system variable *!xuvtop*. For each element a subdirectory is present, with a subdirectory for each ion. The filename prefix for each ion follows spectroscopic notation ; eg Fe XIV is fe_14.

There are three primary ASCII files for each ion (energy levels - fe_14.elvlc; radiative data and wavelengths - fe_14.wgfa; electron excitation data - fe_14.splups)

The energy levels (.elvlc) are obtained from NIST. Where necessary, these are supplemented by other laboratory and theoretical values. The radiative data (.wgfa) are taken from published literature and where necessary, supplemented by new calculations. The wavelengths given in the .wgfa files are the best available values and should accurately reproduce the observed spectra.

The electron excitation data are assessed and fitted using the Burgess and Tully (1992) method, as described in Dere et al. (1997). All the atomic data in the CHIANTI database have been visually displayed and assessed for accuracy and any sporadic errors which sometimes creep into published results.

The original sources are documented in each data file, where also additional and detailed comments written by the CHIANTI member that assessed that particular ion can be found.

2.2 Extra files and data

Some additional data files are needed in various calculations.

Most software allows the selection of these files, from either a 'standard' selection provided within the database, or by using user defined files that are included in the current working directory, provided they have the proper file extension.

For example, it is possible to create a user defined 'myfile.dem'. If the file is in the working directory, then the file will automatically be appended to the list of available DEMs from the CHIANTI database.

In other cases, it is possible to select the file by using a widget that allows the user to change directory.

Any user-defined file must be in the same format as those already provided (also including a 'comment' section at the end of the file)

2.2.1 The selection of ions

A *masterlist.ions* file keeps a list of all the ions in the database and is in the *!xuvtop/masterlist* directory. As default, some routines (for example those that calculate line intensities) read this list.

In some cases, it is possible to instead use a user-defined list of ions, to speed the calculation, or to directly supply the routine with a list of ions, via a KEYWORD.

2.2.2 Elemental abundances

There is a great deal of controversy over the variation (or not!) of elemental abundances in the upper solar atmosphere. Various methods have been used to determine the elemental abundances in the transition region and corona. Reviews on this subject include Meyer (1985, 1993), Widing and Feldman (1992), Mason (1992).

Options are available within the routines to choose different elemental abundances. Files with various elemental abundances are provided in the directory *!xuvtop/abund* (e.g.: Allen, 1973, Grevesse *et al*, 1991, Meyer, 1985, Waljeski *et al*, 1994). Element abundances are given as usually as Log10 values, relative to H, that has a Log10 value of 12.

User-defined abundance files can be used, as long as they have a .abund file extension.

2.2.3 Ionisation ratios

The ionisation ratios have been taken from the published literature. There are large discrepancies for the iron ions between Arnaud & Raymond (1992) and Arnaud & Rothenflug (1985). Shifts on the order of 0.1-0.2 dex are found in the temperatures corresponding to peak ion abundances. The peak values of the ionisation ratio typically differ by 10-20%. These differences warrant further investigation. Detailed studies of the formulations used to calculate ionisation and recombination rates can be found in e.g. Jordan (1995).

Files giving collisional ionization equilibria are provided in the *!xuvtop/ioneq* directory.

User defined ionisation files should have a .ioneq file extension.

2.2.4 Differential Emission Measure

The emission measure distribution in the solar atmosphere is a complex issue. Starting with the pioneering work by Pottasch (1964), spectra in the UV wavelength range have been used to determine the distribution of material as a function of temperature, following various methods. More details can be found in Section 13.

Files specifying various standard differential emission measures distributions for different solar features (e.g. Dere and Mason, 1993) are in the *!xuvtop/dem* directory. The Log T and Log DEM values are listed in two columns.

User-defined DEM files should have a .dem file extension.

2.2.5 Other files

Other files are in other miscellaneous directories. For example, !xuvtop+'/ip/chianti.ip' has the ionization potentials for all the ions.

!xuvtop+'/continuum/ contains data used by the routines that calculate the continuum. For example, gffgu.dat contains the free-free gaunt factors of R. S. Sutherland, 1998, MNRAS, 300, 321.

3 Optically thin emission lines

For a review on *Spectroscopic Diagnostics in the EUV for Solar and Stellar Plasmas* see e.g. Mason and Monsignori Fossi (1994).

The intensity $I(\lambda_{ij})$, of an optically thin spectral line of wavelength λ_{ij} (frequency ν_{ij}) is

$$I(\lambda_{ij}) = \frac{h\nu_{ij}}{4\pi} \int N_j\ A_{ji}\ dh \quad [\text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$$

where i, j are the lower and upper levels, A_{ji} is the spontaneous transition probability, N_j is the number density of the upper level j of the emitting ion and h is the line of sight through the emitting plasma. In low density plasmas the collisional excitation processes are generally faster than ionization and recombination timescales, therefore the collisional excitation is dominant over ionization and recombination in populating the excited states. This allows the low-lying level populations to be treated separately from the ionization and recombination processes.

The population of the level j can be expressed as:

$$N_j(X^{+m}) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} N_e$$

- $N(X^{+m})/N(X)$ is the ionization ratio of the ion X^{+m} relative to the total number density of element X (e.g.: Arnaud and Rothenflug, 1985, Arnaud and Raymond, 1992);
- $Ab(X) = N(X)/N(H)$ is the elemental abundance relative to Hydrogen;
- $N(H)/N_e$ is the Hydrogen density relative to the free electron density, often assumed to be equal to 0.83, as hydrogen and helium are usually completely ionised for hot optically thin plasmas.
- The level populations $\frac{N_j(X^{+m})}{N(X^{+m})}$ are determined within CHIANTI by solving the statistical equilibrium equations for a number of low-lying levels of the ion including all the important collisional and radiative excitation and de-excitation mechanisms.

For allowed transitions we have $N_j(X^{+m})A_{ji} \sim N_e$. Assuming $Ab(X)$ constant over the line of sight, we have:

$$I(\lambda_{ij}) = Ab(X) \int C(T, \lambda_{ij}, N_e) N_e N_H dh$$

the function

$$C(T, \lambda_{ij}, N_e) = \frac{h\nu_{ij}}{4\pi} \frac{A_{ji}}{N_e} \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X^{+m})}{N(X)} \frac{N(X)}{N(H)} \quad [\text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}],$$

called the *contribution function*, contains all of the relevant atomic physics parameters and is strongly peaked in temperature.

In the literature there are various definitions of *contribution functions*. Aside from having values in in either photons or ergs, sometime the factor $\frac{1}{4\pi}$ is not included. Sometimes a value of 0.83 for $N(H)/N_e$ is assumed and included. Sometimes the element abundance factor is also included. Any of the above (or any other) variations also affect the definition of a line intensity in terms of the contribution function and the DEM. In the following we will refer to the functions $C(T, \lambda_{ij}, N_e)$ and $G(T, \lambda_{ij}, Ab(X), N_e) = Ab(X)\ C(T, \lambda_{ij}, N_e)$ (i.e. the contribution function that contains the abundance factor).

If we define, assuming that is a single-value function of the temperature, the differential emission measure $DEM(T)$ $[cm^{-5}K^{-1}]$ function as

$$DEM(T) = \ N_e N_H \frac{dh}{dT}$$

the intensity can be rewritten:

$$I(\lambda_{ij}) = Ab(X) \int_T \ C(T, \lambda_{ij}, N_e)\ DEM(T)\ dT \quad [\text{ergs cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}]$$

The DEM gives an indication of the amount of plasma along the line of sight that is emitting the radiation observed and has a temperature between T and $T + dT$.

4 The software

A number of Interactive Data Language (IDL) procedures are also provided as part of the CHIANTI database. These include routines to read the various CHIANTI database files, calculate levels populations, line intensities, and temperature dependent and density dependent line intensity ratios.

Most of our efforts have gone into developing the database and the IDL routines that exist have been written to meet readily apparent needs.

New software is being developed, and will soon be available.

We expect that end-users will develop their own IDL (or Fortran or C) programs to meet their own specific interests. However, we encourage them to send us comments or suggestions for improvements.

All the IDL routines have been documented with extensive headers and examples.
Descriptions of the various options that are available are given in the document header of each IDL procedure. Please read them carefully.
For example, you can use

```
IDL > xdoc,'synthetic'
```

to see the documentation in the header.

The CHIANTI routines can be grouped into three classes:

- Low-level routines, that for example read the files in the database, or perform the level population calculations. These are not described here.
- Intermediate level routines, that perform more complex operations. These routines usually output arrays or structures, produce plots and postscript or ascii files. Most of them have a long list of options, commanded via KEYWORDS. Please read the headers.
- Higher-level widget-type routines. These routines are more user-friendly, and are complementary of the above class. These routines call intermediate level routines to perform the calculations. The number of options in these routines is sometimes lower than that one of the intermediate level ones. This was done to keep the widgets simple. On the other hand, these higher-level routines have many extra features that the lower level ones do not have.

  Examples of both intermediate and higher-level routines are given here.

For the first two classes of routines, by simply typing the name of the routine, a description of how to call the routines, with examples, is printed. For example,

```
IDL > temperature_ratios
IDL > temperature_ratios,ion,wmin,wmax,Log10(tempmin),Log10(tempmax),$
IDL > temperature,ratio,description,$
IDL >  [pressure= ,density= , psfile= , outfile= ]
IDL >
IDL > i.e.:
```

```
IDL > temperature_ratios,''c_5'',40.,50.,5.,7.,temp,rat,desc
```

Another way to see the keywords of a routine is to e.g. use:

```
IDL > chkarg,'temperature_ratios
.....
.....
---> Call: pro temperature_ratios,ions,wmin,wmax,tempmin,tempmax,$
temperature,ratio,description,$
pressure=pressure,density=density,psfile=psfile,outfile=outfile
```

To date, CHIANTI has been run mainly on Sun, Dec Unix workstations and on PCs with Linux. Its directory structure is not presently consistent with the naming conventions for VMS.

5 Installing CHIANTI and initial setups

To run any CHIANTI procedure, the following is needed:

- access to the CHIANTI database. This is done by defining the system variable !xuvtop, that should point to the CHIANTI database top directory.
- Access to the CHIANTI IDL routines. The directories where the CHIANTI IDL procedures are should be in the IDL !PATH.
- The IDL system variable !ioneq should be defined and point to the default ionization equilibrium file to be used.

Within SolarSoft

If you are using SolarSoft you should have the setup already organised so as to have the path of the CHIANTI IDL procedures added to IDL_PATH. This is done automatically by using

ssw_path,/chianti

that includes the required Chianti IDL paths in the SSW !PATH.

Otherwise

The easiest way to set the !xuvtop and !ioneq variables is to use the USE_CHIANTI procedure, e.g.:

```
IDL > use_chianti, '/home/data/chianti/',ioneq='arnaud_raymond_lmf'
```

That simply does:

```
IDL > defsysv,'!xuvtop','/home/data/chianti/'
IDL > defsysv,'!ioneq_file','arnaud_raymond_lmf'
```

The routine can also be called without parameters:

```
IDL > use_chianti
```

in which case the top directory is defined through the CDS_SS_DERE enviroment variable (assuming that was previously defined), and the 'mazzotta_etal.ioneq' file is used as default.

Alternatively, you might whish to add the above definitions to your IDL_STARTUP file.

After following the above steps, it will be possible to run the CHIANTI routines from any directory.

Now, a description of the various higher-level routines that are present within the CHIANTI software tree is given.

6 Looking at level populations

To plot the populations of the first 4 levels of Si III as a function of density at a temperature of 3 x 10^4 K:

```
IDL > plot_populations,'si_3',3.e+4,4
```

Optionally, output files can be created.

7 Looking at the different ionisation equilibria

If you are interested to see the differences between the various ionisation equilibria for e.g. Mg, you can use:

```
IDL > plot_ioneq,'Mg'
```

You will be able to select one of the files, and optionally create a postscript file of the plot.

If you are only interested in e.g. the Mg VIII, Mg IX, Mg X ions, you can type:

```
IDL > plot_ioneq,'Mg', ion=[8,10]
```

If, instead, you are interested in obtaining the temperature at the maximum ionisation fraction for e.g. Mg X, you can use:

```
IDL > print, max_temp ('Mg X')
```

You will be asked to select an ionisation equilibrium file.

8 Density and temperature diagnostics from line ratios

Spectroscopic diagnostic line ratios in the UV wavelength range have been used extensively to determine the electron density and temperature in the solar atmosphere (cf Dere and Mason, 1981, Gabriel and Mason, 1982, Mason, 1991, Mason and Monsignori Fossi, 1994). The theoretical intensity ratios from individual ion species provide a measurement of electron density which is independent of any assumptions about the volume of the emitting region. This is of particular importance in the transition region and coronal structures. The electron density (which determines the electron pressure) is an essential parameter in the study of energy transfer mechanisms. The routines that can be used are described below.

8.1 The CHIANTI_NE and CHIANTI_TE procedures

The IDL procedure which calculates line intensity ratios as a function of electron density is called CHIANTI_NE. Another IDL procedure to calculate ratios sensitive to electron temperature is called CHIANTI_TE. For example,

```
IDL > chianti_te
```

Or

```
IDL > chianti_ne
```

User interactions with the main widget setup the wavelength range and other parameters that are described individually below. On the left hand side are controls for wavelength and electron density or temperature selection and on the right hand side for ion selection.

8.1.1 Ion selection

Select first the element and then the ion stage using the pull-down menus. Only those elements and ions currently available in the CHIANTI database are displayed for selection.

8.1.2 Wavelength ranges

There are up to 4 wavelength ranges that can be defined in order to restrict the calculation (and the number of lines). At least one should be defined. Default is to calculate all lines from 1 to 1700 Å.

8.1.3 Electron Density/Temperature Range

For CHIANTI_NE, select the electron number density range ($\mathrm{Log}_{10} N_e$) over which the intensity ratios are calculated. Default values are 10^6 to 10^{14} cm^{-3}. The intensity ratios are calculated at constant temperature corresponding to the peak ionic abundance T_{max}, unless the value of the temperature is typed in.

For CHIANTI_TE, select the electron temperature ($\mathrm{Log}_{10} T_e$) over which the intensity ratios are calculated. Default values are 10^4 to 10^8 K. The intensity ratios are calculated at a constant electron number density corresponding to 10^8 cm^{-3}, unless a different value is typed in.

8.1.4 minimum intensity ratio

The relative intensity of all the lines found in the wavelength range is calculated. Only the lines that have an intensity (relative to the brighter one) greater than 0.0001 (by default) are selected and displayed.

8.1.5 Units for the ratio plot

The ratios can either be calulated from the relative intensities in ergs (default) or photons.

8.1.6 Controlling the procedure

The action of both CHIANTI_NE and CHIANTI_TE is controlled via the buttons in the central panel of the display. From left to right these are:

QUIT - click on this to exit from the program, all plot windows are also deleted.

CALCULATE LINE INTENSITIES - using the wavelength ranges as defined in the widgets above. Two plots will apear in the window - on the left the $N_i * A/N_e$ and on the right the intensity ratios, where N_i is the level population and A is the radiative transition probability (s^{-1}). A list of spectral lines in the given wavelength range for that ion is displayed in the message window. The reference index is in the first column, then the wavelength, intensity and transition.

PLOT RATIO - prompts for and then plots specific line intensity ratios, using line indices available from the list. The ratios within a particular ion can be stored for later use using the SAVE button. To allow for blended lines in the observed spectra, multiple line indices can be given for the numerator and denominator. The format is fairly flexible but the nominator and denominator specification must be separated by a '/'. Otherwise the line indices can be separated by spaces or commas. The ratio values can be plotted either with a linear or a log scale.

HARDCOPY - the menu under this button will allow a variety of hardcopy plots (ratio plots or intensity plots) and the line details (+refs), which gives a record of the input. A line ratio has to be defined.

SAVE - it is sometimes useful to save the plotted line intensity ratios to study several different ions. You will be asked to enter file name to store ratio data. A line ratio has to be defined.

In the CHIANTI_NE case, a .CH_NE will be appended. An IDL structure called NE_RATIO will be saved. It has the TAGS: DENSITY,RATIO, TEMPERATURE, UNITS, COMMENT, DESC. The first two have the arrays of the densities and ratios, TEMPERATURE has the value of the constant temperature used, while the last three have a description of the units used, how the calculation was performed, and a description of the lines used to defined the ratio.

In the CHIANTI_TE case, a .CH_TE will be appended. An IDL structure called TE_RATIO will be saved. It has the TAGS: TEMP, RATIO, DENSITY, UNITS, COMMENT, DESC. The first two have the arrays of the temperatures and ratios, DENSITY has the value of the constant density used, while the last three have a description of the units used, how the calculation was performed, and a description of the lines used to defined the ratio.

Please note that previous versions of the above routines did not create the TEMPERATURE (DENSITY), UNITS, COMMENT tags.

The save file can be restored and replotted outside of CHIANTI_NE and CHIANTI_TE using the procedures PLOT_CHIANTI_NE and PLOT_CHIANTI_TE respectively, or used within user-defined procedures.

DELETE PLOT WINDOWS - to clear the ratio plots from the screen.

8.2 The PLOT_CHIANTI_NE and PLOT_CHIANTI_TE procedures

The ratio values stored in the save files created with the CHIANTI_NE and CHIANTI_TE routines can be replotted outside of CHIANTI_NE and CHIANTI_TE using the procedures PLOT_CHIANTI_NE and PLOT_CHIANTI_TE respectively. For example,

```
IDL > plot_chianti_te
```

Or

```
IDL > plot_chianti_ne
```

If no files are specified, a widget allows you to select any '*.CH_NE' or '*.CH_TE' files.

A LOG keyword allows the user to have the plot in a log scale.

It is also now possible to interactively modify the X and Y ranges and to create a postscript file. Users can modify these routines to e.g. over-plot observed data points.

8.3 The DENSITY_RATIOS procedure

The routine DENSITY_RATIOS plots the variation of line intensities with electron density, allowing density diagnostics to be studied. As an example, we can look for density sensitive line ratios of O V in the 1000 to 1500 Å wavelength region for densities between 10^8 and 10^{13} cm^{-3}:

```
IDL >density_ratios,'o_5',1000.,1500.,8.,13.,den,rat,desc
```

two windows will open and plot the relative intensities of a few O V lines. To choose the ratio of 1371.294 to 1218.393 Å line, select first the 1371.294 Å line, and click on 'Continue'. Another widget will appear to select the denominator. Select the 1218.393 Å line and then click on 'Continue'. This will chose the ratio of 1371.294 to 1218.393 which will be plotted in a new window. Values of the density and intensity ratio will be put into the variables den and rat and desc will contain a descriptive string.

```
IDL >  print, desc
IDL >  O  V    1371.294/1218.393
```

The DENSITY_RATIOS procedure also allows to calculate the ratio at user-defined value of constant temperature. Blends are accounted for via a selection of lines.

8.4 The TEMPERATURE_RATIOS procedure

To calculate temperature sensitive line ratios of C IV for lines between 100 and 1600 Å for temperatures between 10^4 and 10^6 K:

```
IDL >   temperature_ratios,'c_4',100.,1600.,4.,6.,temp,rat,desc
```

As with density_ratios, a widget will appear that will allow you to select the numerator. Select the 384.173 and 384.189 Å lines as these will typically be blended in most spectrographs. Then click on 'Continue'. Select the 1550.772 Å line for the denominator and then click on 'Continue'. The ratio of (384.173 + 384.189 Å) to the 1550.772 Å line as a function of temperature will be plotted and stored in the variables rat and temp, respectively. The TEMPERATURE_RATIOS procedure also allows to calculate the ratio at user-defined values of either constant pressure or constant density.

```
IDL > print, desc
IDL > C  IV     384.173/1550.772
```

8.5 Calculating temperatures by using different ions

Note: If you are interested in **determining an isothermal temperature by using the ratio of lines emitted by different ions (and/or elements)**, then a possible way is to first calculte the contribution functions of the lines you are interested, and then calculate their ratio. Note, however, that such determinations can be very inaccurate, since they depend on the ionisation equilibrium chosen (and eventually on the element abundance).

9 Calculating contribution functions

To calculate the contribution function ($erg\ cm^3 s^{-1} sr^{-1}$ by default) vs. temperature at a specified abundance, ionization equilibrium and pressure or density for the Fe XXIV line at 255.1 Å:

```
IDL >  gofnt,'fe_24',250.,260.,temperature,g,desc
```

temperature, g are the arrays with the temperatures and the G(T) values. It is possible to calculate the G(T) at either constant electron density or pressure, via the KEYWORDS DENSITY or PRESSURE.

The routine GOFNT allows the user to select a number of lines. If this is done, then the total sum of the G(T)'s of the selected lines is returned and plotted.

Optional outputs can be created. The default units are $erg\ cm^3 s^{-1} sr^{-1}$, unless the KEYWORD /PHOTONS is set, in which case the units are $photons\ cm^3 s^{-1} sr^{-1}$.

10 Calculating continuum intensities

Procedures for calculating the continuum due to free-free (bremsstrahlung) and free-bound (radiative recombination) are now included. Their names are 'FREEFREE' and 'FREEBOUND', respectively.

The routine FREEFREE uses the free-free gaunt factor calculations of Sutherland (1998).

For example, to calculate the free-free continuum intensity per unit emission measure (10^{-40} erg cm^3 s^{-1} sr^{-1} Å^{-1} at a temperature of 1.e+6 K, for wavelengths at 1 Å intervals between 1 and 50 Å:

```
IDL > freefree,1.e+6,findgen(50)+1.,ff
```

The routine FREEBOUND calculates the free-bound (radiative recombination) continuum following the discussion in Radiative Processes in Astrophysics by Rybicki and Lightman except that we have substituted the observed energy levels for the hydrogenic energy levels.

11 Calculating radiative losses

A procedure ('RAD_LOSS') calculates the total radiative loss rate as a function of temperature for specified set of abundances and/or ionization equilibria.

12 Calculating line intensities and creating synthetic spectra

In general, the routine SYNTHETIC can be used to calculate CHIANTI line intensities. This routine has a large number of keywords. For example:

```
IDL > synthetic, 100., 200., 1., 1.e+15, wvl, spectrum, list_wvl, list_ident
```

will create a synthetic spectrum with a resolution of 1 Å between 100 and 200 Å for a specified set of abundances and differential emission measure at a constant pressure of 1.e+15 (N_e T cm^{-3} K). The output arrays wvl, spectrum contain the wavelengths and the intensities (in erg cm^{-2} s^{-1} sr^{-1} Å^{-1} by default). The output arrays ist_wvl, list_ident contain the list of wavelengths and descriptions of the lines that made up the spectrum.

Windows will pop up so that the user can select the abundance file, the ionization equilibrium and the differential emission measure. A spectrum is created by convolving with a Gaussian profile with a FWHM of 1 Å.

If the /CONT keyword had been set, then the continuum would also have been calculated and added to the spectrum. This can be a fairly time-consuming calculation (but that can be speeded up – see the header).

One thing that you may have noticed is that CHIANTI can be slow. This is largely because some of the ions, such as in the boron isoelectronic sequence, contain over 100 energy levels. Solving the levels populations in these cases can be time consuming. We have already changed the way the level populations are calculated, compared to the Version 2 and are working on other updates. For the moment, a viable option to speed the calculations is to eliminate some of the ions in the calculations, something that can be done in various ways by using various KEYWORDS. In any case, it is advisable to not calculate spectra over large wavelength ranges.

To plot the spectrum and interactively identify lines:

```
IDL > synthetic_plot, wvl, spectrum, list_wvl, list_ident, 2.
```

by clicking the left mouse button, a list of predicted lines within 2 Å of the selected wavelength will be printed out along with their predicted intensity. Clicking the right mouse button will exit the procedure.

12.0.1 Create a spectrum in the isothermal approximation

```
IDL > isothermal, 100., 200., 1., [1.e6,1.5e6], wvl, spectrum,$
IDL >  list_wvl, list_ident, edensity=1.e9
```

calculates an isothermal synthetic spectrum with a resolution of 1 Å between 100 and 200 Å for a specified set of abundances and differential emission measure at a constant density $N_e = 10^9$ cm^{-3}. The output arrays wvl, spectrum contain the wavelengths and the intensities (in erg cm^{-2} s^{-1} sr^{-1} $Å^{-1}$ by default). The output arrays ist_wvl, list_ident contain the list of wavelengths and descriptions of the lines that made up the spectrum.

12.0.2 Create a latex file with the line details

You can also create a latex file with a list of line identifications and intensities using the LATEXWVL_DEM procedure:

```
IDL > latex_wvl_dem,100.,200.,1.e+15,mini=1.
```

windows will pop up so that you can select the abundance, the ionization equilibrium and the differential emission measure files. This will create by default a file linelist.tex in the user's home directory, by default. Only lines with an intensity greater than 1. (mini) are included in the file. The routine has many KEYWORDS. Please read the header. **If you do not have it already, you will need the package longtable.sty that you can find where this document is**. Then, you have to latex the file three times, and optionally xdvi it.

```
unix > latex linelist.tex
unix > latex linelist.tex
unix > latex linelist.tex
unix > xdvi  linelist
```

12.0.3 Create an ascii file with the line details

As similar routine outputs an ascii file, instead of a latex one:

```
IDL > ascii_wvl_dem,100.,200.,1.e+15,mini=1.
```

Please note that all the above procedures will soon be complemented/ replaced by a new package of routines, with extended features, and also employing high-level routines.

12.1 The CHIANTI_SS procedure for SOHO CDS/SUMER

The IDL procedure which calculates synthetic spectra for the SOHO CDS/SUMER is called CHIANTI_SS.

12.1.1 Selecting the wavelength range

In order to provide easy selection of the wavelength range, it is possible from the main window to select the instrument and (for CDS) the associated detector. This choice will automatically load the relevant wavelength range.

The wavelength sliders are provided to allow the user to fine tune the wavelength range over which the calculation is performed.

12.1.2 Selectable parameters

-Plasma Pressure. The spectra are based on calculations at a constant pressure, which is the simplest assumption for the solar atmosphere. The units used are (Ne Te cm^{-3} K).

-Ionization equilibrium.

-DEM. Once a selection of DEM is made, the DEM values are plotted.

-Element abundance. When a particular abundance is selected, the abundance values to be used are listed in the message window.

12.1.3 Controlling the procedure

The action of CHIANTI_SS is controlled via the buttons in the central panel of the display. From left to right these are:

QUIT - click on this to exit from the program

CALCULATE SPECTRUM - using the setup as defined in the widgets, calculate a new synthetic spectrum.

LINEAR INTENSITY PLOT - this is a toggle button which will toggle between linear and logarithmic plotting on the spectrum's intensity scale.

HARDCOPY - the menu under this button will allow a variety of hardcopy plots and listings. The spectrum plot plus setup details is meant to give a concise record of the input and result.

SAVE - since the calculation of the spectrum can take several minutes, it is useful sometimes to save the spectrum for later use. The program saves the line list (and associated data) in an ascii file, named by the user. This file can be read outside of CHIANTI_SS using the function RD_CHIANTI. All files are given the suffix .CH for easy identification.

RESTORE - this button gives the user a choice of saved files to restore. The chosen one is automatically loaded onto the screen display.

REPLOT - if the wavelength range selection or plot scaling is changed, press this button to get the data replotted within those limits.

BROADENED - hit this button if you wish the instrumentally broadened spectrum to be plotted. The synthetic spectra are convolved with the default spectrograph psf.

RAW - this will ensure that the raw (unbroadened) synthetic spectrum is displayed.

BOTH - both the raw spectrum and the instrumentally broadened version are displayed. This is useful to see what lines are contributing to a profile.

Clicking the cursor on any part of the displayed spectrum will give a listing of the lines within 0.5 Angtroms of that wavelength.

13 The calculation of the DEM

Given a set of observed spectral intensities, the problem is to invert a system of integral equations like the previous one. The procedure CHIANTI_DEM solves the system and calculates the $DEM(T)$.

The inversion problem itself is not simple and requires some assumptions about the nature of the solution. A series of workshops was sponsored in 1990/91 to study differential emission measure techniques (Harrison and Thompson, 1992). It was found that most codes eventually gave consistent results, but that the DEM derived depends rather critically on the methods used to constrain the solution and the errors in the observed intensities and atomic data.

It is advisable to select a number of well resolved, unblended lines which are not density sensitive, emitted by various elements over a wide temperature interval. Appropriate values of the pressure (or density) and the elemental abundances must be chosen according to the region of the Sun being observed. The pressure value can be obtained once the values of the temperature and the density are estimated. To estimate the electron density the procedure CHIANTI_NE can be used. The temperature can be estimated for example using the procedure CHIANTI_TE.

The contribution functions $C(T, \lambda_{ij}, N_e)$ can be calculated using CHIANTI_DEM either at constant pressure or at constant electron density. It is also possible to vary the elemental abundances before starting the fit to deduce the DEM.

Many papers have been written on solar elemental abundances. See e.g. Meyer (1993) Widing and Feldman (1992), Mason (1992, 1995). A possible approach in determining elemental abundances is to use the detailed shape of the DEM distribution for ions from the same element and apply an iterative procedure to normalize the curves for different elements (e.g. Fludra and Shmelz 1995, Del Zanna et al. 1995).

The CHIANTI_DEM procedure

The main IDL routine which has been written to perform a differential emission measure analysis of EUV spectra using the CHIANTI atomic database is CHIANTI_DEM. Other procedures required to run CHIANTI_DEM are GET_CONTRIBUTIONS , DEM_FIT, ZION2SPECTROSCOPIC and Z2ELEMENT. The resulting DEM may then be used by other procedures to calculate a synthetic spectrum.

This package of routines will be replaced in the future by new more versatile versions.

The main inputs required by CHIANTI_DEM are :

- **the file with the observed fluxes**. It can be selected using a widget-type browse from within CHIANTI_DEM or using the optional keyword FILE_INPUT='myfilename' . It must contain 5 columns of unformatted data (separated by at least one space). The 5 fields are:

  1) the observed wavelength λ_{obs} [Å].

  2) The observed flux I_{obs} in $ergs\ cm^{-2}s^{-1}sr^{-1}$.

  3) The corresponding error σ_{obs} on the flux in $ergs\ cm^{-2}s^{-1}sr^{-1}$.

  4) The value of $\delta\lambda$ [Å]. All the theoretical lines that may have contributed to the observed lines, i.e. that have a theoretical wavelength λ_{theo} in a $\lambda_{obs} \pm \delta\lambda$ range will be searched for. This value should correspond to the spectral resolution of the instrument at that wavelength.

  5) The identification, written as a string of up to 20 characters. For example:

  171.114 4811.0 1443.0 0.25 Fe IX

  174.604 4005.0 1202.0 0.25 Fe X

  180.448 3877.0 1163.0 0.25 Fe XI bl Fe X

  195.149 3443.0 1033.0 0.25 Fe XII

- **the pressure** N_eT $[cm^{-3}K]$ **or the density** N_e $[cm^{-3}]$, passed to the routine via a keyword.

- the **ionization equilibrium file**, selected using a widget.

- **the elemental abundances file**. A selection of files are already stored in the CHIANTI package, but user-defined files in the working directory can also be used. Any **.abund* file present in the CHIANTI database **or** in the working directory can be selected through a widget from within CHIANTI_DEM. The selected file can also be edited.

- **An output file name** must also be supplied via a keyword (e.g. OUTPUT= 'active_region'). Various files will be generated by CHIANTI_DEM having file names created by adding suffixes to the output file name.

Once the file with the observed fluxes is read, another IDL procedure, GET_CONTRIBUTIONS, is called by CHIANTI_DEM in order to calculate the contribution functions $C(T, \lambda_{ij}, N_e)$ at the given constant density or pressure.

GET_CONTRIBUTIONS searches the CHIANTI database for all the theoretical lines that may have contributed to the observed lines, i.e. that have a theoretical wavelength λ_{theo} in a $\lambda_{obs} \pm \delta\lambda$ interval.

Then, for each theoretical line selected, it calculates the C values for the temperature interval log(T)= 4.0 - 8.0 in steps of log(T) = 0.1.

If a constant pressure is selected, for each ion the contribution function is calculated at an electron density N_e equal to the ratio of the pressure and the temperature of maximum ionization fraction.

The $C(T)$ values are stored by GET_CONTRIBUTIONS in the output file *output.contributions* that can be used later, if required, to re-calculate the DEM, changing various parameters (e.g. the abundances), without having to start again and read the CHIANTI database, which can take a long time.

The observed lines with no theoretical counterparts are automatically excluded. If this happens, you might consider starting again with a larger $\delta\lambda$, to see if there are theoretical lines in the vicinity of the observed one.

Then you are asked to select an *.abund file present in the CHIANTI database or in the working directory, and eventually edit it, if you want to change some abundances.

The $G(T)$ are calculated, multiplying each theoretical line by the abundance factor. The theoretical lines contributing to each blend are sorted by intensity and then their G(T) can be plotted if the keyword PLOT_GT was activated. It is recommended to do this the first time, to check if there are some observed lines which are heavily blended with lines of other elements. It might be better to exclude such lines in a second run.

The $G(T)$ for each blend are then summed and plotted, and the calculation of the DEM starts, using the fitting routine DEM_FIT. A series of parameters can change the result (DEM), especially the number and position of the mesh points of the spline that represents the DEM. The fitting procedure is based on Bevington's *Data Reduction and Error Analysis for the Physical Sciences.* fortran programs.

The iteration is controlled using key-words (see below).

A series of outputs are created, all having extensions of the output name. For example, using *test* as the output name:

- *test.contributions*: The first three lines contain the abundance file, the ionization equilibrium file names, and the constant value of the pressure or the density adopted. Each subsequent line contains the observed wavelength λ_{obs}, the theoretical one λ_{theo}, the element and ionization stage, the $C(T)$ values and the specification of the transition.

- *test.dem*: Is the file where the $DEM(T)$ values are written, in a format suitable for input to the CHIANTI_SS procedure which may be used to calculate a synthetic spectrum from the DEM.

- *test.general*: Is the file where general information is stored.

  The abundance file, the ionization equilibrium file and the pressure used are written at the beginning.

  Then there is one line for each observed line, with the identification present in the input file, the observed wavelength λ_{obs}, the observed flux I_{obs}, the calculated flux I_{theo} , the error on the flux σ_{obs}, the value $(\frac{I_{theo}-I_{obs}}{\sigma_{obs}})^2$ and finally the value of $\frac{I_{theo}}{I_{obs}}$

  After this line, there is one line for each theoretical line contributing to the blend, with the identification, the theoretical wavelength λ_{theo}, the configuration and terms, and the contribution (as a percentage) of each line in the blend to I_{theo}.

- *test.out*: This file , toghether with *test.dem*, can be used to reproduce the results using user-written software. It contains: the identification present in the input file, the observed wavelength λ_{obs}, the observed flux I_{obs}, the calculated one I_{theo} , the error on the flux σ_{obs}, and the logarithmic values of the temperature and the DEM for each observed line. This temperature is the value where the product $G(T) * DEM(T)$ has a maximum.

- three optional postscript files: *test_gt.ps ; test_dem.ps ; test_4plots.ps* .

  The first one has the $G(T)$ of all the lines then used for the fit, with all the contributions for each line summed (the labels refer to the identifiacation given in the input file).

  The file *test_dem.ps* has the $DEM(T)$ with the scales set as in the interactive session. The points are plotted at the temperature where the product G(T)*DEM(T) has a maximum. It is possible to label the points with the comment string present in the input file, or to use the dominant ion in the blend.

  The file *test_4plots.ps* has some additional plots. The upper-right figure of *test_4plots.ps* plots the values $\frac{I_{theo}}{I_{obs}}$ versus the temperature where G(T) has it's maximum.

- It is also possible to have postscript files of the G(T) functions, using the keyword PLOT_GT.

13.1 Controlling the procedure

The action of CHIANTI_DEM is controlled via the following keywords.

- FILE_INPUT: optional; if not set, you are prompted to select the observation file using a widget-type search.

- ARCSEC: optional; set this if the intensities are specified in units per arcsec^{-2}.

  The default units are $ergs\ cm^{-2}s^{-1}sr^{-1}$.

  Note that the default units from NIS_CALIB.PRO are $phot\ cm^{-2}s^{-1}arcsec^{-2}$.

- PHOT: optional; set this if the intensities are specified in units per steradians^{-1}.

  The default units are $ergs\ cm^{-2}s^{-1}sr^{-1}$.

  Note that the default units from NIS_CALIB.PRO are $phot\ cm^{-2}s^{-1}arcsec^{-2}$.

- OUTPUT : required; the name for the output. Suffixes will be added to this name when creating the various outputs.
- FILE_GT: if **not** set, the routine GET_CONTRIBUTIONS is called. **Either** the pressure or the density must be set in this case.

  If set, it has to specify the name of the file previously created by GET_CONTRIBUTIONS, where all the contribution functions $C(T)$ are stored.
- PRESSURE: the value of the pressure (Ne T). Required if you do **not** already have the contribution functions C(T) (i.e. if you **do not** set FILE_GT). **Either** the pressure or the density must be set in this case.
- DENSITY : the value of the electron density (Ne). Required if you do NOT already have the contribution functions C(T). **Either** the pressure or the density must be set in this case.
- CUT_GT: optional; if set, only those theoretical lines that have a $MAX(C(T))$ greater than the value set, are kept; it is useful to set this value in order to reduce the number of lines in the file where the $C(T)$ are stored. If not set, a default value of 10^{-30} is adopted.
- N_MATCHES: optional; in the unlikely event that more than 20 (default value for N_MATCHES) theoretical lines corresponding to an observed line are found, the routine stops. In this case, you have to start again setting N_MATCHES equal to a greater number.
- PLOT_GT: optional; if set, plots of the $G(T)$ of the theoretical lines contributing to each observed line not excluded are created. It is possible to change the scale and create postscript files of these plots, interactively.
- EXCLUDE_OBS_WVL: optional; if set, has to be an array that specifies the wavelengths of the lines that you want to exclude from the fit. Note that even if you set this keyword and run GET_CONTRIBUTIONS all the theoretical lines found corresponding to all the lines in the input file are written in the $C(T)$ file. It is only in the fit that the lines are excluded.
- MESH_POINTS: optional; it is an array that specifies the mesh points for the spline that represent the fitted DEM, in log(T). If not set, the default values [4,4.5,5,5.5,6,6.5,7,7.5,8] are assumed.
- N_ITER: optional; it is the maximum number of iterations of the fitting routine. If not set, a default value of 20 is assumed. Changing this value alone might not affect the fit, since the value of DCHISQ_M is monitored at each iteration to check for convergence.
- DCHISQ_M: optional; if not set, a default value of DCHISQ_M= $1 \cdot 10^{-5}$ is assumed. For each iteration, the χ^2 and it's variation are calculated. As long as the iteration achieves a relative improvement in χ^2 greater than DCHISQ_M , another iteration will be performed.
- DEM_FILE: optional; if set you are prompted to choose a DEM file to be used initially, instead of the default constant value of 10^{22}. You can either choose one of the files in the CHIANTI database or any you have in the working directory. A plot of the DEM is created. The values in the file are marked as crosses, the mesh points are marked with triangles.
- QUIET: optional. Set to avoid various messages and the details of the result.

There are also some actions controlled via the keyboard.

When you are asked for an answer (**[y/N]**) *yes* or *no* you should either type in **y** or **n**. The capital letter in **[y/N]** means that the default choice is **n** which is what you get if you simply hit the **return key**. In case you have **[Y/n]**, hitting the **return key** is the same as choosing **y** .

13.2 Examples

You must specify the output file name and the value of the pressure (or the density). The input file name is optional.

```
IDL > CHIANTI\_DEM,OUTPUT='test',FILE\_INPUT='test\_obs', PRESSURE=1e16 , /PLOT\_GT
```

Select the ionization equilibrium file (e.g. Arnaud & Raymond). If there are no problems about N_MATCHES, the routine will select the lines having $max(C(T)) \geq 10^{-30}$ and write the $C(T)$ values to the file *test.contributions.*

Then you'll be asked to select an abundance file and if you want to edit it. Pick up the Feldman abundances. Then the $G(T)$ are calculated, multiplying each theoretical line by the abundance factor, sorted (within each blend) by their $max(G(T))$ value, and plotted (see Fig. 1).

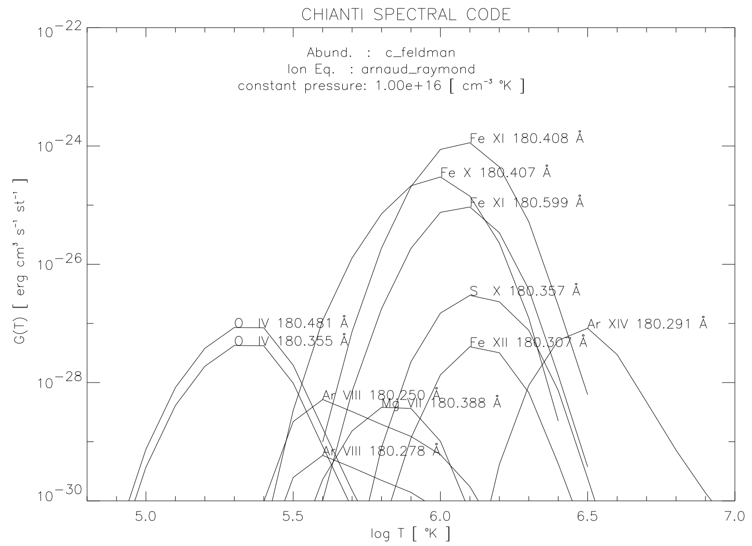

Figure 1: One of the G(T) plot of the test case

It is recommended that you check the plots at least once, to see if there are some observed lines that it might be better to exclude in a second run, for example because they are blends. Also check if your identifications are consistent with the lines found in the CHIANTI database.

The G(T) for each blend are then summed, and plotted (see Fig. 2).

At the end of the fit, the files *test.dem, test.general, test.out* are created.

Have a close look at these outputs, and check if there are emission lines not well represented by the fit or with no theoretical counterparts.

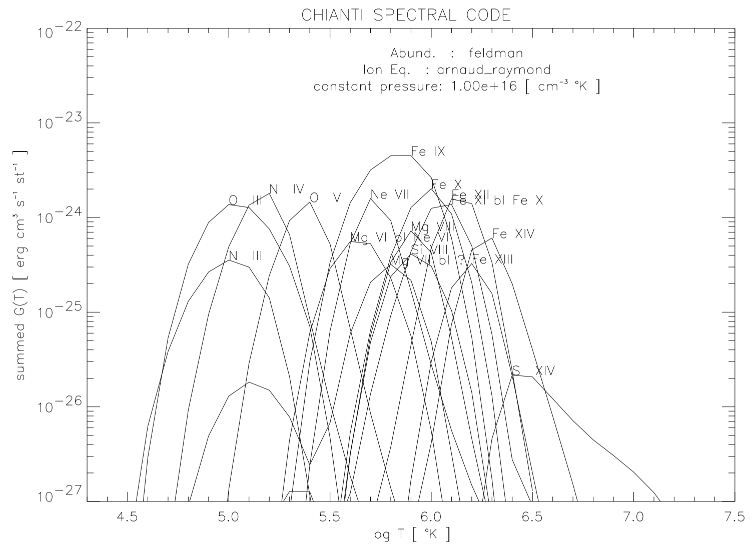

Figure 2: The summed-G(T) plot of the test case: *test_gt.ps*

You can use the routine a second time, excluding some of the lines, and/or varying some of the fitting parameters. In particular, changing MESH_POINTS or starting from an appropiate DEM can affect the resulting DEM. For example:

```
IDL> CHIANTI\_DEM,OUT='test',FILE\_IN='test\_obs',FILE\_GT='test.contributions', \$
IDL> EXCLUDE\_OBS\_WVL=[ 284.153 ] ,\$
IDL > MESH\_POINTS= [ 4.85, 5.6, 6.25, 7.0 ],N\_ITER=40
```

The files *test.dem, test.general, test.out* will be created.

Eventually, also the files *test_dem.ps test_4plots.ps* may be created.

Fig. 3 shows the resulting DEM. The error bars on the points simply reproduce the error on the observed fluxes.

The Fig. 4 is self-explanatory. The DEM figure is repeated in the upper-left plot with the same scale of the previous plot.

The file *test.out* , toghether with *test.dem*, can be used to reproduce these plots using user-written software. If the only concern is the postscript output, then users just have to copy the routine in the working area and modify the top procedure PRINT2D_PLOT.PRO that controls the postscript device. The default is landscape.

13.3 Some final remarks

This package is mostly intended to be a quick method to obtain a DEM which can then be used to calculate a synthetic spectrum, to be compared with the observed data.

Try to give as input lines covering a broad range in temperatures, and that are not density sensitive.

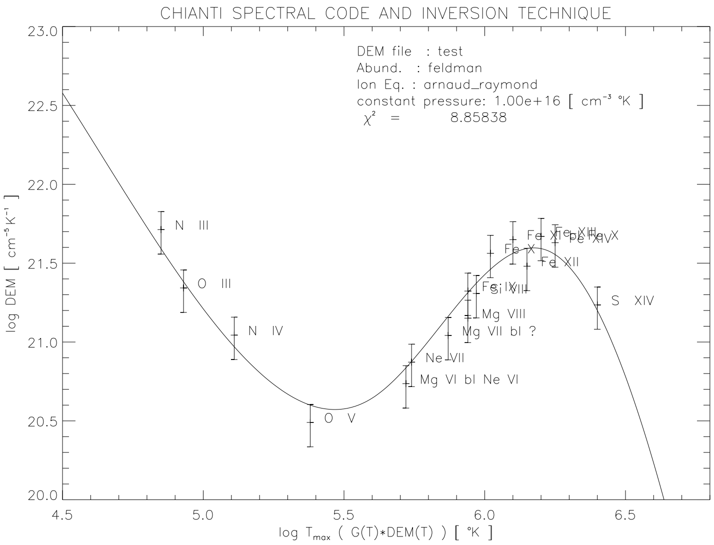

Figure 3: The DEM plot of the test case: *test_dem.ps*

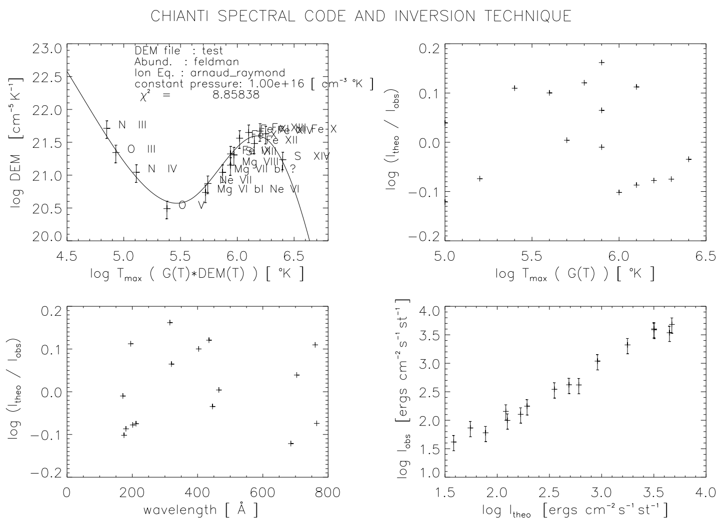

Figure 4: The 4 plots of the test case: *test_4plots.ps*

Try to adjust the location of the mesh points.

If the resulting DEM does not give a good fit to the data, it might be a good idea to start again calculating the $G(T)$ with different abundances or to check the effect of blends.

Try a different DEM as a starting point, but be careful about the end points at lower and higher temperatures where usually there are no constraints (no observed lines).

Consider the possible effect on the DEM of different structures along the line of sight. It is important to realise that the DEM gives an indication of the amount of plasma at different temperatures *along the line of sight*, assuming *constant* density or pressure. It is not therefore possible to infer direct information about the variation of the temperature with height from this function. The inclusion of density-sensitive lines in the fit may also cause problems.

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14 References

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