CORONAL DIAGNOSTIC SPECTROMETER
SoHO

CDS SOFTWARE NOTE No. 50

Version 1.0 5 November 1997

Differential Emission Measure analysis Using CHIANTI

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1 Introduction

CHIANTI, developed by Dere, Landi, Mason, Monsignori Fossi and Young (c.f. Dere *et al*, 1996), consists of a database of atomic data and IDL procedures for calculating spectroscopic emission line intensities at wavelengths greater than 50 Å from optically thin astrophysical spectra as a function of density and temperature.

The name CHIANTI (a beautiful Tuscan area famous for the wine) was suggested by Brunella Monsignori Fossi, who died suddenly in January 1996.

The best available atomic data have been used and the original sources are documented in each data file. It is anticipated that the atomic data will continue to be updated regularly as new data are calculated or measured in the laboratory.

The database has a tree structure, with the top directory designated *xuvtop*, corresponding to the enviroment variable CDS_SS_DERE. For each element a subdirectory is present. A *masterlist.ions* file keeps a list of all the ions in the database and is in the *xuvtop/masterlist* directory. Files with various elemental abundances are in the directory *xuvtop/abund*. Files giving collisional ionization equilibria are in the *xuvtop/ioneq* directory. Files specifying the differential emission measures for various solar features are in the *xuvtop/dem* directory.

Additional information can be found at the CHIANTI homepage:

http://wwwsolar.nrl.navy.mil/chianti.html

The CHIANTI database and IDL procedures can also be downloaded from louis14.nrl.navy.mil (132.250.160.129), via an anonymous ftp (*louis14.nrl.navy.mil*) in the directory *pub/chianti* . CHIANTI has been incorporated into the CDS science analysis software.

The CHIANTI package is also available at the Arcetri Astrophysical Observatory, Florence, Italy:

http://www.arcetri.astro.it/science/chianti/chianti.html

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.

2 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} is

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

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 (Arnaud and Rothenflug, 1985, Arnaud and Raymond, 1992);
- $Ab(X) = N(X)/N(H)$ is the elemental abundance;
- $N(H)/N_e$ is the Hydrogen density relative to the free electron density.
- The level populations $\frac{N_j(X^{+m})}{N(X^{+m})}$ are determined 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:

$$I(\lambda_{ij}) = Ab(X) \int C(T, \lambda_{ij}, N_e) N_e N_H dh \quad [\mathrm{ergs\ cm^{-2}\ s^{-1}\ st^{-1}}]$$

the function $C(T, \lambda_{ij}, N_e)$, 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*. 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:

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

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 $T + dT$.

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 (see the CDS software note No. 37) 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).

3 The CHIANTI_DEM procedure

To run the CHIANTI_DEM procedure, access to the CDS IDL directories and CHIANTI database is needed. The environment variable CDS_SS_DERE should point to the CHIANTI database top directory.

The resulting DEM may then be used by the CHIANTI_SS procedure to calculate the synthetic spectrum (see the CDS software note No. 33).

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 $ergs\ cm^{-2}s^{-1}st^{-1}$.

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

  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.

3.1 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 $ergs\ cm^{-2} s^{-1} st^{-1}$.

  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 $ergs\ cm^{-2} s^{-1} st^{-1}$.

  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** .

3.2 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).

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.

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', $

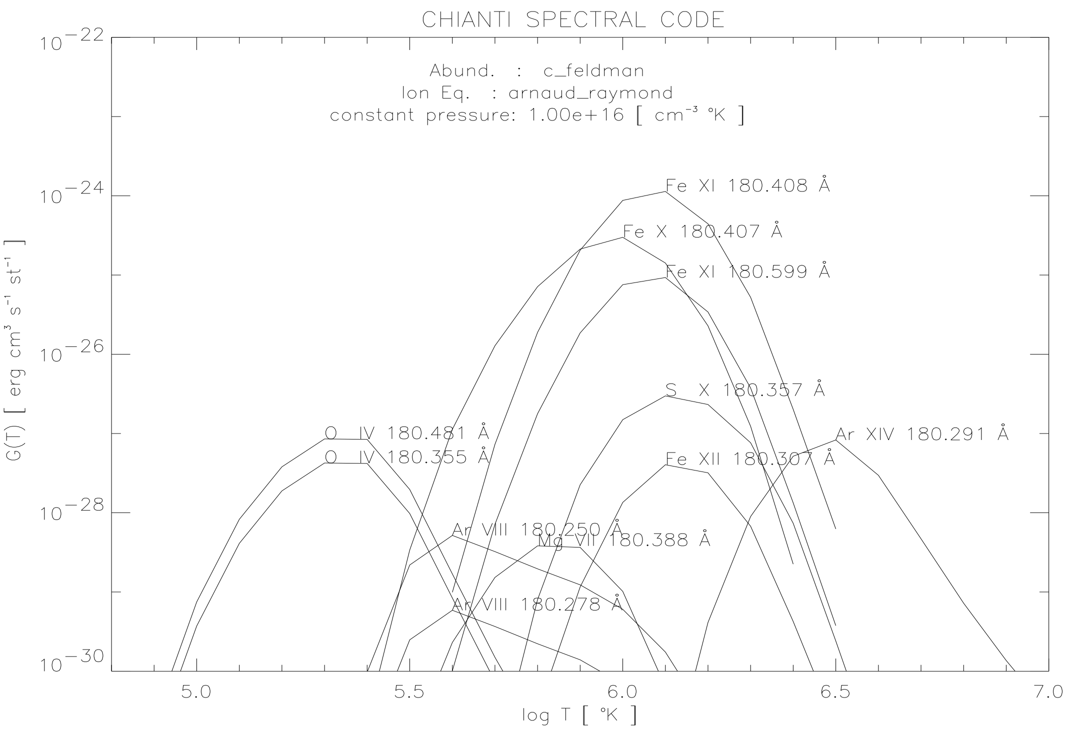

Figure 1: One of the G(T) plot of the test case

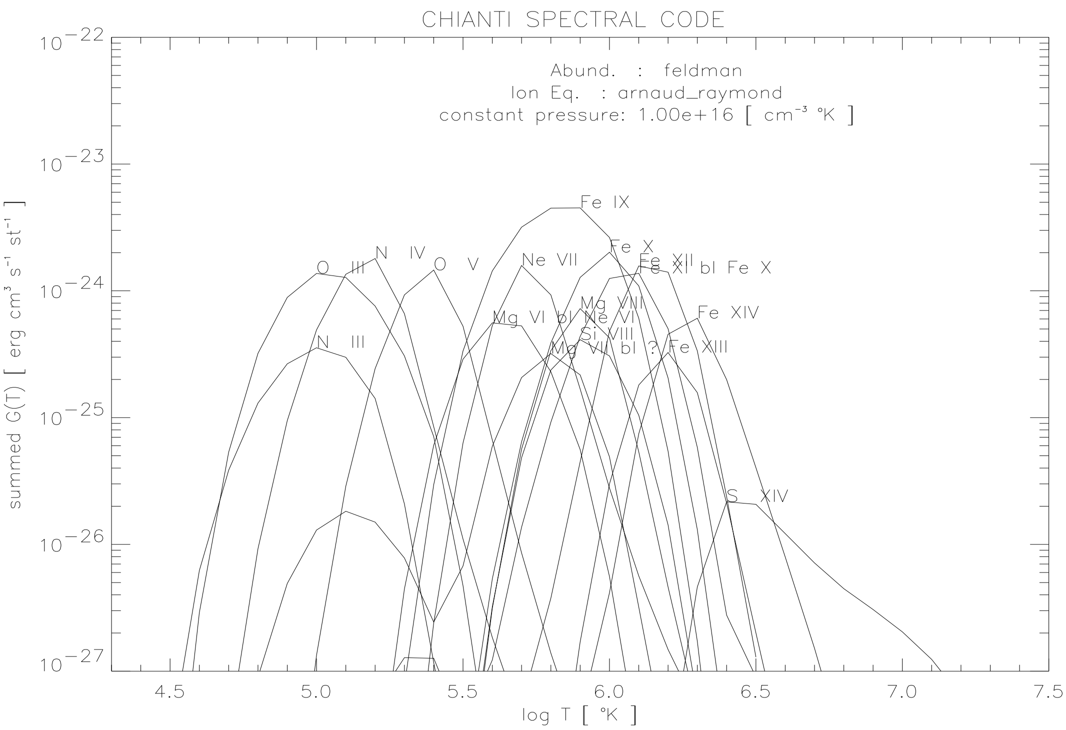

Figure 2: The summed-G(T) plot of the test case: *test_gt.ps*

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.

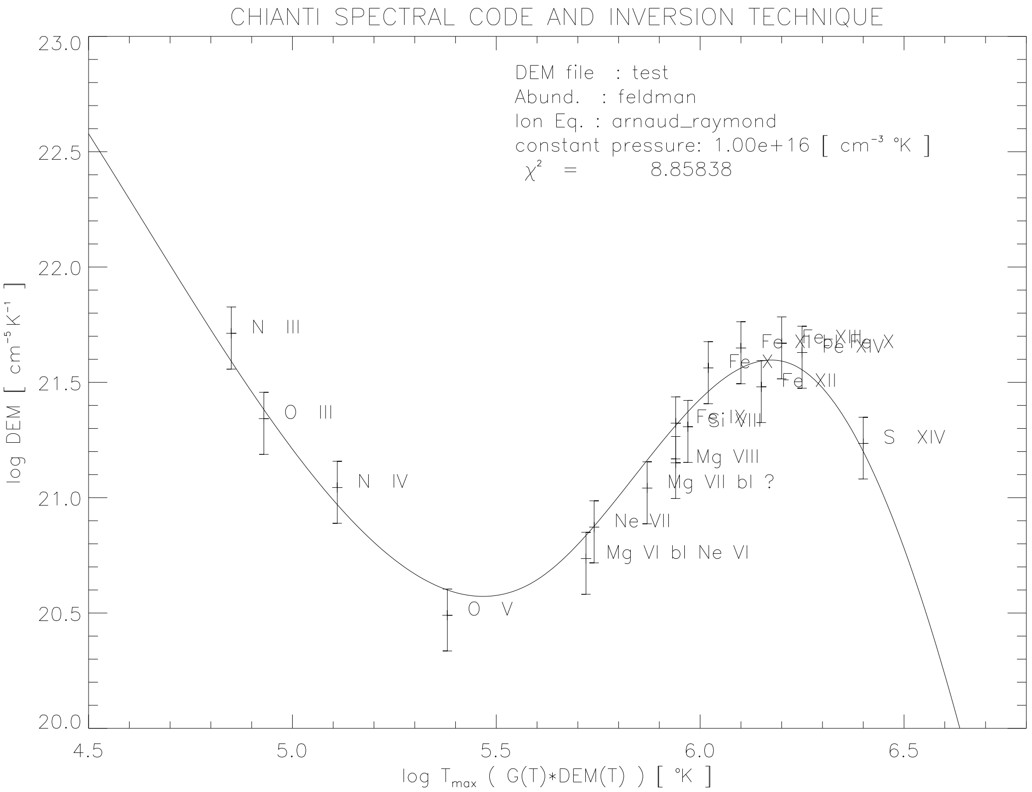

Figure 3: The DEM plot of the test case: *test_dem.ps*

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.

3.3 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.

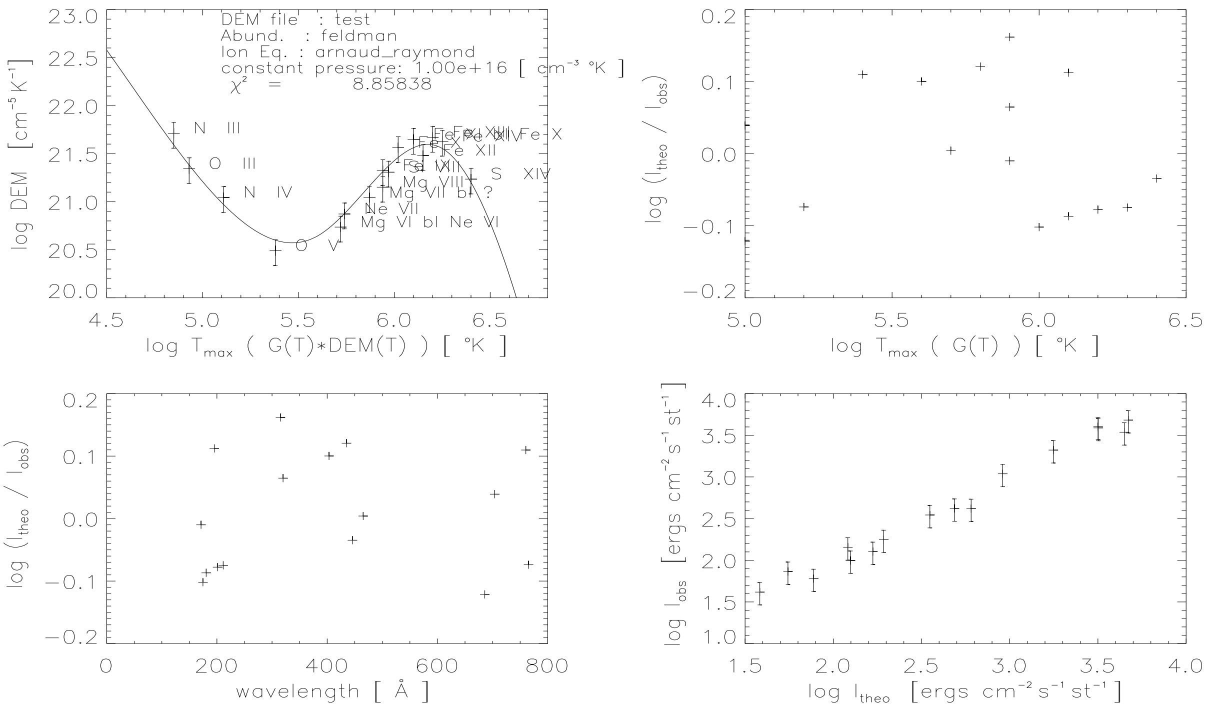

Figure 4: The 4 plots of the test case: *test_4plots.ps*

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

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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