TEMPERATURE AND DENSITY DIAGNOSTICS OF ACTIVE REGION OBSERVED WITH CDS NIS

E. Landi, M. Landini

Department of Astronomy and Space Science, Univ. of Florence, ITALY

ABSTRACT

We study the Differential Emission Measure distribution of two pairs of active and quiet regions of the solar atmosphere and investigate their temperature and density structure. Use is made of the Arcetri Method for DEM and density diagnostics. An iterative method for determining the DEM is presented; it allows to select physically meaningful DEM distributions having a definite temperature along the line of sight. Density sensitive lines are identified and density diagnostics is performed for all the four different spectra. Comments are made on the density versus temperature curves obtained for each region. Simple constant pressure model are not satisfactory and constraints on temperature and density distributions are discussed.

1. Introduction

The Coronal Diagnostic Spectrometer (CDS) on Soho is a grazing/normal incidence spectrograph, aimed to produce stigmatic spectra of selected regions of the solar surface in six spectral windows of the extreme ultraviolet from 150 Å to 785 Å (Harrison et al. 1995).

This spectral band is extremely rich of emission lines of a large number of highly ionized ionic states and its study represents an unique tool for a detailed diagnostic of temperature, density and chemical composition of the solar transition region and corona. Moreover it is a unique laboratory for testing atomic physics models and theoretical calculations of collision rates and transition probabilities.

The large number of emission lines that are observed in the solar spectrum, coupled to the large amount of atomic data now available (CHIANTI - Dere et al. 1997. The Arcetri Spectral Code - Landi and Landini 1997a, ADAS - Summers et al. 1996) and a new temperature and density diagnostic technique (Landi and Landini 1997b), allow to do a detailed temperature and density diagnostics of the solar transition region and corona.

In the present poster we have applied this new diagnostic technique to the intensities of lines emitted by Active and Quiet Regions of the solar atmosphere observed with the NIS spectograph, and comparison are performed among temperature and density models of the different sources.

2. The theoretical method

2.1. Differential Emission Measure determination

Several methods for calculating the Differential Emission Measure have been developed, using different algorithms and approximations; a comprehensive description of the most important ones and a critical assessment and comparison of their reliability can be found in Harrison and Thompson (1992).

We used a new method to evaluate the Differential Emission Measure which adopts an iterative procedure described in Landi and Landini 1997b (hereafter paper I) and uses density independent lines.

Here we present a very brief summary of the theoretical method. For further details we refer the reader to paper I.

The intensity emitted by a thin plasma in a line is given by

\[ I_{ij} = \frac{1}{4\pi} \int \frac{N_j(X^{+m}) A_{ij} dh}{h} \text{ph cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]  \hspace{1cm} (1)

We can define the Contribution Function as follows:

\[ G_{ij}(T, N_e) = \frac{N_j(X^{+m})}{N(X^{+m})} \frac{N(X)}{N(H)} \frac{N(H)}{N_e} \frac{A_{ij}}{N_e} \]  \hspace{1cm} (2)

The usual definition of the Differential Emission Measure \( \varphi(T) \) is assumed

\[ \varphi(T) = N_e^2 \frac{dh}{dT} \]  \hspace{1cm} (3)

A trial Differential Emission Measure \( \omega(T) \) is adopted; using a Correction Function \( \omega(T) \), the true Differential Emission Measure is

\[ \varphi(T) = \omega(T) \varphi_0(T) \]  \hspace{1cm} (4)
and we can define the effective temperature $T_e$ as

$$\log T_e = \frac{\int G_{ij}(T) \varphi_0(T) \log T \, dT}{\int G_{ij}(T) \varphi_0(T) \, dT}$$  \hspace{1cm} (5)$$

It may be easily shown that:

$$I_{ij} = \frac{1}{4\pi} \omega(T_i) \int G_{ij}(T) \varphi_0(T) \, dT$$  \hspace{1cm} (6)$$

Using equation 6 for several lines with different $T_i$ the correction $\omega(T_i)$ for each line may be computed and a new approximated Differential Emission Measure $\varphi(T_i)$ evaluated.

A spline function is drawn through the $\varphi(T_i)$ and this function is taken as the new trial Differential Emission Measure. Then the procedure is repeated until the $\omega(T_i)$ are all equal to 1 within the errors, or the best $\chi^2$ is reached.

The program is also allowed to constrain Differential Emission Measure distribution having a top temperature $T_{max}$. Figure 4 shows an example of such a type of solution.

2.2. The density evaluation

We used the temperature and density diagnostic procedure shown in Landi and Landini 1997b, that is briefly summarized in this section.

With a good approximation it is possible to express $G_{ij}(T, N_e)$ as

$$G_{ij}(T, N_e) = f_{ij}(N_e, T) g(T)$$  \hspace{1cm} (7)$$

where $g(T)$ is function of temperature alone, identical for all the lines of the same ion and mainly due to the ionization equilibrium; $f(N_e, T)$ is mainly determined by the population of the upper level and is almost a linear function of log $T$.

A new effective temperature $T_{e,eff}$ may be evaluated

$$\log T_{e,eff} = \frac{\int g(T) \varphi(T) \log T \, dT}{\int g(T) \varphi(T) \, dT}$$  \hspace{1cm} (8)$$

and an effective emission measure $L_{ij}(N_e)$ may be computed as

$$L_{ij}(N_e) = \frac{I_{obs}}{G_{ij}(T_{e,eff}, N_e)}$$  \hspace{1cm} (9)$$

The diagnostic method relies on the observation that if we plot all the L-functions of the same ion calculated with the line fluxes derived from a well-calibrated spectrum versus the electron density all the curves meet in a common point $(N_e^*, L(N_e^*))$. Moreover the L-functions of not density dependent lines must overlap and cross the same point as the others.

An example is given in Figure 1.

3. The observation

The above outlined method has been applied to the s24 observation belonging to the NISAT observing program, performed on April 9th 1996 from 13.13 U.T to 14.11 U.T.

The observation was performed using the Normal incidence Spectrograph covering the spectral intervals 310 - 380 Å and 510 - 640 Å: it concerned a region near the solar disk center about 20 arcsec × 140 arcsec wide. The field of view included two small active regions emerging from a diffuse quiet background.

Detailed analysis has been performed of both the active regions and of two selected portions of the quiet background.

A set of more than 100 lines has been identified and measured: they cover a vast temperature interval from Fe I to Fe XVI; the interval includes also a large number of density sensitive lines.

Counts rate and errors are evaluated using the standard CDS package. Also a cosmic ray cleaning routine has been used in order to remove any spurious feature; conversion to intensity has been performed according to the pre-flight calibration. The correction factors to the NIS intensity calibration found by Landi et al. 1997 have been applied to the measured intensities.
4. Results

4.1. The Differential Emission Measure

The plasma Differential Emission Measure was evaluated using either the maximum temperature option or the usual Differential Emission Measure definition over the temperature interval $10^4$ to $10^8$ K.

The results of the Differential Emission Measure analysis are the following:

- both quiet regions show similar temperature distribution; they peak at about $1.25 \times 10^8$ K and require very small amount of gas warmer than $1.6 \times 10^6$ K.

- both active regions are similar, they peak at about $1.6 \times 10^8$ K and require gas at $2.5 \times 10^6$ K.

- Figure 2 and Figure 3 show the comparison between a quiet and an active region where the larger amount of hot gas in the active region is shown.

- In all the four spectra problems arise with Mg VII, VIII, IX lines which usually do not to agree with lines from other element's ions with similar temperature. It is possible that the adopted Feldman Magnesium abundance is higher than the real abundance of the emitting regions. It is interesting to notice that there is some evidence that the Magnesium abundances may change from one region to the other.

Figure 4 gives an example of the Differential Emission Measure distribution for the same active region when a top temperature at about $1.6 \times 10^8$ K is constrained. It is interesting to note that the strong maximum of the "free" Differential Emission Measure has disappeared in the constrained Differential Emission Measure and has been replaced by a monotonically increasing function.

4.2. The electron density

Examples of the effective emission measure (L-functions) versus the electron density are given for Si IX and Mg VIII, just to show the common crossing of the lines. It is possible to see from Figure 5 that the
crossing point of the L-functions is very precise, potentially allowing a very precise density diagnostics. Mg VIII lines observed in NIS 1 (Figure 6) are density insensitive in the range $10^8$ - $10^{10}$ cm$^{-3}$ and are potentially diagnostically for coronal hole densities. The Mg VIII L-functions are coincident within the experimental uncertainties for any density greater than $10^8$ cm$^{-3}$ (confirming the Si IX density value measured in Figure 5). It is possible that line 313.8 is blended, as observed by Brooks et al. 1997, though the other component of the blend is not known.

We have applied this procedure on all the ions whose lines are observed by NIS spectrometer in order to determine the electron density of the emitting plasma as a function of the effective electron temperature $T_{eff}$ associated with each density measurement. We have repeated this study for both the active and quiet regions in order to study any difference between the two different physical conditions.

The results for an active and a quiet regions are displayed in Figure 7 and Figure 8. The results can be summarized as follows:

- the electron density in the quiet regions are rather scattered and ranges between $2 \times 10^8$ cm$^{-3}$ and $4 \times 10^9$ cm$^{-3}$ in the temperature interval between $1.1 \times 10^6$ K and $1.6 \times 10^6$ K.

- large uncertainties occurs also for active regions which appear somewhat denser showing electron density ranging from $3 \times 10^8$ to $1 \times 10^{10}$ cm$^{-3}$ in the temperature regime from $1.5 \times 10^6$ to $1.7 \times 10^6$ K.

- indication exists that the density increases with temperature in both quiet and active Sun. A similar behavior has been observed also in SERTS (Landi and Landini 1997b, Young et al. 1997). This behavior is in contrast with constant pressure models.

- In both active and quiet Sun Fe XII and Si X have always a nearly identical effective electron temperature $T_{eff}$, nevertheless the measurements of their electron density lead unexpectedly to very different values. This behavior is seen also in SERTS data (Young et al. 1997, Brosius et al. 1996).

4.3. Synthetic Spectra

Using the evaluated Differential Emission Measure distribution the synthetic spectra for NIS1 and NIS2 sections of one active and one quiet regions have been computed. We have adopted $N_e = 1 \times 10^9$ cm$^{-3}$ for quiet Sun and $N_e = 3.2 \times 10^9$ cm$^{-3}$ for active Sun. The choice of this value for the electron density is reasonable but ambiguous since it is not able to represent properly the electron density of the emitting region, as witnessed by Figure 7 and Figure 8. For this reason some discrepancy between the observed density sensitive lines and the theoretical ones is expected for the ions whose measurements of electron density has provided values different from the adopted one.

In Figure 9 to Figure 12 the synthetic spectra with the line identifications for the strongest features are compared with the observed spectra of one quiet and
one active region. A general good agreement is observed for both NIS 1 and 2 and the Arcetri Spectral Code is able to simulate all the observed lines, with few exception particularly when very weak lines are involved.

Nevertheless several points deserve special attention:

- As already pointed in the Differential Emission Measure section, the Magnesium abundance adopted for the calculation of the theoretical spectrum is higher than the real one, as witnessed by the Mg lines from Mg V to Mg X. A factor 2 seems to be a reasonable correction for the Mg abundance. More precise measurement will be provided in Landi and Landini 1997c.

- There is strong evidence for some problems in Silicon abundance. As for Magnesium, the adopted Silicon abundance seems to be too high compared with the real one. Si VIII, IX and X observed in NIS 1 are too high relative to all the lines of the other elements. NIS 2 Si XII line seems to agree slightly better with observation. Also for Silicon abundance a correction of a factor $\approx 2$ is required. A similar result has been outlined by Landi and Landini 1997b.

- As expected, some relatively density sensitive pairs of lines are not in agreement with observation. This is due to the density value scatter discussed in section 4.2. This is a further evidence that the density structure of the emitting regions requires more accurate models.

- the strong feature at 606 Å and 607 Å are second order He II 304 Å and Si XI 303.3 Å, not yet included in the synthetic evaluation because they are second order lines. Using the second order NIS 2 sensitivity it is possible to evaluate their real intensities and compare them with the first order lines.
5. Conclusions

We have analyzed two pairs of active and quiet Sun regions, determining their Differential Emission Measure distribution, the electron density of each of these regions as a function of electron temperature and some corrections to Silicon and Magnesium element abundances. Use has been made of the Arcetri diagnostic technique for the analysis; this technique allows also to constrain the Differential Emission Measure to have a maximum temperature $T_{\text{max}}$. Comments are made on the comparison between the resulting Differential Emission Measure functions obtained with and without this constrain.

For this kind of study a large quantity of high quality atomic data is required. In recent times some extensive databases have been created for matching the increasing need of theoretical transition probabilities, such as ADAS and CHIANTI. In the present study we make use of the Arcetri Spectral Code (Landi and Landini 1997) which is an updating of the old version (Monsignori Fossi and Landini 1996) using the CHIANTI database and additional data for ions not included in the CHIANTI database yet.

REFERENCES


Landi, E. and Landini, M., 1997c, Temperature and density diagnostics of active region observed with CDS NIS, in preparation

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