AN EMPIRICAL TEST OF DIFFERENT IONIZATION BALANCE CALCULATIONS IN AN ISOTHERMAL SOLAR PLASMA.

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ABSTRACT

By examining solar observations using the Normal Incidence Spectrometer (NIS) within the Coronal Diagnostic Spectrometer (CDS) on board SOHO, an isothermal region in the lower solar corona was chosen for analysis by three different temperature diagnostic techniques. These techniques are the line-ratio method, the Differential Emission Measure and the Emission Measure analysis. All three methods should in theory yield the same temperature. Using these powerful diagnostic methods, the reliability of all widely used ionisation balance calculations, namely those of Shull & Van Steenberg (1982), Arnaud & Rothenflug (1985) and Mazzotta et al (1998) have been empirically tested for the first time. It has been found that the temperature obtained does not depend on the ionization balance calculation used.

1. INTRODUCTION

EUV emission line diagnostics of astrophysical plasmas has been one of the most widely used techniques to measure the plasma’s physical parameters such as electron density and temperature, chemical abundances and plasma Differential Emission Measure. These techniques rely on observations and on the knowledge of a large number of theoretical atomic parameters and transition probabilities, which underpin the line emission processes. Uncertainties in these theoretical parameters will affect the results.

Diagnostic tools for investigating the physical parameters of the solar corona have strongly improved during the last few years. Big databases of updated atomic data and transition probabilities have been created, such as CHIANTI (Dere et al. 1997, Landi et al. 1999), ADAS (Summers 1993) which help into the analysis of the huge amount of EUV observations of the solar corona collected by SOHO, both with high resolution spectrometers, such as CDS (Harrison et al. 1995) and SUMER (Wilhelm et al. 1995), and with narrow bandwidth imaging telescopes (EIT, Delaboudiniere et al. 1995).

Theory of atomic physics on one side and detailed observations on the other have largely evolved together helping to enrich each other in the process.

One of the most important parameters in the evaluation of the expected line emission from an optically thin source is the emitting ion abundance, as it encompasses the largest part of the temperature dependence of the line intensity. Temperature, element abundance and Differential Emission Measure diagnostics largely depend on the assumed ion balance (Gianetti et al. 1999).

This quantity is available in literature from a few theoretical computations under the assumption of ionization equilibrium, but no attempt to assess the quality of these computations using observed solar spectra has been made so far. Such an assessment is not an easy task, due to the complicated and largely unknown temperature structure of the solar atmosphere as seen along the line of sight.

However off-limb observations of a quiet sun region may likely provide a reasonable isothermal source to investigate ion abundances of different species. The assumption that quiet solar corona observed at a proper height over the limb may be isothermal has been recently verified by Feldman et al. 1999 using SUMER spectra measured at the solar equatorial limb with an east-west slit. This simplified temperature structure of the emitting plasma is of great help to assess the reliability of the current equilibrium ion fractions computations.

The aim of this paper is to examine the temperature values measured from an isothermal solar plasma adopting three ionization balance calculations available in the literature; Shull & Van Steenberg (1982); Arnaud & Rothenflug (1985) incorporating the latest revisions to the iron ions by Arnaud & Raymond (1992); Mazzotta et al. (1998).

If no problem arises from atomic physics data a single temperature value must satisfy all the observed lines of different ions of the same element. If the ion balance calculations are incorrect, this will appear as disagreements amongst the temperature measurements obtained using different datasets.

Due to the high temperatures in the lower solar corona, the strong resonance lines of ions that should be abundant at these temperatures are located in the UV and EUV portions of the spectrum, thus falling into the range of wavelengths that the Coronal Diagnostic Spectrometer (CDS) on SOHO can detect. The wavelength region covered by this instrument allows us to investigate lines formed in a very large temperature interval ($10^5 - 3 \times 10^6$ K), making it an ideal instrument for our study.

The paper is structured as follows: in Section 2. the
CDS observations are presented and data reduction is described. The theory of line emission is outlined in Section 3. Sections 4. to 6. describe the application of three different diagnostic techniques to the observations using the three ionization equilibrium datasets, and the results are discussed in Section 7.

2. THE OBSERVATIONS

The Coronal Diagnostic Spectrometer (hereafter CDS) is an imaging spectrograph, whose primary objective is the study of the solar corona through line and continuum emission between 150 Å and 780 Å. CDS is composed of two distinct spectrometers sharing the same telescope: the Grazing Incidence Spectrometer (hereafter GIS) covering four spectral ranges: 151-221, 256-341, 393-492 and 659-785 Å; and the Normal Incidence Spectrometer (hereafter NIS) covering the ranges 307-379 and 513-633 Å. Full details of the CDS instrument may be found in Harrison et al (1995).

In order to maximise the number of spectral lines available for examination, the observational data used for the analysis covered the full spectrum available to the CDS-NIS. Furthermore, a field of view was selected that included the solar limb and the lower corona in order to be able to select an appropriate isothermal emitting region. The data used were taken on March 13 1997. The centre of the field of view has heliocentric coordinates of (-93, -3.1) arcseconds, in a quiet Sun region; the field of view has dimensions of 182 x 60 arcseconds and can be seen in Figure 1. Due to the geometry of the emitting region, each off-limb slit position in solar X has a spectrum originating from an almost plane-parallel layer of the solar coronal plasma, which may be considered isothermal if the temperature is only a function of radial distance from the solar centre.

The data have been reduced, cleaned from cosmic rays and calibrated into ergs/cm²/s/str using standard routines available in the CDS software.

The main guidelines in choosing an isothermal region that will yield a good spectrum for analysis are that the region needs to be sufficiently far from the transition region and that the spectral lines of the region need to have as high a signal/noise ratio as possible. Spectral lines from He I to O VII have been used to check the presence of transition region plasma; the optimum region in the field of view was found once these lines had become nearly indistinguishable from the background noise, and a maximum possible signal/noise ratio for coronal lines had simultaneously been found to be the case at a solar X of -98° from the solar centre. The emission from the selected raster position has been averaged along the solar Y direction.

3. THEORY OF THE INTENSITY INTEGRAL IN AN ISOTHERMAL PLASMA.

The intensity integral of an optically thin emission line is given by

\[ I_{ji} = \frac{G_{ji}(T)}{4\pi} \int h N_{\text{e}}^2 dE = \frac{G_{ji}(T)}{4\pi} <EM> \]  

where \(<EM>\) is the Emission Measure which, in an isothermal case, is independent from temperature, and \(G_{ji}(T)\) is the Contribution Function defined as:

\[ G(T, N_e) = \frac{N_j(x^{+m}) N(x^{+m}) N(x) N_H A_{ji} h \nu_{ji}}{N(x^{+m}) N(x) N_H N_e N_e} \]  

where the terms (a) to (c) are explained below:

(a) Relative population of the excited level \((j)\); this is dependent on atomic physics and is only weakly dependent on temperature, but may be strongly dependent on density.

(b) Relative abundance of the ionic species. This is obtained from the ionization balance calculations. This term is dependent on atomic physics and is very temperature sensitive.

(c) Abundance of the element relative to hydrogen.

In this work, use is made of the CHIANTI database (Dere et al 1997 and Landi et al. 1999) to calculate term (a). Use is also made of three different ion abundance data sets (Shull & Van Steenberg 1982), hereafter SHULL; Arnaud & Rothenflug (1985) plus Fe from Arnaud & Raymond 1992, hereafter ARNAUD: Mazzotta et al (1998), hereafter MAZZ) to calculate term (b), and of the element abundances of Feldman (1992) to calculate term(c).

Generally, however, the observed emission originates from a plasma which is not strictly isothermal. As there is no plasma structure in the present quiet Sun data set and the temperature dependence of \(h\) is continuous we can define the Differential Emission Measure (DEM) \(\psi(T)\):

\[ I_{ji} = \frac{1}{4\pi} \int G_{ji}(T) \psi_{ji}(T) dT \]  

However, due to the finite \(dT\) interval used in the DEM evaluation and to the intrinsic temperature resolution limits due to the width of the \(G(T)\) functions, an isothermal solution for \(\psi_{ji}(T)\) appears as a very narrow function, almost a Dirac delta function, when is plotted versus temperature.

4. THE DIFFERENTIAL EMISSION MEASURE

To verify that the chosen emitting region is isothermal, the DEM of the plasma was measured using all the density insensitive lines observed in the present dataset and the iterative technique described in detail by Landi & Landini (1997), where the reader is referred to for details. This analysis was repeated using the three different ion fraction data sets SHULL, ARNAUD and MAZZ in order to check the impact of the differences in these three datasets on the DEM shape and on the value of the temperature where the DEM peaks. In all cases element abundances were taken from Feldman 1992.

During the DEM analysis, some of the used lines have been removed from the analysis. Their discrepancies are mostly due to the presence of instrument scattered light from the solar disk, affecting the coolest ions of our dataset. Also Fe ions were removed because of gravitational dragging, as mentioned by Feldman et al. 1999.
The resulting DEM curves are displayed in Figure 2, as obtained by adopting the three different ionization balance calculations. The DEM plots show that the plasma is isothermal within 0.1 in log T and that the chosen emitting region is therefore adequate for further analysis. The temperature values obtained using the DEM analysis are identical using the three different ion fraction datasets: log T = 6.05 ± 0.05 (T in K). The uncertainties are taken from the temperatures of the ions at the extremes from each DEM plot.

5. LINE RATIO DIAGNOSTICS APPLIED TO ISOTHERMAL PLASMAS.

Selected line pairs emitted by different ions of the same element have been used to measure the electron temperature of the emitting plasma. In order to verify the density insensitivity of the selected line pairs, the ratios were calculated for three sample values of the density typical of quiet and active solar regions (10^8, 10^9 and 10^10 cm^{-3}). The temperature values obtained are tabulated in Table 1 for the three different ionization balance calculations. The limited density sensitivity present in some lines affects the log temperature values of less than 0.01. The mean temperature values calculated for each of the ionization balance calculations are reported in the last row of Table 1, together with their standard deviations.

6. AN EMISSION MEASURE ANALYSIS FOR ISOTHERMAL PLASMAS.

From Equation ??, for an isothermal plasma the Emission Measure can be evaluated as:

\[ <EM> = 4\pi \frac{I}{G(T, N_e)} \]  (4)

In an isothermal case, from Equation 1, if there are no problems arising from atomic physics or ionization balance calculations, by plotting \( \frac{I}{G} \) vs. T for all the given spectral lines, the curves on the graph should cross each other at the point \( (T_e, \frac{1}{4\pi} <EM>(T_e)) \), thus supplying the \( \frac{1}{4\pi} <EM> \) of the emitting plasma. An example is given in Figure 3 using all the observed lines. Note that most lines cross inside a small region in I/G - T space but there are also a few lines relatively far outside this region; these discrepancies are due to the problems outlined in Section 4.

This property of spectral line intensity can be used to infer the electron temperature of the emitting plasma. The temperature can be obtained by considering the crossing...
<table>
<thead>
<tr>
<th>LINE RATIO</th>
<th>ARNAUD</th>
<th>SHULL</th>
<th>MAZZ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Log(T) at Log(N_e)</td>
<td>Log(T) at Log(N_e)</td>
<td>Log(T) at Log(N_e)</td>
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<tr>
<td></td>
<td>8</td>
<td>9</td>
<td>10</td>
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<tr>
<td>Mg X (628)</td>
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\[
\langle T \rangle = 6.01 \\
\sigma_{\langle T \rangle} = 0.03
\]

Table 1. The table shows the calculated temperatures from the line ratio method for three different ionization balance calculations, namely from ARNAUD (Arnaud & Rothenflug 1985 and Arnaud & Raymond 1992 for Fe-ions), SHULL (Shull & Van Steenberg 1982) and MAZZ (Mazzotta et al 1998). Temperatures are in Kelvin and electron density is quoted in units of cm\textsuperscript{-3}. The mean temperature values are shown in the last row.

<table>
<thead>
<tr>
<th>Ion fractions</th>
<th>Log(\langle T \rangle)</th>
<th>\sigma \log(\langle T \rangle)</th>
<th>Log(\langle EM \rangle)</th>
<th>\sigma \log(\langle EM \rangle)</th>
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</thead>
<tbody>
<tr>
<td>ARNAUD</td>
<td>6.04 ± 0.12</td>
<td>27.05 ± 0.64</td>
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<td></td>
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<tr>
<td>SHULL</td>
<td>6.04 ± 0.11</td>
<td>26.95 ± 0.58</td>
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<td></td>
</tr>
<tr>
<td>MAZZ</td>
<td>6.04 ± 0.15</td>
<td>27.14 ± 1.01</td>
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</table>

<table>
<thead>
<tr>
<th>Ion fractions</th>
<th>Log(\langle T \rangle)</th>
<th>\sigma \log(\langle T \rangle)</th>
<th>Log(\langle EM \rangle)</th>
<th>\sigma \log(\langle EM \rangle)</th>
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<tbody>
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<td>6.04 ± 0.03</td>
<td>26.78 ± 0.10</td>
<td></td>
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<tr>
<td>SHULL</td>
<td>6.03 ± 0.02</td>
<td>26.76 ± 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MAZZ</td>
<td>6.02 ± 0.03</td>
<td>26.71 ± 0.15</td>
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</table>

Table 2. The mean values obtained for the temperature and the \langle EM \rangle for an electron density of Log(N_e) = 9 using the Emission Measure Analysis as a diagnostic: mean of crossing pairs (top) and "stripe" analysis (bottom).
Figure 2. The DEM is shown here for the three different ionization balance calculations.

Figure 3. The I/G functions of all the available spectral lines from the chosen plasma plotted against temperature.

Figure 4. The Emission Measure Analysis is shown here for the Arnaud & Rothenflug (1985) / Arnaud & Raymond (1992) ionization balance calculations. The darkest shades correspond to largest numbers of overlapping areas.

points of each pair of lines and calculating the mean of the crossing temperatures; the values resulting from the Emission Measure analysis carried out using the three different ion fraction datasets are reported in Table 2.

A more meaningful approach is to consider for each line the "stripe" obtained by the observed intensity plus and minus the uncertainty. Each pair of observed lines defines an area in the I/G vs. logT plot and the region common to the largest number of stripes supplies the best temperature and emission measure and their uncertainty. One example of this technique is displayed in Figure 4, where the Contribution Function have been calculated using the ARNAUD dataset for ion fractions. A clear structure can be distinguished and a single dominant temperature peak is clearly visible.

Each line generates a 'stripe' in the I/G vs T space, whose width is given by the uncertainty associated with the line. As a consequence, this "stripe" analysis indicates regions in < EM > - T space that are delineated by these uncertainties. Therefore, a solution for determining the uncertainties on the obtained (To, < EM >) values might be to find the size of the tem-
temperature interval at which, for example, 68% (or 1/e) of the lines cross. The obtained temperature and $<E/M>$ values are presented here in Table 2.

7. DISCUSSION AND CONCLUSIONS

These results obtained from the DEM analysis clearly show that we have an isothermal plasma in the selected region. Furthermore, they show that for any given ionization balance calculation, the temperature diagnostic techniques used all agree with one another within the uncertainty values that are present. This confirms that the diagnostic methods used are consistent within their uncertainty values for an isothermal plasma.

The results show also that for any given diagnostic technique, all three ionization balance calculations gave the same temperature value and uncertainty.

However strong discrepancies have been observed for the coolest ions observed in the present dataset (Mg VII, Al VII and Al VIII). This lines could be affected by scattered light but a problem in the ionization balance cannot be excluded.

The $<E/M>$ analysis indicates that the scatter about the mean values for MAZZ is large compared to those of SHULL and ANRAUD, which are relatively similar in size, although the SHULL data had slightly less, for both electron density values of $\log N_e = 8$ and $\log N_e = 9$. The "stripe" $<E/M>$ analysis shows prominent peaks in the data and regions of concentration in $I/G-T$ space, that agreed with the temperature values of the line ratio method and the DEM.

This is a very strong confirmation that the coronal region being analysed is isothermal, and that the use of different ionization datasets does not introduce any further uncertainty on the obtained results.

The ionization balance calculations have given only marginally differing results, showing that, within the uncertainties of the calculations, the same temperature result are obtained for each of the ionization balance calculations of Arnaud & Rothenflug (1985), SHULL & VAN Steenberg (1982) and MAZZotta et al. (1998).

It can be concluded that no major problems have been found in the ionization balance calculations, although the calculations of MAZZotta et al. (1998) show slightly more variance in the obtained results. Their modifications to the ionization balance calculations have not influenced the results significantly, although they have introduced a slightly higher scatter in them. This means that for the case of an isothermal plasma the diagnostic techniques are robust against changes and uncertainties in the ion fraction calculations used, so that these do not need to be considered as a source of major uncertainty in the present and similar work.

In addition, the "stripe" Emission Measure Analysis which has been presented, used also as temperature diagnostic in an isothermal plasma, clearly shows the region of temperature of the emitting plasma and provides a diagnostic method which is stable to large deviations from the mean by several lines.

REFERENCES


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