INVESTIGATION OF A COLOUR-COLOUR METHOD TO DETERMINE SOLAR ATMOSPHERIC TEMPERATURES USING SOHO/EIT DATA

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ABSTRACT

This paper examines the double filter ratio method proposed recently by Chae et al. (2002), for determining temperatures in the solar atmosphere. Chae’s paper takes two filter ratios (TRACE 195/171 Å and 284/195 Å ) which, when plotted against each other, provide a colour-colour curve for determining a wide range of unambiguous plasma temperatures. We extend this method to SOHO/EIT data of a flare loop on the north east solar limb in an attempt to obtain the temperature profile along the structure. In doing so, we find Chae’s method to be troublesome with many data-points sitting off the colour-colour curve. Also, when applying this method to EUV data at these three wavelengths it was found that outside the range of 0.7 - 4 MK the errors for the instrument response functions were large; thus the values outside the above range could not be trusted and the range of temperatures used with this technique had to be limited. These inconclusive results may be due to the dynamic nature of the cooling flare plasma. However, it may also be that for the spatial resolution of EIT, a loop could consist as a bundle of sub-resolution, multi-thermal plasma threads. Even for the simplified scenario of two strands of differing temperatures along the line of sight, it is clear that the filter ratio plot is unable to pinpoint a precise value or even give a correct overall average temperature value.

Key words: Coronal loops – EUV – temperature diagnostically.

1. INTRODUCTION

Recent interest has centred upon determining the fundamental plasma properties within loops - namely their temperature (T(s)) and density (ρ(s)) profiles along the structure (s) coupled with any plasma flows or driven periodicities. In particular, two avenues of investigation have been to (i) calculate loop thermal profiles from observations and then match this with a T(s) from a 1D hydrostatic model that will yield a unique localised heating profile (H(s)), or (ii) fold your model calculations through some instrument response function (such as the TRACE EUV filters) and compare the results with observations.

Aschwanden et al. (2000, 2001) use filter ratios of SOHO/EIT (Solar and Heliospheric Observatory/Extreme ultraviolet Imaging Telescope) and TRACE (Transition Region And Coronal Explorer) EUV bands (171 Å to 195 Å) to argue that the near isothermal loops observed indicate an H(s) weighted towards heating at the loop base. However, Priest et al. (2000) found cases of uniformly distributed heating, whilst Reale (2002) found cases of apex dominant heating, when analysing the same Yohkoh/SXT loop on the limb of the Sun. The single filter-ratio technique has been criticized as being too simplistic and the concept of the differential emission measure (DEM) must be employed as a means of calculating the amount of emitting material present in an optically thick environment, such is the case in the corona.

Schmelz et al. (2001) derive a DEM distribution for several pixels along an isolated loop using spectral-line data from SOHO/CDS (Coronal Diagnostics Spectrometer) and broadband data from Yohkoh/SXT (Soft X-ray Telescope). They found that the calculated T(s) is clearly inconsistent with an isothermal and therefore footpoint heated loop. Schmelz (2002) took the analysis one step further by reproducing what SOHO/EIT would observe of the aforementioned SOHO/CDS loop and obtains an isothermal structure. Martens et al. (2002) however, explains that the TRACE isothermal results are due to the existence of a broad, flat plateau in the DEM from ≈0.7 MK - 2.8 MK. Since SOHO/EIT and TRACE narrowband filters fall within this range,
The CH two filter ratio method has been introduced as a possible answer to the problem of the single filter ratio analysis method. This colour-colour method assumes that the same plasma volume is filled with isothermal plasma which has a temperature $T_{\text{iso}}$. The emission ($E_\lambda$) which an EUV imager (in this case SOHO/EIT) observes from this region in the three EUV lines ($\lambda = 171, 195$ and 284 Ångstroms) is given by

$$E_\lambda = \rho^2(s)I_\lambda[T_{\text{iso}}(s)]$$  \hfill (1)

where $I_\lambda$ is the instrument response function for a given $\lambda$. If we take the ratio of these emissions for different wavelengths, assuming that emission measure and therefore density is independent of wavelength, we can see that the ratios can be written as

$$C_1(s) = \frac{E_{284}}{E_{195}} = \frac{I_{284}}{I_{195}},$$ \hfill (2)

$$C_2(s) = \frac{E_{195}}{E_{171}} = \frac{I_{195}}{I_{171}}.$$ \hfill (3)

where $C_1$ and $C_2$ are now functions of temperature and element abundances. Plotting $C_1$ against $C_2$ provides a colour-colour curve for the unique determination of temperature. Therefore the principle is that we can now use a pair of observed $C_1$ and $C_2$ values to try and determine the unique temperature profile of a structure in the solar atmosphere.

Fig 2 shows the theoretical curve of $C_1$ and $C_2$ based on the standard temperature responses given by the standard SOHO procedure EIT_FLUX.PRO using the Arnaud & Raymond ionisation equilibrium (1992) and the coronal abundance (Feldman 1992). It can be seen that the curve has a twofold shape, the inner side giving transition region temperatures and the outer side having coronal temperatures.

### 3. OBSERVATIONS

The above method was investigated using a SOHO/EIT dataset taken on 18 March 1999. A 195 Å image taken using SOHO/EIT is displayed in Figure 3 and shows the exact location of the target flare loops on the northeast limb; the loops became visible at around 04:10:54 UT, ~10 mins after a flare occurred. This 195 Å data is interspersed every few hours with a 171/195/284/304 Å cycle with a cadence of only 6 mins (i.e. it takes ~720 secs to get all three images). The triplet (171 Å, 195 Å and 284 Å) used for this analysis was taken at around 07:00 UT (see Noglik et al., 2005 for more detailed information of these flare loop observations).
Figure 2. SOHO/EIT colour-colour diagram with various specific temperatures identified along the curves (assuming Feldman coronal abundances).

Figure 3. Location of the loop on the northeast limb. The whole sun image is a SOHO/EIT image at 195 Å while the close-up of the loop is TRACE 171 Å; both images were taken shortly after 06:00 UT on 1999 March 18.
This flare loop system was chosen for two reasons; firstly it is seen to be very bright in all of the three passbands (171 Å, 195 Å and 284 Å), and secondly because of its fortuitous location on the north east limb of the Sun (shown in Fig 3) which means that there should be little contaminating emission from other solar sources. Fig 4 shows the three different filter passband images which display clearly the loop structure. The loops are marked with crosses which were the points chosen for the CH analysis. It can be seen that all the points chosen lie along the loop in all of the three passbands. These crosses were chosen by sight as the central pixel of a $3 \times 3$ pixel box. The logarithmic values of $C_1$ and $C_2$ were found for each of the nine pixels contained within the box surrounding the 13 chosen points and then averaged over the box.

4. RESULTS

Fig 5 shows the thermal profile of the loop plotted on the c-c diagram with a limited temperature range of 0.7 - 3.5 MK. The range for this c-c diagram has been shortened as it was found that the errors associated with the temperature response functions at extremely hot and cool temperatures were far too large for the values to be trusted, especially at 284 Å due to the low intensity values received at this wavelength. The profile was measured by calculating the average intensity ratios of $(\log E(195) - \log E(171))$ and $\log E(284) - \log E(195))$ for the $3 \times 3$ pixel boxes centred on the chosen points. The points along the loop are numbered on the diagram to show the change in positions on the c-c diagram.

It is noted that for true filter ratio measurements, the observed intensity will not only contain the plasma loop emission but also emission from background and foreground plasma. However, in doing this analysis we found that background noise subtraction made very little or no impact on the results. This is in line with Schmelz et al. (2003) who analysed a selection on ten coronal loops, five which were on the limb and five on the disc, taken with SOHO/EIT. Schmelz et al. also found that the effect of background subtraction did not affect the EIT temperature analysis, stating that background subtraction especially does not affect the analysis for loops on the limb of the Sun, unless the emission is so weak that it is barely visibly over the background, which is obviously not true in this case.

From Fig 5 it can be seen that the data points along the loop structure do not sit at all on the c-c curve or even within the error bars of the c-c curve, the points also appear to move in a completely random way. Hence, it is very difficult to associate a particular temperature with each chosen location (1-13). Therefore, using EIT data with this method, has proved difficult. A possible explanation for the loop points sitting off the c-c curve could be the effect of a multi-thermal atmosphere, which is discussed in section 5.

5. A MULTI-THERMAL ATMOSPHERE

The question, as to whether we are resolving spatially the basic structural elements of coronal structures such as loops, is still unanswered. Lens et al. (1999) deduced from long-lived TRACE loops that the structures may consist of a bundle of filamentary loop threads at a range of temperatures which, when averaged over, give the appearance of isothermal loops. Cargill and Klimchuk (2004) consider a Yohkoh SXR loop to be made up of $10^6$ individual strands. Priest et al. (2002) argue that TRACE loops are highly fragmented, consisting of 10 finer threads. The c-c method at this EIT resolution (5” pixel size) may mean we are averaging our temperature analysis across a bundle of different temperature
fibres.

Therefore, we looked at whether a multi-thermal atmosphere could be responsible for the position of the points under the cool end of the c-c diagram. Thus, considering a multi-thermal atmosphere, we see that the points would be pushed off the curve by some amount as

\[ \frac{\Sigma E_i}{\Sigma \xi} \neq E_{T_{\text{pix}}}, \quad (4) \]

where \( E_i \) is the emission from a specific temperature at a given wavelength, \( \xi \), and \( E_{T_{\text{pix}}} \) is the emission that would be given from the average of all the temperatures viewed along the line of sight. If these inconclusive SOHO/EIT results were the result of looking at an optically thin environment with the target being observed through a multi-thermal atmosphere, a sum of intensities from a number of different EUV emitting sources would be seen. However, this problem should have been reduced given our location on the limb.

As a first approximation, consider the case where there are only two distinct temperature plasmas (T_1 and T_2) along the line of sight. Also, let us assume that these plasmas are at the same density. Thus, we have

\[ C_1(s) = \frac{E_{284}(T_1) + E_{284}(T_2)}{E_{195}(T_1) + E_{195}(T_2)}, \quad (5) \]

\[ C_2(s) = \frac{E_{195}(T_1) + E_{195}(T_2)}{E_{171}(T_1) + E_{171}(T_2)}, \quad (6) \]

for \( C_1 \) and \( C_2 \) respectively. In Fig 5 there is a dashed box drawn around the observed data points from the SOHO/EIT data, indicating the region of space on the diagram we took to overlap with the data points. We found three temperature pairings (T_1 and T_2) which would place the combined filter ratio point (C_1, C_2) within this region of space. These T_1 and T_2 values were also limited to our temperature range of 0.7 - 3.5 MK for the c-c curve. The temperature pairings were found by doing a simple search of all the possible two temperature solutions and matching the solutions with the co-ordinates associated with each corner of the box. These are listed in Table 1. These temperature pairs were the only solutions found for these specific co-ordinates on the c-c diagram, however other temperature pairings could place the points elsewhere on the diagram. Hence, it is possible with a multi-thermal atmosphere to reproduce the observed c-c result. However, this is a simplistic solution and the actual answer to the problem is likely to be much more involved, possibly having more than two plasma strands in the line of sight with differing temperatures.

6. FUTURE MISSIONS

Considering the above method and its challenges in the light of future instrumentation,
then although the problem of background subtraction/contamination will remain, improving the temporal resolution along with pixel size this c-c method could still be a very useful diagnostic tool. SDO (Solar Dynamics Observatory) is planned to observe seven EUV wavelengths (304 Å, 171 Å, 193 Å, 211 Å, 335 Å, 94 Å, and 131 Å) opening new perspectives on the solar corona. Six of these seven EUV channels observe ionised iron and will allow the construction of temperature maps using many more filter ratios (instead of just two there will be a possibility of five different filter ratios) showing the solar corona from below 1 MK to above 20 MK, with a sustained cadence of just 10 secs. The Orbiter mission should get down to a pixel size of 70 km and hence be able to determine possible individual flux tubes. EUVI (Extreme Ultraviolet Imager) on board STEREO will also have full Sun coverage with twice the spatial resolution of SOHO/EIT and an improved cadence.

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REFERENCES


Table 1. Temperature pairings used in multi-thermal atmosphere analysis.

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<th>$T_1$ (MK)</th>
<th>$T_2$ (MK)</th>
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<tr>
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<td>0.9</td>
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<tr>
<td>1.8</td>
<td>0.7</td>
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