OBSERVATIONS AND MODELS OF SOLAR ACTIVE REGION LOOPS

E. Landi\textsuperscript{1} and M. Landini\textsuperscript{2}

\textsuperscript{1}Artep, Inc, Ellicott City, MD 21042, USA and Naval Research Laboratory, Washington DC, 20375-5320, USA
\textsuperscript{2}Università degli Studi di Firenze, Largo E. Fermi 2, 50125, Firenze, Italy

ABSTRACT

In the present work SOHO/CDS observations of a quiescent active region loop are compared to a steady-state, dynamic loop model, with three different heating functions. Predicted temperature and density profiles of the loop are compared to observations from CDS. The space of parameters of the model is investigated. We find that no agreement can be found between model predictions and observations. We also analyze several SUMER intensity maps of active region solar loops in order to compare the observed relative brightnesses of their footpoints and of their coronal section, with predictions from loop models having uniform cross section and different heating functions. We find that the loop models overestimate the footpoint emission by orders of magnitude. We speculate that a significant decrease of the cross-section near the footpoints, is the most likely solution to the discrepancy.

Key words: Loops; active regions; loop models.

1. INTRODUCTION

Results from imaging instruments working at X-ray, UV and EUV wavelengths have shown that plasma loops are a fundamental component for both the quiet and active solar corona. Therefore, their understanding is an essential requirement for an accurate knowledge of the structure of the solar atmosphere, as well as for unveiling the elusive mechanism(s) that heat the solar corona. However, we are still left with a confused understanding of loop physics, and even the most basic questions are still unanswered.

Temperature diagnostics using filter ratios from SOHO-EIT, TRACE and Yohkoh-SXT has shown that observed temperature profiles are much more constant than predicted by standard theoretical models (Neupert et al. 1998). These results led Aschwanden et al. (2000) to suggest that coronal loops with temperatures in the range $1-2.5 \times 10^7$ K are not under steady-state conditions, but Reale & Peres (2000) showed that the very small temperature gradient could be due to the presence of many unresolved standard loops at different temperatures. Imagers-related studies have failed to provide a coherent picture on loop heating. For example, soft X-ray loops observed by Yohkoh have been shown to be equally compatible both with steady, uniform heating (Klimchuk & Porter 1995), and with nanoflares occurring randomly in sub-resolution strands (Cargill & Klimchuk 1997). In another well studied Yohkoh loop, the heating was found to be uniform (Priest et al. 2000), concentrated near the footpoints (Aschwanden 2001), and concentrated near the apex (Reale 2002). No definitive results on the nature of loop heating have been obtained.

The present paper has two main aims. First, we will compare CDS measurements of the temperature profiles along active region loops with predictions from a 1-dimensional, steady-state, dynamic loop model, calculated by adopting three different functional forms for the heating. Second, we will use SUMER images of active region loops recorded simultaneously in lines from ions formed in the corona and at lower temperatures to investigate the relation between footpoint and coronal plasma in coronal loops, both by analyzing high-resolution images and by comparing measured and predicted relative line intensities. We find that constant-section models fail to reproduce observations, and suggest that these discrepancies might be explained with variable cross-section models.

2. THEORETICAL MODEL

In the present work, we have made use of the Arcetri Loop Code (ALC), described by Landi & Landini (2004). The ALC consists of a 1-dimensional, stationary, non-static model where velocities are nonnegligible and subsonic everywhere in the loop, so that shocks cannot develop at any point. The loop is also assumed to be toroidal, with constant or variable cross-section. The model solves the equations of
Figure 1. Composite intensity map obtained with CDS in Fe XVI, and the EIT-171 channel. The shape of the selected loop is overplotted. Magnetic field contours from MDI have also been displayed to show the loop footpoints. The EIT emission is visible due to the different background intensity.

conservation of mass, momentum and energy, along with the equation of state, allows for a user-chosen heating function and it adopts very accurate radiative losses term from CHIANTI (Dere et al. 1997). The input parameters for the model are:

1) the total loop length $L_{\text{loop}}$ (from observations)
2) the inclination $\alpha$ of the loop plane relative to the vertical (from observations)
3) the plasma pressure $p_0$ at the footpoints (from observations, or chosen by the user)
4) the conductive flux at the footpoints $F_0$ (chosen by the user)
5) the velocity parameter $a$ (chosen by the user)
6) the shape of the energy input $H$ (chosen by the user)

Once these values are defined, the loop model is completely defined. The use of $L_{\text{loop}}, p_0$ and $\alpha$ as input parameters derived from the observations allows the user to fully exploit the observations to constrain the loop model, by limiting the free parameters to $a, F_0$ and $H(z)$, whose space can be easily explored. Further details of the ALC can be found in Landi & Landini (2004).

3. OBSERVATIONS

The observations used to accomplish the first goal of the paper were recorded on April 29th 1997 with CDS, EIT, MDI on SOHO and SXT on Yohkoh. A more complete description of these observations is given in Brkovic et al. (2002).

The CDS observations have been carried out using the $2'' \times 240''$ slit on the NIS, scanning a $243.6'' \times 240.2''$ field of view centred at $(-100'', -400'')$. The exposure time for each slit position was 60 s, and 19 spectral lines were extracted. The selected lines allow the electron density to be measured using pairs of Fe XII and Fe XIII lines. EIT, SXT and MDI observations were taken within two hours from the CDS scan, and were coalignd to CDS monochromatic images. We have selected a loop shape in the field of view and we have divided it into 21 subsections of approximately the same length. The loop shape is shown in Figure 1. The background radiation, determined by averaging the emission of the pixels adjacent to each subsection, was removed.

The observations used to accomplish the second goal of the paper have been taken with SUMER. We have used rasters of four different active regions taken at Sun centre, that included coronal and chromospheric/transition region lines, so that loop plasma at temperatures could be observed simultaneously. A complete description of the data is given in Landi & Feldman (2004). The available datasets allowed us to produce intensity maps for both coronal and cooler lines. We display in Figure 2 the intensity maps for the dataset taken on March 23, 1996, obtained by summing all the counts under the line profiles, and subtracting a linear background.

Figure 2 shows that loop footpoints, that should be visible in the C IV and S V maps, are very difficult to identify: their emission must be at most a small fraction of the background emission. This implies that the coronal plasma loops and the transition region and chromospheric plasma emitting the active region radiation observed by spectrometers and imagers are not directly correlated.

3.1. Heating function

The comparison between model predictions and observations has been carried out comparing predicted density and temperature profiles with CDS measurements. The uncertainty in the velocity profile has prevented its comparison with predicted velocities. As input, we have used the plasma pressure $p_0 = 0.9 \pm 0.2$ dyne cm$^{-2}$, the total loop length of the loop $L_{\text{loop}} = 150000 \pm 15000$ km and its inclination of 80$^\circ$ from the vertical as measured from CDS images. Theoretical profiles have been calculated by assuming three different heating functions $H(z)$: uniform heating, exponential heating concentrated at the footpoints, exponential heating concentrated at the loop top. In the case of exponential heating, we have varied its scale height $H_0$.

By varying the parameters $a$ and $F_0$ we have investigated the effects on the temperature and density profiles of the presence of plasma velocity and of non-negligible conductive flux at the footpoints. The chosen values are: $F_0 = 0, -10^6, -5 \times 10^6, -10^7$ erg cm$^{-2}$ s$^{-1}$; $a = 0, 10^{-31}, 10^{-30}, 10^{-29}$. The real velocities corresponding to these values of
Figure 2. Intensity map of the active region observed on March 23, 1996. The three bottom panels display areas where coronal loop footpoints are likely to be, marked by diamonds. C IV 1548 Å is formed at $\approx 10^5$ K; S V 786 Å is formed at $\approx 1.6 \times 10^5$ K; Ne VIII 770 Å is formed at $\approx 6.3 \times 10^5$ K.

a range from 0 ($a = 0$) to 70 km s$^{-1}$ ($a = 10^{-29}$). An example of the comparison is shown in Figure 3, for the case with exponential heating concentrated at the footpoints. The other heating functions provide qualitatively similar results: the predicted temperature profile is too smooth and the loop top temperature is too high. The presence of non-negligible velocities and of conductive flux at the footpoints only worsens the disagreement. In conclusion, none of the proposed heating functions is able to reproduce the observations.

4. LOOP CROSS-SECTION

Inside the SUMER dataset in Figure 2 we isolated a loop structure and measured the intensity of Ne VIII, C IV and S V lines emitted by the whole loop. In order to compare their relative intensity with model predictions, we have used the ALC model with total length of the loop of 57500 km and inclination of 7.4°, determine from the maps. Since no pressure diagnostic is available in this dataset, we have calculated the model predictions for $p_0=0.09$, 0.9 and 9 dyne cm$^{-2}$; we have also selected $F_0$ to be 0 and $-1(1, 5, 10, 50) \times 10^6$ erg cm$^{-2}$ s$^{-1}$, and log$a=0$, -31, -30.3, -30, -29.3 and -29. We have assumed the same three different heating functions we used for the CDS dataset. In the exponential case, we selected a heating scale height of 16000 km.

The total intensity of the three lines was predicted as a function of the loop parameters. The ratios between the predicted Ne VIII intensity and the other two lines, and the observed count rates of the Ne VIII line, were used to determine the expected count rates of the C IV and S V lines, to be compared with SUMER observations. The observed Ne VIII intensity is $\approx 3200$ phot cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. Considering the results from all the loop simulations, the C IV and S V count rates are expected to be in the range $I_{C IV} = 6200-59500 \quad I_{S V} = 21500-161000$

Since C IV and S V are emitted by the footpoints only, they are expected to be spread among only few pixels around the footpoints at the edges of the loop structure in Figure 2. The observed intensity levels (in counts) for the C IV and S V lines in the vicinity of the footpoints of the selected structure
range between 100 and 800 counts (C IV) and 50 and 300 counts (S V); these values include both the foot-
point emission and the background. It is reasonable
to assume that the background-subtracted foot-
point emission in C IV and S V is smaller than those levels
by at least a factor of three or more, thus deepening
the disagreement with the predicted values.
Even allowing for atomic physics errors in the pre-
dicted intensities, for an inaccurate background sub-
traction in the Ne VIII loop, and for a multipixel
footpoint size, the difference between the predicted
and observed count rates for C IV and S V is very
large, the former exceeding the latter by at least a
factor 25 (C IV) and 250 (S V).
We suggest the variable loop cross-section as a pos-
sible solution to this discrepancy. To show this, we
have used the ALC model adopting a variable cross-
section, assuming that the loop section is given by
\[
\sigma(nT) = S_M \left[ a + (1 - a)(\tanh(nT))^5 \right]
\]  

(1)

where \( n \) and the ratio \( a = \frac{S_m}{S_M} \) are the two param-
eters that determine the loop cross section, where \( S_m \)
and \( S_M \) are the minimum and maximum values of
the loop cross-section. The rest of the model and in-
put parameters are identical to the uniform-section
model described above. With the arbitrary choice
of \( F_0 = -1 \times 10^7 \) erg cm\(^{-2}\) s\(^{-1} \), \( p_0=0.9 \), \( n = 20 \) and
\( \frac{S_m}{S_M} = 40 \), and adopting an input proportional to
the square of the electron density, the predicted count
rates are
\[
I_{C\ IV} = 0.041 \times I_{N_e\ VIII} \quad \Rightarrow \quad I_{C\ IV} = 339 \\
I_{S\ V} = 0.0013 \times I_{N_e\ VIII} \quad \Rightarrow \quad I_{S\ V} = 233
\]

These values are much closer to the observed count
rates for C IV and S V and they are also much smaller
than those obtained with a uniform cross-section
model. We also note that the temperature profile of
the loop shown in Figure 4 is much more isothermal
than in the case with constant cross-section, in line
with other SOHO and TRACE results. The tempera-
ture profile along the loop is displayed in Figure 4.

5. CONCLUSIONS

The comparison of model predictions with CDS and
SUMER observations has shown that

1) Predicted density profiles are in broad agreement
with observations, although uncertainties are high,
and a few discrepancies are found;
2) Uniform and exponential heating concentrated at
the top are unable to reproduce the observed tem-
perature, whose profiles are not uniform as observed,
and whose top temperature is too high;
3) Exponential heating concentrated at the foot-
points produces more uniform temperature profiles,
but the top temperature is still too high;
4) The predicted footpoint emission is overestimated
by orders of magnitude;
5) A variable cross-section might be a possible so-
lution to both the temperature profile disagreement,
and for the overestimation of footpoint emission.

REFERENCES