Hinode EUV Imaging Spectrometer Observations of Active Region Loop Morphology: Implications for Static Heating Models of Coronal Emission

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Abstract

Theoretically, magnetic fields are expected to expand as they rise above the photosphere and into the corona, so the apparent uniform cross-sections of active region loops are difficult to understand. There has been some debate as to whether coronal loops really have constant cross-sections, or are actually unresolved and composed of expanding threads within the constant cross-section envelopes. Furthermore, loop expansion is critical to the success or failure of hydrostatic models in reproducing the intensities and morphology of observed emission. We analyze Hinode EIS (EUV Imaging Spectrometer) observations of loops in active region 10953 and detect only moderate apex width expansion over a broad range of temperatures from log $T_e/K = 5.6$ to 6.25. The expansion is less than required by steady-state heating models of coronal emission suggesting that such models will have difficulty reproducing both low and high temperature loop emission simultaneously. At higher temperatures ($> \log T_e/K = 6.3$) the apex widths increase substantially, but the emission at these temperatures likely comes from a combination of multiple loops. These observations demonstrate the advantage of EIS over previous instruments. For the first time, active region loops can be examined over a broad temperature range with high temperature fidelity and the same spatial resolution. The results therefore provide further clues to the coronal heating timescale and thus have implications for the direction of future modeling efforts.

Key words: Sun: corona — Sun: magnetic fields — Sun: UV radiation

1. Introduction

Yohkoh SXT and TRACE observations indicate that active region coronal loops have constant cross-sections along their lengths (Klimchuk et al. 1992; Watko & Klimchuk 2000). This is contrary to expectations from theoretical studies of solar magnetic fields that suggest coronal loops should expand with height. This contradiction has led to the suggestion that coronal loops imaged by TRACE and SXT are not fully spatially resolved. De Forest (2007) recently argued that TRACE observations reveal that SXT data of coronal loops do not resolve the filamentary strands within the loops and that future EUV observations with higher spatial resolution than TRACE will ultimately show that TRACE also does not resolve the fundamental strands. This conjecture has been vigorously contested by others (J. A. Klimchuk, private discussion).

The resolution of this debate is of crucial importance for modeling efforts directed towards understanding the coronal heating mechanism in active regions, bright points, and the full Sun. Such modeling is plagued by difficulties associated with cutting down the range of parameter space and understanding the heating time-scale. Hydrostatic models can reproduce the observed intensities and morphology of high temperature solar plasma in active regions (Warren & Winebarger 2006) and the full Sun (Schrijver et al. 2004), but always seem to require substantial loop expansion to improve agreement with the observations. Furthermore, these models have a harder time reproducing the lower temperature emission; the simulated upper transition region intensities are generally too bright. Even this situation can be remedied, however, if the volumetric heating rate is reduced and loop expansion is introduced in the simulations (Brooks & Warren 2007).

Therefore, it is of great importance to establish observationally whether coronal loops expand and if so by how much. Studies with TRACE data do indicate that longer loops have
larger cross-sections at their apex (Aschwanden et al. 2000; Schrijver 2007). Hydrostatic models, if correct, also suggest the possibility that loops could expand in inverse proportion to the magnetic field strength averaged along the loop (Brooks & Warren 2007). This suggests that longer (higher temperature) loops could have larger cross-sections. The unprecedented spatial resolution of Hinode XRT at high temperature (10 MK) and associated diagnostic information and broad temperature coverage of EIS will allow us to address this topic in detail.

Here we present initial results from our study of active region loop widths with EIS and XRT. In this short paper, we examine three examples and specifically address the following questions:

- Do hotter (longer) coronal loops have larger cross-sections?
- Do the cross-sections of high temperature loops increase along their lengths?
- What is the filling factor as a function of height along the loops?

This last question bears on the topic of whether the loops are truly resolved and on understanding the true size scales of structures in the corona. Expanding threads within a constant cross-section envelope would tend to produce a filling factor that increases with height. Here we analyze loop structures in AR 10953 with particular emphasis on loops observed on 2007 May 2. A complete analysis of a larger sample will be presented elsewhere.

2. Observations

Hinode was launched from Uchinoura Space Center on 2006 September 23 JST (Kosugi et al. 2007). On board are a Solar Optical Telescope (SOT), X-Ray Telescope (XRT), and an EUV Imaging Spectrometer (EIS). The three instruments were designed to study the flow of mass and energy from the solar photosphere through the chromosphere and into the corona. They are described in Tsuneta et al. (2007), Golub et al. (2007), and Culhane et al. (2007), respectively.

Hinode tracked solar active region 10953 during its passage across the disk from 2007 April 26 to May 9. An example X-ray image of the region is shown in figure 1 with the EIS field of view (FOV) overlaid. The data are uncalibrated but have been cleaned for cosmic ray hits. EIS performed a scanning observation over the FOV with its 1’ slit. The exposure time was 15 s at each position. 20 spectral windows were recorded but we only examine data from 8 of those windows in this paper. Only 256 pixels were read-out in the Y-direction. The EIS data have been cleaned of cosmic ray hits and hot pixels. The detector bias and dark current have also been subtracted and the absolute intensity calibration has been applied. The units are thus erg cm−2 s−1 sr−1 Å−1.

The leading active area of the region shows a cusp shaped structure in its southern part and this area shows distinctive individual loops when observed in the EUV with the EIS spectrometer. Figure 2 shows a series of raster images from the 8 EIS wavelength windows investigated. The dominant intensities in these windows are tentatively identified to come from spectral emission lines from a series of Fe ions formed at log $T_e$/K = 5.6 to 6.4. The images in this figure have been created from single Gaussian fits to the spectra except for Fe X 184.5 Å and Fe XIII 203.8 Å where double Gaussian fits were used. The progression of active region structure with temperature can be seen moving left to right and top to bottom in the figure. Note that loops that appear distinctive in upper transition region and lower coronal emission lines (Fe VIII–XII) appear more diffuse at temperatures closer to those of the XRT filter image in figure 1 (Fe XV, XVI).

2.1. Variation of Loop Apex Width with Temperature

Concentrating on the brightest loop structures in the Fe XVI 262.98 Å raster image, it does appear to have a considerably larger width than its lower temperature counterparts as seen in, for example, the Fe X 184.5 Å and Fe XII 195.12 Å images. We measured the width of this structure near the apex along a slice-line represented with the letter D in figure 2 by fitting a Gaussian plus polynomial function to the intensity profile along the line and determining the FWHM of the Gaussian profile.

The intensity profiles were smoothed using a boxcar method with a bin size of 3 pixels and normalized to the maximum intensity along the slice-line. The intensity cuts were then fitted with a function of the form

$$f(x) = h \exp(-z^2/2) + a + bx + cx^2$$

where $h$ is the height of the Gaussian distribution, $z = (x - x_0)/w$, $x_0$ is the center of the Gaussian, $w$ is the standard deviation of the Gaussian, $a$ is a constant, and $b$ and $c$ provide linear and quadratic terms. An example of the fit is shown in the left hand panel of figure 3.

The intensity profile along the line at each temperature is shown in the right hand panel of figure 3. The figure clearly shows the broadening of the profile with temperature. The FWHM values of the Gaussian as a function of temperature are given in table 1 under the column denoted ‘loop 1’. They show that the apex width is $5.9'$ at 0.3 MK and $20.6'$ at 2.5 MK.

<table>
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<tr>
<th>$\log T_e$/K</th>
<th>FWHM (km)</th>
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<tr>
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<td>loop 1</td>
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* Loops 2 and 3 are discussed in section 3. If no value is given it indicates that the fit was unsatisfactory. The temperatures are those of the maximum fractional abundance in ionization equilibrium taken from the ADAS database (Summers 2004).

The detector bias and dark current have also been subtracted and the absolute intensity calibration has been applied. The units are thus erg cm−2 s−1 sr−1 Å−1.
better than 2" by the Nyquist criterion. Although a value close to this was measured pre-launch (Korendyke et al. 2006) a dedicated detailed effort has not yet been made to measure the resolution on orbit. Considering the pre-launch measured resolution, the apex width values would only be marginally affected by its subtraction in quadrature and the trend for higher temperature loops to have larger apex widths would be preserved. For example, if $w_{\text{loop}} = \sqrt{w_{\text{obs}}^2 - w_{\text{instr}}^2}$, where $w_{\text{loop}}$ is the real loop width, $w_{\text{instr}}$ is the instrumental width, and $w_{\text{obs}}$ is the measured observed width, then $w_{\text{loop}}$ at 0.3 MK becomes 20.6 instead of 20.7.

The width increases by $\sim 40\%$ in the 1–2 MK range (Fe X–XIV) and there is a further factor of three increase in the 2–2.5 MK range (Fe XV–XVI). The emission at these temperatures, however, has become more diffuse and it is difficult to ascribe the broadened Gaussian to the emission from only one loop. That is, emission at higher temperatures may come from a combination of multiple loops. The values in table 1 are broadly consistent with the FWHM values presented by Schrijver (2007).

2.2. Variation of Filling Factor and Width along the Loop

The intensity of an optically thin spectral line arising from the transition from level $j$ to level $i$ can be expressed as follows

$$I_{j \rightarrow i} = \frac{hc}{4\lambda \pi A} A(Z) \int G(T_e, N_e) f dV$$

where $A(Z)$ is the abundance of element $Z$, $G(T_e, N_e)$ is the contribution function that contains all of the relevant atomic
physics parameters, $A$ is an area factor, $N_e$ is the electron density, $f$ is the filling factor, and $V$ is the plasma volume. Assuming that the loop cross-sectional area can be represented by a circle and that each position corresponds to a circular tube, $dV$ can be written as $d\pi(w/2)^2$, where $ds$ is the length of the tube and $w$ is the loop width. Under further simplifying assumptions about the nature of the $G$ function (Mason & Monsignori-Fossi 1994) the filling factor can be expressed as

$$f = \frac{I_{j-i}}{N_e^2 w^2} \times \frac{4}{C \pi ds}$$

(3)

where $C$ is a constant. By measuring the loop width and electron density at a particular position it is possible to estimate the filling factor using the above equation. In this paper, we are only interested in the trend of any change in filling factor along the loop, so it is simplest to consider only the non-constant term in equation (3) and normalize it by its maximum value along the loop. This implicitly assumes that the tube length is the same at each position.

In order to measure the electron density we used the Fe XIII 203.8/202.0 Å diagnostic line ratio. This diagnostic measures
the electron density at around $\log T_e/K = 6.2$ and is sensitive in the range $\log N_e/cm^{-3} = 8.5$ to 10.5. The Fe XIII 203.8 Å feature is blended with an Fe XII line at 202.7 Å. The latter line intensity was extracted from the total intensity of the feature by including another Gaussian profile in the spectral fits. The Fe XIII 203.8 Å feature is a blend of two components which were summed together both in the spectral fitting and in the calculation of the corresponding contribution function (obtained from the CHIANTI database, Dere et al. 1997; Landi et al. 2006). Figure 4 shows the intensity ratio and density maps obtained for the two Fe XIII lines.

Since the density diagnostic ratio is sensitive to plasma at the formation temperature of Fe XIII, we used the Fe XIII 203.8 Å line for the loop width measurements. The same method as subsection 2.1 was adopted and the width was measured at positions along the loop where a clean intensity profile could be obtained. The slice-lines at these positions are overlaid on the lower left panel of figure 2 and labeled A–D. Although the EIS raster does not fully scan the entire extent of the cusp structure in the XRT image (figure 1), it is clear from that image that the loop that dominates the emission in Fe XVI extends symmetrically around so that position D is identified as closest to the “classical” loop top. The brightest portion of the loop, however, is closer to position B. The density and intensity were measured at each of these positions and the variation of these parameters is shown in figure 5.

The loop width does appear to show some increase from A–D of the order of 70%. The density falls by a factor of 1.8 but the intensity falls more rapidly (by a factor close to 3) so that the density drop off is counterbalanced and the filling factor is seen to fall by a factor of 2.4. It may be that the brightest portion has some contribution from another loop, as seems possible for Fe XVI, but position A looks cleaner and even considering just positions A and D would not change the result. Even assuming some non-classical shape to the loop and that position C is actually the real loop top, the intensity falls from A to C while the width shows an increase. This still results in a filling factor decrease. In order for the filling factor to remain constant, or increase, we would need the loop width and intensity to remain constant while the density decreases, and this is not observed in this example.

3. Generality of Results

Although the results of the previous section were obtained from the analysis of one loop structure, we are currently building up a data base of good loop observations to repeat the study on a larger sample. In order to find a good example for presentation in this paper, however, we examined a number of other loop observations from that data base. Our impression is that the result that loop apex widths increase as a function of temperature is of a general nature. A similar effect can be seen in Fe XI–XIV observations for a number of other cases. Figure 6 shows two such examples observed in the same active region on April 27 and May 3. The EIS rasters started at 19:15 UT and 10:29 UT, respectively, and were obtained using the same observing sequence as used for the loop analyzed in the previous section. Thus the same emission lines were observed. The data reduction, line fitting, and analysis methods used were all the same as in the previous sections.

Figure 6 shows raster images in the Fe XI–XIV emission lines and the FWHM values derived using the same methods as before are given in table 1. Loop 2 refers to the one observed on May 3 and loop 3 refers to the one observed on April 27. The observations taken on April 27 were interrupted by Hinode eclipse so only a region around loop 3 is shown. The FOV in the lower panels is one quarter of the FOV in the upper panels.
The apex widths of loops 2 and 3, measured along the slice lines marked ‘A’ in figure 6 increase by about 55% and 40% between 1 and ∼2 MK, respectively. This indicates only moderate expansion in this temperature range and is consistent with the results found for the loop analyzed in the previous section. The reason that the Gaussian fits to the intensity cuts across the loops at temperatures above 2 MK are unsatisfactory is that the emission at these temperatures has again become more diffuse. Large values showing a width increase of greater than a factor of 2 are found for loop 3, but the authors do not consider the fits convincing. Nevertheless, the analysis of loops 2 and 3 lends support to the results obtained in the previous section.

The result that no significant expansion is found around single loops (as measured using the Fe XIII 203.8 Å line) was expected from observations from previous missions and was confirmed here. To further lend support to this finding we also measured the widths of loops 2 and 3 near their footpoints using the Fe XIII line (slice lines marked ‘B’ in figure 6). Values of 2810 km and 6070 km were found, respectively. From comparison with the results of table 1 we can see that little or no expansion is evident at the loop apex in either case.

The results on filling factors presented here are somewhat more tentative than the results on loop widths. For loops 2 and 3, however, we have already shown that the ratio of apex to base loop width is close to unity and by measuring the electron density at these locations we can at least tentatively lend further support (or otherwise) to the findings for loop 1. For loop 2, we find base and apex densities of $\log N_e/cm^{-3} = 9.37$ and 9.19, respectively. For loop 3 we find values of $\log N_e/cm^{-3} = 9.42$ and 9.12, respectively. Following the same filling factor analysis as before, these results indicate that the filling factor increases from the base to the apex by 20–25%, contrary to the results from the previous section. The crucial difference appears to be the detection of moderate expansion along the axis in the previous case.

4. Conclusions and Discussion

We have presented initial observational results from our study of coronal loops from Hinode/EIS and XRT. EIS raster images of loop structures observed on May 2 and obtained in Fe VIII–XIV emission lines, with high temperature fidelity, show a moderate increase in the loop apex width with temperature. In the Fe XV–XVI lines the loop structures have significantly larger apex widths, but the emission may come from multiple loops at these temperatures. The results do indicate that hotter (longer) loops have larger widths and this is consistent with previous studies made using broad-band filter images from, e.g., TRACE, SOHO/EIT, and Yohkoh/SXT. These results have also been cited as evidence of granular braiding induced coronal field-line reconnection as the primary heating mechanism for coronal loops (Schrijver 2007).

We also confirm previous results that measurements of the width around one loop indicate that there is only moderate expansion along the loop length. A width increase of around 70% is detected. Such expansion around the loop axis or at its apex is less than required by steady-state numerical heating models of coronal emission: Schrijver et al. (2004) stated that substantial expansion of at least a factor of three was needed in their full Sun visualizations even for loops formed at temperatures as low as $\log T_e/K = 6.0$ (the peak of the EIT 171 Å filter response — Brooks & Warren 2006). So the results here are insufficient to account for the expansion needed in their models. The bright point modeling of Brooks and Warren (2007) also indicates that expansion of at least a factor of two is needed for loops formed above 2 MK but that expansion of around 40% would be sufficient in the 1–2 MK
range. Those values are more consistent with the observed width values derived here but may not be directly applicable to this dataset. It is clear that direct modeling of this specific active region would be needed to confirm whether the observed width increase for hotter (longer) loops is as predicted, but it does seem that the observations remain inconsistent with the models. Analysis of two other loops observed in the same active region on May 3 and April 27 also supports these findings. It will therefore be difficult for steady-state heating models to simultaneously reproduce the observed low and high temperature coronal emission and this has implications for understanding the coronal heating timescale and for the direction that future modeling efforts should take.

Combining electron density and loop width information, we have examined the filling factor variation around the loop. It was found from this analysis that the filling factor does not increase with height along the loop axis. This is contrary to what would be expected if the observed loop was not fully spatially resolved and in fact consisted of expanding magnetic field threads within a constant cross-section envelope. Analysis of loops 2 and 3, however, indicate the opposite conclusion: the filling factor was found to increase by 20–25% from the loop base to the apex in these cases.

A more comprehensive study would ideally utilize simultaneous emission measure analysis and density diagnostic measurements of a much larger sample of cleaner loops. Our study will be expanded in this direction and a definitive statement on filling factors awaits the results of that analysis.

It has been argued that TRACE resolves individual loop structures within the X-ray loops observed by Yohkoh SXT because of its superior spatial resolution. Applying that argument here one would expect XRT to be better able to resolve individual loop structures than EIS. Figure 2, however, clearly shows loop structures in lines formed at lower temperatures (log $T_e/K = 5.6–6.2$) that appear more diffuse at higher temperatures (log $T_e/K = 6.3–7.0$). Therefore, it would appear that the corona is less structured at higher temperatures and that the emission, at different temperatures, may come from a combination of multiple loop structures at different stages of heating and cooling. This may have implications for understanding how the corona is heated.

Finally, this paper demonstrates the advantage of EIS studies of coronal loops over observations from previous instruments. Studies of the size scale of coronal structures have been subject to criticism on the grounds that they have been based on restricted temperature observations, of perhaps different loops, from broad-band filter instruments with perhaps significantly different spatial resolution at different temperatures. For the first time, EIS will allow us to image coronal structures simultaneously over a broad range of temperatures with high temperature fidelity and the same spatial resolution.

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