OBSERVATION AND MODELING OF CORONAL “MOSS” WITH THE EUV IMAGING SPECTROMETER ON HINODE

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ABSTRACT

Observations of transition region emission in solar active regions represent a powerful tool for determining the properties of hot coronal loops. We present the analysis of new observations of active region moss taken with the Extreme Ultraviolet Imaging Spectrometer (EIS) on the Hinode satellite. EIS observations of a density sensitive Fe xii line ratio suggest moss densities of approximately 1010 cm−3 and pressures of 3 × 1016 cm−3 K. We find that the moss intensities predicted by steady, uniformly heated loop models are too intense relative to the observations, consistent with previous work. To bring the steady heating model into agreement with the observations a filling factor is required. Our analysis indicates that the filling factor in the moss is nonuniform and varies inversely with the loop pressure. The intensities predicted by steady uniform heating are generally consistent with the EIS moss observations. There are, however, significant discrepancies for the coolest emission line available in the data we analyze.

Subject headings: Sun: corona

1. INTRODUCTION

Understanding how the solar corona is heated to high temperatures is one of the most important problems in solar physics. In principle, observations of emission from the solar corona should reveal important characteristics of the coronal heating mechanism, such as the timescale and location of the energy release. In practice, however, relating solar observations to physical processes in the corona has proved to be very difficult. One of the more significant obstacles is the complexity of the solar atmosphere, which makes it difficult to isolate and study individual loops, particularly in the cores of solar active regions.

One circumstance in which the line of sight confusion may be reduced is observations of coronal “moss.” The moss is the bright, reticulated pattern observed in many EUV images of solar active regions. These regions are the footpoints of high-temperature active region loops, and are a potentially rich source of information on the conditions in high-temperature coronal loops (see Peres et al. 1994; Berger et al. 1999; Fletcher & de Pontieu 1999; de Pontieu et al. 1999; Martens et al. 2000).

A particularly useful property of the moss is that its intensity is predicted to be proportional to the total pressure in the coronal loop (Martens et al. 2000; Vourlidas et al. 2001), which is an important constraint for coronal loop modeling. For steady, uniform heating models the pressure and the loop length completely determine the solution up to a filling factor (see Rosner et al. 1978). Recently Winebarger & Warren (2007) used this property of the moss in conjunction with a magnetic field extrapolation to infer the volumetric heating rate for each field line in the core of an active region. This allowed them to simulate both the soft X-ray and EUV emission without making any assumptions about the relationship between the volumetric heating rate and the magnetic field (Mandrini et al. 2000).

One limitation of this approach is that the filling factor is left as a free parameter and is adjusted so that the soft X-ray and EUV emission best match the observations. Observations of both the intensity and the electron density in the moss would determine the filling factor and remove this degree of freedom. A more fundamental question is how relevant steady heating models are to coronal heating. Recent work has shown that high-temperature coronal emission (~3 MK) can be modeled successfully with steady heating (e.g., Schrijver et al. 2004; Lundquist et al. 2004; Warren & Winebarger 2006). However, pervasive active region Doppler shifts (e.g., Winebarger et al. 2002) and the importance of nonequilibrium effects in modeling the observations of lower temperature loops (e.g., Warren et al. 2003), suggest an important role for dynamical heating in the solar corona.

The purpose of this paper is to address two issues: (1) determining the densities, pressures, and filling factors in the moss, and (2) checking the consistency of observed moss intensities with steady heating models. For this work we use new observations from the Extreme Ultraviolet Imaging Spectrometer (EIS) on Hinode. EIS has an unprecedented combination of high spatial, spectral, and temporal resolution and provides a unique view of the solar corona.

2. EIS MOSS OBSERVATIONS

The Hinode satellite was launched on 2006 September 23. The EIS instrument on Hinode produces high-resolution stigmatic spectra in the wavelength ranges of 170–210 and 250–290 Å. The instrument has 1" spatial pixels and 0.0223 Å spectral pixels. Further details are given in Culhane et al. (2007) and Korendyk et al. (2006).

Despite the fact that Hinode was launched close to the minimum in the solar activity cycle there have been several active regions available for observation. For this work we analyzed Hinode observations of NOAA active region 10940 from 2007 February 2 at about 10:42 UT. An application of the Fe xii and Fe xiii density diagnostics to these data are described by Doschek et al. (2007a). These observations show areas of moss that are relatively free from contamination from other emission in the active region and are well suited for this application. The observing sequence for this period consisted of stepping the 1" slit over a 256" × 256" region taking 15 s exposures at each position.

These data were processed to remove the contribution of CCD background (pedestal and dark current), electron spikes, and hot.
pixels, and converted to physical units using standard software. We then fit the calibrated data assuming Gaussian profiles and a constant background. The resulting rasters for some of the strongest lines are shown in Figure 1.

To identify the moss in this region we adopt the very simple strategy of looking for the brightest Fe\textsubscript{XII} $\lambda$186.88 emission in the region with bright Fe\textsubscript{XVI} emission. As is shown in Figure 2, this line is very sensitive to density. The line intensity relative to Fe\textsubscript{XII} $\lambda$195.12 rises by about a factor of 10 as the densities rises from $10^9$, which is typical of active region loops at this temperature, to $10^{11}$ cm$^{-3}$, which is at the high end of what we expect to observe in the moss. The result of using a simple intensity threshold to identify the moss is shown in Figure 1 with contours.

We have calculated the emissivities for these line using the latest version of the CHIANTI atomic physics database (e.g., Landi et al. 2006). We use the ionization fractions of Mazzotta et al. (1998) and the coronal abundances of Feldman et al. (1992). A temperature of 1.35 MK is assumed. To determine the emissivities for Fe\textsubscript{XII} $\lambda$195.12 we sum the contributions from the transitions at 195.067, 195.083, 195.119, 195.146, and 195.179 Å. Transitions at 186.854, 186.887, and 186.891 Å contribute to the emissivities for Fe\textsubscript{XII} $\lambda$186.88. There is a weak blend of S\textsubscript{XI} $\lambda$186.84 with Fe\textsubscript{XII} $\lambda$186.88 (Young et al. 2007), but the inspection of other active region data indicates that it contributes only a few percent to the total intensity.

Before considering the predictions of steady heating models we compute the densities for each position in the raster directly from the Fe\textsubscript{XII} line ratio. These results are shown in Figure 2 and indicate that the line ratios generally do not lie close to the low- or high-density limits. In addition, this density map shows that, as expected, the moss regions identified by the intensity contours generally lie in the regions of highest density.
In Figure 3 we show the Fe\textsubscript{xi} intensity and density histograms from region of the active region shown in Figure 1. The distribution of Fe\textsubscript{xi} k\textsubscript{186.88} intensities suggest that there is nothing unique about the moss intensity threshold we have selected. The distribution of intensities is continuous and there is no obvious feature in the distribution identifying the moss. The distribution of densities in this region is also continuous and the demarcation between the moss and the rest of the active region is somewhat ambiguous. The moss region we have identified is characterized by high densities relative to the rest of the active region. There are, however, some features that have high densities but are not associated with high-temperature loops.

Our average moss density is about $10^{10}$ cm\textsuperscript{-3}, which is several times higher than the moss densities of $2 \times 10^9$ cm\textsuperscript{-3} reported by Fletcher & de Pontieu (1999). Our impression is that the active region loops in this region are brighter than those studied by Fletcher & de Pontieu (1999), but more systematic analysis will be required to confirm this.

The high spectral resolution of EIS allows us to measure line shifts and widths. In Figure 2 we also show the Doppler velocity and nonthermal velocity maps from this region derived from the Fe\textsubscript{xi} k\textsubscript{195.12} line. The nonthermal velocity is derived assuming an instrumental broadening of 2.5 pixels (Doschek et al. 2007b) and a temperature of 1.35 MK. In contrast with the density, the moss is not characterized by large values for the nonthermal velocity. The nonthermal velocities are elevated relative to the faintest regions in the raster, but there are other features with larger line widths, but lower densities.

Strong line shifts also do not appear to be a feature of the moss. It should be noted that to calculate the Doppler shift from the EIS observations a sinusoidal oscillation in the line centroid must be removed from the data. This oscillation is caused by thermal variations in the instrument during each orbit. We have made a preliminary correction by assuming that the velocity along the slit at each position averages to zero. This assumption should be regarded with some caution. In addition, it is difficult to establish the rest wavelength and we assume that the average velocity in the raster is zero. While significantly more work is needed to investigate these instrumental effects, this preliminary analysis does not indicate flows of more than a few km s\textsuperscript{-1} at these temperatures in the moss.

3. MODELING EIS MOSS OBSERVATIONS

In this section we discuss the application of steady heating models to observations of the moss with EIS. To begin we calculate the plasma emissivities as a function of both temperature and density for the ions relevant to EIS using CHIANTI. The plasma emissivities are related to the observed intensity by the usual expression

$$I_x = \frac{1}{4\pi} \int c_x(n_e, T_e) n_e^2 \, ds,$$

where $n_e$ and $T_e$ are the electron density and temperature and $ds$ is a coordinate along the field line. For this work we will assume that the emission from the footpoint is oriented along the line of
sight and that \( ds \) represents the depth of the emitting layer in the transition region. Note that what we refer to as the emissivity (\( \varepsilon /C_{15} \)) is actually the emissivity divided by \( n_{e}^{2} \). For many strong emission lines this quantity is largely independent of the density. In this context, however, including the density dependence explicitly is important since many of the EIS emission lines have emissivities that are sensitive to the assumed density. Our calculations cover the range \( \log n_{e} = 6–13 \) and \( \log T_{e} = 4–8 \).

Equation (1) suggests that the emission should scale as the square of the pressure. However, with increasing energy flux into the transition region the emitting region in the moss is compressed according to
\[
ds \propto 1/P_{0}
\]
(2)
(see Martens et al. 2000, eq. [24]; also see Vourlidas et al. 2001) and the intensity scales linearly with pressure
\[
I_{k} \propto fP_{0},
\]
where \( P_{0} = 2n_{e}T_{e} \) is the base pressure. We will generally consider relatively short, high-temperature loops that have a constant pressure. The parameter \( f \) is the filling factor and has been introduced to account for the fact that only a fraction of the observed volume may actually be filled with emitting plasma.

These previous results have been based on scaling laws. To explore the variation of the observed emission with base pressure more precisely we have calculated a family of full solutions to the hydrodynamic loop equations using a numerical code written by Aad van Ballegooijen (e.g., Schrijver & van Ballegooijen 2005). We consider total loop lengths in the range \( L = 10–100 \text{ Mm} \) and maximum temperatures in the range \( \log T_{\text{max}} = 2.5–7.5 \text{ MK} \), which are typical of active region cores. The loops are assumed to be oriented perpendicular to the solar surface and to have constant cross sections (see Klimchuk et al. 1992 for a discussion of cross section observations for high-temperature loops). For consistency with our emissivity calculations we use the more recent radiative loss calculations given in Brooks & Warren (2006).

Each solution to the loop equations gives the density and temperature as a function of position along the loop \([n_{e}(s), T_{e}(s)]\). We interpolate to find the emissivity for each observed EIS spectral line from the calculated density and temperature in each computational cell. We then integrate the emissivity at heights below 5 Mm to determine the total footpoint intensity using equation (1). The resulting intensities are displayed in Figure 4 and are generally consistent with earlier work which showed that the moss intensities are proportional to the pressure and independent of the loop length (e.g., Martens et al. 2000; Vourlidas et al. 2001). The linear relationship between the intensity and the pressure breaks down for some of the hotter lines for the lowest pressures we have considered. For these solutions the peak temperature of formation for the line is closer to the apex temperature and there is some emission from along the loop leg.

For each line we perform a fit of the form \( I_{k} = a_{k}P_{0}^{b_{k}} \) to the calculated intensities. Only pressures above \( 10^{16} \text{ cm}^{-3} \text{ K} \) are considered in the fits. The exponent, which is also shown in Figure 4,
is generally close to 1. One approximation that has been made in earlier theoretical work that is not strictly valid is that the emissivity is independent of the density. Our calculations account for this and are more accurate.

These model calculations suggest the following recipe for deriving the loop pressure and filling factor from the observations. The Fe\text{\textsc{xii}} \lambda186.88/\lambda195.12 ratio shown in Figure 4 can be used to infer the pressure. The pressure then can be used to determine the expected intensities in each of the Fe\text{\textsc{xii}} lines. The filling factor is derived from the ratio of the simulated to observed intensities. Since EIS observes many coronal emission lines we can test the model predictions for other emission lines formed at similar temperatures.

For each of the 1416 spatial pixels identified as moss in these data we use the Fe\text{\textsc{xii}} \lambda186.88/\lambda195.12 ratio to determine the base pressure in the loop. As has been found in many previous studies, the simulated intensities are much higher than what is observed. To reconcile the observed and simulated intensities we introduce a filling factor for each point derived from the Fe\text{\textsc{xii}} \lambda195.12 intensity. As shown in Figure 5, the distribution of filling factors is approximately Gaussian with a peak at about 16% and standard deviation of about 4%. The mean filling factor we derive here is generally consistent with previous results. The analysis of Martens et al. (2000) suggested that a filling factor of 10% is required to bring typical moss intensities into agreement with soft X-ray loop observations. Fletcher & de Pontieu (1999) derive a filling factor of about 10% using several different density diagnostics and assumptions about the geometry. The analysis of soft X-ray loops by (Porter & Klimchuk 1995) yielded filling factors ranging from below 10\(^{-3}\) to greater than 1. The bulk of their filling factors, however, are consistent with the range of values that we find.

Figure 5 also shows that the filling factor is inversely proportional to the base pressure. Previous work with transition region emission lines in the quiet Sun and active regions has suggested a similar result. Griffiths et al. (1999, 2000) for example, found that the observed relationship between the line intensity and the density in the transition region indicated that the emitting volume was smaller in active regions than in the quiet Sun. However, they did not differentiate between the compression of the transition region (eq. [2]) and the cross sectional area occupied by the loop. Our analysis accounts for this and indicates that high-pressure loops have a smaller cross sectional area. Skylab-era (e.g., Feldman et al. 1979) results also indicated relatively small filling factors that varied from quiet regions to active regions.

![Fig. 5.—Top: Distribution of the pressures in the moss. Middle: Distribution of filling factors in the moss. Bottom: Scatter plot of the filling factor and the base pressure.](image1)

![Fig. 6.—Scatter plots of simulated vs. observed intensity for moss observed with EIS. The simulated intensities include a filling factor derived from the Fe\text{\textsc{xii}} \lambda195.12 line. The intensities in each emission line are normalized to the maximum observed intensity. An additional factor of 4 has been used to scale the Si\text{\textsc{vii}} intensities.](image2)
These results, however, were primarily based on the analysis of transition region emission observed above the solar limb. Spicules are important contributors to this emission and the relationship between spicules and active region loops is unclear. Our results apply specifically to high-temperature active region loops.

We note that the analysis of cooler loops has suggested filling factors of the order of unity (e.g., Del Zanna & Mason 2003). These loops have much lower pressures than the hot active region loops that we have studied here and these relatively high filling factors may be consistent with our result that the filling factor varies inversely with the pressure.

To compare the model calculations with the observation we have made scatter plots of observed intensity versus simulated intensity (including the filling factor) for a number of emission lines. These plots are shown in Figure 6 and indicate a reasonable agreement between the steady heating model and the observations. The agreement is particularly good for Fe \(\lambda 188.23\) and Fe \(\lambda 203.82\). The simulated Fe \(\lambda 184.54\) intensities are about 20% too high and the simulated Fe \(\lambda 202.04\) are about 10% too low. These discrepancies are not alarming considering the uncertainties in the atomic data.

There are, however, rather significant discrepancies in the Si \(v\) \(\lambda 275.35\) intensities. The simulated intensities are generally about a factor of 4 larger than what is predicted from the steady heating model. The correlation between the simulated and observed intensities is also poor. This discrepancy is different than what is traditionally found in the comparison of steady heating models with observations. Many previous studies (e.g., Vourlidas et al. 2001; Athay 1981) have found that the observed emission is too bright relative to the models, leading to the suggestion that the observed emission is a superposition of classical transition regions and cool, low-lying loops. In contrast, we find that the observed intensities are too weak relative to the model. Previous work, however, has emphasized much cooler transition region emission (\(\sim 10^5\) K).

It is possible that considering loop expansion, nonuniform heating, or nonequilibrium effects may provide a better match between the simulation and the observations at these temperatures, but we have not yet performed these calculations. It is also possible that there are errors in the atomic data for this line or that the instrumental calibration is not correct at this wavelength. More extensive analysis, including the observation of more lines formed at a similar temperature, will be required to resolve this issue. The EIS spectra have revealed many more emission lines formed at relatively cool temperatures (e.g., Mg \(v\), Mg \(vi\), and Mg \(vii\)) than was anticipated before launch and new observations which include these lines are currently being carried out (see Young et al. 2007 for a review of the available EIS diagnostics).

4. DISCUSSION

We have presented an initial analysis of active region moss observed with the EIS instrument on Hinode. We find that the intensities predicted by steady, uniformly heated loop models are too large and a filling factor is required to bring the simulated intensities into agreement with the observations. The mean filling factor we derive here (\(\sim 16\%\)) is similar to that determined from earlier work with steady heating models. Furthermore, we also find that the filling factor in the moss must be nonuniform and appears to vary inversely with the loop pressure. The intensities predicted by steady uniform heating are generally consistent with the EIS moss observations. There are, however, significant discrepancies for the coolest emission line available in the data we analyze.

The next step is to use the methodology outlined here to simulate all of the active region emission (including the high-temperature loops) and compare with EIS observations. New observations which cover a broader array of emission lines formed at lower temperatures will allow us to investigate the problem with Si \(v\) line more fully. Finally, we emphasize that while we find reasonable agreement between the moss intensities and steady heating, we cannot rule out dynamical heating processes, such as nanoflares (e.g., Cargill & Klimchuk 1997; Cargill & Klimchuk 2004). The X-ray emission observed in this region clearly has a dynamic component (Warren et al. 2007), and it would be surprising if nonequilibrium effects did not play some role in the heating of this active region.

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