The Temperature and Density Structure of an Active Region 
Observed with the Extreme-Ultraviolet Imaging Spectrometer on Hinode

George A. DOSCHEK, John T. MARISKA, and Harry P. WARREN 
Space Science Division, Naval Research Laboratory, 4555 Overlook Avenue, SW, Washington, DC 20375, USA 
george.doschek@nrl.navy.mil 
Len CULHANE 
Mullard Space Science Laboratory, University College London, Holmbury St Mary, Dorking, Surrey, RH5 6NT, UK 
Tetsuya WATANABE 
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588 
Peter R. YOUNG 
STFC, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire OX11 0QX, UK 
Helen E. MASON 
Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, 
Wilberforce Road, Cambridge CB3 0WA, UK 
and 
Kenneth P. DERE 
Department of Computational and Data Sciences, George Mason University, 4400 University Drive, Fairfax, VA 22030-4444, USA

(Received 2007 June 6; accepted 2007 August 14)

Abstract
The Extreme-Ultraviolet Imaging Spectrometer (EIS) on Hinode produces high resolution spectra that can be combined via rasters into monochromatic images of solar structures, such as active regions. Electron temperature and density maps of the structures can be obtained by imaging the structures in different spectral lines with ratios sensitive to either temperature or density. Doppler maps and ion temperature maps can be made from spectral line wavelengths and profiles, respectively. In this paper we discuss coronal temperature and density distributions within an active region, illustrating the power of EIS for solar plasma diagnostics.

Key words: Sun: corona — Sun: UV radiation

1. Introduction

The Extreme-Ultraviolet Imaging Spectrometer (EIS) was launched (2006 September 23) on the Hinode spacecraft from Uchinoura Space Center in Japan. An overview of the Hinode mission is given by Kosugi et al. (2007). EIS provides the capability to make maps that have both high spectral (resolution of about 4000) and high spatial resolution (about 2") of coronal electron temperatures and densities for large quiet and active solar structures. This paper presents coronal electron temperature and density maps of an active region that demonstrate the plasma diagnostic power of EIS. We discuss the electron densities in different parts of the active region and show the temperature structure of an active region using monochromatic images of lines emitted over a broad range of temperatures. Similar, related work has been done previously with the Coronal Diagnostics Spectrometer (CDS) on the Solar and Heliospheric Observatory (SOHO) by Mason et al. (1999).

EIS observes lines from ions formed in the lower transition region (e.g., He II, O V), upper transition region (e.g., Si VII), corona (e.g., Fe XII–Fe XVI), and flare plasma (e.g., Ca XVII, Fe XXIV). In this paper we consider primarily the typical quiet and active region coronal plasma. Cooler transition region plasma is discussed by Young et al. (2007a).

2. The EIS on Hinode

The EIS instrument is described by Culhane et al. (2007) and Korendyke et al. (2006). EIS is a representative of a new generation of instruments, which regard high spatial imaging and high spectral resolution as equally important. EIS produces spectra and images in two narrow wavelength windows in the EUV: 170–210 Å, and 250–290 Å. Light entering the instrument is focused by a parabolic mirror onto the entrance aperture of the spectrometer. Several entrance apertures are available: a slit (1" or 2" in width), or a slot (40" or 266" in width). The solar north/south height of the slits and slots is 512". Light admitted by the entrance aperture is diffracted by a grating and the diffracted monochromatic images are focused onto two CCDs with pixel sizes equivalent to 1" spatial resolution at the Sun. Therefore, the true EIS spatial resolution is nominally 2".

EIS operates in several modes. For the data described in this paper, the 1" slit was used and was rastered west to east across an active region in 1" steps with exposure times at each step of 15 s.

3. Observations and Data Reduction

Although Hinode was launched close to solar minimum, several extensive active regions have been available for
observation. We discuss observations of a large active region (AR 10940) observed on 2007 February 2 near 11 UT. EIS obtained a raster scan of this region near disk center using its 1" slit stepping west to east in steps of 1". The slit length was windowed to be 256" and the west to east scan range was also defined to be 256". Observations were obtained in 19 spectral lines covering a range of temperatures represented by ions formed in the lower transition region (He II) through the corona up to a temperature of about $6 \times 10^6$ K (Ca XVII). With exposure times of 15 s the raster took about 1.25 hours to complete. Although the western and eastern portions of the active region were observed at different times, all spectral lines at any given position in the active region are observed at the same time. Inspection of Extreme-Ultraviolet Imaging Telescope (EIT) images from the SOHO reveals that the overall configuration of the active region changed very little during the EIS raster time interval.

The data were reduced using the EIS software package. This package subtracts the background from each spectral line, despikes (cosmic ray hits) the data, and converts data numbers to physical units (erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Å$^{-1}$). Although background was subtracted, we still performed an additional background subtraction to ensure proper subtraction for every pixel. This was done by computing the composite spectrum for the image (sum over all pixels) and then locating a suitable background portion of the profile for determining the background in each pixel spectrum. EIS data reduction software does not yet correct the data for slight spacecraft pointing drift. It also does not correct the centroid wavelength of the lines for a few pixel variability caused by temperature variations in EIS over each orbit. However, these corrections are not important for obtaining density and temperature measurements, and will be neglected in this paper.

Data which are bad due to cosmic ray hits are replaced by interpolated data for image display purposes. However, the error arrays returned by the software flag these bad data points. In fitting Gaussians to profiles with bad data points, zero weights should be given to these points. However, for the purpose of obtaining overall intensities for this particular paper, we have included the interpolated data. These data should be good approximations for statistically good data, which is the only data we consider in detail in this paper. The interpolations should be good because the good data are statistically well-determined, thus well-determining the boundaries of the interpolation.

Figure 1 shows monochromatic images of the active region in six spectral lines from different iron ionization stages representing a range of temperatures. Even a casual glance at the figure immediately reveals considerable morphological differences between the images in hot lines like Fe XV compared with the images in a cold line like the Fe VIII line. The temperatures of the lines in ionization equilibrium are
Fig. 2. Top panels: Intensity ratios of lines from the indicated ions. These ratios are a qualitative measure of temperature over the active region. Bright is higher temperature than dark; bottom panels: intensity ratios of density sensitive spectral line for the indicated ions. Bright is high density; dark is lower density.

given by, e.g., Mazzotta et al. (1998). In the cold line open, bright, fan-like extended loops are observed that are bright at their bases and fade with height. In the Fe XV image more amorphous appearing loop structures are seen, confined to the northwest part of the active region. At the typical quiet Sun coronal temperature represented by Fe XII, bright and fainter closed loops and extended fan-like structures are seen, as well as more confined spot-like regions that are difficult to characterize in shape. They may represent very small closed loops.

4. Results

4.1. Density Diagnostics

The temperature distribution of the active region, or more precisely the emission measure distribution, can be computed at each pixel location using the 19 observed lines. However, rather than carry out this analysis for this paper, we show a sample of the qualitative temperature distribution by simply taking the ratio of lines from adjacent ions. Typical results are shown in figure 2 (top panels). The range of temperatures represented in these three panels, proceeding from left to right, is approximately: $0.5 - 1.0 \times 10^6$ K, $1.1 - 1.4 \times 10^6$ K, and $1.8 - 2.3 \times 10^6$ K.

Again, even a casual glance reveals that fan-like loop structures are cooler (darker) in temperature than neighboring regions along their lengths, e.g., the ratio of Fe X/Fe VIII is smaller in the fan-like loops than in the regions that are shown as bright in the figure. Similarly, the Fe XII/Fe XI ratios show how the temperature changes over large areas of the active region, and the ratio of Fe XV/Fe XIV shows where temperature variations occur in the hotter plasmas in the active region. These observations can be made much more quantitative with a complete emission measure distribution calculation, combined with various theoretical models in attempting to understand energy release and transport in active regions.

The electron density distribution in the active region can be obtained quantitatively by forming density sensitive ratios of appropriate spectral lines. We have used density sensitive line pairs for Fe XII, Fe XIII, and Fe XIV. Specifically, we use the Fe XII line pair, $(186.85 + 186.89)$ Å, $195.12$ Å (one line is a blend of two transitions); the Fe XIII line pair, $(203.80 + 203.83)$ Å (again, a blend of two lines), $202.04$ Å; and the Fe XIV line pair, $264.79$ Å, $274.20$ Å. There is a weak Fe XII blend
in the longer wavelength Fe XIII line which was approximately removed before analysis. The second line in each pair above is a transition terminating on the ground level of the ion. Other weak blends for some of these lines are under investigation as discussed by Young et al. (2007b) but should not alter the line intensities significantly.

The line ratios can be converted to actual electron density ratios using the CHIANTI atomic physics database (Landi et al. 2006). The ratios, particularly the Fe XII and Fe XIII ratios, are quite sensitive to electron density over the range of densities found typically in the quiet Sun corona and in active regions. Thus the diagnostics are excellent indicators of density variations.

Figure 2 (lower panels) shows active region maps of the electron densities for the three ions (bright = high densities). The range of densities is from about $5 \times 10^8$ to $1 \times 10^{10}$ cm$^{-3}$. Again, as with temperature variations, density variations can be seen at a glance over a large solar area with high spatial resolution. And although not discussed in this paper, each pixel also contains the wavelength centroid and profile of the line, thus giving considerable Doppler dynamic information for the entire active region.

Figure 3 shows a plot (upper left) of the electron density for Fe XII versus the intensity of the ground state Fe XII line for the brightest structures in figure 1. The cut-off intensity for the brightest structures is somewhat ill-defined and was determined by examining the intensities at various intensity levels in figure 1. For figure 3 we take an Fe XII cut-off intensity of $2.23 \times 10^9$ erg cm$^{-2}$ s$^{-1}$ sr$^{-1}$. In figure 3 a linear least squares fit to the data is indicated by the solid line. The slope of this line shows that the density is on average roughly proportional to the emission measure. The large scatter around this fit is due to the fact that for a given density there is clearly a large range of emitting volumes in the active region.

Similar results to Fe XII for the density sensitive Fe XIII and Fe XIV ratios are also shown in figure 3 (the cutoff intensities are clearly shown in the figure). The results for Fe XIII are nearly identical to those for Fe XII. Because the Fe XII and Fe XIII lines are so close in wavelength, we have computed the Fe XIII densities for the same pixels as for the Fe XII line, and therefore plot the densities against the Fe XII intensity. The densities might still disagree, as the distribution of temperature along the line-of-sight through each pixel might not be the same. In fact, there are a group of Fe XIII data points that show a nearly constant density with increasing intensity. More investigations will be required to understand fully these results.

The densities of the brightest structures in Fe XIV are about 0.4 dex lower than for the cooler iron ions. We do not use the same pixels as for the Fe XII and Fe XIII lines because the Fe XIV line is recorded on the long wavelength detector, and precise co-alignment of the two detectors is still being studied. For all three ions the least squares fit density is approximately proportional to the emission measure. A comparison of densities for different ions is important for models of loop evolution, e.g., the multi-thread model of Warren et al. (2003). These models predict density as a function of temperature as loops heat up and then cool.

Finally, in figure 3 we show a histogram (bottom right) of the Fe XII data. This figure has an approximately Gaussian distribution with a full width at half maximum indicating a range of densities from about $2.9 \times 10^9$ to about $9.4 \times 10^9$ cm$^{-3}$. There are no densities below about $10^9$ cm$^{-3}$. At the typical Fe XII electron temperature of about $1.4 \times 10^6$ K this lower density indicates a lower limit to the electron pressure in the bright structures of this active region of about $1.4 \times 10^{15}$ cm$^{-3}$ K. At the lowest intensities considered in
the true plasma path length along the line-of-sight to the path which for a structure such as a loop can be defined as the ratio of electron density measurements is the filling factor. This factor, also FeXII and FeXIII, approaching figures 1 and 2 frequently also have high densities for FeXII somewhat surprising is that the densities in the dark regions the need for high spatial resolution to resolve the complexity.

Another aspect of the density measurements that is somewhat surprising is that the densities in the dark regions of figures 1 and 2 frequently also have high densities for Fe XII and also Fe XIII, approaching 10^8 cm^{-3}. This result seems not to be due to statistical uncertainties in the Fe XII line ratios, although in weaker regions the densities are more uncertain due to counting statistics than in the bright regions. It may be due to a problem with the atomic physics, e.g., uncertainties in radiative decay rates or excitation rate coefficients, or it may in fact be real. The contrast in images displayed on computer monitors and in prints sometimes is not nearly as large as it appears to the eye. If these high densities external to the bright loops are real, then the active region under discussion in this paper may have been imbedded in a weakly emitting large complex of high density loops. This implies much smaller path lengths in these loops than in the bright loops.

One way to quantify these weakly emitting loops is to divide the logarithmic Fe XII intensity into equal log intervals and compute the average density in each interval and the number of pixels in the interval. We have divided the entire Fe XII logarithmic intensity range between the maximum and minimum intensities in the image into 10 equally spaced intervals. The average electron density in these intervals and the number of pixels in each interval are shown in figure 4. This figure shows that the lowest densities reach typical active region quiet Sun densities, but most of the pixels have densities greater than 5 x 10^8 cm^{-3}.

4.2. Filling Factors

An important coronal quantity that can be obtained from electron density measurements is the filling factor. This factor, which for a structure such as a loop can be defined as the ratio of the true plasma path length along the line-of-sight to the path length inferred from EUV images of the loop, is a measure of how well the loop is spatially resolved by the imager. Since current models of loops frequently postulate unresolved fine strands within the loops, measurements of filling factors are important as they give direct information on the fine structure of the loops.

As an example, consider the nested loops very low near the middle of the X pixel range in the Fe XII panel of figure 1. The brightest and most obvious of these loops in figure 1 is seen to be part of a group of nested loops in TRACE movies of this active region. These loops are shown blow-up and isolated in figure 5 for lines of Fe XI, Fe XII, and Fe XIII, along with the positions in what appear to be parts of two loops (see arrows in figure 5) for which we have made specific measurements. We have calculated path lengths through the loops along the line-of-sight of EIS from the Fe XII image using the measured line intensities and electron densities at the X and Y positions shown. We emphasize that we are simply demonstrating a technique with EIS data in this paper, and we are not doing a detailed modeling of these particular loops. Detailed modelling would benefit from the comprehensive TRACE coverage of this active region in time as well as its somewhat better spatial resolution for resolving individual loops.

The measured line intensities have been approximately corrected for the background emission by averaging a few intensities measured for the darkest parts of the Fe XII image in figure 5. These regions are not devoid of emission, but contain extremely faint structures that do not display as identifiable loops. This emission is somewhat variable within figure 5 by about 30%.

The path lengths are related to the background subtracted line intensity using CHIANTI. CHIANTI returns a calculated intensity per unit line-of-sight emission measure for the spectral line under consideration as a function of temperature for a given electron density. Using the Fe XII densities and assuming emission at the maximum of the line contribution function, we obtain the path lengths given in table 1. Electron densities and temperature sensitive line ratios at the positions
Measurements of electron densities and temperature sensitive line intensity ratios at the positions of the two loops indicated in table 1. Positions 1 through 5 correspond to loop 1; positions 6 through 10 to loop 2. The Fe XII/Fe XIII intensity ratios correspond to an isothermal temperature of about $1.4 \times 10^6$ K at position 1 to about $1.8 \times 10^6$ K at position 10.

Table 1. Loop path lengths (arcseconds).

<table>
<thead>
<tr>
<th>Loop</th>
<th>X-pixel</th>
<th>Y-pixel</th>
<th>Path length</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.1</td>
<td>27.1</td>
<td>4.4</td>
</tr>
<tr>
<td>1</td>
<td>10.0</td>
<td>21.2</td>
<td>3.3</td>
</tr>
<tr>
<td>1</td>
<td>12.5</td>
<td>15.2</td>
<td>3.1</td>
</tr>
<tr>
<td>1</td>
<td>17.2</td>
<td>11.1</td>
<td>8.5</td>
</tr>
<tr>
<td>1</td>
<td>23.8</td>
<td>9.1</td>
<td>3.6</td>
</tr>
<tr>
<td>2</td>
<td>30.6</td>
<td>10.1</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>36.1</td>
<td>11.7</td>
<td>8.5</td>
</tr>
<tr>
<td>2</td>
<td>42.1</td>
<td>15.1</td>
<td>2.4</td>
</tr>
<tr>
<td>2</td>
<td>47.4</td>
<td>18.9</td>
<td>4.5</td>
</tr>
<tr>
<td>2</td>
<td>53.2</td>
<td>24.1</td>
<td>5.2</td>
</tr>
</tbody>
</table>

Note also in figure 5 that the brightest of the two loops is cooler towards its apparent loop footpoint in the northeast quadrant of the image (compare the Fe XI and Fe XII images). Thus this loop is multithermal. As mentioned, data from TRACE also indicate that it is in fact part of a nest of loops.

Furthermore, the data in figure 5 clearly show that the two prominent loops become progressively more fuzzy as the ionization stage increases, i.e., hotter loops are more amorphous than cooler loops. This result has been known since Skylab and is still not explained. It is dramatically illustrated in figure 5.

5. Summary

We have shown the capabilities of EIS for investigating electron density and temperature variations at coronal temperatures in active regions. We have derived ranges of density for a particular active region and densities and path lengths for two apparent loops in the active region. The densities external to bright loops also appear high, and we have investigated the distribution of density as a function of number of pixels in the observed part of the active region. The results in this paper will be refined and clarified further by investigating many more active regions.

Hinode is a Japanese mission developed and launched by ISAS/JAXA, collaborating with NAOJ as domestic partner, and NASA (USA) and STFC (UK) as international partners. Scientific operation of the Hinode mission is conducted by the Hinode science team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the post-launch operation is provided by JAXA and NAOJ, STFC, NASA, ESA (European Space Agency), and NSC (Norway). We are grateful to the Hinode team for all their efforts in the design, build, and operation of the mission. GAD, JTM, and HPW acknowledge support from the NASA Hinode program.

References

Young, P. R., et al. 2007b, PASJ, 59, S857