EMISSION MEASURE DISTRIBUTION FOR DIFFUSE REGIONS IN SOLAR ACTIVE REGIONS

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ABSTRACT

Our knowledge of the diffuse emission that encompasses active regions is very limited. In this paper we investigate two off-limb active regions, namely, AR 10939 and AR 10961, to probe the underlying heating mechanisms. For this purpose, we have used spectral observations from Hinode/EIS and employed the emission measure (EM) technique to obtain the thermal structure of these diffuse regions. Our results show that the characteristic EM distributions of the diffuse emission regions peak at log $T = 6.25$ and the coolward slopes are in the range 1.4–3.3. This suggests that both low- as well as high-frequency nanoflare heating events are at work. Our results provide additional constraints on the properties of these diffuse emission regions and their contribution to the background/foreground when active region cores are observed on-disk.

Key words: methods: observational – Sun: abundances – Sun: atmosphere – Sun: corona – Sun: transition region – Sun: UV radiation – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

Our knowledge on how the solar corona is heated and maintained at a million degrees kelvin, when the photosphere below is at 5800 K, is still far from being comprehensive. Active regions (ARs) are ideal observing targets for probing the underlying heating mechanisms, as they are the locations of profound heating processes. In addition, they show a wide distribution of physical parameters. Accurate measurements of such parameters are critical in the formulation and constraint of coronal heating theories. For extended discussions on coronal heating, refer to, e.g., Klimchuk (2006) and Reale et al. (2010).

Topologically, ARs possess different structures like the core loops primarily seen at $\approx 1–2$ MK (Tripathi et al. 2010b, 2011; Viall & Klimchuk 2012, and references therein), warm loops at $\approx 1$ MK (Del Zanna & Mason 2003; Tripathi et al. 2009; Ugarte-Urra et al. 2009), and the cool fan structures at the edges of the ARs at $< 1$ MK (Schrijver et al. 1999; Winebarger et al. 2002; Warren et al. 2011; Young et al. 2012). In addition to the visible loop structures, there is a substantial amount of diffuse emission in and around the active regions (Del Zanna & Mason 2003; Viall & Klimchuk 2011; Del Zanna et al. 2014). Diffuse emission regions may be defined as regions with no resolvable structures. They may, however, appear to be loop-like structures at higher resolution. In fact, the emissions from confined loop structures are just about 20%–30% higher than the background/foreground diffuse emission (Del Zanna & Mason 2003; Viall & Klimchuk 2011; Del Zanna et al. 2014). O’Dwyer et al. (2011) investigated the density and temperature structure of a limb AR. The authors reported that AR plasmas are multi-thermal and the electron densities fall off as a function of distance from the core, as was also obtained using the white light observations of the corona.

AR heating has often been debated between effectively steady heating (high-frequency nanoflares) and impulsive heating (low-frequency nanoflares). In the former scenario, the delay between heating events is smaller than the cooling/draining timescale of the plasma, leading to conditions that are similar to constant heating. Impulsive heating, however, suggests that the delay between heating events is longer than the cooling/draining timescale of the plasma, i.e., the plasma gets some time to cool down before another heating event takes place. The properties of 1 MK warm loops seem to favor impulsive heating (Warren et al. 2003; Ugarte-Urra et al. 2009; Tripathi et al. 2009; Klimchuk 2009). However, the heating of core loops is a matter of strong debate (Tripathi et al. 2010b, 2011; Winebarger et al. 2011; Warren et al. 2011, 2012; Viall & Klimchuk 2012, 2013; Dadashi et al. 2012; Bradshaw et al. 2012; Winebarger et al. 2013). Recent analyses suggest that active regions during the early part of their evolution seem to show an emission measure (EM) distribution (EMD) that is consistent with impulsive heating, while during the latter part of their evolution, the variability of the core becomes more gentle and the EMD is more consistent with high-frequency nanoflare heating (Ugarte-Urra & Warren 2012; Del Zanna et al. 2014).

The study of diffuse emission has not been explored in detail. The main aim of this paper is to study and probe the heating mechanism in the diffuse part of active regions. Direct observations of heating processes are not yet possible, as these events happen on scales much smaller than the resolvable limits with the available present-day instrumentation (Klimchuk 2006). EM diagnostics have been advocated (see, e.g., Tripathi et al. 2010b) as one of the possible indirect modes of studying the heating mechanisms, among others, such as Doppler shifts (Brooks & Warren 2009; Tripathi et al. 2012; Winebarger et al. 2013; Dadashi et al. 2012) and the recently developed time lag analysis (Viall & Klimchuk 2012).

Here, we have employed the technique of EM to study the diffuse emission in active regions. In addition, we estimate the EM($T$) distribution of topologically different regions in off-limb AR 10939 and AR 10961, i.e., warm and core loop structures, and compare with the EM($T$) of the diffuse emission regions with the aim of probing the thermal structure in diffuse regions and thereby their heating mechanisms. Del Zanna (2013) presented a revised radiometric calibration, due to the degradation of...
the detector’s response of the Extreme ultraviolet Imaging Spectrometer (EIS) instrument over time since the launch date of the Hinode mission. The revised calibration has been accepted by the EIS team and has been provided in the solarsoftware package. In this work, we have applied the revised calibration on intensities to obtain the EM and compared with that obtained using the unrevised intensities. The rest of the paper is organized as follows. In Section 2, we describe the data used in this study and the reduction procedures applied. In Section 3, we discuss an instrumental effect: the diffraction bands that are observed in our data sets. We describe our data analysis method and present our results in Section 4, followed by a summary and discussion in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

For this analysis, we have used the off-limb AR 10939 and AR 10961 data sets obtained on 2007 January 26 and 2007 July 8, respectively, from the EIS (Culhane et al. 2005, 2007) on board Hinode. EIS rastered AR 10939 with a 1′ slit over an area of 128′′ × 128′′, with a 26.5 s exposure at each position and with a step size of 1′. The observing study of AR 10939 was a full spectral observation. Similarly, AR 10961 was rastered with a 1′ slit over an area of 256′′ × 256′′, with a 15 s exposure at each position and with a step size of 1′. This observing sequence consisted of 17 spectral windows, out of which 11 spectral lines have been used in the current study. Tables 1 and 2 show the list of the spectral lines used in this study, along with their wavelengths and peak formation temperatures. The peak formation temperatures were obtained from recent Chianti ionization equilibrium calculations (Chianti v7.1; Dere et al. 1997; Landi et al. 2013).

The data are reduced using the standard procedure eis_prep.pro4 and are corrected for EIS slit, tilt, and satellite orbital variation. Using eis_autofit.pro5, a single Gaussian line fit is applied to the data to derive the intensity maps, except for the Mg vi λ268.99, Fe xiii λ197.86, Fe xii λ188.22, Fe xii λ195.12, Fe xii λ203.83, Ca xiv λ193.87, and Ca xv λ201.00 lines. In the latter cases, multiple Gaussian fitting is applied to subtract the blended line contributions. The He ii λ256 line is one of the EIS core lines, with the lowest formation temperature available in the EIS spectral range. However, especially in the case of active regions, the interpretation of this line gets complicated by blends with Si x λ256.37, Fe xii λ256.41, and Fe xii λ256.42 (Young et al. 2007). Hence, we do not include the He ii λ256 line in this work. The rest of the available lines are very weak in the off-limb structures and hence could not be used. The Fe vii λ185.21 (log $T = 5.6$) line is blended with the Ni xvi line, which peaks in the AR core plasma, and de-blending is essential to estimate the Fe vii plasma parameters. In AR 10961 data, the respective Fe vii line could not be de-blended because of the unavailability of other Ni xvi line observations, while in the case of AR 10939, de-blending is performed by estimating the contribution of Ni xvi to the Fe vii line through observations of the Ni xvi λ195.27 line.

Disentangling the diffuse emission regions from the rest of the active region is a non-trivial task that is very crucial for this work.

4 ftp://sohoftp.nascom.nasa.gov/solarsoft/hinode/eis/doc/eis_notes/
5 ftp://sohoftp.nascom.nasa.gov/solarsoft/hinode/eis/doc/eis_notes/

### Table 1

List of Spectral Lines Used to Study the EM over Topologically Different Areas within Active Region 10939, Along with the Calculated Intensities and the Line Fitting Errors of a Sample of Masked Regions (m2, m5, m8, and m10) in the Respective Wavelengths

| Spectral lines | Intensities and Fitting Errors |
|----------------|-------------------------------|
| Ion           | Wavelength (Å) | log $T$ | Intensity Correction Factors | m2    | m5    | m8    | m10   |
| Mg vi         | 268.990        | 5.65   | 1.11                          | 132 ± 2 | 287 ± 3 | 596 ± 3 | 966 ± 5 |
| Si vii        | 275.350        | 5.80   | 1.14                          | 110 ± 1 | 215 ± 2 | 426 ± 2 | 631 ± 4 |
| Fe viii       | 185.210        | 5.80   | 1.35                          | 336 ± 4 | 626 ± 6 | 1325 ± 8 | 2278 ± 13 |
| Fe vii        | 186.600        | 5.80   | 1.39                          | 215 ± 3 | 404 ± 4 | 895 ± 5 | 1352 ± 9 |
| Fe xii        | 197.860        | 5.90   | 1.16                          | 128 ± 1 | 176 ± 1 | 251 ± 1 | 247 ± 2 |
| Fe xii        | 188.500        | 5.90   | 1.43                          | 195 ± 2 | 271 ± 3 | 400 ± 3 | 438 ± 4 |
| Fe x         | 174.531        | 6.05   | 1.57                          | 1852 ± 82 | 2193 ± 97 | 2785 ± 96 | 2746 ± 123 |
| Fe x         | 184.537        | 6.05   | 1.35                          | 794 ± 6 | 910 ± 7 | 1154 ± 7 | 1265 ± 10 |
| Fe xi        | 188.217        | 6.15   | 1.45                          | 2393 ± 20 | 2664 ± 25 | 3207 ± 25 | 3673 ± 35 |
| Fe xi        | 180.401        | 6.15   | 1.47                          | 1513 ± 6 | 1618 ± 7 | 1927 ± 8 | 2406 ± 11 |
| Si x          | 258.374        | 6.15   | 1.35                          | 882 ± 5 | 1033 ± 5 | 1292 ± 5 | 2334 ± 9 |
| Si x          | 261.060        | 6.15   | 1.29                          | 406 ± 3 | 456 ± 3 | 569 ± 3 | 865 ± 5 |
| Fe xii        | 195.120        | 6.20   | 1.00                          | 1093 ± 3 | 1310 ± 4 | 1558 ± 4 | 2054 ± 6 |
| Fe xii        | 192.394        | 6.20   | 1.13                          | 2781 ± 4 | 3179 ± 6 | 3727 ± 6 | 5227 ± 10 |
| Fe xii        | 202.040        | 6.25   | 1.00                          | 2759 ± 9 | 3216 ± 10 | 3608 ± 9 | 4147 ± 13 |
| Fe xii        | 203.827        | 6.25   | 1.02                          | 1712 ± 9 | 2595 ± 10 | 3623 ± 10 | 9615 ± 20 |
| Fe xiv        | 274.204        | 6.30   | 1.10                          | 1629 ± 5 | 2300 ± 6 | 3293 ± 6 | 6290 ± 11 |
| Fe xiv        | 284.163        | 6.35   | 1.32                          | 6527 ± 16 | 11322 ± 20 | 21790 ± 25 | 39060 ± 44 |
| S xiv         | 256.700        | 6.40   | 1.42                          | 383 ± 4 | 622 ± 5 | 1444 ± 7 | 3234 ± 13 |
| Fe xiv        | 262.980        | 6.45   | 1.25                          | 344 ± 3 | 779 ± 4 | 2539 ± 6 | 4337 ± 10 |
| Ca xiv        | 193.870        | 6.55   | 1.04                          | 18 ± 1 | 94 ± 1 | 435 ± 2 | 541 ± 3 |
| Ca xiv        | 201.000        | 6.65   | 0.99                          | 84 ± 10 | 61 ± 3 | 280 ± 3 | 313 ± 5 |

**Notes.** True errors will also include radiometric calibration errors of about 22% of the intensities (Lang et al. 2006), in addition to the fitting errors. Refer to Table 3 for the intensities of the rest of the masked regions. Intensity units are in ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The intensities given here are not corrected with the revised radiometric calibration presented by Del Zanna (2013), and the required intensity corrections can also be found here.
Figure 1. Fe XV intensity image of AR 10961 tracked from close to the center of the Sun (2007 August 1) to the limb (2007 August 8). All the images have been plotted with the same field of view of 297′′×197′′ in order to help us track any AR structure through the solar rotation. Though all the AR data have been plotted with the same y-axis scale, the scalings in the x-axis are different. This is because the apparent heliographic longitude (the solar X coordinate) of the AR changes vastly over the solar rotation, unlike the latitude (the solar Y coordinate).

(A color version of this figure is available in the online journal.)

Table 2

List of Spectral Lines Used to Study the EM over Topologically Different Areas within Active Region 10961, Along with the Calculated Intensities and the Line Fitting Errors of a Sample of Masked Regions (m3, m7, m9, and m11) in the Respective Wavelength

| Ion     | Wavelength (Å) | log T (K) | Intensity Correction Factors | m3     | m7     | m9     | m11    |
|---------|----------------|-----------|-------------------------------|--------|--------|--------|--------|
| Si vii  | 275.350        | 5.80      | 1.23                          | 19 ± 1 | 37 ± 1 | 136 ± 2| 132 ± 2|
| Fe viii | 185.210        | 5.80      | 1.35                          | 43 ± 2 | 104 ± 4| 341 ± 5| 578 ± 7|
| Fe x    | 174.531        | 6.05      | 1.57                          | 939 ± 84|1171 ± 122|1569 ± 127|1988 ± 153|
| Fe xi   | 184.537        | 6.05      | 1.35                          | 275 ± 3| 351 ± 5| 591 ± 6| 726 ± 7|
| Fe xii  | 188.217        | 6.15      | 1.45                          | 682 ± 3| 781 ± 5| 1190 ± 6| 1614 ± 8|
| Fe xiii | 195.120        | 6.20      | 1.00                          | 1471 ± 3|1724 ± 4| 2367 ± 5| 3289 ± 7|
| Fe xiv  | 202.040        | 6.25      | 1.00                          | 1522 ± 3|1883 ± 8| 2331 ± 9| 2889 ± 11|
| Fe xv   | 203.827        | 6.25      | 1.02                          | 574 ± 4| 920 ± 7| 1739 ± 9| 3992 ± 15|
| Fe xvi  | 274.204        | 6.30      | 1.18                          | 604 ± 3| 953 ± 5| 1383 ± 6| 2555 ± 9|
| Fe xv   | 284.163        | 6.35      | 1.42                          | 1689 ± 6|3240 ± 11|5258 ± 14|10343 ± 22|
| Fe xvi  | 262.980        | 6.45      | 1.34                          | 57 ± 2 | 164 ± 3| 409 ± 4| 953 ± 6|

Notes. True errors will also include radiometric calibration errors of about 22% of the intensities (Lang et al. 2006), in addition to the fitting errors metioned in this table. Refer to Table 4 for the intensities of the rest of the masked regions. Intensity units are in erg cm⁻² s⁻¹ sr⁻¹. The intensities given here are not corrected with the revised radiometric calibration presented by Del Zanna (2013).

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| Ion     | Wavelength (Å) | log T (K) | Intensity Correction Factors | m3     | m7     | m9     | m11    |
|---------|----------------|-----------|-------------------------------|--------|--------|--------|--------|
| Si vii  | 275.350        | 5.80      | 1.23                          | 19 ± 1 | 37 ± 1 | 136 ± 2| 132 ± 2|
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| Fe xiii | 195.120        | 6.20      | 1.00                          | 1471 ± 3|1724 ± 4| 2367 ± 5| 3289 ± 7|
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| Fe xv   | 203.827        | 6.25      | 1.02                          | 574 ± 4| 920 ± 7| 1739 ± 9| 3992 ± 15|
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| Fe xv   | 284.163        | 6.35      | 1.42                          | 1689 ± 6|3240 ± 11|5258 ± 14|10343 ± 22|
| Fe xvi  | 262.980        | 6.45      | 1.34                          | 57 ± 2 | 164 ± 3| 409 ± 4| 953 ± 6|

Notes. True errors will also include radiometric calibration errors of about 22% of the intensities (Lang et al. 2006), in addition to the fitting errors metioned in this table. Refer to Table 4 for the intensities of the rest of the masked regions. Intensity units are in erg cm⁻² s⁻¹ sr⁻¹. The intensities given here are not corrected with the revised radiometric calibration presented by Del Zanna (2013).

Hence, it is essential to track the active region from the center of the Sun to the limb, which may give some ideas regarding the evolution of different structures in the active region. The six images in Figure 1 display the intensity images of AR 10961 obtained in the Fe XV line from 2007 August 1 to 2007 August 8, tracking the evolution of the active region from the disk center to the limb. The Fe XV spectral line, whose peak formation temperature is at log T ≈ 6.35, is the strongest Fe line in the EIS/Hinode spectrum at AR conditions, and the core structures that are primarily at a few million degrees can be well studied at this temperature regime. Thus, by tracking the particular AR core at Fe XV temperatures, the diffuse regions...
could be confidently constrained to be well outside the core structures.

The intensity corrections required for the revised radiometric calibration were obtained using eis_ltds.pro (available in the ssw libraries; Del Zanna 2013), which provides a factor by which the revised intensities differ with the unrevised ones. The revised intensities have been obtained by applying these correction factors to the initial intensities obtained from the data. From here onward, we will be calling the initial intensities and the respective EMDs unrevised intensities and unrevised EMDs, while the intensities corrected according to the revised radiometric calibration and the corresponding EMDs will be referred to as revised intensities and revised EMDs.

3. DIFFRACTION BANDS

The reduced data of both of the above-mentioned off-limb active regions show diffraction bands (Figure 2) in the quiet regions beside the active regions. These bands are clearly seen in high-temperature lines (Fe xii–Fe xv), being most prominent in the Fe xv line (Figure 2). These are probably similar to the cross-shaped diffraction patterns seen with AIA on board SDO and TRACE during flares (see, e.g., Raftery et al. 2011; Lin et al. 2001). In our case, the scattered light forms bands rather than crossed-spike patterns. This is probably due to the active region being a broad structure of enhanced brightness at the off limb when compared to the flaring regions (P. Young 2013, private communication). The bands always trace the edges of the active regions and may arise due to the large intensity contrast produced by the active region over the off-limb background values.

For AR 10939, Fe xv intensity at the successive bands falls off approximately as 5%, 3%, 1%, and 0.3% of the brightest part of the AR core (∼39,000 erg cm⁻² s⁻¹ sr⁻¹) at distances of approximately 10″, 20″, 30″, and 40″. Some of the observed emission at the locations of the bands comes from actual on-disk solar features, so these percentages represent upper limits on the diffracted core component. We use this information later to estimate the possible contamination in the diffuse emission above the limb. These factors mentioned above would depend on how big/bright the source is in that particular raster, while the AR 10961 raster shows only a trace of such bands, as the exposure time is much shorter (15 s) than the exposure time of the AR 10939 raster (26.5 s). AR 10961 data has another active region in the full field of view, and it would be inappropriate to estimate the intensities of such bands, as they have contamination from nearby structures.

4. DATA ANALYSIS AND RESULTS

The motivation behind this work is to probe the heating mechanism of the diffuse emission regions. Off-limb AR data are ideal to spectroscopically study the topologically different areas within the active region, especially the diffuse emission regions, as these regions could be isolated without much contamination from the core of the active regions as well as warm 1 MK loops. A detailed description of the spectroscopic techniques for deriving physical parameters like electron density and temperature along with the EM of the emitting plasma has been given in Mason & Fossi (1994) and Tripathi et al. (2010a). EM is a function of the temperature and density of the emitting plasma. The observed intensity can be correlated with the EM as

\[
\text{Intensity}(I) = A_{c} \times EM \times C_{\lambda},
\]

where \(A_{c}\) is the elemental abundance and \(C_{\lambda}\) is the contribution function containing all the relevant atomic parameters like transition probabilities, ionization fraction, etc. Earlier works showed that, for ARs, EM obeys a power law \(EM(T) \propto T^\alpha\) up to a peak near 3 MK (Dere 1982; Dere & Mason 1993). While plotting the EM with respect to temperature on a log–log scale, \(\alpha\) is the slope of a best-fitted straight line up to the peak EM. The slope \(\alpha\) represents the temperature distribution of multi-thermal plasma along the line of sight.

For both ARs, eis_pixel_mask.pro is used to choose a sample of topologically different areas within active regions, like hot core loops, comparatively cooler warm loops, and the diffuse emission regions, by masking pixels in polygon mode. It is crucial to make sure that each box contains only one type of feature, i.e., they should not have any contamination from other regions. We have used eis_mask_spectrum.pro to retrieve the spatially averaged spectra over each chosen pixel group (box).

Estimation of the EM from averaged spectra is not trivial. As the masked regions are selected manually, the box sizes are not the same for all regions. It is important to understand the effects of varying box sizes in the estimation of EM in order to compare our results with other similar works. Hence, we chose a set of seven randomly oriented boxes, each with a sub-box over AR 10961. Thus, in total, there are 14 regions, as shown in Figure 3 (left) for the analysis, and their respective EM plots are shown in Figure 3 (right). The EM plot clearly shows that choosing different boxes with different sizes in a particular area in the field of view does not vastly change the EM.

The color scheme (loadc=5) we chose for Fe xv images (Figure 3 (left) and Figures 4 and 5 (top right)) is found to be the best in representing the AR. The color transition from blue to yellow distinguishes the topologically different regions in the AR from the diffuse parts on the outskirts of the AR toward the core, respectively. Figures 4 (top panel) and 5 (top panel) display the intensity images for AR 10939 and AR 10961, respectively, obtained in the Si vii (left), Fe xiii (middle), and Fe xiv (right) bands.
Fe xiii (right) lines. The Fe xiii intensity image of AR 10939 (Figure 4, top right) is overplotted with the 11 masked regions (m1, m2, ..., m11) chosen for estimation of the EM. We have divided these regions into different sets based on their locations. Set 1 is comprised of the first four regions, namely, m1, m2, m3, and m4, which are selected in the diffuse emission region well above the AR core. Set 2 is comprised of regions m5, m6, and m7, which are located at the boundary between the core and the diffuse emission region. Set 3 is comprised of regions m8, m9, m10, and m11 in the core of the active region. Similarly, the Fe xiv intensity image of AR 10961 (Figure 5, top right) is overplotted with the selected 12 masked regions (m1, m2, ..., m12). These regions are again divided into four groups following the same criteria as discussed above in the case of AR 10939.

Initially, averaged spectra have been obtained from all the masked regions from AR 10939 and AR 10961 in all the spectral windows mentioned in Tables 1 and 2, respectively. Spectral lines are fitted with a modified version of eis Autofit.pro to read the output structures from eis_mask_spectrum.pro. For AR 10939, estimated intensities for a sample masked region from each set (m2—set 1, m5—set 2, m8 and m10—set 3) are given in the Table 1, and the intensities of the rest of the masked regions are given in Table 3. Similarly, for AR 10961, estimated intensities for a sample region from each set of masked regions (m3—set 1, m7—set 2, m9 and m11—set 3) are given in Table 2, and the intensities of the rest are given in Table 4. The masked regions discussed in Tables 1 and 2 fall as a strip, with which variations of spectroscopic parameters as a function of distance from the core of the AR can be explored. The EM is derived using the method discussed by Pottasch (1963), Jordan & Wilson (1971), and Tripathi et al. (2010a). Even though there are many true inversion DEM codes currently available, this method is objective and provides consistent results when compared to the other methods. Also, the results obtained using the Pottasch method are similar to those from the other DEM inversion codes.

In order to derive the EM, it is necessary to provide electron density as an input parameter. Therefore, we have used Fe xiii (λ202.04 and λ203.83) lines to derive the densities for each region, as they are one of the best coronal density diagnostics available to EIS. Table 5 shows the estimated densities of all the masked regions chosen over both the ARs. For each spectral line, the EM at the peak formation temperature, $T_{\text{max}}$, is approximated by assuming that the contribution function is constant and equal to its average value over the temperature range $T_{\text{max}} \pm 0.15$ and zero at all other temperatures. We use the ionization equilibrium values as given in Chianti (v7.1; Dere et al. 1997; Landi et al. 2013) and consider both photospheric (Grevesse & Sauval 1998) and coronal (Feldman 1992) abundances.

As listed in Tables 1, 2, 3, and 4, the intensities in each spectral line show an increasing trend from the diffuse emission regions (set 1) toward the core of the AR (set 3). The Fe xiii electron densities also show an increasing trend from set 1 to set 3. In each set, the derived electron densities are remarkably similar among the chosen masked regions (Table 5), except for m10 and m11 (set 3). The regions show higher densities when compared to m8 and m9 (set 3) and also vary among themselves, which could be because of the possible contaminations from the underlying moss regions. These trends observed in intensities and densities suggest that similar structures were chosen in each set, and they also distinguish the regions chosen among different sets as topologically different.

The middle rows (rows 2 and 3) in Figure 4 display the EMD for all the different sets of masked regions chosen over AR 10939, estimated with unrevised and revised intensities, respectively. In both cases, the EM distributions for sets 2 and 3 are shown in the middle and right panels of rows 2 and 3. The EMDs belonging to set 3 are plotted with two different symbols. The regions m8 and m9 are plotted with pluses and m10 and m11 are plotted with triangles. This is to make a distinction between core regions without and with possible moss region.
Figure 4. Top (row 1): intensity image of AR 10939 in Si vii (left), Fe xii (middle), and Fe xv (right) with white boxes (m1, m2, ..., m11) representing the 11 masked regions chosen for DEM analysis. Middle rows show the EMDs of all the masked regions estimated with unrevised (row 2) and revised (row 3) intensities, respectively. The bottom row shows the revised EMDs of a sample diffuse region (left), a core region (middle), and the same core region after background subtraction (right), with their corresponding linear fits and the derived slopes.

(A color version of this figure is available in the online journal.)
contamination. Though almost all the curves of set 2 and set 3 show a very similar trend, the EMDs for all the regions in set 3 lie above those for set 2. In addition, the peaks of the EM curves for all the regions in set 3 are at higher temperatures than those of set 2 regions. The peak of the EM for set 3 mostly lies around $\log T = 6.55$. However, the EMD for regions m10 and m11 in set 3 (plotted with triangles) also shows a definite peak at $\log T = 6.25$, which is characteristic of moss regions (Tripathi et al. 2010a). In comparison, the EMD of set 2 peaks at a lower temperature of $\log T \sim 6.3$. The revised radiometric calibration broadens the peak of two (m5 and m6) out of the three masked regions chosen in this set, with the EM decreasing more slowly with temperature in the range $\log T = 6.25$–6.45, while the third one (m7), which shows a double peak with the original calibration, namely, at $\log T = 6.25$ and $\log T = 6.40$, prominently shows only the second peak at $\log T = 6.40$ with the revised calibration.

We have studied the slopes of the EM and hot to warm ratios for the regions in set 2 and set 3. The ratio of hot to warm emission is determined by taking the ratio between the peak EM and the EM obtained at Fe x and Si vii. The slope, however, is obtained between the temperature corresponding
to peak EM and the EM of Fe x at log $T = 6.05$. The slope of unrevised EM for sets 2 and 3 ranges between 2.3 and 4.2 and the ratios of hot to warm emission vary between 3.8 and 7.3 when warm emission is considered at log $T = 6.05$. These ratios increase to a range of 9–28 when considering Si vii as warm emission. The revised calibration makes the slope comparatively shallower, in the range of 1.5–3, with the hot to Fe x emission varying between 2.8 and 5.4 and the hot to Si vii varying between 8 and 24.

The left panels of row 2 and 3 in Figure 4 show the EMD of diffuse regions classified as set 1, comprising m1, m2, m3, and m4. Both EMD curves (unrevised and revised) for all four regions are strikingly similar and show a definite peak at log $T = 6.25$, i.e., at the peak formation temperature of Fe xiii, except that the peak of the revised EMDs is broader at Fe xiii and Fe xiv temperatures. For each of these curves, the estimated value of the EMD slopes, $\alpha$, along with the EM ratio of the hot plasma to the warm plasma (Fe x and Si vii), are given in Table 6. The slopes are computed between log $T = 6.25$ and log $T = 6.05$. The active region spectra for AR 10939 are full spectral scans, and the obtained EMDs provide a complete picture of the thermal structure of the regions. Therefore, we
conclude that the peak of the EMD for diffuse regions lies at log \( T = 6.25 \).

The masked regions chosen in sets 1, 2, and 3 (m8 and m9) are located approximately 50′′, 25′′, and 10′′ from the brightest part of the core (where in set 3, m10 and m11 fall). Using the results of Section 3, we estimate a maximum contamination from diffracted core emission at these locations in Fe xv to be less than 0.3%, 2%, and 5%, respectively. This is about 117, 780, and 1950 erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\), which is less than 2%, 7%, and 9% of the actual observed Fe xv intensity at these locations. Therefore, it is safe to conclude that the contamination from the diffracted emission does not significantly impact our EM measurements.

If one assumes that the diffuse emission seen above the core in set 1 is equivalent to the diffuse emission present along the line of sight in the studied core regions in set 3, i.e., equivalent to the foreground/background emission along the line of sight, then it is possible to subtract the diffuse contribution from set 3 to obtain the emission from the core plasma itself. When we do this using an averaged EMD from all the masked regions in set 1, the EM slopes of the core regions (set 3) increase by 0.64 to 0.94, i.e., the distributions become steeper. The bottom row (row 4) in Figure 4 shows the best linear fits to a sample diffuse region (left), a core region (middle), and the same core region after background subtraction (right), with the corresponding slopes. The core observations may also be contaminated by warm loops in the foreground and background, so this must be considered only a partial correction. Because of their characteristic EMD peaking at Fe xiii, slope corrections using the diffuse region EMD are expected to make the core region distribution steeper. We caution, however, that the magnitude of the correction is very uncertain. Both the emissivity and the line-of-sight depth of the diffuse plasma could be considerably different at the altitude of set 3 than at the altitude of set 1.

AR core EMDs (set 3) show a clear rollover at about log \( T = 6.3 \), most likely due to contamination from the underlying moss regions, whose EMDs are known to peak at log \( T = 6.25 \) (Tripathi et al. 2010a). The EMD slopes would get steeper by about a factor of 0.2 (set 3a) and 0.8 (set 3b) when estimated with respect to this rollover peak, rather than with respect to the EM peak. Since we are interested primarily in the coronal loop top emission and not the emission from footpoint moss regions, the slopes presented here are estimated with respect to the peak EM.

Tripathi et al. (2011) studied AR 10961 when it was near disk center, when full spectral scan observations were available. Their goal was to measure the EM slope of inter-moss regions (i.e., of the AR core). Because of the on-disk observing geometry, lines of sight through the inter-moss regions included contributions from higher altitude diffuse emission above the core. To estimate the magnitude of these contributions, they examined additional lines of sight outside the core and made adjustments to account for gravitational stratification. The diffuse emission was thereby estimated to contribute between 5% and 40% of the total EM at log \( T = 5.8 \) along the line of sight through the core. Our limb measurements of this same active region give comparable results. Figure 5 shows that, at this temperature, the diffuse emission (set 1) is roughly 20% of the core emission (set 3). The boundary region emission (set 2) is roughly 30% of the core emission. This suggests that the method used by Tripathi et al. (2011) to remove the diffuse component from their core measurements is reasonable. They estimated a potential error in the EM slope of less than 0.1.

We caution that the observing geometries are completely different for these two studies and that a horizontal integration through a point above the limb may be much different from vertical integration through the same point. In addition, we could not study the effect of gravitational stratification at the height of the AR core, even by assuming the diffuse emission to be unresolved loop structures. This is because measuring the loop length is not possible in our case, taking the diffuse nature of the region into account. Hence, our results may not be comparable with the results of Tripathi et al. (2011).

Our earlier on-disk study of AR 10961 (Tripathi et al. 2011) benefited from a full spectral scan, which we do not have for our present limb study of this region. The lack of spectral lines hotter than log \( T = 6.45 \) prevents us from fully characterizing the core plasma, but we can obtain a rather complete picture of the diffuse and boundary region plasma. Similar to the analysis performed for AR 10939, we have chosen different regions (shown in the top right panel Figure 5) and have grouped them in different sets, namely set 1, set 2, and set 3. The unrevised (row 2) and the revised (row 3) EMDs for set 2 and set 3 are plotted in the middle and right panels, and those for set 1 are plotted in the left panels in Figure 5. Similar to AR 10939, we have plotted the EM for m9 and m10 with pluses and regions m11 and m12.

### Table 5

| AR 10939 | AR 10961 |
|----------|----------|
| Masked Regions | Density \( (n_e \text{ cm}^{-3}) \) | Masked Regions | Density \( (n_e \text{ cm}^{-3}) \) |
| set 1 | m1 | 8.0e+08 | m1 | 5.9e+08 |
| m2 | 8.6e+08 | m2 | 5.3e+08 |
| m3 | 8.5e+08 | m3 | 5.4e+08 |
| m4 | 7.1e+08 | m4 | 5.7e+08 |
| m5 | 7.3e+08 | m5 | 5.5e+08 |
| set 2 | m5 | 1.2e+09 | m6 | 7.8e+08 |
| m6 | 1.1e+09 | m7 | 7.1e+08 |
| m7 | 1.2e+09 | m8 | 7.5e+08 |
| set 3 | m8 | 1.5e+09 | m9 | 1.1e+09 |
| m9 | 1.5e+09 | m10 | 1.3e+09 |
| m10 | 6.5e+09 | m11 | 2.4e+09 |
| m11 | 4.1e+09 | m12 | 2.4e+09 |

**Note:** Set 1 represents the diffuse emission region, set 3 represents the AR core regions, and set 2 is the boundary between the AR core and the diffuse regions.

### Table 6

| Unrevised | Revised (Del Zanna 2013) |
|-----------|--------------------------|
| Masked Regions | slope \( (\alpha) \) Fe xv/Fe xv Si vii/Fe xv slope \( (\alpha) \) Fe xv Si vii/Fe xv |
| AR 10939 | m1 | 2.90 | 3.1 | 19.7 | 2.04 | 2.3 | 17.2 |
| m2 | 3.08 | 3.2 | 21.6 | 2.22 | 2.4 | 18.8 |
| m3 | 2.95 | 3.3 | 9.5 | 2.08 | 2.5 | 8.3 |
| m4 | 2.87 | 3.2 | 14.1 | 2.01 | 2.4 | 12.3 |
| AR 10961 | m1 | 2.31 | 2.5 | 15.4 | 1.44 | 1.8 | 12.5 |
| m2 | 2.79 | 2.3 | 37.9 | 1.92 | 2.4 | 30.8 |
| m3 | 3.45 | 4.4 | 55.5 | 2.58 | 3.2 | 45.1 |
| m4 | 2.31 | 2.6 | 13.0 | 1.45 | 1.9 | 10.6 |
| m5 | 4.15 | 6.2 | 108.2 | 3.29 | 4.6 | 87.9 |
with triangles to differentiate between with regions with and without possible moss contribution. The EMDs for set 2 and set 3 appear very similar to those for AR 10939, except that we do not find the peak above log $T = 6.45$. This is because we do not have spectral lines at those temperatures (above Fe xvi temperature) in this study. (Tripathi et al. 2011 found that the core EM peaked at log $T = 6.55$ when observed on the disk.) Therefore, these data are not adequate for studying the active region core heating and also to probe the variation in the slopes of the AR core with background subtractions using an averaged diffuse region EMD, as was done with AR 10939. However, this region is still useful for studying the diffuse region due to the fact that the EM for the diffuse region peaks at log $T = 6.25$, as established earlier for AR 10939 using the full spectral scan (assuming that the active regions are similar).

The bottom left plot in Figure 5 shows the EMD for diffuse regions, named set 1, comprising m1, m2, m3, m4, and m5. The peak of the EMD is again at Fe xiii at log $T = 6.25$. We determined the slope of the EM curves (between log $T = 6.25$ and log $T = 6.05$) for all five regions in set 1 and studied the ratio of hot (Fe xiii) to warm (Fe x, as well as Si vii) emission. The values are provided in Table 6. Figure 5 shows that the EM curves of set 1 (high-altitude diffuse emission) differ from the EM curves of set 3 (core) of AR 10961 by a factor of 2–3, which corresponds to roughly a factor of 2–3. Similarly, EM curves of set 1 differ from set 3 of AR 10939 by a factor of 2–4. The EMD itself is comparable or slightly larger for AR 10939 (Figure 4) when compared with AR 10961.

5. SUMMARY AND DISCUSSION

It has now been established that there is a significant amount of plasma at higher coronal temperatures that does not appear in a structured form, such as distinct loops, when viewed with current instrumentation. Rather, the plasma appears as diffuse emission spreading over a large area. The emission from coronal loops is only about 20%–30% higher than this fuzzy emission (see, e.g., Del Zanna & Mason 2003; Viall & Klimchuk 2011). Therefore, just explaining the heating of structured loops is not enough for understanding the heating of solar active regions in particular and the corona in general. This study aims at understanding the characteristics of these diffuse regions and their possible heating scenario. Keeping this science goal in mind, we have probed two active regions, AR 10939 and AR 10961, observed off limb on 2007 January 26 and 2007 July 8, respectively, using EM diagnostics techniques.

We have distinguished the diffuse emission region from the rest of the AR by tracking the AR from the disk center to the off-limb, which provided us with a better constraint for selecting topologically different areas within the AR. We have chosen different sets of masked regions, designated 1, 2, and 3, to isolate, respectively, diffuse emission regions, the boundary between the diffuse regions and the core, and the core itself. EMDs have been obtained for each of the masked regions using the Pottasch method (see, e.g., Pottasch 1963; Jordan & Wilson 1971; Tripathi et al. 2010a). We also compare the EMDs of such topologically different regions.

In EMDs, the slope $\alpha$ and the EM ratio of hot and warm plasma may indicate the possible mechanisms responsible for heating the plasma. For example, a shallower slope suggests that along a given line of sight, there are comparable amounts of hot ($\approx$few MK) and warm ($\approx$1 MK) plasma co-existing, implying a low-frequency nanoflare heating, often called simply impulsive heating. In comparison, a steeper slope indicates much less warm plasma than hot plasma, implying a high-frequency nanoflare heating, often referred to as steady heating, where the plasma is maintained at a given temperature. Much importance has been given to the estimation of the slope $\alpha$ for active region cores and has always been debated between low- and high-frequency nanoflare heating (Tripathi et al. 2010b, 2011; Winebarger et al. 2011; Warren et al. 2011, 2012; Viall & Klimchuk 2012; Dadashi et al. 2012; Bradshaw et al. 2012; Reep et al. 2013; Winebarger et al. 2013), while the diffuse emission associated with the AR has been poorly understood.

Guennou et al. (2013) showed that the uncertainty in the estimation of the slope can be ±1 and depends on both the atomic physics uncertainties and the number of spectral lines used to constrain the distribution. This may represent the upper limit of the errors involved. Tripathi et al. (2011) suggested the total uncertainty involved in the EM estimation to be $\approx$50%, which includes the radiometric and line fitting errors associated with intensities, and the uncertainties associated with the atomic physics and the Pottasch method.

The estimated power-law slope $\alpha$ and the EM ratios of all the diffuse emission regions studied here are given in Table 6. The EMDs of all these regions show that the EM peaks at log $T = 6.25$. The distributions show a monotonic increase from log $T = 5.6$ to log $T = 6.25$ and then starts to decrease at higher temperatures. In general, eight out of the nine diffuse emission regions analyzed here showed a power-law slope between 2.3 and 3.5, except for region m5 from AR 10961, which showed a much higher slope ($\alpha = 4.18$) and EM ratios (108 when taken with Si vii and 6.2 when taken with Fe x) than the others. The implications of the revised radiometric calibration vastly changes the earlier results. It produced comparatively shallower slopes in the range of 1.4 and 2.6 and lowers the hot to warm plasma ratio.

The EMD of the core regions, which can only be studied for AR 10939, shows consistency with previous studies. The peak of the EM is found to be around log $T = 6.55$, which is also consistent with the EM peak obtained in previous studies (Tripathi et al. 2010b, 2011; Winebarger et al. 2011; Warren et al. 2011, 2012; Winebarger et al. 2013).

A sample of masked regions chosen from both the active regions that are discussed in Tables 1 and 2 can be used to probe the variation of spectroscopic parameters like intensity, density, etc., along with the EMD slope ($\alpha$) as a function of distance from the core AR, which is just over the limb. These samples comprise m2 (set 1), m5 (set 2), m8, and m10 (set 3) for AR 10939 and m3 (set 1), m7 (set 2), m9, and m11 (set 3) for AR 10961, which fall as a strip that includes both the core plasma and the diffuse emission plasma above the core. Tables 1 and 2 clearly show that the intensities and densities decrease from the core toward the diffuse regions as a function of distance from the limb, in agreement with O’Dwyer et al. (2011). The power-law slope of those sample masked regions from AR 10939 are 3.0 (m2), 3.2 (m5), 2.4 (m8), and 2.7 (m10). Similarly, the slope of the sample masked regions from AR 10961 are 3.4 (m3), 3.5 (m7), 3.4 (m9), and 4.0 (m11). However, we note that the slopes determined in the core of the active region for AR 10961 do not represent the true EMD slope, as a full spectrum for this AR was not available. The highest temperature line in the available raster is Fe xvi, whereas the core emission peaks higher at log $T = 6.45$. Note also that these slopes were measured with the uncorrected data. Slopes measured with the revised calibration are smaller by about 0.9, at least for the diffuse regions where we have studied the differences.
Table 7
Average Power-law Slopes Obtained over Different Sets of Masked Regions of AR 10939

| Masked Regions | Power-law Slope (α) | Unrevised | Revised |
|----------------|---------------------|-----------|---------|
|                |                     | No BG     | BG subtracted | No BG | BG subtracted |
| set 1          | 2.95                | 2.08      |          | 3.52  | 4.29         |
| set 2          | 2.97                | 2.42      |          | 3.55  | 3.08         |
| set 3a         | 2.42                | 3.24      | 2.26     | 3.25  | 3.25         |
| set 3b         | 3.52                | 4.29      | 2.84     | 3.55  | 3.55         |

(Table 6). Based on the uncorrected data, we conclude that the slope does not have an obvious dependence on distance from the solar surface. Table 7 shows the average slopes of EMDs, with and without background/foreground subtraction, for AR 10939. A background/foreground subtraction from the unrevised and revised core EMDs, using an averaged unrevised and revised EMD of the studied diffuse regions, respectively, steepened the slope by ≈0.8 & 0.85. We stress that the background/foreground subtraction is uncertain due to the unknown variation of diffuse emission with altitude (both its horizontal line-of-sight depth and its emissivity).

The differences in the slopes between the two ARs can be attributed to the fact that they are two different ARs at different instances in their lifetime. At the time of observation, AR 10939 and AR 10961 were 6 and 13 days old (Solar Monitor). The heating properties of active regions (low- versus high-frequency nanoflares) have been shown to depend on the age of the AR (Schmelz & Pathak 2012; Ugarte-Urra & Warren 2012) and the magnetic field strength of the AR (Warren et al. 2012; Del Zanna et al. 2014). Significant errors can come from the difference in the number of spectral lines constraining the distribution (Guennou et al. 2013).

The slopes of the EMD curves and the hot to warm ratios for diffuse regions obtained in this study are within the range of values obtained for active region cores. These results suggest that the diffuse emission regions are heated and maintained in a way similar to the hot emission in the cores of active regions. The slope is similar among the different parts of the active regions (Table 7). The EM slopes of the diffuse emission outside the core are generally in the range of 2. Thus, they are consistent with both low-frequency and high-frequency heating, especially considering the uncertainties in the measurements. However, a more detailed analysis with many active regions and theoretical modeling should be performed before making any definite conclusions. The results obtained in this study provide further constraints on the properties of diffuse emission in active regions.

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