EVIDENCE OF WIDESPREAD HOT PLASMA IN A NONFLARING CORONAL ACTIVE REGION FROM HINODE/X-RAY TELESCOPE

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ABSTRACT

Nanoflares, short and intense heat pulses within spatially unresolved magnetic strands, are now considered a leading candidate to solve the coronal heating problem. However, the frequent occurrence of nanoflares requires that flare-hot plasma be present in the corona at all times. Its detection has proved elusive until now, in part because the intensities are predicted to be very faint. Here, we report on the analysis of an active region observed with five filters by Hinode/X-Ray Telescope (XRT) in 2006 November. We have used the filter ratio method to derive maps of temperature and emission measure (EM) both in soft and hard ratios. These maps are approximate in that the plasma is assumed to be isothermal along each line of sight. Nonetheless, the hardest available ratio reveals the clear presence of plasma around 10 MK. To obtain more detailed information about the plasma properties, we have performed Monte Carlo simulations assuming a variety of nonisothermal EM distributions along the lines of sight. We find that the observed filter ratios imply bi-modal distributions consisting of a strong cool (log $T \sim 6.3 - 6.5$) component and a weaker (few percent) and hotter (6.6 < log $T$ < 7.2) component. The data are consistent with bi-modal distributions along all lines of sight, i.e., throughout the active region. We also find that the isothermal temperature inferred from a filter ratio depends sensitively on the precise temperature of the cool component. A slight shift of this component can cause the hot component to be obscured in a hard ratio measurement. Consequently, temperature maps made in hard and soft ratios tend to be anti-correlated. We conclude that this observation supports the presence of widespread nanoflaring activity in the active region.

Key words: Sun: activity – Sun: corona – Sun: X-rays, gamma rays

1. INTRODUCTION

The solar corona, once thought to be heated in a quasi-steady fashion, has proven to be much more difficult to explain than early observations suggested. Developments over the last few years point to a different picture in which coronal loops are heated impulsively when a nanoflare occurs, but density is much slower to respond. By the time chromospheric evaporation has raised the density significantly, the coronal plasma has cooled to temperatures far below the peak value. Low densities combined with rapid initial cooling means that the hot phase contributes relatively little to the total emission measure (EM) of a heating and cooling event. Hydrodynamic simulations predict that the EM of the hottest plasma is 2–3 orders less than that of the dominant coronal plasma (Klimchuk et al. 2008). The emitted radiation is correspondingly faint. Ionization nonequilibrium effects may diminish the hot component even more (Reale & Orlando 2008; Bradshaw & Cargill 2006).

Recent observations suggest that very hot plasma may indeed be present at low levels in nonflaring active regions (Zhitnik et al. 2006; Urnov et al. 2007; Patsourakos & Klimchuk 2008; McTiernan 2009; Schmelz et al. 2009). We have therefore undertaken a focused investigation to determine as precisely as possible the amount of very hot plasma in one particular active region and to evaluate whether it is consistent with nanoflare heating. We use wide-band multilayer imaging observations (Reale et al. 2007) from the X-Ray Telescope (XRT; Golub et al. 2007) on board the Hinode mission (Kosugi et al. 2007). These observations have the advantage of a strong signal compared to spectrometer observations of individual spectral lines. The disadvantage is that each band is sensitive to a range of plasma temperatures. To distinguish hot from cool plasmas, we use different filter combinations as described below.

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The major problem is to screen out the dominant cooler emitting components which may inhibit the detection of the minor hot component. 

The XRT is sensitive to the emission of plasma in the temperature range $6.1 < \log T < 7.5$. The CCD camera has a 1 arcsec pixel and the FWHM of the point-spread function (PSF) is $\approx 0.8$ arcsec (Golub et al. 2007). We consider the same data as those already illustrated in Reale et al. (2007). The $512 \times 512$ arcsec$^2$ field of view includes active region AR 10923 observed close to the Sun center on 2006 November 12. The filters used were Al$_{\text{poly}}$ (F1), C$_{\text{poly}}$ (F2), Be$_{\text{thin}}$ (F3), Be$_{\text{med}}$ (F4), and Al$_{\text{med}}$ (F5), with exposure times of 0.26 s, 0.36 s, 1.44 s, 8.19 s, and 16.38 s, respectively. The selected data set covers 1 hr, starting at 13:00 UT, and the time interval between one exposure and the next in the same filter is about 5 minutes (12 images in each filter). This active region was monitored by the XRT all along its passage from the east to the west limb. It flared several times during this period. However, during the selected hour no major flare and no significant rearrangement of the region morphology occurred (the average of the root-mean-square (rms) intensity deviation of the individual pixels is $\approx 12\%$), so that we can average over the whole hour. We used the up-to-date standard XRT software to preprocess the data, including corrections for the read-out signal, flat-field, CCD bias. The observed images were co-aligned with a cross-correlation technique.

Each XRT filter has a different response to plasma temperature, described by a function $G_j(T)$, where $j$ indicates the filter order number. Thinner filters F1 and F2 are more sensitive to the emission of cooler plasma than thicker filters F4 and F5. Images of the same region in different filters provide information about the temperature of the emitting plasma. If the emitting plasma is isothermal and optically thin along the line of sight, the ratio between signals in thick and thin filters is a function of the temperature only. Reale et al. (2007) devised a special filter ratio from a combination of all available filters (combined improved filter ratio, CIFR), which optimizes for the signal-to-noise ratio (S/N) and reveals a very fine thermal structure of the active region.

The analysis presented here also considers several standard ratios of single filters, and we take an up-to-date filter temperature calibration with a special fine tuning to make the analysis entirely self-consistent (see Appendix). Figure 1 shows the temperature response functions of the filters. Five available filters allow to define 10 different ratios of single filters. We will exclude the ratio F2/F1 from our analysis because the dependence on temperature is double-valued over a large range. We are then left with nine relevant ratios. The six ratios with F2 and F1 in the denominator, and also CIFR, are able to diagnose plasmas down to $\log T \approx 6$, i.e., relatively cool plasma; the two ratios with F3 in the denominator down to $\log T \approx 6.2$; and the ratio F4/F5 down to $\log T \approx 6.3 - 6.4$. An important point is that the coolest plasma detectable by the last ratio is about twice as hot as the coolest plasma detectable by the first two ratios. The F4/F5 ratio is a monotonic function of $\log T$ in the range $6.4 \leq \log T \leq 7.5$. We have set minimum acceptance thresholds to compute the ratios. All pixels with signal below 200 DN/s for F1, 100 DN/s for F2, 30 DN/s for F3, 2 DN/s for F4, and 10 DN/s for CIFR have been masked out.

**3. ANALYSIS AND RESULTS**

**3.1. Data Analysis**

Figure 2 shows temperature and EM maps obtained with CIFR (left column) and with the hard (F4/F5) filter ratio. To improve the S/N, the F4/F5 maps are obtained after binning over boxes of $4 \times 4$ pixels. We have estimated the uncertainties on temperature and EM in each pixel from the photon counts derived from the DN in each filter, with a conversion factor obtained assuming an average spectrum at central temperature about $\log T = 6.7$ (the conversion factor does not change much in the range $6.5 \leq \log T \leq 7$). Error propagation to temperature and EM has been applied according to Klimchuk & Gary (1995). The uncertainties are globally consistent with the average rms fluctuations of the temperature and EM values of the pixels surrounding a given pixel (Reale & Ciavarella 2006).

The average errors in temperature and EM obtained from CIFR in each pixel are around 0.004 ($\sim 1\%$) and 0.015 in the log, respectively, in regions of high signal (e.g., soft-hot region, SH in Figure 4), and 0.008 and 0.03 in regions of low signal (e.g., hard-hot region, HH in Figure 4). The errors from F4/F5 in each $4 \times 4$ pixel box are around 0.05 and 0.2, respectively, in regions of high signal, and 0.1 and 0.25 in regions of low signal.

The difference in resolution and detail definition is immediately apparent: the softer ratio maps show much better-defined structuring. While the soft ratio detects plasma mostly in the range $6.3 < \log T < 6.6$, the hard ratio appears to detect hotter components to $\log T > 7$. In particular, we find hot plasma at the boundary of dense structures and in an extensive region on the center left of the active region, where the EM is instead low. We also notice that the temperature maps do not look similar, while the EM maps to some extent do, e.g., we find high EM in the same zones of the active region.
Therefore, we find different thermal conditions using different filter ratios. In particular, relatively hot regions in the CIFR and other soft filter ratios appear as relatively cool in the hard filter ratio. This is not trivially expected and deserves further investigation, that we will show later.

Our interest is also to exploit the multiband imaging observation to obtain quantitative information about the thermal distribution of the plasma both along the line of sight and across the active region.

Important information comes from the so-called EM versus temperature diagram (EM($T$), e.g., Orlando et al. 2000). This diagram is a histogram of the distribution of the EM in temperature bins. To build this histogram, we consider the maps of temperature and EM obtained with a given filter ratio and sum the EM of all pixels with a temperature in a certain bin. Figure 3 shows EM($T$) obtained from the relevant filter ratios, including CIFR; the bin size is the same as the temperature resolution of the filter response functions, i.e., $\Delta \log T = 0.1$. The distributions obtained with soft simple filter ratios and with CIFR mostly overlap: they are strongly peaked at $\log T \approx 6.4$ and fall by about three decades in a temperature range $6.2 < \log T < 6.7$. EM($T$) obtained with both the intermediate filter ratios F4/F3 and F5/F3 are similar to those from the soft filters, but differ in several respects: they are slightly shifted to higher temperatures (peaking at $\log T \approx 6.5$); they have a somewhat smaller amplitude; and they decrease with temperature less slowly on the hot side (decreasing by 2.5 decades at $\log T = 6.8$). EM($T$) obtained from the hard filter ratio F4/F5 peaks at the same temperature and with the same amplitude, but its hot tail extends to $\log T > 7$ still at about a few percent of the peak. The error in each EM value is negligible in this scale.

Our question is now whether the hot component found with the hard filter ratio is real or just, for instance, an artifact of higher uncertainties due to the shallow dependence of this ratio on temperature and to the lower photon statistics.

In order to investigate this issue, we first recall from Figure 2 that regions of enhanced temperature occur at different locations in the soft and hard filter ratio maps. The maps appear anti-correlated. Now we identify two $64 \times 64$ pixel ($16 \times 16$ boxes in F4/F5 maps) subregions that are reasonably homogeneous,
as indicated in Figure 4. The one to the left has enhanced
temperatures in the hard ratio map, and the one to the right
has enhanced temperatures in the soft ratio maps. We refer to
these as the HH and SH regions, respectively.

The EM(T) distributions obtained separately for the two sub-
regions are shown in Figure 5. We immediately see that they are
very different from each other. They are also qualitatively differ-
ent from the distribution for the whole active region. Their am-
plitude is much smaller because they include much less plasma.

EM(T) of the SH region (right panel) is narrow in all filter
ratios, including the hard ratio. None of the distributions has a
hot tail, with all dropping to essentially zero by log T = 6.8. The
peaks of the distributions are all clearly at a higher temperature
(log T ≈ 6.5 - 6.6) than those of the whole active region
(log T ≈ 6.4 - 6.5).

EM(T) of the HH region (left panel) is different in several
aspects. First, EM(T) of the hard ratio is considerably hotter than
all the others: it is quite broad and its peak is at log T ≈ 6.9 with
a hot tail extending beyond log T = 7. It appears to be detached
from the other distributions, and its amplitude is smaller by a
factor of 50. The EM(T) of the other filter ratios are consistently
narrow and peaked at log T ≈ 6.4 - 6.5. This is slightly cooler
than the peaks in the SH region. The small but clear temperature
difference is highly significant, as we will show. It explains the
anti-correlation that is evident in the hard and soft temperature
maps of Figure 2. The key result is that in regions where the hard
ratio extends to high temperatures (e.g., left frame in Figure 4)
the soft ratios peak at slightly lower temperatures than in regions
where the hard ratio is confined to cooler temperatures (right
frame in Figure 4).

It is important to remember that the plasma is multithermal
along each line of sight, whereas our EM(T) distributions
were obtained by assuming that it is isothermal. Important
questions are therefore: can we combine the information from
our measurements into a coherent picture? Are filter ratio
diagnostics reliable? Do they provide sensible information? Is
hot plasma really hot or are we being fooled by large errors
in T associated with the shallow ratio versus T curve of the
F4/F5?

3.2. Monte Carlo Simulations

There are multiple nonlinear effects that complicate the
derivation of temperature maps and EM distributions. These
include the nonuniform thermal distribution along the line of
sight, its variation from pixel to pixel, the differing sensitiv-
ities of the filters, and the nonlinear weighting of the thermal
components through the filter responses. In order to assess quan-
titatively all such effects we perform Monte Carlo simulations
including all realistic ingredients.

Our approach is to create synthetic images of approximately
homogeneous subregions similar to the HH and SH regions of
Figures 4 and 5, and then to generate EM(T) distributions exactly
as we did for the real data. We take the subregions to be 64 ×
64 pixels in size, and we assume that EM(T) along the different
lines of sight within each subregion are variations on the same
“parent” distribution EMlos(T). The parent distribution has a
parameterized form. We vary one or more of the parameters at
each pixel by randomly sampling from a probability distribution
(either normal or log normal). This gives us an input EMlos(T)
at each pixel from which we compute intensities corresponding
to observations made with the different filters. As a final step,
we modify the intensities with Poisson noise to mimic photon
counting statistics.

The EMlos(T) parent distributions are either single or double
step functions (top-hat functions). The amplitude (σEM) and
central temperature (Tlog T) of the step function can vary, but
its width (d log T) is fixed for the entire subregion simulation.

From the parent EMlos(T), we compute the corresponding
emission value for each of the five filters. We then randomize
the emission values, according to Poisson statistics on photon

Figure 3. Emission measure distribution vs. temperature for the whole active
region (with emission above threshold of acceptance) obtained from available
filter ratios: soft filter ratios (thin solid lines), CIFR (histogram), F5/F3 (dotted
line), F4/F3 (dashed line), F4/F5 (thick solid line). The latter is obtained from
the map binned over boxes of 4 × 4 pixels.

Figure 4. Maps of temperature as in Figure 2 obtained with CIFR (green scale)
and hard (F4/F5) filter ratio (blue scale). The red boxes mark the regions of
different temperature regimes analyzed separately: the one on the left is hotter
in the hard filter ratio (hereafter hard-hot region), and the one on the right is
hotter in the soft filter ratios (hereafter soft-hot region).
counts. The DN rate is first integrated on the exposure time to obtain the total DN counts. The DN counts are then converted to photon counts, which are randomized and then converted back to DN counts and DN rate. The five new DN rates are assigned to a pixel and the whole procedure is repeated 64 × 64 times to build a 64 × 64 pixel image.

The resulting image is analyzed as done for the real XRT images, i.e., derive temperature and EM maps with the filter ratio method and build the related EM(T). We apply the same rebinning, the same constraints, and the same acceptance thresholds as those used for the real data. We obtain an EM(T) distribution for each filter ratio.

We show end results of this procedure in Figures 6–9 in a format similar to—and with the same resolution as—that used in Figures 3 and 5. The histogram in each panel is the total distribution for each filter ratio.

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The effect is clearly to broaden the soft EM(T)’s. A spurious hot component appears in the hard filter ratio, but only for the cooler case, again due to poor photon counting statistics. An important conclusion is that observed distributions like those in the left panel of Figure 5 cannot be produced by single component input distributions: high temperature values in the hard ratio can only occur when the emitting plasma is all cooler than diagnosed in the soft ratios.

In Figure 8, two examples show the effect of adding the second hot component to the input EMlos(T). The stronger cool component has the same parent EMlos(T) as shown on the left of Figure 7. The parent EMlos(T) of the hot component, another step function, is centered at log $T = 6.8$ and has a width of $d\log T = 0.15$ on the left and 0.2 on the right. The input distribution is broadened further by randomizing the central temperature with $\sigma_{\log T} = 0.05$ and 0.1, respectively. The figure shows that the presence of the second hot and weaker component naturally leads both to an increase of the temperature of the EM(T) from the soft filter ratios and to the detection of a single peaked hot component from the hard filter ratio. The medium filter ratios F5/F3 and F4/F3 both produce a distribution with a peak around $T = 6.4$ but with a hot tail extending to $T \approx 7$. The distributions in the soft and hard filter ratios look very similar to the ones observed from the HH subregion on the left in Figure 3. The central temperatures, amplitudes, and widths all agree well. The high tails predicted for the medium filter ratios is not observed, however.

Figure 5. Emission measure distributions vs. temperature for the hard-hot (left) and soft-hot (right) subregions marked in Figure 4. Lines as in Figure 3.
Figure 6. Emission measure distributions vs. temperature obtained from Monte Carlo simulations of images in the five XRT filters of the active region observation. We show the parent EM(T) (histogram), and those obtained in the same filter ratios as those in Figure 3 and 5 (same lines), except for CIFR. From left to right and top to bottom it is assumed a single component parent EM(T) centered at log $T = 6.2$, 6.3, 6.4, and 6.5, respectively and a width $d \log T = 0.1$. The EM(T) is randomized only for the amplitude with $\sigma = 30\%$.

Figure 7. Same as Figure 6 but randomizing the EM(T) also for central temperature with $\sigma[\log T] = 0.1$ around log $T = 6.2$ (left) and with $\sigma[\log T] = 0.05$ around log $T = 6.4$ (right).
In our opinion, Figure 8 provides the best approximations to the EM(T) derived from the observed HH subregion, at least for the types of input distributions that we have so far explored. In particular, they produce a hot component in the hard ratio at the same time that they produce a cool component with sufficiently high temperature (peaking at log $T \approx 6.4$) in the soft ratios. These are important constraints that must both be satisfied. The total EM summed over temperature also agrees well with the observations, i.e., to within 20% for all filters except for F3 ($\sim 30\%$).

We now turn our attention to the SH subregion, whose EM(T) is shown on the right of Figure 5. In contrast with the HH subregion, all of the filter ratios, including the hard ratio, give a single quite narrow EM(T) distribution peaking at log $T \approx 6.5$. The left panel of Figure 9 shows that this distribution can be recovered from a narrow input EM$_{\text{los}}(T)$ with the same peak temperature. However, the right panel shows that it can also be recovered if the input EM$_{\text{los}}(T)$ contains a weaker hot component. The hot component is not detected even by the hard ratio because the much stronger cool component is hot enough to dominate the observed signal. This would not be the case if the cool components were slightly cooler, because the sensitivity of the hard filters is a steep function of temperature in this range. The hard filters are nearly blind to plasma cooler than log $T = 6.4$, and if this plasma were invisible, the hard ratio would be dominated by the hot component, even though it is inherently weaker (Figure 1).

Thus, the data are consistent with a picture in which a weak hot component is present everywhere, and the only significant difference between HH and SH type subregions is that the cool component is slightly cooler in the HH subregions.

4. DISCUSSION

In this work, we have analyzed an active region observed by Hinode/XRT in 2006 November, i.e., in the first phase of the Hinode mission. The observation is made with five filters which can be combined into 10 different but not entirely independent filter ratios to provide temperature diagnostics. We have optimized the S/N by averaging over 1 hr of observation,
i.e., 12 images per filter, in the absence of flaring activity and any other considerable variation. The new achievement is to include in the analysis the ratio of the filters of intermediate thickness (Be_med, F4, and Al_med, F5)—the thickest ones available in this observation—which screen out the emission of plasma below \( \log T = 6.3 \) and are sensitive, therefore, to possible weak hotter plasma components. We have derived temperature and EM maps for all filter ratios (except for the softest one) for the signal above a high acceptance level. By combining the values obtained at individual pixels, we have built EM distributions as a function of temperature which show evidence of a hot plasma tail up to \( \log T > 7 \). From inspection of the temperature maps, we realize that there is a clear correlation between regions detected as hot in the soft filter ratios and regions detected as cool in the hard filter ratio and vice versa (i.e., an anti-correlation).

To investigate this point further, we have first extracted the EM distribution from two regions of the different kind. The distribution of the former type is characterized by a single narrow component with the peak at \( \log T \approx 6.5 \) in all filter ratios. The distribution of the latter type is instead split into a cool component peaking at \( \log T \approx 6.4 \) detected by the soft filter ratios and a hot component at \( \log T \approx 6.9 \) detected by the hard filter ratio. In order to interpret this result correctly we have performed Monte Carlo simulations to build realistic synthetic XRT images in all five filters starting from model parent EM distributions along the line of sight. We find that both kinds of EM distributions derived from the data can be coherently explained with a single type of line-of-sight parent distribution consisting of a high cooler component at \( \log T \leq 6.5 \) and lower hotter component extending to \( \log T \approx 7 \). The difference between obtaining a single or split distribution is determined by the peak temperature of the cool component. If it is below \( \log T = 6.3 \), the hard filter ratio is able to detect the hot component, otherwise the cool component invariably obscures the other one.

We are unable to obtain a perfect match between simulations and data results for a variety of reasons. First, although we have performed a fine tuning of the hard filters calibration through detailed feedback on the data there is still room for some uncertainty. In particular, it is possible that the thickness of one of the intermediate filters is even smaller than obtained from the tuning, i.e., we have applied the minimum possible correction to obtain consistent results. This assumption is conservative and we may obtain even hotter EM component after applying possible less conservative corrections. Small calibration tuning on the F3 (Be_thin) filter response may improve the agreement of results from ratios involving this filter. Second, we have assumed very simplified forms of the parent EM distribution along the line of sight. The results are clear as such and do not require more refined forms. In any case, we prefer here not to push the temperature resolution of our EM analysis at any step beyond the one offered by the filter calibration, i.e., \( 0.1 \) in \( \log T \).

This also includes the randomization of the parameters. Finally, our analysis does not account for the inherent organization of the plasma in coherent magnetic loops. We do not pretend here to enter into the fine details of the EM distribution.

Going back to the morphology of the active region, we propose that hot plasma is widespread in the active region but that its detection depends somehow inversely on the local level of activity. In particular, the hot plasma may be difficult in high-pressure loops, where the dominant cool component is relatively hot, and easier to detect in fainter structures, where the dominant component is relatively cool. This scenario is consistent with what we find when we overlap the temperature maps obtained with the soft and hard filter ratios with an EM obtained with the 171 Å filter onboard Transition Region and Coronal Explorer (TRACE), which is sensitive to plasma at \(~1 \) MK. We immediately realize that the central green loops (in the SH subregion) are anchored to moss structures detected by TRACE which are typically interpreted as the footpoints of high-pressure loops (e.g., Peres et al. 1994; Fletcher & de Pontieu 1999). Longer loops detected by TRACE are clearly cool structures which occupy volumes complementary to the hotter structures detected with XRT. Hot (blue) regions are generally faint localized at the boundaries.

Our analysis has therefore revealed clear evidence for small quantities of very hot plasma that is widely distributed throughout the active region. The diagnosed temperatures are characteristic of flares (\(~10 \) MK) though no flares occurred within about 2 hr of the observations. This provides strong evidence for the nanoflare picture of coronal heating. The EM of the hot components (\( \log T \geq 6.6 \)) is about 3% of the cool one in both parent EM_\( \log T \)'s of Figures 8 (right) and 9 (right). We mention that similar results are obtained from the analysis of the same active region observed 2 days before (10 November), in a period when the region was even more quiet. We have run nanoflare simulations with our Enthalpy-Based Thermal Evolution of Loops (EBTEL) code (Klimchuk et al. 2008) and have no difficulty producing EM distributions with this property. A similar EM distribution has been also obtained in Reale & Orlando (2008) with a simulation of a loop heated by nanoflares localized at the footpoints and lasting for 3 minutes, taking deviations from ionization equilibrium into account.

The standard nanoflare model envisions that many unresolved strands at different stages of heating and cooling should coexist within close proximity of each other. It therefore predicts a broad EM distribution along each line of sight. (The distribution could be rather narrow for a bright coronal loop that is heated by a storm of nanoflares confined to a short time window.) Should...
nanoflares be ruled out in those parts of the active region where we find no detectable signal in the hard ratio? They cannot be ruled out for the following reason.

The hard filters are much more sensitive to hot plasma than to cool plasma. For example, the sensitivity of F5 is 10 times greater at 10 MK than at 3 MK. As noted above, however, nanoflare simulations predict an EM that is at least 100 times smaller at the hotter temperature. The observed signal will therefore be dominated by the cooler plasma. Even with the hardest filter, there is a tendency for small but significant amounts of hot plasma to be masked by more dominant cool plasma.

The hot component is a minor component of the total EM distribution, much smaller (about 3%) than the cooler ~3 MK dominant component. The small EM of the hot component explains why it has been so elusive so far: it is overwhelmed by the cooler component along the line of sight and can be detected only after cutting the cool component off. This screening is efficient but not completely performed through the single thick filters: the EM(T) distribution obtained with the ratio of the filters shows that most but not all of the dominant 3 MK plasma is masked out. The final cut is allowed by the temperature diagnostics provided by the filter ratio.

In conclusion, the thick filters of Hinode/XRT detect hot flare-like plasma in an active region outside of proper flares. This plasma is widespread and steady, and its amount is consistent with that predicted by nanoflare models, which receive great support here as candidate to explain coronal heating.

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APPENDIX A

FINE TUNING OF FILTER CALIBRATION

In this paper, we use the recently updated XRT filter thickness calibration (N. Narukage et al. 2009, in preparation). The high quality of the XRT observations here analyzed allows to test this new instrument calibration. While changes in transmissivity with respect to the old calibration are in general limited for all the filters used here (of the order of up to about 15%), the effect on the temperature and EM diagnostics can be significant. This is particularly true in the case of the ratio of hard filters (F4/F5) which spans a rather narrow range compared to other filter ratios.

By comparing the distributions of measured filter ratio values with ratios expected from the filter temperature responses for all filter combinations, we can investigate possible inconsistencies. In our data, we find that with the new calibration the ratio of the two thickest filters yields values in a range not entirely compatible with the expected range, as shown in Figure 11. None of the other filter ratios present similar obvious mismatches. The left panel of Figure 11 shows the distribution of measured F4/F5 ratio values, while the right panel shows the expected filter ratio as a function of temperature according to the official calibration (dashed line) and after the corrections that we devised here (solid line, the cool branch marked by the dotted line is excluded for the temperature diagnostics); the horizontal line represents the peak of the observed ratio distribution. This shows that for a large number of pixels the measured ratio of hard filters lies outside the range of values allowed by the current release of the filter calibration, pointing to an obvious problem with the temperature response of one or both involved filters.

We therefore devised a procedure to empirically estimate a correction factor needed to bring the observations back into agreement with the expected values and investigated the plausibility of this correction. We find this correction factor with an iterative method: we use the distribution of EM as derived from the thick filter analysis as input to synthesize the expected

Figure 11. Left: distribution of F4/F5 ratio pixel values of the observed active region. The peak is normalized to one. Right: dependence of F4/F5 ratio values on temperature (log) as computed with the current release of the filter calibration (dashed line) and after the fine tuning from feedback with the data, described in this Appendix (solid line, dotted below log $T = 6.4$). The horizontal line marks the peak of the distribution in the left panel.
As a further step, we examined all other filter ratios to extract additional information potentially useful to determine which filter is most likely responsible for the mismatch with observations, and therefore it is most sensible to correct. Figure 12 shows the expected filter ratios for eight filter combinations, using the new calibration after our correction. The horizontal lines in each plot delimit ranges of the observed filter ratio distributions within 10% of the peak, and the vertical lines indicate the corresponding temperature range. As expected, the ratios of thin filters give consistent results. Before correction, the observed ratios of $F5/F3$ ($Al_{med}/Be_{thick}$) corresponded to a wider temperature range with respect to $F4/F3$ ($Be_{med}/Be_{thick}$), in particular covering higher temperatures. This is not expected considering that $F4$ should be relatively more sensitive to hotter plasma than $F5$, as indicated by their ratio as a function of temperature (see Figure 11). We interpret this as a possible suggestion that the $F5$ filter response is the one needing the most significant correction. We find that the correction factor of $\sim 10\%$ found with the procedure described above yields more consistent results. Therefore, in our analysis we assume an increase of about 10% to the response of the $F5$ filter while the response curves of all other filters remain as provided by the current XRT calibration. We note that this correction factor is quite reasonable as it corresponds to a variation in filter thickness of about 3%, which is compatible with the uncertainties in filter thickness as derived through laboratory measurements.

Finally, we apply a minor correction to the filter responses to correct an artifact of the too coarse temperature resolution for the definition of the temperature responses. As shown in Figure 11 (dashed line) the ratio of the medium filters presents an inflection around $log T \sim 7.0$ due to the insufficient temperature resolution around the peak of the filter responses. This causes an artificial dip in the derived distribution of EM. We find that a small correction ($< 2\%$) is sufficient to correct for this problem, as shown in Figure 11. Further minor corrections are applied in the low temperature range to obtain further minor improvements. The final correction factor between the current calibration release and our procedure is between 5% and 10%.

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Figure 12. Dependence of ratio values on temperature (log) as computed after finely tuned calibration for eight different filter ratios. The dashed horizontal lines mark the ranges of the observed filter ratio distributions (as the one shown in Figure 11) within 10% of the peak. The dashed vertical lines bound the corresponding temperature ranges.

emission in each of the two filters, and then apply correction factors to the filter temperature responses in order to reproduce the observed distributions of emission observed in both filters. From the inspection of the changes of the filter responses between the original and the newly released calibration, we find that for most filters the changes in assumed filter thickness roughly correspond to a constant scaling factor (at least in a range of temperatures where the response is highest), and therefore we consider a sensible choice to modify the response by applying a simple scaling factor. At this stage the correction can be applied indifferently to any of the hard filters. Operatively, we chose to act on the $F4$ filter by increasing its response in steps of 5%. We found that an increase by about 10% allows to match the observed values. We note however that this is the minimum correction factor needed.