The Role of Magnetic Field Disturbances in the Heating of Active Region Loops

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Abstract. Hot emissions from coronal plasma with $T > 4$ MK are examined in two active regions observed by the Atmospheric Imaging Assembly (AIA) on the Solar Dynamic Observatory (SDO). The intensity maps in Fe XVIII 94 Å are created and the emission intensity in the brightest loops in these regions are measured. The corresponding magnetic maps of these active regions are constructed using the magnetograms from Helioseismic and Magnetic Imager onboard SDO. The photospheric magnetic field is characterized in terms of magnetic disturbances, such as flux emergence and flux cancellations in the surrounding sunspots, and the total magnetic flux is measured. The energy giving rise to high-temperature plasma is found to be deposited in the corona as a result of magnetic reconnection, likely caused by the dynamics of the magnetic field at the photosphere. The observations confirm that the hot plasma is strongly correlated with magnetic flux emergence or cancellation.

1. Introduction
The solar corona with a temperature of one million degrees Kelvin is 200 times hotter than the chromosphere, its lower boundary. The part of the solar corona that is topologically connected to active regions is responsible for most of the energy released in the corona [1–3]. Within the corona, the core of active regions encompasses closed magnetic fields with temperatures above 4 MK. To maintain this temperature against radiative losses, energy is continuously supplied to the corona [4]. The origin of this energy is thought to be magnetic fields generated at the photosphere, which in combination with the dynamic processes at the chromosphere, create an efficient mechanism that could transfer the energy to the corona. How this energy is dissipated in the corona is a matter of strong debate between competing coronal heating theories.

There are two major theories, usually referred to as reconnection models and wave heating models [5]. The main questions these theories are concerned with are how the free magnetic energy or wave energy dissipates and what the origin of these energies is. In reconnection models, the energy is released at tangential discontinuities between magnetic configurations displaced by continuous random foot-point motions [6]. The magnetic energy pumped into the field is then either released in real-time or stored in the field to be released later. As a result, plasma heating can be either steady, referred to as nano-flare heating, or transient, known as flares [5, 7]. The magnetic reconnection models are credited with heating plasmas to high temperatures.

In wave heating models, the interactions between magnetic field lines and the convective flows at the photosphere generate waves that travel along the magnetic field lines releasing their energy in the corona [8–14]. The wave heating models, such as Alfvén wave turbulence models developed by [15, 16], can create sufficient heat to maintain a peak temperature of about 2.5
MK in the coronal part of the loop. However, the modeled heating is not strong enough to heat the plasma to a temperature of about 4 MK observed in the core of the active regions [17]. Therefore, it is certainly possible that a combination of both heating mechanisms is at work in the corona.

Observations of the solar corona with the EUV Imaging Spectrometer (EIS) and X-Ray Telescope (XRT) on Hinode and the Atmospheric Imaging Assembly (AIA) on the Solar Dynamics Observatory (SDO) have revealed that active regions have broad temperature distributions [17–21]. The distribution of coronal plasma with temperature is related to a physical quantity known as Differential Emission Measure (DEM). The DEM is defined as

$$\phi(T) = N_e^2 \frac{dh}{dT}$$

where $\phi(T)$ is the DEM, $N_e$ is the plasma density, $T$ is the plasma temperature, and $h$ is the distance along the line of sight [22]. Therefore, the measurements of the intensities of different ions from their respective spectral lines are used to determine the plasma’s DEM distribution as a function of temperature. The DEM curve derived from the observations is an important constraint for models of plasma heating [22].

For example, [17] measured temperature distributions in a sample of 15 active regions, in the areas between the loop footpoints, known as inter-moss regions. They analyzed observations of EIS and the Fe XVIII emission in AIA 94˚A, and showed that the temperature in the core peaked near 4 MK. Their results highlighted that the integrated high-temperature emission from the core correlates with the total unsigned magnetic flux of the region, while the emission at lower temperatures is inversely proportional to the magnetic flux. [23] examined high-temperature emissions from several active regions observed by XRT and AIA on 2014 December 11. Their DEM analysis provided observational constraints in the temperature of the active-region cores.

The first active region in this study was analyzed by [24]. The authors used observations from the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) sounding rocket instrument. They observed a pervasive, faint Fe XIX 592.2 Å line emission formed at 8.9 MK over an area of more than 60% of the active region size. They associate this high temperature with nanoflares occurring on individual sub-resolution strands within coronal loops.

[25] also observed the second region in our study, AR 12234, on 2014 Dec 11, during the second suborbital rocket flight of the Focusing Optics X-ray Solar Imager (FOXSI-2), which observed the Sun in hard X-rays. They used a combination of XRT and FOXSI-2 data and measured the DEM distribution of the coronal plasma in this region. They found the DEM to decrease from about $10^{22} \text{ cm}^{-5} \text{ K}^{-1}$ at temperature $T = 3 \text{ MK}$ to about $10^{14} \text{ cm}^{-5} \text{ K}^{-1}$ at $T = 20 \text{ MK}$. The DEM distribution in the temperature range 4-10 MK was approximately a power law. These highly sensitive FOXSI-2 observations provide strong evidence for the high-temperature plasmas in the cores of active regions. [25] attribute this high temperature in the coronal plasma to nanoflare heating.

In the present article, an observational study of the high-temperature plasma in the core of active regions is shown. The role of flux emergence and flux cancellation in triggering magnetic reconnection and the heating of the coronal loops is investigated.

2. Observations

The objective of this paper is to study hot plasma from two selected active regions, and show how the emission from these regions corresponds with complex magnetic structures such as flux emergence or flux cancellations. We primarily use observations from AIA.

The AIA instrument is a normal incidence instrument that provides multiple simultaneous high-resolution, full-disk images of the corona and transition region up to 0.5 $R_\odot$ above the solar limb [26]. The instrument has a 1.5-arcsec spatial resolution and 12-second temporal resolution.
and is sensitive to temperatures from 0.4 MK to 20 MK. Images in this paper are from the AIA 94, 171, 193, and 1700 Å channels. The AIA 94 Å channel includes emission from the Fe XVIII 94 Å spectral line, which is formed at a temperature of about 7 MK.

In our previous study, [27] analyzed 48 active regions. In this paper, the focus is on two of those active regions for detailed study. For the two active regions shown in Figures 1 and 2, the map of Fe XVIII 94 Å emission intensity $I_{\text{hot}}(x,y)$ is created. Then the brightest loop in the region is selected and the intensity at a distinct position along the loop is measured.

The AIA 94 Å wavelength is blended by warm plasmas with temperatures of 1-2 MK. [17] and [28] estimated the intensity of the warm plasma from the intensities of AIA 171 Å and 193 Å. It is measured as

$$I_{\text{warm}}(x,y) = 0.39 \sum_{i=0}^{3} a_i \left( \frac{fI_{171}(x,y) + (1-f)I_{193}(x,y)}{116.54} \right)^i,$$

(2)

where $x$ and $y$ are pixel positions, $f = 0.31$ is the relative weight of the 171 Å channel, and the scaling factors (116.54 and 0.39) have been introduced for convenience. All intensities are expressed in units of Digital Number (DN) per second per pixel. The coefficients $a_i$ of the polynomial are $-7.31 \times 10^{-2}$, $9.75 \times 10^{-1}$, $9.90 \times 10^{-2}$ and $-2.84 \times 10^{-3}$. The correct Fe XVIII intensity $I_{\text{hot}}(x,y)$ is inferred by subtracting $I_{\text{warm}}(x,y)$ from the observed intensity $I_{94}(x,y)$.

Figure 1. Time-averaged AIA intensity maps for the active region NOAA 11726 observed on 2013 April 23, dataset number 43 in [27]. Top panel shows the AIA image in (a) 171 Å, (b) 193 Å, and (c) 94 Å. Panel (d) shows the intensity map as predicted by equation (2). Panel (e) shows the corrected Fe XVIII intensity obtained by subtracting panel (d) from panel (c). The small red box is at the position where the intensity is measured. Panel (f) shows the co-aligned LOS HMI magnetogram. The red box is the area where the magnetic flux is measured.

The construction of the Fe XVIII intensity map is shown in Figure 1 for the active region NOAA 11726 observed on 2013 April 23. This active region was analyzed by [24] in Fe XIX 592.2 Å line emission with a temperature of 8.9 MK observed by EUNIS.
Panels (a), (b), and (c) show the AIA intensity maps observed in the 171, 193, and 94 Å wavelengths, respectively. The center of the maps has coordinates $X_s = 657.6$ arcseconds and $Y_s = 272.6$ arcseconds. To create these maps, we averaged the observed intensities over 100 frames, which is about 20 minutes of observations. The labels in each figure show the maximum intensity in DN s$^{-1}$ pix$^{-1}$. Figure 1(d) denotes the warm emission $I_{\text{warm}}(x,y)$ as predicted from equation (2), and Figure 1(e) shows the corrected Fe XVIII intensity $I_{\text{hot}}(x,y)$, which is obtained by subtracting panel (d) from panel (c).

In the moss regions where the warm emissions emanate, there exist both positive and negative signals with an amplitude of a few DN s$^{-1}$ pix$^{-1}$. Therefore, in the label of Figure 1(e), both the minimum and maximum values of the derived signal, $-11.4$ DN s$^{-1}$ pix$^{-1}$ and $40$ DN s$^{-1}$ pix$^{-1}$, are included and the intensity is scaled accordingly. Figure 1(f) shows the LOS magnetogram.

The magnetic structure of this region is complex and has small scale mixed polarity features. The red rectangle is the area of the active region where a total magnetic flux of $20.3 \times 10^{21}$ Mx is measured. As the figure indicates, there is new flux emerging in this region. The high intensity in this region is possibly the result of complex magnetic composition marked by a large sunspot and flux emergence.

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**Figure 2.** Time-averaged AIA intensity maps for the active region NOAA 12234 observed on 2014 Dec 11, dataset number 48. Top panel shows the AIA image in (a) 171 Å, (b) 193 Å, and (c) 94 Å. Panel (d) shows the intensity map as predicted by equation (1). Panel (e) shows the corrected Fe XVIII intensity obtained by subtracting panel (d) from panel (c). The small red box points to the position where the intensity is measured. Panel (f) shows the co-aligned LOS HMI magnetogram.

Figure 2 shows the intensity maps and the LOS magnetogram for the active region NOAA 12234 observed on 2014 Dec 11. The center of the maps has coordinates $X_s = -168.6$ arcseconds and $Y_s = 86.4$ arcseconds. This region was studied by [25] who found the plasma to be heated to temperatures of above 10 MK. The mean intensity measured in the small red box (Figure 2(e)) is $19.4$ DN s$^{-1}$ pix$^{-1}$ and the total magnetic flux measured in the large red box (Figure 2(f)) is $6 \times 10^{21}$ Mx. The high intensity of this region is associated with a sunspot with a
complicated magnetic structure represented by entangled polarity and flux emergence. [25] associate this brightening with nanoflares that heat the plasma to temperatures above 10 MK. [29] consider this brightening to be due to the dynamic evolution of the magnetic field resulting in flux cancellation in the photosphere and ensuing magnetic reconnection in the chromosphere. The magnetic reconnection results in the heating of the coronal plasma.

3. Analysis
In our previous study, [27] used visual inspection of the intensity images and magnetograms similar to Figures 1 and 2 and categorized the magnetic complexity of 48 active regions based on the existence of sunspots, nonpotential structures, and the flux emergence and flux cancellation. They concluded that although sunspots and nonpotential fields likely play a role in the heating of the solar corona, the flux emergence and flux cancellation play a dominant role in creating the complex magnetic environment that precedes and triggers reconnection. Here, the focus is on the 48 active regions analyzed in terms of the existence of flux emergence and flux cancellation.

Figure 3. (a) Intensity $I_{\text{hot}}$ of the brightest Fe XVIII loops as a function of total magnetic flux $\Phi$ (for the active regions studied by [27]) according to flux emergence or cancellation parameter EC. The dashed vertical line indicates the dividing line between large and medium-sized regions, $\Phi = 1.5 \times 10^{22} \text{ Mx}$. (b) The cumulative distribution functions of Fe XVIII intensity for the medium-sized regions to the left of the vertical line. Kolmogorov-Smirnov tests indicate that the intensity depends significantly on the EC parameters.

Figure 3(a) shows the scatter plot for the intensity $I_{\text{hot}}$ of the brightest Fe XVIII loop in active regions versus the magnetic flux $\Phi$. The blue symbols illustrate evidence for emerging flux (EC = 1), the red symbols denote canceling flux (EC = 2), and the green symbols indicate there is neither (EC = 0). The figure shows that regions with intensities $I_{\text{hot}} > 10 \text{ DN s}^{-1} \text{pix}^{-1}$, tend to have larger magnetic flux, where $\Phi > 1.5 \times 10^{22} \text{ Mx}$ and they mostly have flux emergence or cancellation. Therefore, in our statistical investigation, we focus on the regions with $\Phi < 1.5 \times 10^{22} \text{ Mx}$ so that we can have an accurate understanding of the relation between the high intensity and the EC parameter.

Figure 3(b) presents the cumulative probability distributions of $I_{\text{hot}}$ for EC=0 (green curve) and EC> 0 (blue curve) with $\Phi < 1.5 \times 10^{22} \text{ Mx}$. The statistical method we use is the Kolmogorov-Smirnov (K-S) test. The K-S shows the difference between the distribution functions of the two samples. If the distance between the two samples is large, as is the case with
our datasets with $D = 0.765$, then the two samples are not drawn from the same distribution, and their dependence on each other is significant. Therefore, the dependence of $I_{\text{hot}}$ on the flux emergence and cancellation parameter is statistically significant.

4. Discussion

The coronal loops presented here have emission measure distributions that correspond to temperatures in the range of 8-10 MK. To maintain this temperature, energy has to be continuously supplied to the corona. The magnetic reconnection resulting from stressed magnetic field lines with large magnetic perturbations can inject the energy needed to heat the plasma to these high temperatures. However, the classic picture of magnetic reconnection [7, 30] where the granule scale footpoint motions of order of a 1-2 km/s braid and stress the magnetic field lines and result in nanoflares can not heat the plasma to temperature $> 4$ MK. Alternative mechanisms for injecting energy into the corona and creating stronger nanoflares need to be proposed.

In this study, it was shown that high-temperature emissions are observed at the core of the active regions. The intensity of the brightest loop for the active regions was measured. Using the results from this study in combination with our previous study [27], we found a strong correlation between the intensity $I_{\text{hot}}$ and the magnetic complexity of these regions, in particular with magnetic flux emerging or canceling in these regions. This study confirms that the complex mixed-polarity fields that exist at the feet of coronal loops and the magnetic flux cancellation at the footpoints of these loops could heat the active region cores.

The flux emergence into the corona from the convection zone and the interaction between the newly emerging field with the preexisting field could produce intense reconnection events in the corona between the old and new flux systems [31–36].

In this study, the intensity of the hot plasma ($T > 4$ MK) identified as the brightest point in the core of the active regions was measured. However, most of the plasma observed by AIA has temperatures in the range of 1-3 MK. Some of the regions studied by [27] were found to have intensities $I_{\text{hot}} < 3$ DN s$^{-1}$ pix$^{-1}$ corresponding to this lower temperature range. These regions usually do not have a complex magnetic structure. Therefore, the source of energies in these active regions could be the small-scale footpoint motions at the photosphere. There are 3D MHD models of the coronal loops based on solar granulations that can produce 1-3 MK temperatures in the active regions [15, 37, 38]. Although these models can not heat the plasma to temperatures of $> 4$ MK observed in the active regions' cores, they are capable of heating the plasma to temperatures of 1-3 MK.

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