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Heating of active region cores: Impulsive or steady?

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Abstract. The question of active region heating has proven to be highly challenging since its discovery in 1940s. The recent observational facilities have shed new lights towards the understanding of this problem. In this paper we review some of the new measurements to study the heating mechanisms in the hot core loops of active regions using the observations recorded by Solar Ultraviolet Measurements of Emitted Radiation (SUMER) onboard SoHO and the Extreme-ultraviolet Imaging Spectrometer (EIS) aboard Hinode. These new measurements show that the properties of hot core loops are consistent with by impulsive heating – low frequency nanoflare - scenario. However, the evidences are not strong enough to rule-out steady heating completely. Further measurement using better spectral resolution and temperature coverage is required, which will be provided by Interface Region Imaging Spectrometer (IRIS) and Solar-C in near future.

Keywords : Sun: corona – Sun: EUV radiation – Sun: magnetic field – Sun: dynamics

1. Introduction

The problem of solar coronal heating has been one of the most difficult subjects in astrophysics since its discovery in 1940s. In spite of major developments in observational and computational capabilities the solution remains illusive. See Klimchuk (2006) for an excellent review on the Subject. The problem of coronal heating can be defined in another way. Withbroe & Noyes (1977) estimated that total energy losses, including both radiative and conductive losses, is roughly 10^7 ergs cm^{-2} s^{-1} and 10^5 ergs cm^{-2} s^{-1} from active regions and quiet Sun respectively. Therefore, in order to sustain the corona and active regions, we must provide above amount of energy. Where and how does the energy come from is the main question.

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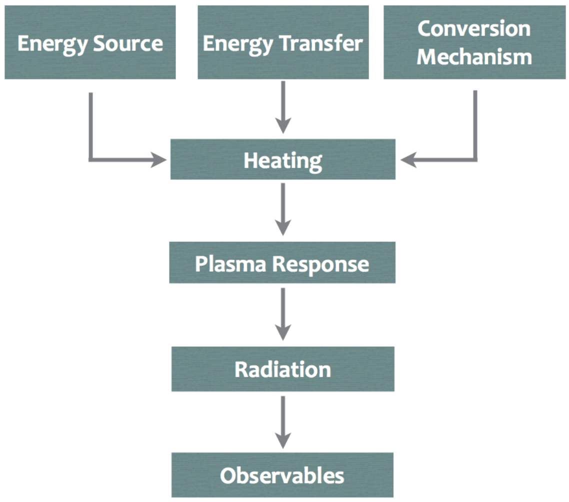

Figure 1. Flowchart describing the problem of solar coronal heating. The figure is adopted from Klimchuk (2006) and modified.

The problem of solar coronal heating can be divided into a few sub-problems as suggested by Klimchuk (2006). Fig.1 – adopted from Klimchuk (2006) and modified – shows a block diagram where each blocks correspond to one sub-problem. According to Fig.1, in oder to fully address the problem of solar coronal heating, first of all we must identify a source of the energy. Then we worry about how is the energy transferred from one layer of atmosphere to another. Finally, how does the conversion of the energy into heat occurs. The block diagram further suggests that once the conversion of energy into heat has taken place, the plasma responds to the heat and radiation starts. How exactly the plasma responds is another fundamental problem. The radiation from the plasma can be recorded using direct imaging and/or spectral imaging of the solar atmosphere which can be studied in detail.

Simultaneous multi-wavelength observations of solar atmosphere from photosphere to the corona reveals that all the structures seen in the upper atmosphere – chromosphere, transition and corona – of the Sun are strongly associated with strong magnetic field regions seen in the photosphere Fig.2 displays images of different layers of atmosphere simultaneously recorded. As can be concluded, the regions where the sunspots are seen in photospheric observations (bottom left image) show a variety of structures in the other images showing chromosphere and corona. In addition, those are the brightest regions in the upper atmosphere. This suggests that the ultimate source of energy is magnetic field, which is rooted in the photosphere and being churned around due the highly turbulent convective motions. The convective motion in-turn perform mechanical work on the magnetic field lines which will increase free energy in the corona with a rate given by Poynting flux. Choudhuri et al. (1993) showed that this energy is more than sufficient to heat and sustain the corona.

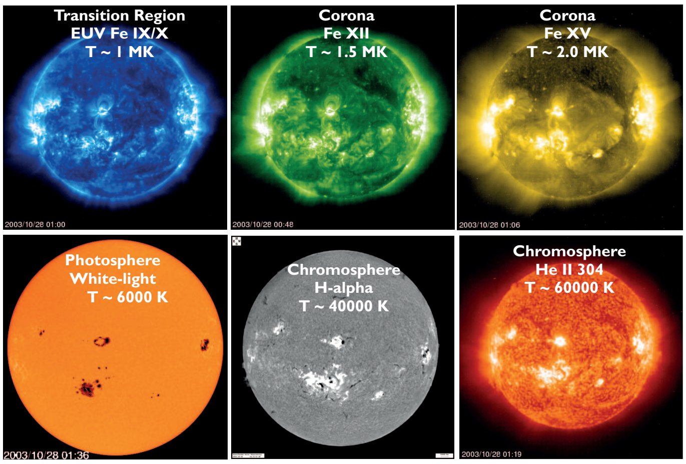

Figure 2. Layers of solar atmosphere imaged simultaneously on 28-October-2003 at different wavelengths. Images are courtesy SoHO MDI, EIT and Kanzelhöhe Solar Observatory.

However, conversion mechanism of free energy to heat is unknown. Parker (1983, 1988) suggested that due to continuous manipulation of the footpoints, the coronal field lines will be braided leading to formation of numerous small scale current sheets and energy release may take place impulsively by means of magnetic reconnection.

The continuous movement of footpoints due to convective motions will also give rise to different types of magneto-hydrodynamic (MHD) waves. These waves can also carry energy to the upper atmosphere. Recently different modes of MHD waves have been observed in the photosphere and chromosphere having energy much larger than it is needed to heat the corona (see e.g., Morton et al. 2012). Different mechanisms have been proposed for dissipation of waves such as phase mixing, resonance absorption etc. Antolin et al. (2008) showed that dissipation of waves is also highly impulsive process in transition region and corona. Therefore, the question remains as to how to distinguish between reconnection related energy release and wave related energy release.

2. Low-frequency and high-frequency heating

It has been suggested that if time scale of dissipation is smaller than Alfvénic time scale ($t_d < t_A$) then it is very likely that the dominant heating mechanism is wave related. However, if dissipation time scale is larger than the Alfvénic time scale ($t_d > t_A$) then it is most likely that the dominant heating mechanism is related with magnetic reconnection (see e.g., Walsh & Ireland 2003). It must be noted, however, that since there are very many different wave modes have been detected recently (see e.g., Morton et al. 2012), the dissipation time scale should be considered with respect to the time scale of other modes too in addition to Alfvénic mode.

Considering the above scenario, a detailed knowledge of the frequency of heating events can provide important constraints on the mechanism of coronal heating, i.e., heating related to magnetic reconnection might lead to low frequency dissipation (heating events) and wave related heating may give rise to high frequency heating events (see also Winebarger 2012). In order to distinguish between high and low frequency heating events, it is required to define them. In the low (high) frequency heating scenario, the time delay between two heating events is larger (smaller) than the cooling time of the plasma.

Let us consider a scenario where an observed "coronal loop" is comprised of a number of elemental magnetic strands and all the individual strands are evolving independently to each other. On one hand, if this system of magnetic strands are heated via low frequency events, one must observe loops cooling from high temperature to low temperatures and emission measure distribution of the plasma will be rather broad. This is specifically because in this scenario the strands will cool down significantly before it gets reheated again. In addition, there will a definite downflow of plasma - a signature of plasma condensation. On the other hand, in case of high frequency heating, the strands will get re-heated before they get time to cool down. Therefore, in this scenario, loop cooling will not be observed and the emission measure distribution will be narrow. Moreover, the complete loop system will be in quasi-steady state and there will be no plasma flows, although see Mariska & Boris (1983).

3. Observations of active region cores

Active regions, being the brightest regions in the solar corona provide excellent target of opportunity to study the coronal heating problem. The high resolution observations of the Sun suggest that active regions are comprised of different kinds of loop structures such as warm loops, hot loops and fan loops (see e.g., Del Zanna & Mason 2003). These loop structures are characteristically seen at different temperatures. Warm loops are mainly seen at 1 MK temperatures. These are large scale loop structures connecting the two polarities in an active regions. The fan loops are mainly seen at temperatures below 1 MK and usually emanate from sunspot regions and often connect regions away from the active regions, sometimes even trans-equatorial. The hot core loops are seen in the core of the active regions, again connecting the two polarities in an active region, but are seen at high temperatures such as 3-5 MK. In addition to all these loop structures, there are substantial amount of diffuse emission emanating from active regions Del Zanna & Mason (2003); Viall & Klimchuk (2012). In fact, the intensities in distinguishable loop structures are just about 20-30% larger than the background/foreground emission Del Zanna & Mason (2003); Viall & Klimchuk (2012). Therefore, for any coronal heating theory to be viable, it is important to explain the heating and maintenance of different kinds of loop structures along with the emission from diffuse regions.

There have been substantial progress in understanding the heating in 1 MK warm loops and their properties such as loop cooling, temperature distribution and characteristics of plasma flows appear to be consistent with low frequency heating (Winebarger et al. 2002; Warren et al. 2003; Tripathi et al. 2009; Ugarte-Urra et al. 2009; Klimchuk 2009, and references therein). The properties of fan loops are not well understood and therefore not much is known about their heating scenario (Young et al. 2012). The heating of hot core loops, however, has been a subject of hot debate, lately. The problem of heating in the hot core loops gets amplified because of its inherent fuzzy nature(Tripathi et al. 2009; Guarrasi et al. 2010). In addition, the current observational facilities do not allow us to distinguish one single loop in the core of active region.

It has been shown that the moss regions – seen primarily at transition region and lower coronal temperatures [1-2 MK] – are the foot points of the hot core loops seen at 3-5 MK . Therefore, much attention has been paid over the last decade to probe the heating mechanism in hot core loops by studying the properties of moss regions (Tripathi et al. 2010). Antiochos et al. (2003) studied the variation of intensities in the moss regions and found that the intensities did not vary by more than 10%. Warren et al. (2008) studied intensity variation in the hot core loops seen in X-ray images which was again unsubstantial. Tripathi et al. (2010) studied density and temperature structure in active region moss over a short period (few hours) and long period (5 days) and concluded that the density and temperature structure effectively remains the same. These observations provide strong evidence that the heating in the hot core loops is effectively steady. However, it should be noted that all these properties were derived for spatially averaged regions over a few pixels. Therefore, it may not be appropriate to conclude from these observations that the heating is steady.

Warren et al. (2008) also performed forward modelling of the intensities observed in various spectral lines observed in moss regions using a 1D hydrodynamic simulations based on high-frequency heating. Using this simulations, the intensities in high temperature spectral lines were well predicted but there were significant discrepancies

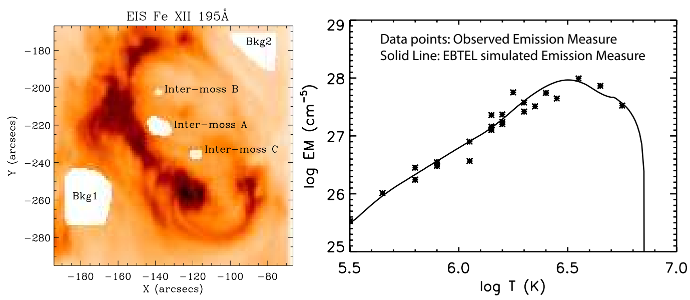

Figure 3. Left Panel: Image of an active region obtained in Fe XII 195Å. The inter moss regions as well as two background/foregrounds regions are labelled. Right panel: the asterisks are the average of emission measure distribution taking into account the background regions. The solid line is the EM(T) obtained using EBTEL simulation. The figure is taken from Tripathi et al. (2011) and modified.

between observed and predicted intensities at lower temperatures. However, just by considering an expansion factor at the footpoints of the loops [right in the transition region], the observed intensities became consistent with theoretically predicted intensities (Warren et al. 2010). Expansion with temperature in transition region has been observed in network regions using SUMER observations (Patsurakos et al. 1999). However, how these network observations are related to those in moss regions is not clear as these two are very different regions when compared topologically.

Since the above mentioned observations are all based on spatially averaged region, we should rely on methods to probe the heating mechanism which do not require a structure to be fully resolved. These methods are Emission Measure (EM), plasma flows (see e.g., Tripathi et al. 2010) and newly developed time lag analysis Viall & Klimchuk (2011).

3.1 Emission Measure

Emission measure provides an understanding of distribution of plasma at different temperatures. As has been stated above, a proper understanding of EM(T) distribution can help us to distinguish between high- and low-frequency heating scenarios by looking at how broad or narrow is the distribution. This has been performed for both moss (Tripathi et al. 2010; Tripathi et al. 2010) as well as for inter-moss regions. Moss regions are essentially the footpoints of the hot loops and inter-moss regions (Warren et al. 2011; Tripathi et al. 2011; Winebarger et al. 2011; Schmelz & Pathak 2012; Ugarte-Urra & Warren 2012) are essentially the coronal part of hot core loops.

In order to study the heating in hot core loops, emission measure distribution in inter-moss regions of a few active regions have been performed using the observations recorded by the Extreme-ultraviolet Imaging Spectrometer (EIS; Culhane et al. 2007) aboard Hinode. All these author quoted above have derived the cool-ward slope of EM(T) curve. The slope of the emission measure curve is essentially a measure of width of the emission measure distribution. The obtained slope varied from one active region to other being roughly 3.2 to 2.5. In addition the ratio between emission measure at $\log T = 6.6$ to $\log T = 5.8$ MK was obtained. It was found that the steeper the slope, the larger was the ratio. Steeper slope and larger ratio suggest that hot core loops are essentially heated by high-frequency nanoflares giving rise to quasi static nature of loops. On the other hand for some active regions, shallower slopes with smaller hot to warm ratio was found suggesting that the loops are heated by low frequency nanoflares.

The left panel of Fig.3 displays an active region image obtained in FeXII 195 Å. Three inter-moss regions which were chosen to derive the emission measure are shown in the left panel. In addition, two regions were selected for studying the contamination of foreground and background emission to the emission from inter moss regions and also their effects in the estimation of cool-ward slope of the EM curve.

The right panel shows the observed (asterisks) and theoretical (solid lines) EM distribution. The observed emission measure (asterisks) were obtained by averaging the EM for three inter moss regions and subtracting the average of EM for two background regions. In addition, effects of gravitational stratification in EUV loops (Aschwanden et al. 2001) were taken into consideration. For details, readers are referred to Tripathi et al. (2011). The theoretical emission measure (solid line) was calculated using EBTEL (Enthalpy based Temperature Evolution of Loops Klimchuk et al. 2008). The simulation was performed using loop half length 2.4×10^9 cm, duration of nanoflare 500 s, amplitude of nanoflare 0.04 erg cm^{-3} s^{-1} with a repetition time of every 8000 s. The loop half length was again estimated from the observations. The simulation mimic a low frequency nanoflare heating scenario. For details see Tripathi et al. (2011).

Warren et al. (2012) studied EM distribution in inter moss regions for a set of active region and found that the cool ward slope varied from one active regions to other. Schmelz & Pathak (2012) studied a few different active regions and found that slope of EM(T) curves for different active regions are different and they may be associated with age of active regions. Ugarte-Urra & Warren (2012) studied the evolution of EM(T) of the core with the age of the active region. They found that the slope was shallower when the active region was young, but became steeper in the later part of the evolution. This is suggestive of the fact that the active region was impulsive in the early phase of the evolution while it became more steadier with time.

3.2 Doppler shift Measurements

Tripathi et al. (2010) studied the EM(T) distribution in moss regions and compared that with the theoretical EM(T) obtained using energy equation in different extreme situations namely – static evolution (when conductive flux from the corona was balanced by radiative losses from transition region), strong evaporation (chromospheric evaporation was balanced by the radiation) and strong condensation (the radiation from moss region is powered by the enthalpy cooling). The observed EM(T) for moss region matched almost perfectly with the theoretical emission measure in case of strong condensation. This basically suggest that the strong intensities from the moss regions are due to strong condensation of plasma which may have been transported to the corona via chromospheric evaporation.

Considering that the above conclusion is valid, the spectral lines at intermediate temperatures [0.8-1.5MK] should show redshifted emission at all times in the moss regions. Recently a few studies have been performed to measure Doppler shift in transition region and coronal lines (Brooks & Warren 2009; Tripathi et al. 2012; Dadashi et al. 2012; Winebarger et al. 2013).

Tripathi et al. (2012) studied the Doppler shifts and its temperature dependence in moss regions using the observations recorded by EIS. In this study, the moss regions were distinguished by defining a low-density cutoff, which was provided by Tripathi

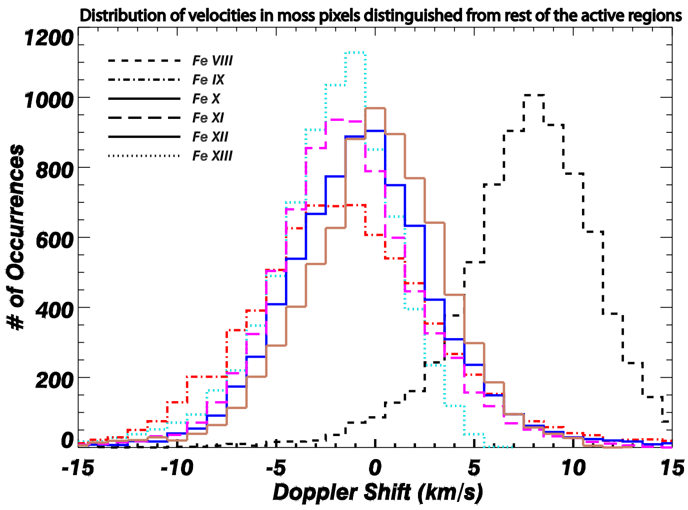

Figure 4. Distribution of velocity in mossy pixels simultaneously derived in different spectral lines. The figure is taken from Tripathi et al. (2012).

et al. (2010). A wavelength calibration method suggested by Young et al. (2012) was applied to data. The Doppler shift in spectral lines with maximum sensitivity between log T=5.85 and log T=6.25 K was studies. Fig.4 shows the velocity distribution in different spectral lines for mossy pixels. Tripathi et al. (2012) found that the velocity distribution peaked at around 0 km s^{-1} and width of the distribution decreased with increasing temperature. In addition, it was found that the mean distribution of the velocity showed blueshift which increased with temperature (see Fig.4). Dadashi et al. (2012) combined observation from SUMER/SOHO and Hinode EIS and studied Doppler shift in moss regions. They found blue shifted emission in moss region in high temperature spectral lines such as Fe XIII, Fe XIV and Fe XV this temperature range. The velocity of upflow (blue shift) increased with temperature. Unfortunately there were no cooler lines in the SUMER study, the Doppler shift could only be studied in hotter lines.

Winebarger et al. (2013) studied Doppler shift in moss regions using SUMER data where lower transition region lines such as C IV [log T = 5.0] and Ne VIII [log T = 5.7] were present in the observational sequence. A few different moss regions were selected in a single active region. All the three regions showed redshifted emission at these temperatures. Average redshifts in the Ne VIII emission line of ~5 km s^{-1} and average redshifts in the C IV emission lines of ~15 km s^{-1} was found respectively.

Combining the above three observations, namely of Tripathi et al. (2012); Dadashi et al. (2012); Winebarger et al. (2013), it is plausible to conclude that the Doppler shift in moss regions show a behaviour similar to that for quiet Sun region (Peter &

Judge 1999) except the Doppler shift in moss region changes from redshift to blue shift at 1MK. Further, the pattern of Doppler shift in moss regions i.e. redshift at lower temperature, turning to blue at around 1MK and increasing blue shift with increasing temperature seem to fit within the criteria of low-frequency nanoflare heating scenario.

4. Summary and discussion

The problem of heating of active region cores has lately attracted substantial attention of the solar physics community. The current measurements of emission measure of the hot core loops seems to give an impression that cores belonging to different active regions are different. Some of the emission measure distributions can be explained by high-frequency nanoflares and some by low frequency. The observations also suggest that there may be some age dependence on the EM(T) distribution (see e.g. Schmelz & Pathak 2012; Ugarte-Urra & Warren 2012; Tripathi et al. 2013). However, more studies are required to established this fact.

The Doppler shift measurements in moss regions and its behaviour of redshifts at lower temperature, turning to zero around a million degrees and eventually showing blue shift is one of the strongest evidence for low frequency nanoflares. The measurements done for moss regions so far is by combining SUMER and EIS which provides us with a broad temperature coverage to study this behaviour. Clearly more measurements are needed. In future the NASA's Interface Regions Imaging Spectrometer (IRIS) when combined with EIS will provide ultimate temperature coverage. This will help study the Dopper shift pattern over a broad range of temperatures. In longer future SOLAR-C will provide with unprecedented spectral resolution and temperature coverage to perform these measurements on more regular basis.

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