The 17th Annual International Astrophysics Conference
IOP Conf. Series: Journal of Physics: Conf. Series 1100 (2018) 012027
doi:10.1088/1742-6596/1100/1/012027

The Heating of Coronal Loops in Solar Active Regions

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Abstract. The active region corona is believed to be heated by magnetic disturbances that propagate into the corona from the convection zone below. A reduced magnetohydrodynamic (MHD) model of Alfvén waves in a coronal loop is presented. The waves are launched in the photosphere from a collection of kilogauss flux tubes, and they reflect at various positions along the loop, leading to counter-propagating waves and turbulence. It is found that turbulent Alfvén waves can produce only enough heat to maintain a peak temperature of about 2.5 MK, less than the temperatures typically observed in active regions (~ 4 MK). We consider an alternative model in which the flux tubes are subject to slow random footpoint motions, but we find that such braiding motions produce less heating than the waves inside the flux tubes. Therefore, models of coronal heating based on small-scale random footpoint motions cannot readily explain the observed high temperatures loops; more energetic “nanoflare” heating events are required. We suggest that such strong heating events may be produced by disturbances associated with flux emergence and large-scale non-potential fields.

1. Introduction
The solar corona is heated to temperatures of several million degrees. The strongest heating occurs in active regions (ARs), which contain closed magnetic loops that confine the coronal plasma. In recent years, the EUV Imaging Spectrometer (EIS) on Hinode has made it possible to measure the intensities of spectral lines from many different ions and determine the differential emission measure (DEM) distributions [1–7]. It was found that the DEM has its maximum value at a temperature of 3 – 4 MK. AR loops undergo continuous heating and cooling, which cause temporal variations in their emission [8–10]. The heating may occur in the form of small, impulsive heating events called “nanoflares” [11–14]. Originally, the term nanoflare was used to describe the sudden release of stored magnetic energy by magnetic reconnection, but more recently the term is used more generally and does not imply any particular physical mechanism. According to nanoflare models, an observed coronal loop consists of multiple strands, each in a different state of its temperature evolution. An important parameter in such models is the time delay between successive heating events on a given strand. If the delay is much shorter than the cooling time, then the temperature and density are approximately constant between heating events, and the heating is effectively steady (“high-frequency heating”). In contrast, if the delay is much longer than the cooling time, the plasma is heated to high temperatures (~ 10 MK) and then cools and drains without being reheated (“low-frequency heating”). Whether ARs have high-frequency or low-frequency heating is a matter of intense debate [15].
The mechanisms of coronal heating have been reviewed by many authors [16, 17]. The brightest loops in ARs are generally rooted in plage areas and sunspot penumbrae, but the loops rooted in sunspot umbrae are usually not very bright. This suggests that interactions of the magnetic field with subsurface convective flows play an important role in coronal heating process (convection is suppressed in sunspot umbrae). Plage regions contain small, kilogauss flux concentrations (“flux tubes”) surrounded by regions of weaker field [18, 19]. The interactions of these flux tubes with granule-scale convective flows are believed to create disturbances that propagate upwards along the magnetic field lines and inject energy into the corona. The details of these disturbances are still unclear. One possibility is that subsurface flows cause twisting and braiding of the coronal field lines, which leads to the build-up of magnetic free energy in the corona [20, 21]. Three-dimensional (3D) MHD simulations of braided fields have shown that thin current sheets are naturally formed in such fields [22–25]. Magnetic reconnection in current sheets may occur in a burst-like manner, producing “nanoflare” heating events [11, 26, 27]. Several authors have developed “realistic” models of magnetic braiding that are either based on observed magnetograms [28–31] or on results from flux emergence simulations [32]. Advanced radiative MHD models have been developed that extend from the upper convection zone into the corona [33–35]. Such models can reproduce many of the observed features of the corona, indicating that magnetic braiding plays an important role in coronal heating.

Theories based on wave heating of the corona also have a long history [36, 37]. Recently, observations have provided strong evidence for the existence of transverse and longitudinal MHD waves in the solar atmosphere [38–43]. The interactions of the photospheric flux tubes with granule-scale flows may create transverse MHD waves that propagate upward along the field lines and dissipate their energy in the corona [44–48]. Alfvén waves are of particular interest because they can propagate over large distances before giving up their energy. Transverse MHD waves can be dissipated in a variety of ways: (1) in the presence of density variations across the magnetic field the waves may be damped by resonant absorption [49–51]; (2) torsional Alfvén waves can interact nonlinearly with the background plasma to produce parallel flows and shocks [52–55]; (3) counter-propagating Alfvén waves interact nonlinearly to produce a turbulent cascade of wave energy [56, 57]. Alfvén wave turbulence (AWT) is believed to play an important role in the heating and acceleration of the solar wind [58–60], and reduced MHD models for the fast solar wind have been developed [61, 62]. In this approximation only the incompressible Alfvén waves are simulated, and other MHD waves are neglected.

Coronal loops may also be heated by AWT. Reduced MHD models have been developed in which the coronal loop is treated as a single magnetic flux tube that extends from the photosphere at one end of the loop to the photosphere at the other end [63–66]. The Alfvén waves are generated by small-scale footpoint motions inside the flux tube. Recently, we presented a more realistic version in which the loop is anchored in multiple flux tubes [67]. Full 3D MHD models of AWT have also been developed [68, 69], and such models show that the turbulent waves can drive strong plasma flows along the loop. In the present paper we review the results from recent loop modeling and discuss the implications for coronal heating. The main difference between the magnetic braiding model and the AWT model is the time scale of the footpoint motions: short-period motions with correlation times less than about 1 minute tend to produce transverse waves, whereas longer-period motions tend to produce magnetic braiding.

2. Coronal Loop Models

The dynamics of transverse waves in AR loops have been simulated using 3D reduced MHD models [63–67]. Horizontal “footpoint” motions are assumed to be present inside the kilogauss flux tubes in the photosphere on length scales of about 100 km, below the resolution of present-day telescopes. The random footpoint motions are caused by granule-scale convective flows, and are assumed to have velocities of about 1.5 km s$^{-1}$ and dynamical time scales of about 1 minute.
The footpoint motions create transverse MHD waves that travel upward along the flux tubes. For simplicity the waves are approximated as incompressible Alfvén waves that are confined to the interiors of the flux tubes, so that we can use the reduced MHD approximation. As the waves propagate upward in height, they are significantly amplified due to the density stratification in the photosphere and chromosphere. The upward propagating waves reflect due to gradients in Alfvén speed and create downward propagating waves. Nonlinear interactions between the counter-propagating waves cause a turbulent cascade of wave energy to small perpendicular length scales, where the energy is dissipated. Such dissipation occurs everywhere along the loop, and is assumed to be the main mechanism for coronal heating. At the chromosphere-corona transition region (TR) about 10% of the wave energy is transmitted into the corona and the remainder is reflected back down. Despite this strong reflection, the transmitted energy is sufficient to heat the coronal part of the loop to temperatures of about 2.5 MK.

![Figure 1. Magnetic structure of a coronal loop heated by AWT. Note that field lines (colored curves) deviate only slightly from the background dipolar field. The inset shows the magnetic flux tubes in the photosphere.](image)

Recently, a version of the AWT model was developed in which the coronal loop is anchored in a collection of photospheric flux tubes [67]. Figure 1 shows the magnetic geometry of the model: the colored curves show the magnetic field lines in the corona, and the inset shows the array of $4 \times 4$ flux tubes in the photosphere at each end of the loop. The flux tubes have square cross-sections and expand with height in the photosphere. Neighboring flux tubes merge at a height of about 520 km in the low chromosphere. The merged field extends from the chromosphere at...
one end of the loop to the chromosphere at the other end, so the TRs are located within the merged field (the coronal loop length \( L_c = 98.4 \) Mm). Alfvén waves with complex transverse wave patterns are generated by imposing random footpoint motions inside each of the 32 flux tubes. The waves are described using the reduced MHD approximation: the magnetic- and velocity perturbations are given by \( \delta B_\perp = \nabla h \times B_0 \) and \( \delta v_\perp = \nabla f \times \hat{s} \), where \( B_0(r) \) is the undisturbed background field, \( \hat{s} \) is the unit vector along \( B_0 \), \( h(r, t) \) is the magnetic flux function, and \( f(r, t) \) is the velocity stream function. The side boundaries of the flux tubes are fixed, and the normal components of \( \delta B_\perp \) and \( \delta v_\perp \) vanish at these boundaries; in the merged field we use periodic side boundary conditions. At the merging height the waves can travel from the flux tubes into the merged field or vice versa.

\[ \text{Figure 2. Heating rate in the AWT model, plotted as function of position } (x, y) \text{ in three cross-sections of the loop: at the merging height (MER1), the chromosphere-corona transition region (TR1) and the loop top (TOP). The upper row shows the heating rate at one instant of time } (t = 3000 \text{ s}), \text{ and the bottom row shows the time average over 2800 s. The color bars at the top show the heating rates on logarithmic scales.} \]

The nonlinear dynamics of the waves are simulated for a period of 3000 s. As in models with a single flux tube, AWT develops everywhere along the loop and produces significant heating in the corona. The magnetic perturbations at the loop top are only about 1 G, while the background field at the top is about 38 G. Therefore, the magnetic perturbations are relatively small and the field lines have small tilt angles relative to the background potential field (see Figure 1). Magnetic braiding does occur in the AWT model, but the braids are highly dynamic and not
close to a force-free state. This is a consequence of the fact that the lower atmosphere is included in the model. It takes about 41 s for the waves to travel from the base of the photosphere to the TR, and a comparable time (47 s) to travel through the corona, so the waves spend most of the time in the lower atmosphere. Also, the high density of the photosphere compared to the corona implies that all perturbations tend to be wave-like [66]. Another feature of the AWT model is that the energy injected into the corona is dissipated very efficiently (on a time scale comparable to the coronal Alfvén travel time), hence there is no long-term energy storage, as is assumed to occur in the magnetic braiding model.

Figure 3. Heating rate as function of time for a co-moving point at the loop top.

Figure 2 shows the spatial distribution of the heating rate $Q(x,y)$ in cross-sections of the loop at the merging height, the TR and the loop top. Note that the instantaneous heating rates (top row) vary by more than 2 orders of magnitude, and most of the heating occurs in thin current sheets and shear layers. At the merging height the strongest heating occurs near the fixed boundaries between the flux tubes (square grid), but in the corona the shear layers are produced by turbulence and are not strongly correlated with the tube boundaries at the merging height. Therefore, the effect of these boundaries does not extend to large height. At the loop top the time-averaged heating rate is nearly uniform across the loop (see lower right panel in Figure 2). Figure 3 shows the heating rate as function of time for a point moving with the turbulent flow at the loop top. Note that the heating is highly variable with strong heating events that occur whenever the tracked point passes through a current sheet or shear layer. The energy dissipated in such “nanoflares” is a combination of magnetic- and kinetic energy. There
are about 13 events with peak heating rates in excess of 0.004 erg cm\(^{-3}\) s\(^{-1}\) and durations of about 20 s, so each event produces about 0.08 erg cm\(^{-3}\). This is small compared to the thermal energy density at the loop top (\(E_{\text{th}} \approx 2.7\) erg cm\(^{-3}\) s\(^{-1}\)), so the simulated heating events are not expected to produce large temperature fluctuations in the corona.

The AWT model produces only enough heat to maintain the coronal loop at a pressure of 1.8 dyne cm\(^{-2}\) and peak temperature of 2.5 MK. As shown in Figures 2 and 3, the heating rate \(Q\) varies strongly in space and time, but the time-averaged rate is nearly constant across the loop and the temperature fluctuations are predicted to be small. In contrast, the observations show that ARs have broad DEM distributions and the peak DEM occurs at temperatures of 3 – 4 MK [2–4]. Therefore, the AWT model cannot explain the observed DEM distributions.

In the AWT model we assume that the side boundaries of the flux tubes are fixed in space, so the model does not take into account that the granule-scale flows also cause lateral displacements of the flux tubes. It is difficult to incorporate such displacements in a reduced MHD model. Therefore, we also constructed a “magnetic braiding” model in which the photospheric flux tubes are removed and the “footpoint” motions are applied directly at the merging height [67]. The imposed footpoint motions have an rms velocities of 1 km s\(^{-1}\), a correlation time of about 400 s, and a perpendicular length scale of 1100 km, which corresponds to a photospheric diffusion constant \(D \approx 200\) km\(^2\) s\(^{-1}\), consistent with observations [70]. We find that the imposed footpoint motions cause quasi-static braiding of the coronal field lines. The magnetic perturbations are again about 1 G at the loop top, similar to the AWT model. However, the magnetic energy is dissipated on longer time scales, and the heating rates involved are much smaller than those in the AWT model. We conclude that neither the AWT model nor the magnetic braiding model can reproduce the observed high-temperatures emissions.

3. Discussion

The broad DEM distributions observed in ARs are believed to be produced by “nanoflare” heating of plasma to temperatures of about 10 MK and subsequent cooling by radiative and conductive losses [15]. To heat a plasma with initial temperature \(T \approx 2\) MK and electron density \(n_e \approx 2 \times 10^9\) cm\(^{-3}\) to an electron temperature of 10 MK requires an energy input of at least 3.3 erg cm\(^{-3}\) per heating event. Equating this energy to the magnetic energy density \(\delta B^2/8\pi\) we find that magnetic perturbations with amplitude \(\delta B_\perp \sim 9\) G are required. Therefore, the magnetic perturbations needed to obtain high temperatures (\(T > 4\) MK) are significantly larger than the values \(\delta B_\perp \sim 1\) G predicted by the AWT and magnetic braiding models. Both models assume the energy input into the corona is provided by granule-scale convective flows acting on kilogauss flux tubes in the photosphere, and the small length scale of such flows (\(\sim 1\) Mm) compared to the loop length (\(\sim 100\) Mm) limits the amount of energy that can be injected. Therefore, it appears that granule-scale flows alone cannot produce the energy inputs for high-temperatures emissions, and other forms of energy input should be considered.

Bipolar ARs are formed by the emergence of \(\Omega\)-shaped loops in the solar atmosphere. During the growth phase of an AR a large amount of magnetic energy is injected into the corona, and new ARs are generally very bright in X-rays. In some ARs smaller magnetic bipoles continue to emerge for several days after the initial growth phase of the region [71]. The opposite polarities of these bipoles move apart over a period of several hours and interact with the other flux concentrations in the region. In the corona the newly emerged field is generally not aligned with the preexisting field, creating electric currents at the boundaries between the old and new flux systems, and the magnetic free energy associated with these currents may be released by magnetic reconnection. We suggest that heating associated with emerging flux is important for some ARs. As an example we consider AR 11726, which was observed with the Extreme Ultraviolet Normal Incidence Spectrograph (EUNIS) rocket instrument [72]. The observers found pervasive faint emission in the Fe XIX 592.2 Å spectral line, which is formed
Figure 4. Active region 11726 on 2013 April 20, three days before the EUNIS flight: (a) magnetogram obtained with SDO/HMI; (b) image in the 1700 Å channel of SDO/AIA.

at a temperature of about 9 MK. Figure 4 shows this AR three days before the rocket flight when the region was near the central meridian. Figure 4(a) shows a magnetogram obtained with the Helioseismic and Magnetic Imager (HMI) on the Solar Dynamics Observatory (SDO), and Figure 4(b) shows a 1700 Å image obtained with the Atmospheric Imaging Assembly (AIA) on SDO\(^1\). Note that away from the large sunspots the magnetic field is complex and contains many small opposite polarity features, which are part of recently emerged bipoles. Therefore, the mixed-polarity field in Figure 4(a) indicates that new flux is emerging in this region. We suggest that magnetic reconnection associated with emerging flux may be responsible for the high-temperature emission observed by EUNIS.

When observed in X-rays, many ARs show the presence of bright S-shaped or inverse S-shaped structures called “sigmoids” [73–77]. The magnetic field of a sigmoid can be described as a sheared arcade and/or a coronal flux rope lying horizontally over the polarity inversion line (PIL). The sigmoid field deviates strongly from the potential field, and contains a large amount of magnetic free energy \((10^{20} \sim 10^{32} \text{ erg})\). Sigmoids are often associated with H\(\alpha\) filaments, flares and coronal mass. The non-potential field can also be detected in photospheric vector magnetograms [78–80]. The energy build-up in the non-potential field may be due to photospheric flux cancellation [81] and/or magnetic reconnection in the corona [82]. It has been

\(^1\) http://www.suntoday.lmsal.com/suntoday
suggested that some of the heating in ARs may be due to the release of magnetic free energy associated with coronal flux ropes [83]. In this case the energy is already present in the corona, and does not need to be injected into the corona through photospheric footpoint motions. The free energy in a coronal flux rope may be sufficient to explain both the heating of the coronal plasma and the occurrence of flares and coronal mass ejections. A possible example is AR 11520, which was observed with the High-resolution Coronal Imager (Hi-C), the X-ray Telescope (XRT) on Hinode, and instruments on SDO [84]. The observers found rapid variability in “moss” regions at the footpoints of hot loops seen in the 94 Å channel of SDO/AIA, and in XRT images. They interpret this variability as a signature of heating events associated with reconnection occurring in the overlying hot coronal loops, i.e., coronal nanoflares. Some of the hot loops in this region overlie the PIL and deviate strongly from the potential field (see Figure 1 in [84]). This suggests that the nanoflare heating in these loops may derive its energy from the non-potential field, not from perturbations that propagate upwards through the footpoints.

In summary, reduced MHD modeling suggests that granule-scale convective flows cannot provide enough energy to heat AR loops to high temperatures \( T > 4 \text{ MK} \). To explain the observed broad DEM distributions, more energetic “nanoflare” heating events are required. Two possible mechanisms for producing strong heating events are discussed: (1) injection of energy by emergence of magnetic flux, and (2) the dissipation of energy associated with a large-scale non-potential field (e.g., in sigmoids). Further observational studies are needed to determine whether such processes play a significant role in producing the observed high-temperature emissions.

Acknowledgments
This project was supported under contract NNM07AB07C from NASA to the Smithsonian Astrophysical Observatory (SAO) and contract SP02H1701R from Lockheed Martin Space and Astrophysics Laboratory (LMSAL) to SAO.

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