What can observations tell us about coronal heating?

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The actual source of coronal heating is one of the longest standing unsolved mysteries in all of astrophysics, but it is only in recent years that observations have begun making significant contributions. Coronal loops, their structure and sub-structure, their temperature and density details, and their evolution with time, may hold the key to solving this mystery. Because spatial resolution of current observatories cannot resolve fundamental scale lengths, information about the heating of the corona must be inferred from indirect observations. Loops with unexpectedly high densities and multi-thermal cross-field temperatures were not consistent with results expected from steady uniform heating models. The hot ($T > 5$ MK) plasma component of loops may also be a key observation; a new sounding rocket instrument called the Marshall Grazing Incidence X-ray Spectrometer will specifically target this observable. Finally, a loop is likely to be a tangle of magnetic strands. The High Resolution Coronal Imager observed magnetic braids untwisting and reconnecting, dispersing enough energy to heat the surrounding plasma. The existence of multi-thermal, cooling loops and hot plasma provides observational constraints that all viable coronal heating models will need to explain.

1. Introduction

Solar physicists agree that coronal heating mechanisms involve the Sun’s magnetic field, but disagree on the details of how magnetic energy is transformed into thermal energy. Theoretically, it is relatively straightforward to heat the corona because the plasma density is low and the amount of thermal energy required quite small. There are numerous coronal heating models,
but the details that distinguish one from another manifest on small spatial scales that cannot be resolved by current observatories. This dilemma implies that direct observational constraints that can be applied to these models have been quite rare.

This situation, which had been the status quo for decades, changed with the launch of new instruments. X-ray imagers such as the Soft X-ray Telescope (SXT; [1]) and the X-Ray Telescope (XRT; [2]) not only could image coronal loops but also could determine plasma properties such as temperature and density as well as monitor cooling. Initial results from X-ray images indicated that loops were in static equilibrium [3]. After the launch of instruments such as the Extreme-ultraviolet Imaging Telescope (EIT; [4]) on the Solar and Heliospheric Observatory (SOHO), the Transition Region and Coronal Explorer (TRACE; [5]) and the Atmospheric Imaging Assembly (AIA; [6]) on the Solar Dynamics Observatory (SDO), solar physicists were somewhat surprised to see loops dominating the images. Figure 1 shows a dramatic example from TRACE. These loops have super-hydrostatic scale heights, serving note that our collective knowledge of coronal physics might need to be revised and updated. Observations of these extreme ultraviolet (EUV) loops began to appear in the literature that were not consistent with the steady uniform heating models that had been the standard since the days of Skylab [7-9].

Active region structures, the brightest and most well defined in the corona, are generally divided into four main groups, primarily characterized by their length, temperature and lifetime [10] (figure 2). The core of the active region is formed of many short, high-temperature (more than 2 MK) loops; these are easily seen in the X-ray images. The footpoints of these hot loops form a reticulated pattern in EUV images, called ‘moss’. The core loops are relatively steady over many hours of observations [11,12]. The longer loops that surround the core are evolving; these loops dominate million degree images, such as the AIA 171-Å image in figure 2, and are often called EUV loops, though they can be observed at X-ray wavelengths as well. Long-lived fans are cool, long structures that occur at the periphery of active regions most clearly observed in the AIA 171-Å image in figure 2. The diffuse background corona permeates all active regions; though there are no distinct loops present, the intensities in the diffuse background can be larger than loop intensities.

In this paper, we review the common observations associated with active region loops and what they can tell us about corona heating. These observables fell into three categories: (i) overdense loops, (ii) long-lifetime loops, and (iii) multi-thermal loops. Here, we use the definition that a loop is a distinct configuration in an observation and a strand is an elementary flux tube where the physical properties of temperature and density are constant perpendicular to
2. Flat temperature profiles

Observations of coronal loops made with these new EUV narrow-band imagers showed temperature profiles that were unexpectedly flat. Analyses of EIT [15] and TRACE [16] 171- and 195-Å images identified target loops and used a standard filter-ratio analysis to find temperature along the loop. The filter-ratio analysis techniques assume that every point along the loop can be characterized by an isothermal plasma; hence Intensity = Response(T) × EM, where T is the plasma temperature, EM = ∫ n_e^2 dl is the plasma emission measure, n_e is the plasma density and dl is the path length.

To find the temperature, T, from the filter-ratio method:

$$\frac{I_{171}}{I_{195}} = \frac{\text{Resp}_{171}(T)}{\text{Resp}_{195}(T)}$$

(2.1)

where $I_{171}$ and $I_{195}$ are the observed intensities and Resp_{171}(T) and Resp_{195}(T) are the temperature response functions of the 171 and 195 channels, respectively. The response functions are provided by the instrument teams and are similar for both EIT and TRACE. The intersection of the intensity and response ratios gives the temperature, which is (more often than not) equal to 1.2 MK. The result is the same, within uncertainties, for different positions along the loop and for different EUV loops observed by both EIT and TRACE. For many different examples, there is no significant change in temperature from the loop footpoints to the loop apex. An example of these results from TRACE is shown in figure 3 [17], which plots the temperature from the method described above normalized to the temperature at the loop apex as a function of position along the loop. The thick line is the distribution expected from the steady-state scaling law [7] modified for gravitational stratification [18]. The thin lines represent the results from observations. The eye is drawn to the few examples that slope down near the footpoints, but most of the distributions are extremely flat, significantly different from those expected from the Rosner–Tucker–Vaiana [7] models. Regardless of the accuracy of the filter-ratio method to determine temperature (see §5), these results indicate that the flat filter ratio along the loop was unexpected.
Figure 3. Normalized temperature versus loop half-length. The dark lower line shows the expected temperature relationship from the Rosner–Tucker–Vaiana (RTV) scaling laws [7]. (From [17]. Reproduced with permission of the AAS.)

3. Overdense loops

Using the plasma temperature calculated with the method described above, the emission measure, EM, can be determined with either individual intensity equation. Assuming the filling factor is 1 and the path length is equal to the loop width, the density is

$$n_e = \sqrt{\frac{EM}{w}}. \quad (3.1)$$

The density generally decreases from the loop footpoints to the loop apex, but many authors have found that these densities are far higher than those predicted by the static models that did a reasonable job of explaining the properties of X-ray loops [16,17,19,20]. Footpoint heating could increase the model densities, but only by a factor of 3 [20], nowhere near enough to account for the observations. The studies have found that these observations do not agree with results from the static solutions of the hydrodynamic equations with uniform heating, which predict a significant footpoint-to-apex temperature increase and corresponding density decrease [17,20]. These results again support that the EUV loops were not consistent with steady, uniform heating.

4. Lifetime

To account for the flat filter ratios and overdensities, it was suggested that EUV loops might be heated impulsively and cooling through the TRACE passbands [21]. This premise implied that the observed loop would appear in the hotter channel images before appearing in the cooler channel images. Figure 4 shows a light curve for a cooling TRACE loop [22]. The loop appears first in the TRACE 284-Å channel, the warmest of the TRACE channels, which is centred on an Fe XV line with a peak formation temperature of log $T = 6.4$. Later, the loop appears in the 195-Å channel, the intermediate temperature channel, which is centred on an Fe XII line with a peak formation temperature of log $T = 6.1$. Finally, the loop appears in the 171-Å channel, the lowest temperature channel, which is centred on an Fe IX line with a peak formation temperature of log $T = 5.9$. These types of light curves indicate that the loops are in fact cooling, as predicted [21].

Since the response functions of the EUV channels cover a range of temperatures, it was required to make some (reasonable) assumptions to estimate both the observed lifetime and the predicted cooling time of the loops [22,23]. They estimate that the appearance of the loop in a given channel corresponds to the time when the intensity of the loop becomes greater than...
Figure 4. Light curves for different TRACE filters. (From [20]. Reproduced with permission of the AAS.) (Online version in colour.)

half the maximum intensity and the disappearance of the loop when the intensity falls below half the maximum intensity. The lifetime of the loop in one channel is simply the difference between these two times, and the delay between the loop from one channel and the next is the difference in appearance times. The delay times allow the estimation of a cooling time. Analysis of TRACE observations [22,23], combined X-ray and EUV observations [24,25], and EUV Imaging Spectrometer (EIS; [26]) observations [27] found that the majority of the loops examined had lifetimes that were significantly longer than those expected based on the calculated cooling times.

Since the EUV loops have flat temperature distributions, the change in temperature along the loop, $dT/ds$, is approximately zero so the conductive loss rate, $E_c$, is also zero. Therefore, the conductive cooling time, $\tau_c$, is large, and the loop cooling will be dominated by radiation. Using estimates of temperature and density from the methods described above and the radiative loss function, i.e. the power emitted over all wavelengths per unit emission measure at a given temperature, the radiative loss rate, $E_r$, and, therefore, the radiative cooling time scale, can be estimated. (One could also compare the thermal and radiative cooling time scales using the common analytical estimates, e.g. [28], eqns 7a and 7b.)

Simulations of one of the evolving EUV loops using a one-dimensional hydrodynamics code show that the long lifetimes cannot be explained if the loop is composed of a single cooling strand [29]. As shown in figure 5, the observed light curve can be reproduced if the loop has several cooling strands, where each strand is heated sequentially and cooling independently. These simulations also reproduce an overdense loop with a flat filter ratio along its length. An observed loop can hence only be modelled as a single, impulsively heated and cooling strand if the observed loop lifetimes are consistent with the cooling time. Because most loops have lifetimes longer than the expected cooling time, most loops have to be multi-stranded.

With the launch of the Solar Dynamics Observatory and the availability of multi-channel, full-Sun images at high, consistent cadence from AIA [6,30], a new technique was developed to investigate the evolution of coronal structures [31]. This technique found the time lag that maximizes the cross correlation between lightcurves in two channels. Maps of the time lags show evidence of cooling throughout solar active regions [32]. These values were found to be consistent with impulsively heated and cooling models [33].

5. Multi-thermal

Since the plasma in each strand of a multi-stranded loop is physically isolated from the plasma in other strands, the temperature in each of these strands can be different. Using data from the
Coronal Diagnostics Spectrometer (CDS; [34]) on SOHO, it was found that an isothermal model could not reproduce the intensities of the spectral lines emitted by the loop structure [35]. The isothermal approximation described in §2 was not sufficient, and a full differential emission measure (DEM) analysis was required. The DEM results showed that the cross-field temperature distribution at each of the chosen pixels along the loop had to be multi-thermal.

Other results using a similar analysis verified that at least some loops observed by CDS were multi-thermal, and, therefore, multi-stranded [36–38]. Note: other loops were isothermal, e.g. [39]. Later results from EIS, which has better spatial and temporal resolution than CDS, were able to confirm the earlier results [40–43]. Finally, it was demonstrated that the flat temperature distributions described in §2 could be explained using the broad DEM distributions required to explain the CDS spectral line observations [44,45].

For multi-thermal plasma,

\[ I \propto \sum \text{Emiss}(T) \times \text{DEM}(T) \times \Delta T, \]  

where Emiss is the emissivity of a given spectral line. (Note: replace Emiss with Resp in the above equation for image data.)

Figure 6 shows an example for a loop observed with EIS using a method called DEM_manual [43,46]. It is a forward-fitting routine that folds a best-guess DEM through the EIS spectral line emissivities to generate a set of predicted intensities. No smoothing is required and no a priori shape (e.g. Gaussian; power law) is imposed on the final DEM curve. DEM_manual was first used to find the best isothermal fit to the background-subtracted loop data. These results are shown as the spike in figure 6a(i), where the emission measure is confined to one temperature bin. The diamonds in figure 6b(i) show the predicted-to-observed intensity ratios for the eight EIS iron lines using the isothermal solution. These results show that the isothermal model is not acceptable, with bad fits to the data and high values of reduced $\chi^2$, which is listed in the upper right corner in figure 6b(i)(ii)(iii). In figure 6a(ii), b(ii) an intermediate result is shown for the same data after the isothermal approximation is dropped and the emission measure is allowed in multiple temperature bins. Note the improvement in the predicted-to-observed intensity ratios and the reduced $\chi^2$. All the data points are now within one or two standard deviations of 1 except for Fe XVI, which is still too low. Figure 6a(iii), b(iii) shows the best fit.

The heating frequency in the highest temperature loops in the solar corona, those in the active region core, remains uncertain. Recently, it was found that the cool-side slope of the emission measure distribution could be used to constrain the heating frequency [47–49]. Several
measurements of the slopes of the emission measure have been made with mixed results [50–54]. These can be difficult to interpret due to contributions of overlying cool structures or the moss footpoints [50] and other errors [55].

6. Hot plasma

Hot plasma, with \( T > 5 \) MK, is predicted to be a natural consequence of nanoflare heating [56]. This material should be readily detectable in active region cores, even for non-flaring regions, and has been detected by a variety of instruments. Some examples include the Hard X-Ray Imaging Spectrometer on Solar Maximum Mission [57], the Mg XII imager onboard CORONAS-F [58], and the XRT on Hinode [59–61]. Note that there are also weak regions that do not show this hot plasma, e.g. [62].
The scientific goal of the Marshall Grazing Incidence X-ray Spectrometer (MaGIXS), a sounding rocket instrument proposed by the NASA Marshall Space Flight Center, is to determine the heating frequency in active region core loops by observing them in high-temperature spectral lines. One observation that MaGIXS will achieve is to determine the relative amount of high-temperature (8–10 MK) to average temperature (3–4 MK) plasma in the corona by observing the Fe XVII, XVIII, XIX and XX spectral lines on a single detector. Like the cool-side slope of the emission measure distribution (see §5), the hot-side slope also reveals the heating frequency. However, in this temperature range, background subtraction does not impact the results. As mentioned above, recent analyses have detected a hot plasma component to active regions (see also [63–67]), but the ability of current instrumentation to determine the high-temperature component of the emission measure distribution is limited [68–70]. Specifically, there exists a ‘blind spot’ in temperature-emission measure space for Hinode XRT and EIS; they cannot detect plasma with temperatures higher than 6 MK and emission measures lower than \(10^{27} \text{ cm}^{-5}\) [69]. Since it is the relative amount of the plasma at these temperatures that identifies the heating frequency, not simply the presence of high-temperature plasma, the MaGIXS-type data are required.

7. Braided loop

Above we have described observations that provide information to discriminate between different heating models. These types of observations are required because the spatial resolution of current observatories is limited and cannot resolve fundamental spatial scales, hence the heating process, in general, cannot be directly observed. The recent launch of the High Resolution Coronal Imager (Hi-C [71]), with an improvement in spatial resolution of approximately 3–4, may reveal some energy release processes [72–74].

Hi-C is a Ritchey–Chretien telescope with a 220 mm diameter primary mirror. The primary and secondary mirrors have a multi-layer coating that reflects only a narrow wavelength window around 193 Å. Hi-C has a similar wavelength response to the AIA 193-Å channel, but its effective area is 5.3 times larger in magnitude. Images are projected onto a 4096 \(\times\) 4096 back-illuminated CCD. The plate scale of the images is 0.1 arcsec/pixel; the field of view of the telescope is 6.8' \(\times\) 6.8'. The payload was launched at approximately 18.50 UT 11 July 2012 from White Sands Missile Range, NM, USA. Hi-C acquired 37 full-frame images from 18.52.49 to 18.56.10 with a 2 s exposure time (5.5 s cadence). The resolution of the images is a result of the point-spread function of the optics and the stability of the pointing control of the rocket. The initial seven frames were blurred due to rocket jitter. We estimate that the remaining 30 images have a resolution of 0.3 arcsec [71]. After the initial 37 full-frame images, Hi-C then obtained 86 partial frame images before the shutter door was closed.

Figure 7 shows a small area of the Hi-C field of view in a region of strong magnetic shear. Figure 7a is an AIA image with approximately 1.2 arcsec resolution. Figure 7b was taken by Hi-C,
and figure 7c is an un-sharp mask of the Hi-C image. The AIA data show a single solar structure, while the Hi-C images reveal significant substructures. The strands resolved in Hi-C appear to be braided and tangled [72]. The tangling and subsequent reconnection of magnetic strands has long been suggested as a method of coronal heating [75]. In the middle of the strand, a small energy release occurs shortly after Hi-C’s flight. These data suggest at least some of the corona is heated by energy released from tangled magnetic fields.

8. Conclusion

We find that observations are finally starting to contribute reliable constraints to coronal heating models. Coronal loops observed in lower resolution (less than 1 arcsec) instruments appear to be multi-thermal; this implies that the fundamental scale size of the loops must be smaller than these instruments can resolve. Indeed, the higher resolution observations made by Hi-C reveal subresolution strands in AIA loops. Additionally, the flat temperature ratio, overdensity and evolution are consistent with a short-nanoflare storm model, where bundles of strands are heated impulsively over a relatively narrow window in time [56]. However, this is by no means an unambiguous argument. Other heating models could reproduce these observational constraints, such as heating happening frequently near the footpoints of the loops. One clear distinction between these two heating scenarios is the presence of hot plasma, which is not easily detected with current instrumentation, but may be with MaGIXS.

The observations detailed in this paper provide constraints to duration, frequency and location of coronal heating. To make continued progress on this effort requires a parallel effort to develop more realistic and detailed models of the theoretical mechanisms themselves with the realistic geometry of the corona.

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References


