THE CORONAL HEATING PROBLEM

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ABSTRACT

The "coronal heating problem" refers to the puzzling fact that the Sun's corona is much hotter than the lower layers of the Sun, which lie closer to its energy-producing core. It would be shocking to find that as you moved away from a campfire the air became many times *hotter* than the fire itself, but this is similar to what happens in the case of the Sun. Over the last six decades, hundreds of theoretical models to explain the corona's high temperature have been proposed. There is still no obvious solution in sight, partly because many difficulties arise in trying to understand why the corona is so hot. For example, scientific models, which propose various heating processes that might solve the coronal heating problem, rely on being proven true or false by observations of the Sun. The best observations of the solar corona are performed by instruments onboard spacecraft that fly outside of the Earth's atmosphere, but spacecraft are incredibly expensive and take many years to develop and build. Only in recent decades has their use in studying the Sun become more practical. Despite these and other difficulties, we re-examine the coronal heating problem in this paper. We point out that spacecraft observations of the Sun show no evidence that the actual heating is occurring locally within the Sun's corona. Instead, observations suggest that the heating occurs in a two-step process. First, the gas-like material that makes up the Sun, called plasma, becomes heated below the corona in the lower layers of the Sun's atmosphere. Second, the heated solar material (plasma) then moves up into the corona along curved paths called coronal loops. Three pieces of new observational evidence for this two-step heating scenario are discussed in the paper: (1) the temperature evolution of coronal loops, (2) the overdensity of hot coronal loops, and (3) upflows in coronal loops[2]. By thinking about the coronal heating problem in terms of the two steps described above, it is possible to narrow down the number of theoretical models that could explain coronal heating in active and quiet regions of the Sun. Note, however, that our arguments do not apply to coronal holes and those parts of the corona which extend far away from the Sun, out into the heliosphere.

[1] This paper is an adaptation based upon Aschwanden, M.J., Winebarger, A., Tsiklauri, D., & Peter, H. (2007). The coronal heating paradox. *Astrophysical Journal*, *659*, 1673-1681; and Aschwanden, M.J. (2001). An evaluation of coronal heating models for active regions based on Yohkoh, SOHO, and TRACE observations. *Astrophysical Journal*, *560*, 1035-1044. Additional information was provided by the following text: Aschwanden, M.J. (2004). *Physics of the solar corona: An introduction*. Springer in association with Praxis Publishing. We thank Dr. Markus J. Aschwanden for his permission to adapt his scientific papers and textbook material for this outreach project. His enthusiasm and willingness to share good quality images from his publications are very much appreciated.

[2] The original paper, "The Coronal Heating Paradox," discussed ten pieces of observational evidence to support the two-step heating scenario.

1. INTRODUCTION

In the early 1940's, physicists Bengt Edlén and Walter Grotrian discovered the true source of strange emission lines in the spectrum of light from the Sun's corona. The emission lines had previously been attributed to a mysterious element, called "coronium," that was thought to exist only on the Sun, but Edlén and Grotrian found that they were in fact due to the presence of iron and calcium that had been stripped of many of their electrons (9 to 13 in the case of iron). For these atoms, the loss of so many electrons meant that the temperature of the Sun's corona had to be at least 1 million kelvins (1 MK). This was a surprising result, since the temperature of the photosphere below was known to be only about 6000 K. How can it be that the temperature of a hot, radiating object like the Sun *increases* as you move away from its center, instead of decreasing as we would naturally expect?

The counterintuitive fact that the Sun's corona is more than 200 times hotter than its lower boundary, the chromosphere, has puzzled solar physicists for over 60 years. The attempt to solve the coronal heating problem by determining and understanding the dominant heating processes in the solar corona has proved to be a difficult task. Many theoretical heating models have been developed by physicists, but difficulties arise because the ultimate test for any heating theory is whether its predictions match observations of the Sun's corona made by instruments onboard spacecraft. One such difficulty involves the spacecraft technology itself. Only since the 1960's has the technology been available to send ships into space to observe the Sun from outside the Earth's atmosphere. Even with sufficient technology in place, the design, implementation and launch of a spaceship make up an expensive and high-risk effort. Therefore, spacecraft missions focused on observing the Sun have not been numerous and the data required to test theories are not plentiful. In addition, some theories are based upon parameters that cannot be measured by existing spacecraft instruments and will not be measurable until scientists create new instrument technology, so these theories cannot currently be tested. Finally, the process of testing theory against experiment is made even more complicated by the fact that available observational data from spacecraft can often be interpreted in different ways. Thus, the acceptance or rejection of theories becomes the subject of scientific debate in the solar physics community and definitive answers to the coronal heating problem are delayed until new observations become available.

Consider a house that is heated by a centralized heating source, for example, a furnace in the basement. In this house, the heat generated in the basement is then distributed throughout the building via air ducts or water pipelines, and this is how the house stays warm. We would like to argue that in a similar way, the hot temperature of the Sun's corona is generated below the corona by a primary heating process located in the solar transition region or upper chromosphere. That is, the heat generation in the case of the Sun does not occur in the corona itself, but rather in the chromosphere below. The hot plasma from the chromosphere is then distributed upward throughout the corona along coronal loops, causing the corona to become very hot. Returning to the idea of a house, it could be said, however, that a centralized heating source in the basement is not required for the house to maintain a warm temperature throughout its rooms. Instead, the heating of the house could be accomplished by an external source. For example, sunlight shining down on the building's windows could cause the air inside to warm up. In a similar way, the Sun's corona could be heated by external waves that actually originate from below the Sun's atmosphere entirely, closer to the core. We will see, however, that such a scenario cannot explain many observations and so lacks observational support. Therefore, if we accept that the primary heating occurs below the corona in the chromosphere and/or transition region, with the hot plasma then being distributed upwards and throughout the corona along loops, then the phrase "coronal heating process" becomes a poor name for the whole procedure. The hot temperature of the corona is not caused by heating processes within the corona itself, but is merely caused by upflows of heated plasma from below.

2. CORONAL HEATING REQUIREMENT

In order for the corona to maintain its million degree temperatures, heat energy must constantly be supplied to it at a rate that matches how fast energy is lost by the corona. If this balance between energy rates were not maintained, then either the corona's overall temperature would continue to grow, or it would continuously cool down, but these cases are not observed. It is clear then that the corona requires a certain amount of energy to stay hot, and it is important to identify which regions of the Sun's atmosphere contribute the most heat energy to the overall energy requirement of the corona. Heating processes that occur in the regions that contribute the most energy to the corona become the most important processes for overall coronal heating. Once we identify these important heating processes, we are on our way to better understanding, and maybe even solving, the coronal heating problem.

To identify the regions of the Sun that contribute the most heat to the corona, it is helpful to examine a soft X-ray image of the Sun, shown in Figure 1 (top panel), that has been obtained with the Soft X-Ray Telescope (SXT instrument) onboard the Yohkoh spacecraft. In this picture, the X-ray emissions from the extended corona have been captured out to a distance of about 2 solar radii from the center of the Sun. Just as we humans use light in the visible wavelengths to observe regular objects around us, X-ray emissions recorded by special telescopes can show us what the plasma in the corona looks like, since the plasma radiates X-rays when it has temperatures exceeding about 1 million kelvins. The power per unit area, F_H, required to heat each of the 36 sectors (i.e., the energy required per second and per m^2) can be estimated from a careful analysis of the brightness of the corona in the soft X-ray Yohkoh image. On the image, the solar corona above the edge of the Sun's apparent "surface" (marked by the inner circle) has been divided into 36 sectors with 10º width each. This is much like cutting the image like a pie into 36 pieces, with the center of the pie located at the center of the sun. A series of analysis steps are then applied separately to each one of the 36 sectors, in order to determine the heating power per unit area required by each sector so that it can appear as bright in X-rays as it does in the picture. First, the brightness of the X-rays in the sector and how this brightness varies with height above the solar surface is compared to a model of the Sun (Aschwanden and Acton, 2001). Based on this comparison, the model outputs number values for certain physical quantities that describe the Sun, such as the electron density at the Sun's surface. The numbers obtained from the model can then be used to calculate the rate at which energy is being lost in that sector due to being radiated away in the form of light. Since the rate of energy loss must be equal to the rate at which heat energy is supplied, as we described earlier, we now know the rate at which heat energy must be supplied to that sector, F_H. When we have repeated this procedure 36 times, applying it to each sector, we are finally done, since we now have a numerical estimate for the rate at which energy is supplied to each and every sector. This is the power required per m^2, F_H, for each sector.

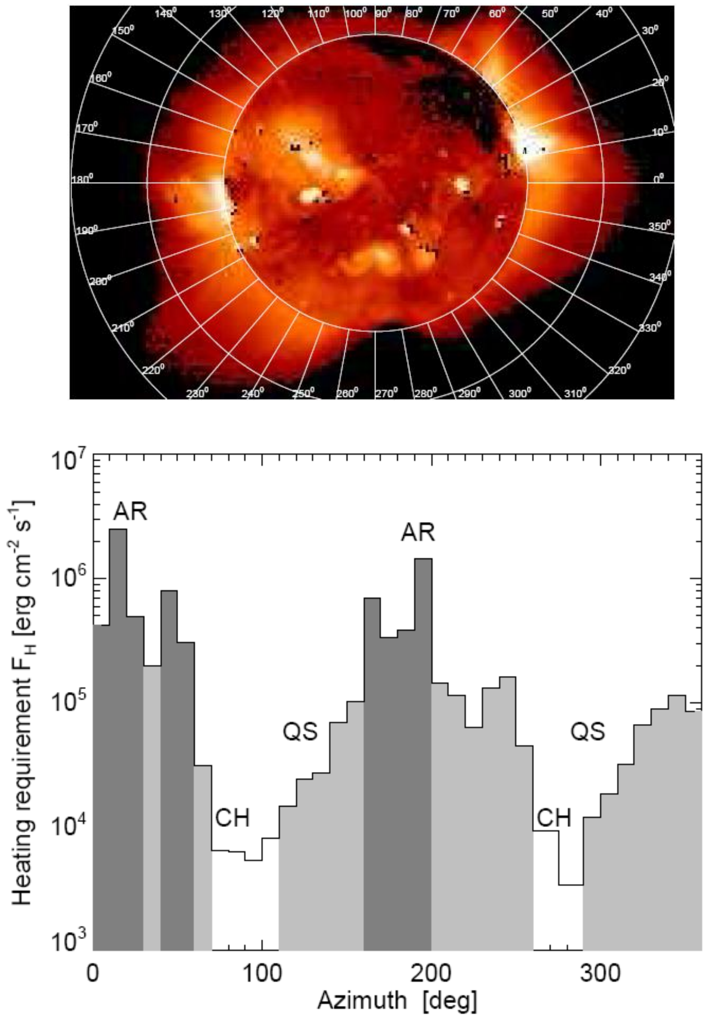

Figure 1. Top panel: A soft X-ray image of the Sun observed on 26 August, 1992, with the Soft X-ray Telescope (SXT instrument) onboard the Yohkoh spacecraft. The Sun's corona has been divided into 36 sectors, each 10º wide. The white circles indicate distances from the center of the sun of r = 1.0, 1.5 and 2.0 solar radii. The apparent solar surface is marked by the inner white circle at r = 1.0 solar radius. Note two active regions at the east and west, a coronal streamer in the southeast and coronal holes in the north and south. Bottom panel: The histogram shows the heating rate requirement in the 36 sectors around the Sun. The labels indicate the locations of active regions (AR – dark gray), quiet-Sun regions (QS – light gray) and coronal holes (CH - white) (Aschwanden, 2001).

The resulting F_H for each of the 36 sectors, calculated by analyzing the X-ray image, is shown in histogram form in the bottom panel of Figure 1. The power is plotted along the vertical axis as a function of the angular position around the Sun, which is marked along the horizontal axis in degrees from 0º to 360º. In the plot, we mark those sectors that contain active regions with dark gray, quiet-Sun regions with light gray, and coronal holes with white. The heating requirement is about $200 \leq P_H \leq 2000$ W/m^2 in active regions, about $10 \leq P_H \leq 200$ W/m^2 in quiet sun regions, and $5 \leq P_H \leq 10$ W/m^2 in coronal holes, which is in agreement with the estimates of Withbroe and Noyes (1977). If we add up the heating energy requirement in those three categories (active, quiet and coronal holes), we find that the active regions demand 82.4% of the heating requirement, the quiet-Sun regions 17.2%, and coronal holes merely 0.4%. It is clear then, that although active regions do not cover a major fraction of the Sun's surface, the part of the coronal volume that is physically connected to active regions still dominates the total energy requirement of the coronal heating problem. Therefore, we mostly focus our arguments in Section 3 on active regions, more specifically on coronal loops in active regions and on the heating processes occurring there, rather than on coronal holes.

3.THREE ARGUMENTS FOR HEATING IN THE CHROMOSPHERE/TRANSITION REGION

3.1 Temperature Evolution of Coronal Loops

In the previous section, we found that nearly all of the energy required to heat the solar corona comes from active and quiet regions of the Sun. These regions consist mostly of closed magnetic field structures, which are curved lines of the Sun's magnetic field that rise up from and return to the solar surface, forming giant arches or loops that do not extend far out into space beyond the Sun itself. Most closed magnetic loops have their highest points less than 1 solar radius above the Sun's surface, and are located towards the equator of the Sun. Hot plasma can flow along the closed magnetic field lines, forming coronal loops. In contrast, the polar regions of the Sun are open-field regions, with magnetic field lines that emerge from the Sun and extend far out into space, forming the interplanetary magnetic field. Plasma particles (electrons and ions) can also flow along open field lines, and indeed they are carried out with open field lines as they expand far into space beyond the corona, forming the solar wind that flows from the Sun in all directions.

We wish to examine the heating processes that may be occurring along coronal loops in active and quiet regions of the Sun. More specifically, we want to compare two possible heating scenarios that may be occurring along a loop in the corona. The first heating scenario proposes that the entire loop of plasma is being directly heated in the corona. We will call this hypothetical process 'coronal heating.' The second possibility is that the heating first occurs below the corona, in the chromosphere or transition region, and then the hot plasma moves up along the closed magnetic loop into the corona. We will refer to this hypothetical mechanism as 'chromospheric heating'. For each of the two cases, we will make predictions of what we would observe happening on the Sun if that hypothesis were accurate. Then we will compare real observations to our predictions, to see which heating scenario has the most observational support.

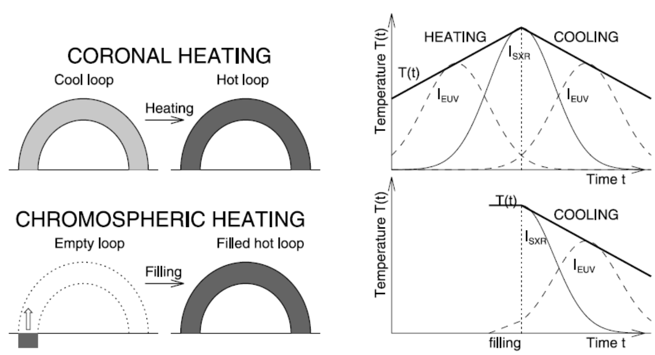

Figure 2. A comparison between the coronal heating scenario (top panels) and the chromospheric heating scenario (bottom panels). Top left: The coronal heating scenario involves the direct heating of a pre-existing cool loop in the corona. Bottom left: In contrast, the chromospheric heating scenario fills an empty loop in the corona with hot plasma from below. Top right: A plot of temperature versus time shows that in the heating phase of the coronal heating scenario a loop should be observable in EUV light and then in soft X-rays (SXR). As the loop of plasma cools, it will fade in X-rays and become bright again in EUV. Bottom right: In the chromospheric heating scenario, the initial brightening in EUV light is missing. Hot plasma from below the corona rapidly fills up the loop and is not directly heated in the corona. Therefore only the cooling phase, from brightness in soft X-rays to brightness in EUV, is expected.

The two competing scenarios — coronal heating and chromospheric heating — are illustrated in Figure 2. First, let us consider the coronal heating scenario, which is shown in the top panel of Figure 2. If magnetic loops are directly heated in the solar corona, then the temperature of a coronal loop should increase over some time interval, as long as the heating rate exceeds the rate at which energy is lost by the loop. A loop that begins cool (less than one million kelvins) will first appear dark when viewed using an extreme ultraviolet (EUV) filter that allows only EUV light to pass through it and be recorded. This is because at low temperatures the plasma is not hot enough to emit light in the EUV band of wavelengths. As the cold loop is locally heated in the corona, it is expected to first brighten up in the EUV filter as the plasma reaches a temperature of between one and two million kelvins ($T \approx 1 - 2$ MK) and becomes hot enough to emit EUV light. As the plasma continues to heat up and the temperature rises, it will then appear dim in the EUV filter since it will begin to emit light of a higher energy and shorter wavelength. As the temperature reaches $T \approx 2 - 4$ MK, the loop should brighten in soft X-ray filters, since it will then begin to radiate X-rays. When the loop starts to go through a cooling phase, the brightening in the light filters should happen in reverse. First the plasma should be bright in the soft X-ray filter and then in the EUV filter as it cools. A complete heating and then cooling phase is shown in a plot of plasma temperature vs. time in the top right portion of Figure 2.

In looking at actual observational data of the Sun, we find that the first part of the coronal loop heating phase (a brightening in EUV) has never been observed, or at least has not been reported in the literature. This could mean one of two things. First, the initial part of the heating phase (EUV brightening) could still be occurring in the corona, but it could be happening very fast - so fast that the instruments, which typically take a measurement every minute, are not able to record it. In this case, our current observations do not contradict the coronal heating scenario. Instead, they are simply not able to show whether it is occurring. The second possible meaning is that the observations show that this heating phase simply does not occur. In other words, the heating of the loop does not occur directly in the corona, and thus the coronal heating scenario is not supported by data.

On the other hand, let us consider the chromospheric heating scenario, where heating occurs in the upper chromosphere or lower transition region, with subsequent upflows of plasma that fill coronal loops. In this case, we would not detect any heating phase in the coronal part of a loop, and hence would not see an initial brightening of the loop in an EUV filter. This heating scenario has been previously modeled with computer simulations. According to recent simulations (Warren et al., 2002, 2003), as soon as the loop starts to fill up with hot plasma, the loop is expected to brighten rapidly in the soft X-ray filter first, during a time interval that is on the order of minutes for typical coronal loops, without any detectable initial brightening in the cooler EUV filters. Therefore, the simulations suggest that in the case of chromospheric heating we would observe only the cooling phase, when the loop cools down from the soft X-ray filters through to the EUV filters, as shown in the bottom panel of Figure 2. Instances of such loop cooling phases, from the Yohkoh spacecraft's soft X-ray filters down to the TRACE spacecraft's EUV filters, have indeed been observed in detail for 11 cases, over time intervals of several hours, without any noticeable EUV signature of an initial heating phase (Winebarger and Warren 2005; Ugarte-Urra et al. 2006). In a single case (Ugarte-Urra et al., 2006) the footpoint of a loop has been closely monitored in EUV during the initial brightening in soft X-rays of that loop. In this case, the full loop was not detected in EUV ($T = 1.0 - 1.5$ MK) until it cooled down from the hotter ($T = 3 - 5$ MK) soft X-ray temperatures.

Although observational data seems to support the chromospheric heating scenario, it is not yet possible to conclude that this scenario represents reality. The observational proof is still lacking in a couple of key areas. Firstly, the initial heating agent of the plasma in the chromosphere has not yet been observed. Secondly, the actual upflow of the plasma through the loop has not been observed using Doppler shift techniques. However, this could be due to instrument limitations, such as low sampling rates and poor resolution.

3.2 Overdensity of Coronal Loops

Coronal loops can only be detected in images of the Sun if they have a density that differs from the density of the background plasma that surrounds them in the corona. This is because the brightness of plasma in EUV light and soft X-rays is proportional to the squared density of the plasma. So, features of the corona which are denser than the background plasma will appear brighter than the background, allowing them to be distinguishable in EUV and soft X-ray pictures. In particular, heated coronal loops appear bright in these types of pictures, and therefore coronal loops must be more dense, or ‘overdense,’ with respect to the background corona. This observed higher density of hot coronal loops is a fact that needs to be explained by every proposed coronal heating theory. If a heating theory cannot account for the observed overdensity of coronal loops, then it must be reworked or discarded.

Consider theories that involve heating processes in the corona that directly and locally heat coronal loops. In such heating processes (for example, magnetic reconnection; see Ashwanden 2001 for a discussion of theoretical models), the density of the plasma in a coronal loop is not expected to significantly increase. We therefore argue that no theory involving local heating in the corona is able to explain the observed brightness, and thus overdensity, of hot coronal loops. In contrast, the plasma density in coronal loops would be expected to increase significantly due to upflows of additional plasma from the loop footpoints. This would require a heating process that acts below the corona, in the upper chromosphere or lower transition region, with hot, dense plasma moving up into coronal loops (as shown in the bottom of Figure 2). This type of heating theory, which we previously referred to as chromospheric heating, could indeed explain the observed brightness and overdensity of hot coronal loops, and is therefore further supported by EUV and soft X-ray observations.

3.3 Upflows in Coronal Loops

The best direct evidence for chromospheric heating, with a subsequent filling of the coronal loop with hot plasma, comes from actual observations of hot upflows from the chromosphere. These plasma flows have been detected by a ‘feature tracking’ analysis of images of the Sun taken by cameras with special filters onboard the TRACE spacecraft. The upflows are observed to exhibit one-way or two-way flows along loops. An example of such upflows is shown in Figure 3. In this case, the upflow has been inferred from feature tracking in TRACE Fe IX/Fe X (171 Å) images of an active region of the Sun on December 1, 1998 (Winebarger et al. 2001). In the top left panel of Figure 3, a bundle of bright, fan-shaped coronal loops can be seen in the TRACE image. Three specific loops are labeled in the figure. As time passes, later images show an increase in brightness that moves along loop 3. Note, however, that these later images have not been included in Figure 3. Instead, from each of these successive images, a strip of the picture has been extracted along loop 3, and the resulting time sequence of 10 strips that maps the brightness or intensity along loop 3 is shown on the right hand side of Figure 3. In this sequence, notice how the peak in intensity moves outward from the loop footpoint, which is located at the left edge of each of the 10 strips.

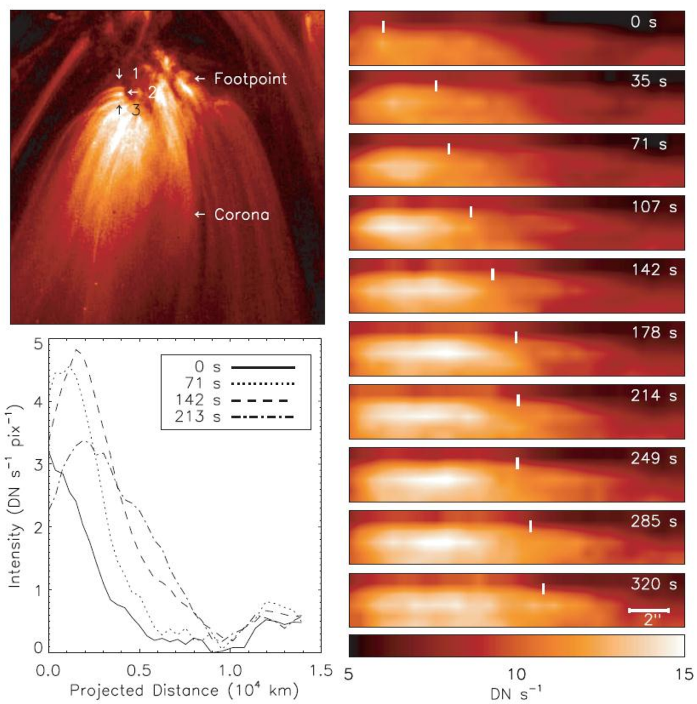

Figure 3. Top left: An image from the TRACE spacecraft in light with wavelengths of about 17.1 nm (171 Å – angstroms) shows fan-like loops in an active region (labeled AR 8396) observed near the Sun’s center on 1 December, 1998, 01:00:14 UT. The field of view of this image is 270 million meters (270 Mm). Right side: The brightness along loop 3 over a segment of 15 Mm is shown at 10 time intervals after 01:40:35 UT. The time after 01:40:35 UT is shown in the top right corner of each strip. The footpoint of loop 3 is always at the left side of each strip. Note how the brightness expands along loop 3, and therefore towards the right hand side of each strip, as time passes. The leading edge of the expanding brightness is

marked with a white bar in each strip. (Winebarger et al., 2001)

By following the movement of the intensity peak, it is possible to measure the distance that the peak has moved along the loop and the time it has taken to move this distance. From these quantities, the velocity (speed) of the flow can be estimated. From this series of images, the projected velocity of the plasma flow was measured for four different loops (loops 1 to 3 and a fourth loop not indicated in the figure). The flows lasted between 2 and 15 minutes, and the projected velocities were found to be in the range of about 5 to 15 km/s. Note that we can speak only of 'projected' velocities, because the camera can provide only a two-dimensional flat image — the orientation of each loop in three-dimensional space is not known for sure, and so there are 'projection effects.' This means that the measured velocities can give only lower limits to the actual flow speeds.

Models of coronal loops that do not include flows (Winebarger et al., 2001) do not predict the dynamic features (moving intensity peaks) that are observed in this example. This suggests that these dynamic features, in plasmas with a temperature of about 1 million kelvins, represent upflows of heated plasma from the chromosphere into the corona. In modeling work that does incorporate flows, coronal loops are shown to require one-way flow speeds on the order of about 10 – 40 km/s (Petrie et al., 2003). This is consistent with the TRACE observations described above, since we already stated that the measured velocities (5 to 15 km/s) represent lower limits only. Therefore, heating theories that include upflowing plasma, such as the chromospheric heating theory outlined in this paper, are further supported by feature tracking in TRACE observations.

4. CONCLUSIONS

We have presented three pieces of observational evidence that suggest that the primary heating process leading to the appearance of hot (over 1 MK) coronal loops takes place in the chromosphere, rather than in the corona itself. Specifically, we have pointed out (1) the absence of observed temperature increases in coronal loops, (2) the overdensity of coronal loops with respect to the background coronal plasma, and (3) observed upflows in coronal loops. Given the arguments, we see strong support for the idea that the major heating source responsible for a hot corona is located in the transition region or upper chromosphere, rather than in the corona. We therefore consider the term "coronal heating" to be rather poor, since the essential heating process does not take place in the corona, but rather in the transition region or upper chromosphere. We suggest that the coronal heating problem should instead be referred to as the "chromospheric heating problem," since the existence of the hot corona is only a consequence of chromospheric heating and the filling of coronal loops afterwards with hot plasma. This shift of the heating source, from the corona to the chromosphere, rules out models that involve the heating of active region loops directly at coronal altitudes, such as wave heating models. Finally, note that our arguments mostly apply to the heating of active and quiet region loops, but not necessarily to open-field regions, such as coronal holes.

5. REFERENCES

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