HEATING EVENTS OBSERVED IN THE QUIET CORONA

A.O. Benz¹, S. Krucker²

¹Institute of Astronomy, ETH-Zentrum, CH-8092 Zürich, Switzerland
²Space Sciences Laboratory, University of California, Berkeley CA 94720, USA

ABSTRACT

The emission measure of the quiet corona, defined by the plasma hotter than one million degrees, has been observed by EIT on SoHO to fluctuate in a large majority of the 1900km x 1900km pixels during the observing time of 42 minutes. In the average, the larger the emission measure in a pixel, the more it fluctuates. Increases in emission measure constitute a major energy input into the corona, suggesting that the lower corona is not just heated, but continuously replenished by chromospheric material heated to coronal temperatures. We test the hypothesis that the coronal heat input may be largely by chromospheric evaporation.

The total energy input by an evaporative event consists of thermal energy, gravitational energy, expansion work and is reduced by radiative and conduction losses at various temperatures during heating. The evaluation of just the thermal energy is critically discussed. It depends on several assumptions and model parameters. Thus the published values of the energy input are only order of magnitude estimates.

We conclude that heating events have revealed an exciting view on coronal heating, but definite statements on their ability to provide all the energy for coronal heating are premature.

Key words: Sun: corona; coronal heating; microflare; nanoflare; evaporation; EUV and X-rays.

1. INTRODUCTION

In the past decade the resolution of quiet corona observations has constantly increased in space, even more in time, but most notably in flux. The fine scale structure (at the scale of a few arcseconds) in radio observations at 21 cm and longer wavelength is very diffuse, if coronal at all (Gary and Zirin 1988). Only recently, soft X-ray observations (Benz et al. 1997) and EUV observations (Harrison 1997) have revealed enhanced emission and thus intense heating above the magnetic network. The network structure, visible best in the chromosphere, is the result of the subphotospheric flow pattern sweeping frozen-in magnetic field lines to the boundary, where the magnetic flux becomes concentrated.

The first dynamic phenomena discovered in the quiet corona were occasional bright points (Golub et al. 1974). About one of them was observed per hour averaged over the whole Sun at the resolution of that time. The number of observed bright points increases with flux resolution. Sensitive observations in soft X-rays by Yohkoh/SXT have revealed a large number of microflares above the network of the magnetic field in quiet regions (Krucker et al. 1997). They have a typical thermal energy content of 10^{26}erg per event and occur at a rate of 1200 events per hour over the whole Sun. More recently, the coronal emission measure in quiet regions has been observed in EUV iron lines and was found to fluctuate locally at time scales of a few minutes in a large majority of pixels including the intraregion cells (Benz & Krucker 1998). At the level of 3 standard deviations, they reported the equivalent of 1.1 x 10^{6} events per hour over the whole Sun.

Here we review the basis of the estimate of the energy input into the corona due to such evaporative events.

2. TEMPORAL VARIATIONS OF THE EMISSION MEASURE

The material content of the corona is conveniently measured in terms of the emission measure, $\mathcal{M}$, of soft X-rays and coronal EUV lines. We define $\mathcal{M} := \int n^{2}A \, ds$, where the integration is along the line of sight in $s$, $A$ is the pixel size, and the density $n$ refers to the plasma in the temperature range given by the emission process, assuming isotropy perpendicular to the line of sight direction.

A formal temperature and emission measure for each pixel at each time step have been determined from observations by the Extreme ultraviolet Imaging Telescope (EIT) on SoHO (Delaboudinière et al. 1995). It imaged a 7' x 7' quiet area near the center of the disk with a pixel size of 2.62'' (1900km on the Sun) and a time resolution of 127.8 s. The observing run lasted from 14:30 to 15:15 UT on July 12, 1996. Some results of these observations have been published by Benz & Krucker (1998) and Krucker & Benz (1998). EIT observed two wavelength bands, 171 A and 195 A, alternatively. They include emis-
sion lines of Fe IX/X and Fe XII, respectively, with diagnostic capabilities for temperatures in the range of 1.1-1.9×10⁶K. These coronal lines dominate the observed parts of the EUV spectrum, and their large photon fluxes provide higher sensitivity than previous observations in soft X-rays. The derived parameters are to be taken as formal values, representing weighted means over the sensitive temperature range.

Figure 1 displays the resulting emission measure of one pixel vs. time. It is an arbitrary example of a total array of 23716 pixels of quiet corona. The average level of emission measure of the pixel is relatively low, indicating that it is not above the network. Note that the emission measure and thus the material content of the corona is significantly changing during the 42 minutes of observation. The square of the density integrated along the line of sight peaked round 15:00 UT after an increase lasting 10 minutes. The decay has a similar time constant. This is a very common property of quiet sun coronal observations by EIT. In fact, only 15% of all pixel do not change significantly in emission measure (Krucker & Benz 1998).

Energy estimates of heating events can be made from input estimates or from radiation output measurements. In the latter case, the line emission has to be integrated over the event and the total radiation estimated from some emissivity code (such as SPEX). More problematic is the estimate of conduction losses. Thus we follow the former way, estimating the input from the energy of the newly added material. Here some of the assumptions made along this estimate are discussed.

An increase in emission measure involves many forms of energies: heating of chromospheric material to coronal temperatures, lifting up the material to the corona (potential energy), expansion of the material from chromospheric density to coronal values, radiation and conduction losses during heating.

The thermal energy is

\[ E_{th} = 3k_B T n_e V \tag{1} \]

for the two particle species. The observable increase in emission measure \( \Delta M \) is defined as

\[ \Delta M = \int \left( (n_{e,0} + n_{e,1})^2 - n_{e,0}^2 \right) dV \tag{2} \]

where \( n_{e,0} \) is the background density before the event and \( n_{e,1} \) is the density of the newly added material. For simplicity let us consider here constant densities in finite volumes \( V_0 \) and \( V_1 \), respectively. The emission measure can easily be evaluated for two extreme cases yielding the same observed enhancement: (i): \( n_{e,0} \gg n_{e,1} \) in the same volume, \( V_0 = V_1 \), i.e. low density material is newly injected into the old volume, and (ii): \( n_{e,0} \ll n_{e,1} \), i.e. high density material is injected into a small part of the old volume, \( V_1 \ll V_0 \). In the first case the density of the newly added material can be estimated from

\[ n_{e,1} \approx \frac{\Delta M}{2\sqrt{M_0} V_0} \tag{3} \]
In the second case the density of the newly added material is

\[ n_{e,1} \approx \sqrt{\frac{\Delta M}{V_1}} \]  

(4)

We will assume the second case in the following and write \( V_1 = qV_0 = A\Delta s_{\text{eff}} \), where \( q \) is the filling factor of the newly added material and \( A \) is the pixel area. The parameter \( s_{\text{eff}} \) represents the line-of-sight thickness corrected for smaller area than the pixel size. It is a model parameter that has been assumed to be 5000 km in previous publications, which may be an overestimate. A lower limit may be estimated from the assumption that most events are small and may be about of the length of a pixel (2000 km) with half its diameter (1000 km). We will continue with the old value here for consistency, but use \( s_{\text{eff}} = 500 \) km in the final estimates. Thus,

\[ E_{\text{th}} \approx 3k_BT \sqrt{\Delta MA\Delta s_{\text{eff}}} \]  

(5)

The gravitational potential energy of a relatively large heating event has been estimated by Benz & Krucker (1998). It amounts to 5.7% of the thermal energy as estimated above (after correcting for a discrepancy in the text of Benz & Krucker, the values in Fig. 2 being correct).

For an expansion along a flux tube of constant diameter \( a \), the electron density decreases from the initial \( n_{e,1} \) in the chromosphere to \( n_{e,2} \) in the corona, where \( n_{e,1} \gg n_{e,2} \). The temperature is not seen to decrease from a very high value, thus the expansion may be modeled as being isothermal. The expansion energy is

\[ E_{\text{exp}} = \int p\, dl \approx 2k_BT_1 a \int n_e \, dl \]

(6)

\[ = 2k_BT_1 n_{e,1} a t_1 \int \frac{dl}{\ell} \]

(7)

\[ = 2k_BT_1 n_{e,1} a t_1 \ln (t_1/t_i) \]

(8)

\[ \approx 2\ln (t_1/t_i) k_BT_1 \sqrt{\Delta MA\Delta s_{\text{eff}}} \]  

(9)

where \( p \) is the total particle pressure, and \( t_i \) and \( t_1 \) are the initial and final extension, respectively, of the newly heated material along the loop. The thermal energy and expansion energy are identical except for the factor \( 2/3 \ln (t_1/t_i) > 1 \).

Conduction and radiation losses occur during the rise phase of an event, and before the peak increase in emission measure is reached. Thus the thermal energy again underestimates the total energy input.

4. ENERGY INPUT vs. OUTPUT

Figure 3 compares the energy input by emission measure increases with the radiation losses of single pixels and time steps. Only the thermal energy content, \( 3n_e k_BT_V \), of the newly heated material is considered. The added particle density, \( n_e \), is derived using an effective height \( s_{\text{eff}} \) of 5000 km. For the temperature, \( T_i \), the line-ratio temperature of the pixel after the time step is used. As the emission measure increase includes noise, originating mostly from photon counting, the observed values must be corrected for the average noise contribution. A method to estimate the noise effect has been derived and described in Benz & Krucker (1998). The total radiative loss is calculated from the derived emission measure and line-ratio temperature using the SPEX software.

Figure 3 suggests two regimes separated at a radiative loss of about \( 8 \cdot 10^8 \text{ erg s}^{-1} \text{ cm}^{-2} \). The pixels with higher brightness are generally associated with the network boundary. The input/output relation appears linear, but seems to have different fits in both regimes. The fact that the regression does not go through the origin suggests additional, unresolved energy input or, depending on the sign, an additional energy loss independent of radiation (such as conduction).

Theory suggests a linear relation between input and output power,

\[ P_{\text{rad}} + a = bP_{\text{imp}} \]

(10)

where \( P_{\text{rad}} \) is the radiative loss and \( P_{\text{imp}} \) is the impulsive power input derived from emission measure increases per unit time. The data in Fig. 3 can be linearly approximated by a least square fit, yielding

\[ b_1 = 2.33(\pm 0.04) \left( \frac{5000 \text{ km}}{s_{\text{eff}}} \right)^{1/2} \]

\[ b_2 = 1.31(\pm 0.04) \left( \frac{5000 \text{ km}}{s_{\text{eff}}} \right)^{1/2} \]

\[ a_1 = 2.3(\pm 0.2) \cdot 10^8 \text{ erg s}^{-1} \text{ cm}^{-2} \]

\[ a_2 = -2.2(\pm 0.2) \cdot 10^8 \text{ erg s}^{-1} \text{ cm}^{-2} \]
in the faint part (subscript 1) and the bright part (subscript 2), respectively.

Using Eq.(10) and the derived parameters $a$ and $b$, the percentage contribution of impulsive energy input to the observed radiative loss can easily be calculated. At a typical value of $5 \cdot 10^5\text{erg s}^{-1}\text{cm}^{-2}$, in the faint pixel regime, it amounts to:

$$\frac{P_\text{imp}}{P_\text{rad}} = 0.20 \left( \frac{s_\text{eff}}{500\text{km}} \right)^{1/2},$$  \hspace{1cm} (11)

whereas at $10^5\text{erg s}^{-1}\text{cm}^{-2}$, typical for the bright pixel regime,

$$\frac{P_\text{imp}}{P_\text{rad}} = 0.19 \left( \frac{s_\text{eff}}{500\text{km}} \right)^{1/2}. $$  \hspace{1cm} (12)

Putting $s_\text{eff} = 500\text{km}$, Eqs.(11) and (12) suggest that a fraction of about 20% of the radiated energy is observed alone in the thermal energy derived from coronal emission measure enhancements. The accurate fraction of impulsive power input depends on the model assumed, most severely on the square root of the average effective line-of-sight thickness.

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5. ENERGY DISTRIBUTION OF HEATING EVENTS

A very different statistics of heating events is more popular. It tries to estimate the energy distribution of single events. To calculate the energy of a whole event e.g. from the thermal energy, the peak of the emission measure has to be determined as well as the background level. The latter may be the preceding minimum. Most important, the event often covers more than one pixel and a possible enhancement in neighboring pixels has to be searched for and pixel enhancements have to be combined to events.

We have used the following simple procedure: The emission measure time series of each pixel have been searched for local peaks. If it exceeds the preceding minimum by more than 3 $\sigma$ (standard deviation of the noise as derived from the observed flux level), it is marked. Neighboring pixels peaking in the same time step (2 minutes) are combined to an event. The thermal energy of the event is calculated from the total emission measure increase (cf. Eq.5). The method has been carefully tested and is described in Krucker & Benz (1998).

A total of 11,150 events $\geq 3\sigma$ have been found by this method in the field of view of $7' \times 7'$ within 42 minutes. Their distribution is displayed in Fig. 4. It follows a well defined power law between $10^{25}$ and $10^{27} \text{erg per event}$. The range from $10^{25}$ to $10^{27} \text{erg per event}$ is consistent with the same power law (Fig.5). The lower limit is given by the sensitivity. As the index is larger than 2, most of the energy seems to be released by the sum of the smallest flares (Krucker & Benz 1998).

The observed $\geq 3\sigma$ events in emission measure enhancements constitute $16 \left(s_\text{eff}/5000\text{km}\right)^{1/2}$ % of the total energy radiated in the field of view during the observing time.

In the following we discuss the robustness of the above result concerning the definition of events. The power-law index does not change much if single-pixel events are excluded (Krucker & Benz 1998). However, a change in the tolerance of combining adjacent peaks into one event has a large effect. Figure 5 compares the condition for simultaneity of the peak times. If the condition is increased from $\pm 1$ to $\pm 3$ minutes, the number of large events increases at the expense of the small events. Therefore, the power-law exponent decreases. Increasing the tolerance may be justified if different parts of a source do not peak at the same time or by motions in the source as reported e.g. by Benz & Krucker (1998). Parnell & Jupp (2000) have found such motions to be rare in TRACE data. On the other hand, the larger tolerance also enhances the probability for chance associations, which is considerable at the observed rate of microflares. The combined events may then artificially grow in area. This is shown in Fig.6 with the distribution of event size. The distribution becomes flatter as the event areas generally increase for larger tolerance. Also very large events, exceeding $4 \times 10^8 \text{km}^2$, appear. We have found all of them to be unrealistic and most likely to be chance associations of more than one flare. Thus, the increase of the timing tolerance has a positive and a negative effect. The evaluation of these two effects and the correct combination of pixels to events need further investigations.

Another effect of event selection is shown in Fig.7. The $>3\sigma$ condition was enhanced to $>6\sigma$. This situation occurs for an instrument with half the sensitivity of EIT. The exponent changes from -2.59 to -2.39, and the low-energy cutoff is shifted to higher energies. Most notably, the number of events at a given energy is reduced and the flare frequency is lower by a factor of 4.2. This latter effect originates from the
higher sigma cutoff that eliminates some of the adjacent pixels with low-level variation. Thus the area of an event tends to shrink and so does the energy. The distribution of flare frequency is therefore shifted to the left in Fig. 7. The effect seems to explain the lower energy distribution observed in TRACE data (Parnell & Jupp 2000; and some of the discrepancies of Aschwanden et al. 2000).

Figure 5. The energy distribution of impulsive heating events for two different tolerances in the timing of adjacent pixel's peak. The power-law index decreases from $2.59 \pm 0.02$ for the $\pm 1$ minute requirement to $2.15 \pm 0.02$ for the $\pm 3$ minute requirement for combining events in adjacent pixels.

6. CONCLUSIONS

We conclude that the energy input into the corona by chromospheric evaporation is best determined from single pixel/single time step analysis. Even this, however, requires some interpretation of the observed fluctuations and is model dependent. Thus the heating rates Eqs.(11) and (12) can only be considered as order of magnitude estimates.

The emission measure enhancements constitute a major energy input into the low, quiet corona. The enhancements have life times between 2 and more than 40 minutes (Berghmans, Clette & Moses 1998), after which the plasma cools below the observational threshold. Thus the low corona, where most of the emission of the quiet Sun in soft X-rays and coronal lines originates and most of the heating must occur, is continuously supplied with freshly heated material. The energy input by emission measure enhancements resembles that of regular flares in active regions. The larger of these microflares in the quiet corona can be further investigated and have indeed revealed some similarities with regular flares (Krucker & Benz 1999). However, the physics and geometry of microflares needs to be further studied.

Figure 6. The area distribution of impulsive heating events observed in the quiet corona. The number of very large events strongly increases from the $\pm 1$ minute requirement to the $\pm 3$ minute requirement for the simultaneity of adjacent peaks.

Figure 7. The energy distribution for different cutoffs in $\sigma$ for the detection and combination of peaks in adjacent pixels. The $>6\sigma$ curve (dashed) represents the results for an instrument with half the sensitivity of EIT.
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