ENERGY DISTRIBUTION OF MICROEVENTS IN THE QUIET SOLAR CORONA

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ABSTRACT

Recent imaging observations of EUV line emissions have shown evidence for frequent flarelke events in a majority of the pixels in quiet regions of the solar corona. The changes in coronal emission measure indicate impulsive heating of new material to coronal temperatures. These heating or evaporation events are candidate signatures of “nanoflares” or “microflares” proposed to interpret the high temperature as well as the very existence of the corona. The energy distribution of these microevents reported in the literature differ widely, and so do the estimates of their total energy input into the corona. Here we analyze the assumptions of the different methods, compare them by using the same data set, and discuss their results. We also estimate the different forms of energy input and output, keeping in mind that the observed brightenings are most likely secondary phenomena. A rough estimate of the energy input observed by EIT on the SOHO satellite is of the order of 10% of the total radiative output in the same region. It is considerably smaller for the two reported TRACE observations. The discrepancy can be explained by flare selection and different thresholds for flare detection. There is agreement on the slope and the absolute value of the distribution if the same methods are used and a numerical error is corrected. The extrapolation of the power law to unobserved energies that are many orders of magnitude smaller remains questionable. Nevertheless, these microevents and unresolved smaller events are currently the best source of information on the heating process of the corona.

Subject headings: Sun: activity — Sun: corona — Sun: flares — Sun: X-rays, gamma rays

1. INTRODUCTION

The heating of the solar corona has been a riddle since the discovery of the high coronal temperature by Edlen and Grotrian in the late 1930s. Does the heating process leave any other signature? There are elaborate investigations and many proposals on possible sources of energy (e.g., review by Narain & Ulmschneider 1996; recent original work by Galsgaard & Nordlund 1996; Hood, Ireland, & Priest 1997; Erdelyi 1998; Sturrock 1999; Sakai, Takahata, & Sokolov 2001), but proof can only come from observations of the corona. Of particular interest are time variations in coronal temperature, density, and energy content, as they may reveal clues on the nature of any nonstationary heating process.

In the quiet corona on which we concentrate here, small brightenings above the network of the magnetic field were first discovered in deep soft X-ray exposures by Yohkoh/SXT (Krucker et al. 1997). The events were reported to have a typical thermal energy of $10^{26}$ ergs and to occur at a rate of $1200 \text{ hr}^{-1}$ extrapolated over the whole Sun. These microevents seem to be present at all times (Pres, Phillips, & Falewicz, in preparation) and also in coronal holes (Koutchmy et al. 1997). Thus they represent a population of continuous dynamic coronal phenomena, quite different from the more sporadic regular flares occurring in active regions that are strongly related to solar activity and its cycle. Microevents also appear different from X-ray bright points discovered by Skylab that emerge at a rate of $62 \text{ hr}^{-1}$ averaged over the whole Sun and persist on average for 8 hr (Golub et al. 1974). The radiative energy loss during the bright point’s lifetime is of the order of $10^{28}$ ergs. They seem to be the place of frequent microevents (Pres & Phillips 1999). More sensitive measurements of microevents became possible with EIT and TRACE. Benz & Krucker (1998) and Berghmans, Clette, & Moses (1998) found independently that the coronal emission measure in quiet regions observed in EUV iron lines fluctuates locally at timescales of a few minutes in a majority of pixels including even the intracell regions. At the level of $3 \sigma$, Krucker & Benz (1998, hereafter KB) reported the equivalent of $1.1 \times 10^6$ coronal microevents hr$^{-1}$ over the whole Sun for SOHO/EIT observations. Benz & Krucker (1998) noted a nearly linear relation between inferred averaged input power and radiative loss per pixel.

In the transition region of the quiet Sun, line emissions have been observed to have localized brightenings and explosive events (Brueckner & Bartoe 1983; Dere 1994) at a rate increasing with instrumental sensitivity (Porter et al. 1987; Harrison 1997). Winebarger et al. (2001) estimate that explosive events observed in SOHO/SUMER line broadenings contain an upward energy flux corresponding to about 10% of the required energy to heat the corona. Habbal (1992) and Brkovic et al. (2000) have pointed out that some of them are associated with a coronal brightening, others are not. Here we concentrate on events that have an impact on the corona. Thus we search for an observable change of the energy density in localized regions of the corona.

The energy of coronal microevents can be estimated from their peak temperature and emission measure or from enhanced line intensities integrated over events. The two methods are orthogonally different, the first measuring the input, the second the output. The two methods split again by the choice of the spatial association: (1) The enhancements in single pixels, thus in a given area on the Sun, can be analyzed individually. The density and thermal energy of...
the new material are difficult to estimate, as the depth of the event cannot be observed. (2) The energy inputs into adjacent brightening pixels can be added to events. The combination of active pixels to events requires some nontrivial assumptions. The advantage of integrating over events lies in the possibility to estimate the depth from shape and size of the projected area. These choices constitute four completely different ways to derive the energy input by microevents. The resulting distributions are critically reviewed and compared below.

The terms “microflare” and “nanoflare” have been introduced as theoretical concepts referring to subresolution reconnection events (Parker 1983). Soon after, observers used them for small flarelike brightenings below previous thresholds in active regions (e.g., Lin et al. 1984; Gary, Hartl, & Shimizu 1997). Here we use the term “microevent” to denote short enhancements of coronal emissions in the energy range of about $10^{24}$–$10^{27}$ ergs in quiet regions. The lower limit is given by current instrumental thresholds, and the upper limit refers to the largest events occurring typically in a quiet region of a few arcminutes’ size within 1 hr.

In § 2 we discuss the variability of the quiet corona and present examples of individual pixels for illustration; the various energies involved are discussed and compared. Event selection and energy distributions are assessed in § 3. We use the data originally presented by KB and Benz & Krucker (1998) as the base to critically review the published event definitions and to investigate their effects. The results are discussed in § 4. Section 5 gives conclusions and suggestions for future work.

2. THE OBSERVATIONAL BASIS

Temporal changes of coronal emissions are ideal to test heating models. In this section, observations of such changes are presented. The energy associated with events is often inferred from the emission measure, $\xi$, of soft X-rays or coronal EUV lines. We define $\xi = \int n_e^2 A ds$, where the integration in $s$ is along the line of sight, and $A$ is the area or pixel size. The electron density $n_e$ refers to the plasma in the temperature range given by the observed emission process, and $n_e^2$ is the spatial average over $A$. The emission measure is proportional to the emission in a line for a given temperature.

In the following, the emphasis is on emission lines observed in the two wavelength bands, 171 and 195 Å, including lines of Fe ix/Fex and Fe xii, respectively, with diagnostic capabilities in the range of the plasma temperatures yielding significant abundances of the two ions. These coronal lines dominate the observed passbands of the EUV spectrum, and their large photon fluxes provide higher sensitivity than previous observations in soft X-rays. Using lines of different ionization states, the emission measure in a range of temperatures can be derived. The ratio of the emission in the two passbands also defines a line-ratio temperature in the range of about $1.0 \times 10^{6}$ K (Moses et al. 1997). The calculation of these basic quantities employs a spectral line code such as SPEX (Mewe et al. 1985) and CHIANTI (Dere et al. 1997).

The derived parameters are to be considered correct only under the approximations of homogeneity, coronal abundances (taken from Meyer 1985), and stationary state. The first approximation has been studied in general (e.g., Jordan et al. 1987; McIntosh, Brown, & Judge 1998). Obviously, the approximation yields weighted means over the pixel in the sensitive temperature range. The assessment of the resulting quality awaits model calculations. The observed variability, temperatures (see below) and densities of the order of a few $10^{9}$ cm$^{-3}$ (Benz & Krucker 1998) justify the third assumption (Schmutzler & Tschamnter 1993). The line-ratio temperature and emission measure have been determined for each pixel at each time step from observations by the Extreme Ultraviolet Imaging Telescope (EIT) on SOHO (Delaboudiniere et al. 1995) and TRACE (Handy et al. 1999) using their particular standard software packages.

2.1. Observed Variability

The variability of the quiet corona near the center of the disk is illustrated in Figure 1. The presented observing run lasted from 14:30 to 15:15 UT on 1996 July 12, when solar activity was almost at the lowest level during the most recent solar minimum. The time resolution is 127.8 s, and the pixel size 2.62 (1900 km on the Sun). The error bars of the emission measure are upper limits estimated from the low $\sigma$ values of the enhancement distribution and will be explained below with Figure 2. They are also the basis to estimate the accuracy of the temperature (Fig. 1, right-hand side).

The pixel shown in Figure 1 is typical for a location above the magnetic network. The emission measure increases significantly twice within 42 minutes with peaks at 15:00 and $\geq 15$:14 UT. A third event at 14:45 UT is marginal. In the event at 15:00 UT the temperature peaks shortly before the emission measure, in agreement with previous reports (e.g., cross-correlation by Benz & Krucker 1999).

Statistics on the variability of all pixels are presented in Figure 2. A large part of the instrumental noise is caused by photon statistics and is thus practically Gaussian. The observed enhancements are normalized to the standard deviation of each pixel, which was derived in the following way (Benz & Krucker 1998): First, the average photon noise $\sigma_{\text{ph}}$ in each pixel was calculated and the distribution was plotted in these units. Then a distribution with maximum Gaussian noise was fitted to the $0$–$3\sigma_{\text{ph}}$ part. A larger noise contribution would exceed the observed distribution near 3 $\sigma$ in Figure 2 by more than 3 times the standard error. Thus the fitted curve represents an effective $\sigma$. It is 20% larger than $\sigma_{\text{ph}}$ and comprises all other sources of noise. Finally Figure 2 was plotted in units of this $\sigma$.

There is a non-Gaussian, enhanced tail in the distribution. Figure 2 shows the temperature in the 29 largest events that significantly over 1 hr, confirming previous results (see § 1).

The temperature of the material causing the emission measure increase is best derived from the largest events. Figure 3 shows the temperature in the 29 largest events that
occurred in a \(7' \times 7'\) field within 42 minutes (data from Krucker & Benz 2000). The observed temperature range is from 0.9 to \(1.6 \times 10^6\) K. The lower limit may originate from the temperature sensitivity of the lines used. The maximum of the observed range is not limited by the observing method. It is consistent with the temperatures derived from Yohkoh/SXT using different filtergrams of the soft X-ray continuum (Krucker et al. 1997). The average temperature of the events plotted in Figure 3 is \(1.34(\pm 0.15) \times 10^6\) K and an average emission measure of \(2.3 \times 10^{44}\) cm\(^{-3}\).

A slight correlation between temperature and emission measure is discernible in the microevents of Figure 3 (cross-correlation coefficient \(r = 0.34, \ n = 29, \ \text{significance} \ p > 95\%\)). The slope of the regression line is relatively flat \((T_6 = 1.246 + 0.041M_{44}, \ \text{where} \ T_6 \ \text{is in units of} \ 10^6 \ K \ \text{and} \ M_{44} \ \text{is in units of} \ 10^{44}\) cm\(^{-3}\)). However, the determination of the above correlation significance does not include the errors of individual measurements. They are of the order of 5% for the emission measure and 10% for the temperature. If they are included, the data displayed in Figure 3 are compatible with no relation between emission measure and temperature.

![Fig. 1.](image1)

**Fig. 1.**—Left: Coronal mission measure of a random 1900 \(\times\) 1900 km pixel in a quiet region of the Sun as determined from EIT high-temperature iron lines. The emission measure is divided by the pixel area \(A_p\). The error bars are conservative upper limits as explained in the text. Right: The formal temperature evolution of the same pixel is shown. No background is subtracted.

![Fig. 2.](image2)

**Fig. 2.**—Distribution of pixels (thin curve) having emission measure enhancements (maximum-minimum) larger than the indicated \(\sigma\) value in the 42 minutes observing time. EIT observations of 23,800 pixels in a \(7' \times 7'\) quiet area are presented. The dashed curve represents the distribution expected from Gaussian noise and was fitted at the low \(\sigma\) values (0-3 \(\sigma\)). The difference between the observed distribution and the noise is the curve shown with error bars.

![Fig. 3.](image3)

**Fig. 3.**—Increase of the emission measure vs. average line-ratio temperatures of relatively large microevents in the quiet corona determined from the line ratio of Fe ix to Fe xii observed by EIT. The pre-event background flux in each line was subtracted before the temperature of the integrated events was evaluated.
2.2. Energy Estimate of Events

Radiation Energy.—The energy of microevents has been estimated from the radiation output in EUV lines. The emission in one line has to be integrated over the event, and the total radiation of the plasma (say 1–300 Å) has to be inferred from some temperature estimate and a line emissivity code. Note that the radiation is considered only during the time the plasma is within the range of sensitive temperatures. Other losses, in particular conduction, may also have to be taken into account to estimate the total energy output. Thus the radiative output underestimates the energy loss. Measuring the radiation output has the advantage that the line-of-sight thickness of the microevent does not have to be modeled. The disadvantage is the assumption of the temperature.

Thermal Energy.—A completely different way to estimate the energy is to measure the thermal energy content at a given time. One observes two lines and determines the temperature from the line ratio. Using the same element at two ionization states, the line ratio defines an average temperature \( T \). This allows us to determine an emission measure relevant for the plasma within the range of temperatures appropriate for the two lines as described above. As the measurements are made at peak flux, more events in a larger energy range can be studied. The results are more reliable because the information from two lines is used.

The thermal energy of the material exceeding a given threshold \( T_0 \) is

\[
E_{\text{th}} \approx 3k_B T \int n_e(T > T_0) \, dV. \tag{1}
\]

Equation (1) includes the contributions of both electrons and ions, assumed to have the same temperature and \( n_e \approx n_i \). The electron density in the source region is determined from the observable increase in emission measure \( \Delta \mathcal{M} \), where

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

For simplicity, the background density before the event, \( n_{e,0} \), and the density of the newly added material, \( n_{e,1} \), are assumed to be constant. They are located, respectively, in the volume \( V_0 \) before the event and in \( V_1 \), the volume into which the new material is injected. As the considered height is much smaller than the density scale height, we neglect gravitational settling. The emission measure can then be evaluated easily for two extreme cases yielding the same observed enhancement: (1) \( n_{e,1} \ll n_{e,0} \) in the same volume \( (V_0 = V_1) \), i.e., low-density material is newly injected into the old volume, and (2) \( n_{e,1} \gg n_{e,0} \), 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

\[
n_{e,1} \approx \frac{\Delta \mathcal{M}}{2 \sqrt{\mathcal{M} q V_0}}. \tag{3}
\]

In the second case the density of the newly added material is

\[
n_{e,1} \approx \sqrt{\frac{\Delta \mathcal{M}}{V_1}}. \tag{4}
\]

Brown et al. (2000) have evaluated some realistic models in detail and have found differences in the derived densities by a factor of 2. We will assume the second case in the following and write \( V_1 = q V_0 = A_{\text{eff}} \), where \( q \) is the filling factor of the newly added material and \( A \) is the observed area. The parameter \( A_{\text{eff}} \) represents an effective line-of-sight thickness of the new material. It includes the filling factor for multipixel events and corrects also for cases with smaller event area than the pixel size. It is a model parameter and has been assumed to be 5000 km in KB, which is probably an overestimate for small events. A lower limit may be estimated from the assumption that the smallest observable events extend about the length of a pixel (2000 km) with half its diameter (1000 km), thus \( A_{\text{eff}} \geq 500 \) km.

Combining equations (1) and (4), the change in thermal energy amounts to

\[
E_{\text{th}} \approx 3k_B T \sqrt{\Delta \mathcal{M} A_{\text{eff}}}. \tag{5}
\]

Enhancements both in emission measure and temperature occur in Figure 1. The thermal energy of the corona can increase either by adding material previously “invisible” (e.g., heated chromospheric material) or by increasing the temperature of coronal material. For illustration we evaluate the event peaking at 15:00 UT. The increase \( \Delta \mathcal{M} = 3.5 \times 10^{26} A_p \text{ cm}^{-3} \) indicates heating of chromospheric material, thus \( \Delta T \approx T \). Even for an \( A_{\text{eff}} \) of only 500 km and without subtracting a background, the required energy is \( 2.6 \times 10^{24} \) ergs. Thus the example suggests that heating new material to coronal temperatures in microevents is a major energy input. Other temperature variations in Figure 1 are of the order of \( 10^4 \) K. The average emission measure of the pixel in Figure 1 is \( 3.7 \times 10^{27} A_p \text{ cm}^{-3} \), where \( A_p \) is the pixel area. At a constant emission measure, the temperature variations would amount to less than 10% of the above energy. Temperature variations at constant emission measure thus constitute negligible heating. Contrary to previous expectations, the dominant variability of the coronal energy content is not in temperature but in emission measure!

The reported thermal energy inputs by emission measure increases have been measured at peak value, but conduction and radiation reduce the thermal energy already during the rise phase of an event. As the rise time in microevents is comparable to the decay time, about half of the radiative loss occurs before the peak. Thus the thermal energy at peak underestimates the total energy input by at least a factor of 2. Brown et al. (2000) have presented more detailed calculations on this problem.

Gravitational Energy.—The gravitational energy of relatively large heating events has been estimated by several authors (e.g., Brown et al. 2000). It amounts to a few percent of the thermal energy estimated above and will be neglected in the following.

Isothermal Expansion.—For an expansion along a flux tube of constant diameter \( a \), the electron density decreases inversely proportional to the enlargement. We assume a homogeneous volume with the initial density \( n_{e,0} \) in the chromosphere expanding homogeneously to the coronal value of \( n_{e,1} \), where \( n_{e,0} \gg n_{e,1} \) and \( n_{e,1} = n_{e,0} l_0/l \). The temperature is not seen to decrease from a very high value, thus the expansion may be modeled as being isothermal. The
expansion energy can then be approximated to
\[
E_{\text{exp}} = \int p\,dl \approx 2k_B T_1 a \int n_e\,dl \quad (6)
\]
\[
= 2k_B T\,n_e\,a\ln(l_1/l_0) \approx 2\ln(l_1/l_0)k_B T_1 \sqrt{\Delta H A \, \Delta x_{\text{eff}}} ,
\quad (7)
\]
where \( p \) is the total particle pressure and \( l_0 \) and \( l_1 \) are the initial and final extensions, respectively, of the newly heated material along the loop. The expansion energy exceeds the thermal energy by the factor \( \gamma \approx 2/3 \ln(l_1/l_0)>1 \). For realistic values of chromospheric and coronal densities, this factor is about 3. The energy is liberated when the injected material cools and concentrates again in a smaller volume. As most of the microevents in the quiet corona seem to take place in closed loops, this is the case for most of the expansion energy.

2.3. Power Equilibrium

The combined input power including heating and expansion may be written in terms of \( P_\text{in} = \Delta E_\text{th}/\Delta t \), where \( \Delta E_\text{th} \) is the observed input of thermal energy in the observing time \( \Delta t \).

\[
P_{\text{in}} \approx \alpha (\beta P_\text{th} + \gamma P_{\text{eff}}) = P_{\text{out}} \approx \mu P_{\text{rad},\text{MK}}^{-1}. \quad (8)
\]
The factor \( \beta \approx 2 \) covers the losses before the emission measure is determined at its peak. It may be noted here that the sum \( \beta + \gamma \approx 5 \) is reduced in case of a small filling factor of the injected material. The factor \( \alpha \) takes into account that the observations are based on the secondary effect of heating and evaporation. As primary plasma motions and waves may result from the energy release, \( \alpha \geq 1 \). For reconnection, \( \alpha \approx 2 \) has been estimated in the MHD limit (e.g., Priest & Forbes 2000).

Equation (8) equates finally the input to the output. In the previous literature, the radiative output \( P_{\text{rad}} \) has been estimated from the observed coronal emission measure (\( \gtrsim 10^6 \) K) and the line-ratio temperature. This ignores the radiation at lower temperature and underestimates the total radiative loss by some factor \( \mu > 1 \). If the coronal material cools from 1.5 \( \times \) 10^6 K to chromospheric values, \( \mu \approx 3 \).

3. EVENT SELECTION AND ENERGY DISTRIBUTIONS

Radiative Output.—Table 1 summarizes the published results on the energy distribution of microevents. All previous studies agree that it can be approximated by a power law,

\[
N(E_{\text{th}}) \approx N_0 E_{\text{th}}^{-b}. \quad (9)
\]
The energy distribution derived from radiation loss by Berghmans et al. (1998) is remarkably flat compared to the others. The global event rate reported by these authors is 4300 hr\(^{-1}\), compared to 1.1 \( \times \) 10^6 by KB. In both studies SOHO/EIT data were used. Berghmans et al. (1998) took a local 3 \( \sigma \) peak and combined to one event all spatially adjacent pixels that brightened more than 2 \( \sigma \). Each of these pixels was considered to be part of this event as long as it stayed above 2 \( \sigma \) during the brightening of the first pixel. The events defined in this manner reach five times larger areas than in KB and possibly include small independent events. Thus the difference mainly originates in how brightened pixels are combined to events rather than in the different way the energy is measured.

Thermal Input.—In the following we concentrate on energy estimates from thermal input and discuss the errors concerning the energy distribution. These are relative errors that arise from comparing energies of different events. It is clear from § 2.2 that the estimate of the total input of an event is still rather uncertain in absolute terms.

3.1. Event Selection

For event selection a simple procedure based on a lower limit given in terms of \( \sigma \) is applied in most cases (e.g., KB; Parnell & Jupp 2000). A local maximum is searched in the time line of a pixel. The preceding local minimum or the start of the series is taken as the background level.

Aschwanden et al. (2000a) have used more restrictive selection criteria. For each pixel they determined the absolute peak in the time series and took the absolute minimum as the background. Thus they accepted only one event per observing time and per pixel, excluding cospatial events. This selection is biased against small events. Second, they required the temporal cross-correlation coefficient between both lines be larger than 0.5 to exclude nonflarelike events. As small events have a smaller signal-to-noise ratio and thus are more likely to be excluded, the criterion again favors large events. The second criterion excludes more than 70% of the detected events.

That an event selection as defined by Aschwanden et al. (2000a) is problematic can be seen in their two completely different event distributions, which depend on the wave-
length in which they select events. The cross-correlation criterion is intended to select only events of the same type, seen clearly at both wavelengths. Hence the selection should give similar flare distributions. This is not the case as their Figure 12 demonstrates.

Are there several kinds of coronal microevents, flarelike and nonflarelike? The temperature distribution in Figure 3 does not suggest different populations of events in EIT data. The energy distributions reported by the various groups decrease continuously with energy; no secondary peaks have ever been noted. The temporal cross-correlation of Fe\textsubscript{ix} and Fe\textsubscript{xii} averaged over all pixels is excellent ($r = 0.46$ at an Fe\textsubscript{ix} delay of 23 s; Benz & Krucker 1999), indicating that the variations in the two lines are well correlated except for noise. We do not find a reason to distinguish between events with different line ratios, i.e., different temperatures.

Both additional selection criteria introduced by Aschwanden et al. (2000a) exclude predominantly small events and therefore reduce the power-law index $\gamma/C_{14}$. The second criterion alone flattens the distribution by 0.3 in the power-law index (Aschwanden et al. 2000b).

### 3.2. Combining Pixels to Events

Figure 4 shows the energy distribution of emission measure enhancements in single pixels. An effective line-of-sight depth of 500 km has been assumed (see eq. [5]). The power-law index in the middle part is $\delta = 6.04$. At high energies, the distribution falls off with a maximum energy at $10^{25}$ ergs. The low-energy cutoff is instrumental. Combining adjacent pixels to events flattens the distribution and extends the maximum energy to $4 \times 10^{26}$ ergs (not shown in Fig. 4, but see Fig. 7).

Combining adjacent pixels to events is a nontrivial matter. Synchrony between peaks is required, and a tolerance must be specified. Tolerances of $\pm 1$ and $\pm 3$ minutes have been used in the literature (see Table 1). At a pixel size of 1900 km, they correspond to lower limits of accepted motions of $16N$ and $5.3N$ km s$^{-1}$, respectively, where $N$ is the number of traversed pixels. $N$ may be up to about 7. Events exhibiting slower motions would be counted as several events. Thus in principle a large synchrony tolerance is desirable to avoid breaking up big events into spurious fragments. We note however that only one moving event in the quiet corona has ever been described in detail (Benz & Krucker 1998). Parnell & Jupp (2000) and Berghmans et al. (1998) have noticed only few such events. Nearly all events emerge and decay on the same spot.

On the other hand, a large tolerance enhances the number of spurious associations. KB have reported an event rate of $0.0115$ pixel$^{-1}$ minute$^{-1}$ above $3 \sigma$. The number must be multiplied by the average event size, 1.63 pixels, to yield the chance association rate of an event with an other independent event. For the four closest pixels, the chance to have a coincident, but unrelated peak within a 2 minute time interval (tolerance of $\pm 1$ minute) is 15%. It becomes 3 times larger and is excessive for a tolerance of $\pm 3$ minutes.

The effect of increasing the tolerance from $\pm 1$ to $\pm 3$ minutes is evident in Figure 5. The power-law index decreases from $2.59/2.02$ for the $\pm 1$ minute tolerance to $2.15/2.02$ for the $\pm 3$ minute tolerance for combining events in adjacent pixels (height model: $s_{eff} = 5000$ km).
events have to be developed based on the experience of well-studied events. If there is a tolerance interval that balances chance associations and break-up, we expect it to be at the lower end of the published range. Thus the power-law indices derived with a tolerance of $\pm 3$ minutes and more should be corrected up.

### 3.3. Height Model

The effective height $s_{\text{eff}}$ (eq. [5]) has been modeled in the literature by a constant in energy and, alternatively, by $b\sqrt{A}$, where $b$ is some constant and $A$ the observed event area. Figure 7 shows the result for the same data evaluated with different height models. The power-law index decreases from 2.59 for a constant height to 2.31 for the $\sqrt{A}$-model, in agreement with the theoretical derivations of Mitra Kraev & Benz (2001, eq. [25]).

Constant $s_{\text{eff}}$ has been assumed in single-pixel analyses and in KB. The $\sqrt{A}$-model is more plausible if events across a large energy range are compared and therefore should be preferred.

### 3.4. Sensitivity

The power-law index from EIT observations is 2.2–2.3 (Table 2, $\sqrt{A}$-model), whereas for TRACE a range of 2.04–2.13 has been reported (Parnell & Jupp 2000). Figure 8 suggests a possible interpretation. Apparently, the slope of the energy distribution also depends on the cutoff used to select peaks. The exponent changes from 2.59 to 2.39 if the greater than $3\Delta t$ condition is enhanced to greater $6\Delta t$. The energy cutoff is shifted to higher energies, and, most notably, the number of microevents at a given energy is lower by a factor of 4.2. The reason for this is that the higher $\sigma$ cutoff eliminates some of the pixels with low-level variation at the limb of events. Thus the area of an event tends to be reduced and so does the derived energy. The distribution in Figure 8 is shifted to lower energy, and its cutoff to higher minimum energy. The effect is slightly more efficient at lower energies, where events have a generally smaller signal-to-noise ratio. The difference between EIT and TRACE results may be an effect of sensitivity. Figure 9 shows a decrease of $\delta$ with increasing cutoff in units of $\sigma$. In both cases the power-law index continuously decreases with $\sigma$. The $\sigma$ for EIT is given by photon noise and is 4.4 times smaller than for TRACE, where it is determined by cosmic ray hits and their cleaning.

### Table 2

**Power-Law Indices $\delta$ of the Energy Distribution of Microflares**

| Source                | $h=\text{const}$ ($\Delta t = \pm 1$) | $h=\sqrt{A}$ ($\Delta t = \pm 1$) | $h=\sqrt{A}$ ($\Delta t = \pm 3$) | $h=\sqrt{A}$ ($\Delta t = \pm 3$) |
|-----------------------|---------------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Parnell & Jupp 2000   | 2.4–2.6                               | 2.0–2.1                           | 2.0–2.1                           | 2.0–2.1                           |
| Aschwanden et al. 2000b | 2.3–2.5                               | 2.2–2.3                           | 2.1–2.2                           | 1.8–1.9                           |
| Krucker & Benz 1998 + this work | 2.3–2.6                               | 2.2–2.4                           | 2.0–2.2                           | 2.0–2.2                           |

**Note.**—Indices are derived by various recent authors from different data and for different model assumptions, tolerance of synchrony in minutes, and flare selection. The reported range for power-law fits at different energies is given.

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**Fig. 6.**—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.

**Fig. 7.**—Frequency distribution of microevent energy for different assumptions on the effective height. The model with a constant height (solid curve) is compared with a model assuming the height given by the square root of the area.
The difference between the instruments concurs qualitatively with Figure 9, but the effect is smaller than predicted, possibly reduced by the higher spatial resolution of TRACE. Despite this general agreement on the power-law index, we note a strong discord with Parnell & Jupp (2000) in the absolute value of the distribution at a given energy. It seems to be lower by more than an order of magnitude relative to KB. The distribution is even lower than in Aschwanden et al. (2000b), who have reduced their event number by severe event selections. There is no agreement yet for the discrepancy, but most likely it is a simple numerical error.

4. DISCUSSION

This second look at the EIT data has shown general agreement with TRACE, if the same methods are used (Table 2). As a best approach, we suggest a small tolerance ($\Delta t = \pm 1$ minutes) in the timing of adjacent pixels to be summed up to events. A height model that assumes a smaller effective line-of-sight thickness for smaller events is probably more appropriate ($h = \sqrt{A}$). Then a power-law index of $\delta = 2.3 \pm 0.1$ results from EIT data (third column in Table 2).

The above height model reduces the observed thermal input energy by microflares from 16% (KB) to about 5% of the radiated output ($\gtrsim 10^6$ K). To account for the nanoflare heating scenario, the observed microevents have to either continue to much lower energies or provide more energy per event than the measured thermal part, or both.

The simple considerations on energy inputs and outputs in §2 suggest that the above percentage may have to be multiplied by a factor of $\alpha (\beta + \gamma) / \mu \approx 3$ to include the other forms of energy involved in microevents. We note that this factor has an upper limit given by the observed energy output. The more energy the observed microevents contain, the less microevents below the current energy threshold may contribute. The latter constitute a part of the unresolved background in the “nanoflare heating” scenario. Thus the background between observable microevents have to either continue to much lower energies or provide more energy per event than the measured thermal part, or both.

The factor $\alpha > 1$ is different from the others as it constitutes a nonimpulsive, possibly nonlocal heating enhancing the background level. A scenario is conceivable where waves travel from the energy release site across magnetic field lines for tens of pixels ($\gtrsim 10^4$ km). The superposition of waves from many events could form a quasi-steady turbulent background. Such an energy input amounts to “dark power” as it does not manifest itself in variability. Its dissipation would heat the coronal background emission measure without changing the Fourier spectrum. The low-energy cutoff of the energy distribution could then be accordingly higher to fit the observed emission measure level.

In view of the simulations and the estimate of $\alpha \approx 2$, the microevents observed in the thermal energy range $5 \times 10^{24}$–$5 \times 10^{26}$ ergs (Fig. 7) suggest a total power input of about 12% relative to the inferred output of the same quiet-Sun field of view.

5. CONCLUSIONS

Nanoflares have originally been introduced as simple energy inputs retaining the high temperature of the corona. Recent observations indicate persistently that microevents behave much more like real flares: heating initially cold
material and increasing the material content of the low corona. As shown by Brown et al. (2000), the transition layer reacts very sensitively to coronal heating and particle impact. Most easily observable in coronal heating is not the primary energy discharge that may well occur in the corona, but the reaction of the chromosphere and the evaporation of hot material. The latter has apparently been observed in microevents of the quiet Sun. Nevertheless, the fact that they are secondary phenomena must not be forgotten when the energy of the whole event is estimated.

In particular the expansion energy, losses during the rise time and the release of other forms of energy have to be added. Microevents are not wavelike, but waves may be excited by the events that travel across field lines and into the upper corona. Although the thermal energy of observed microevents is not sufficient for the coronal heating, microevents are now the best source of information and evidence on the heating process of the quiet corona.

Individual microevents have many physical properties in common with regular flares. However, their location and statistical behavior are different. The observed variability of the quiet corona takes place at low altitudes, mostly below $10^4$ km. This is different from active regions, where extremely bright, quasi-stationary loops extend to more than an order of magnitude larger altitude. The quiet corona at low height appears simpler and more uniform from the point of view of loop length and temperature range. In any case, the microevents are a less sporadic phenomenon than regular flares and are not known to correlate with solar activity. Therefore, contrary to the suggestions by Aschwanden et al. (2000b, Fig. 10), the energy distribution of microevents cannot be directly compared with regular flares. Microevents in quiet regions and flares in active regions form statistically different populations.

It may be noted here that the variability even increases at lower temperatures (Berghmans et al. 1998) and has a maximum in the transition region, where the timescales are shorter and the temporal power spectrum is flattest (Benz & Krucker 1999). This suggests that a more complete modeling of flarelike events at the interface of corona and chromosphere is highly desirable. As the observed variability is not wavelike, it is the best indicator for the relevance of the “nanoflare scenario.” Mitra Kraev & Benz (2001) have proven by simulations the existence of a nanoflare model that can explain the observed facts relevant to the heating of the quiet corona: background level, variability, power spectrum, and energy distribution of the microevents. Nanoflare heating thus cannot be excluded as some previous authors have claimed.

The time of quick progress in microevents is clearly over. Low-corona variability has opened a new, vast, and largely still unexplored field, revealing an astoundingly dynamic “quiet” corona. Only studies that investigate carefully the persisting problems can bring progress. One of them will be the modeling and detailed investigation of even smaller single events at high spatial and temporal resolution.

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