Signatures of a nanoflare heated solar corona ①

Grisha Vekstein
Dept. of Physics, UMIST, Manchester, UK
(in collaboration with Rekha Jain, UMIST)
and Yukio Katsukawa (Univ. of Tokyo).

*) Assume that high coronal temperature is maintained by numerous small flare-like events (nanoflares)

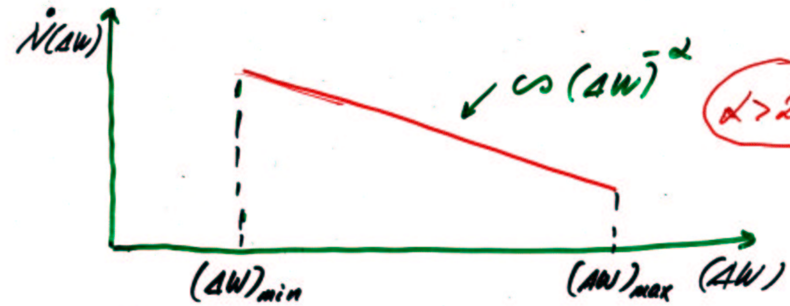
↓

**) How this scenario can be tested without resolving individual nanoflares

↓

statistical properties of hot coronal loops

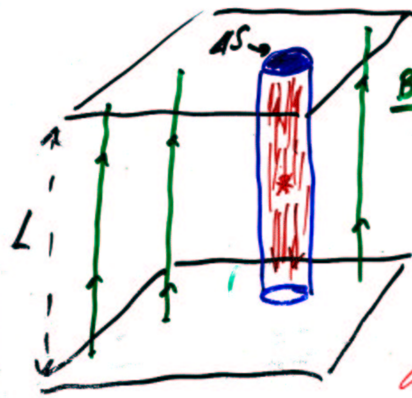
Broad energy spectrum of heating events (nanoflares) ②



$$\int d(\Delta W)\,\dot N(\Delta W) = q\,\frac{(\alpha-2)}{(\alpha-1)(\Delta W)_{min}}$$

q – heating flux per unit area ($q \sim 10^7\, erg/cm^2 s$)

Each nanoflare ⟹ single hot filament



$$2 n_0 \kappa T_0 = B^2/8\pi$$

$$\Delta W = 5 n_0 \kappa T_0 \cdot L \cdot \Delta S$$

↓

$$\Delta S = \frac{16\pi}{5}\frac{\Delta W}{B^2 L}$$

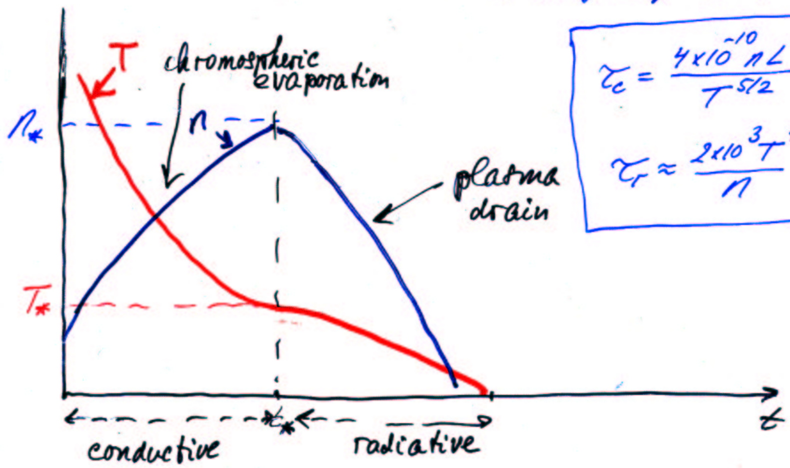
lower limit for ΔS under strongly localized energy dissipation

$(\Delta S)_{min} \sim 10^{14}\, cm^2$

3

Cooling of a hot filament

two-stage process: conductive phase + radiative phase (Cargill, 1994)



$$\tau_c = \frac{4\times10^{-10}\, n L^2}{T^{5/2}}$$

$$\tau_r \approx \frac{2\times10^{3}\, T^{3/2}}{n}$$

$(\Delta t)_h = (\Delta t)_c + (\Delta t)_r \simeq 2t_* \simeq 10^{-4} L^{5/6} B^{-4/3}$

Example: $B \simeq 30\,G$; $L = 10^9$ cm

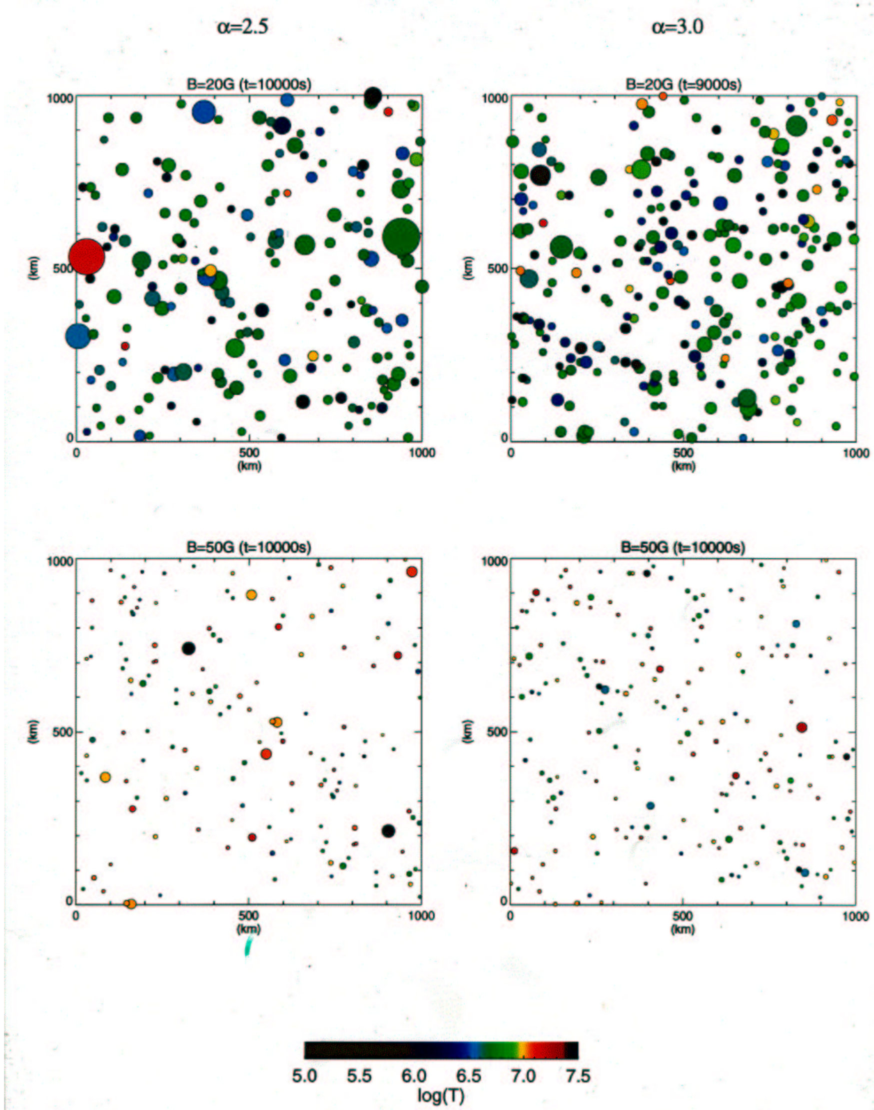
$\downarrow$

$(\Delta t)_h \simeq 10^3$ s

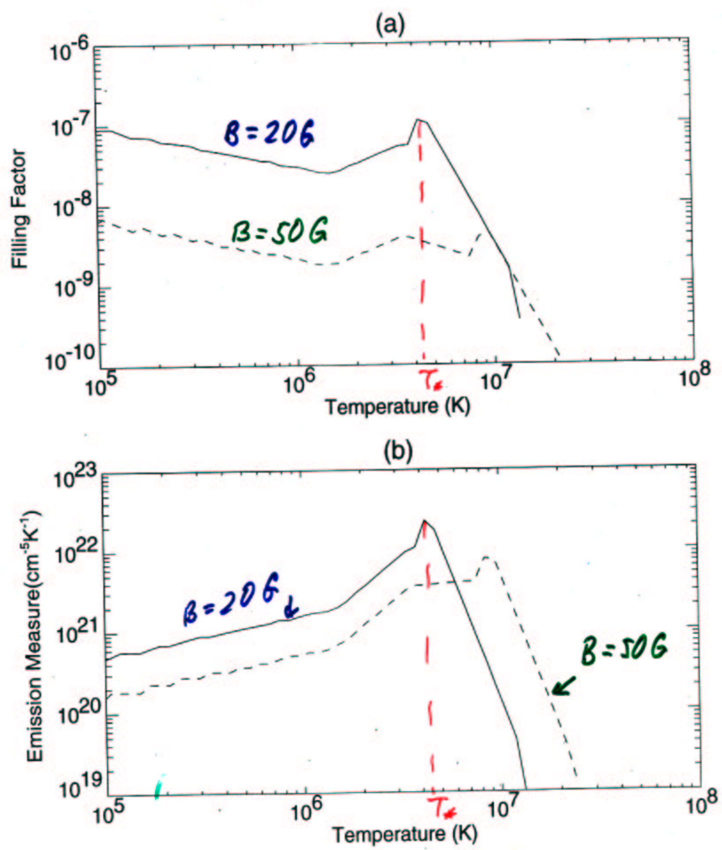
$\downarrow$

$t \gg (\Delta t)_h \rightarrow$ statistical steady state $\rightarrow$ broad distribution of filaments with temperature and density

4



8



6

Scaling laws for active region loops (Vekstein & Katsukawa, ApJ, 2000)

*) Temperature of the loop detected by a broad-range X-ray telescope

$$\boxed{T \simeq T_* = 4\times10^{2} B^{2/3} L^{1/3}}$$

$\underbrace{L \simeq 10^{9}\,\text{cm};\ B \simeq 30\,\text{G}}$

$T_* \simeq 4\times10^{6}\,\text{K}$

$n_* \simeq 3.2\times10^{10}\,\text{cm}^{-3}$

RTV scaling with the pressure inside the filament equal to the external magnetic pressure.

**) Filling factor for the loop

number of hot filaments in the loop

$$N = \dot{N}\times S\times(\Delta t)_h \simeq \frac{q}{(\Delta W)_{min}}\times S\times(\Delta t)_h \simeq$$

Example: $L \simeq 10^{9}$; $B \simeq 30$; $S = 10^{18}\,\text{cm}^2$; $q \simeq 10^{7} \Rightarrow$

$N \simeq 2\times10^{4}$

filling factor
$$\boxed{f \simeq N\times \Delta S/S \simeq 2\times10^{-3}\, q/B^{7/3}L^{1/6}}$$

Normally, filling factor is small ($f \sim 10^{-1} \div 10^{-3}$)

7

xxx) Total thermal energy

$$W_T = 3 n_* T_* f \cdot L \cdot S \approx 10^{-4} q L^{5/6} d^2 B^{-1/3}$$

xxx) Total emission measure

$$(EM)_t \approx n_*^2 f V \approx 2 \times 10^{20} q B^{1/3} d^2 L^{1/6}$$

How these compare with observations?

Active region loops observed with Yohkoh SXT (Cargill & Klimchuk, 1997)

How the above W_T and $(EM)_t$ relate with observational scalings?

(Golub et al, 1980): $W_T \infty \varphi^{3/2} \infty B^{3/2} d^3$

(Shibata et al, 2001): $W_T \infty \varphi^{4/3} \infty B^{4/3} d^{8/3}$

(Fisher et al, 1998): $(EM)_t \infty \varphi^{1.2} \infty B^{1.2} d^{2.4}$

8

TABLE 1

ACTIVE REGION LOOPS OBSERVED BY *Yohkoh* SXT

Parameter (1)	Loop 1 (2)	Loop 2 (3)	Loop 3 (4)	Loop 4 (5)	Loop 5 (6)
$L(10^9$ cm$)^a$	3.82	4.53	3.08	3.20	8.16
$d(10^8$ [illegible]	1.48	1.15	1.55	2.12	1.45
$T(10^6$ K$)^a$	6.39	4.47	7.25	1.88	2.05
$(EM)_t(10^{46}$ cm$^{-3})^a$	21	7.7	0.25	7.5	240
B(G)^b	33	18	44	5.8	4.1
$q(10^6$ ergs cm^{-2} s$^{-1})^b$	3.8	2.7	0.04	1.2	80
f^b	5.6×10^{-2}	1.6×10^{-1}	3.1×10^{-4}	≈ 1	>1

[a] Observed parameters.
[b] Those derived from scaling laws (eqs. [14]–[17]).

9

All the above characteristics depend only on q - the average energy input

How to probe $(\Delta W)_{min}$ and α??

Variability (transient brightnings) in the coronal X-ray emission

Present observational data are quite controversial regarding the spectral index α of transient brightnings (observation of big events with extrapolation to small events)

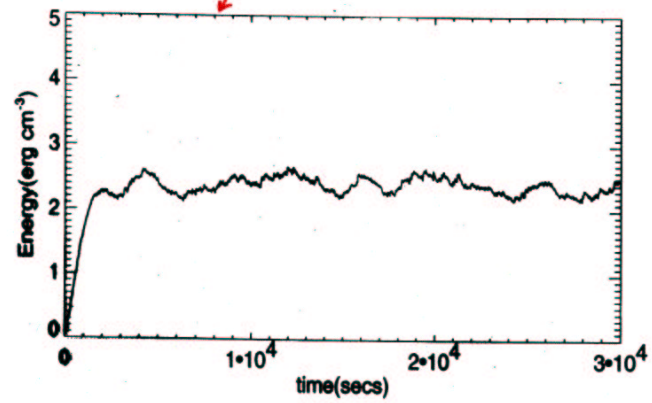
Benz & Krucker, 1998, 2001
Parnell & Jupp, 2000 } $\alpha > 2$

Aschwanden et al, 2000
Berghmans et al, 1999 } $\alpha < 2$

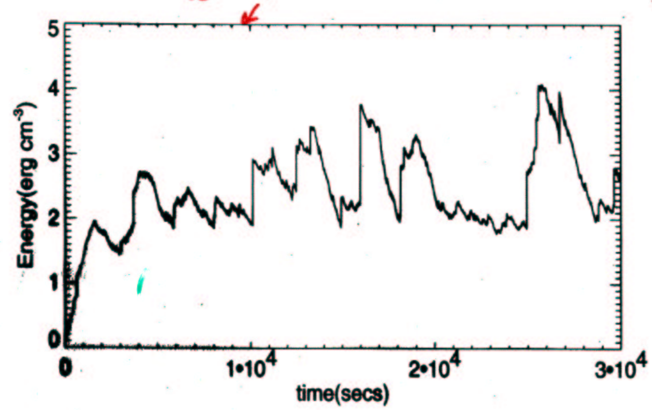
Results are very sensitive to the imposed data analysis procedure as well as to assumptions on the structure of the emmiting plasma (i.e. filling factor)

10

$\alpha = 4$



$\alpha = 2.5$



(11)

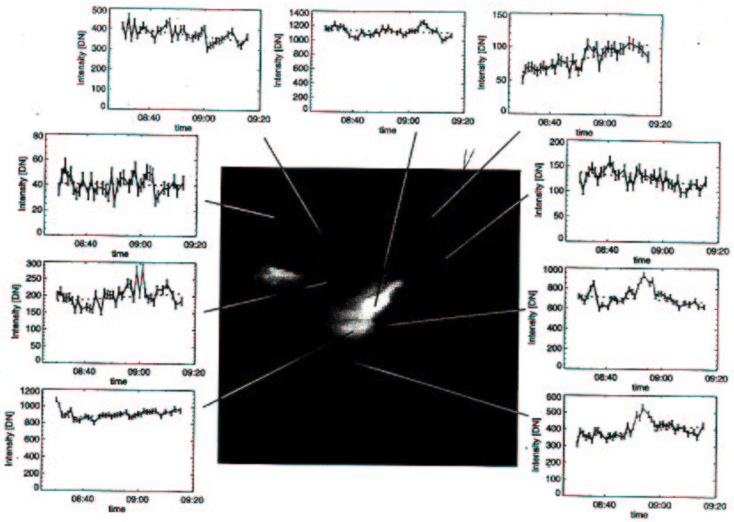


FIG. 1.—Sample light curves of the X-ray intensity of 9 pixels. The horizontal axis is time, and the total duration is one observing sequence (~40 minute The vertical axis is the X-ray intensity and the units are DN (the data number of SXT). The error bars indicate σ_p, the standard deviation due to the phot noise. The thin solid lines represent the removed transient brightenings, and the data points marked with thick solid lines are used. The dashed lines in t panels are the mean intensity levels of the corona I_0 derived from a linear fit (see text). [*See the electronic edition of the Journal for a color version of this figur*

X-ray intensity of individual pixels

(SXT, Katsukawa & Tsuneta, Ap. J., 2001)

(12)

Histogram of the X-ray intensity

What it may look like?

*) all nanoflares have the same energy (ΔW)

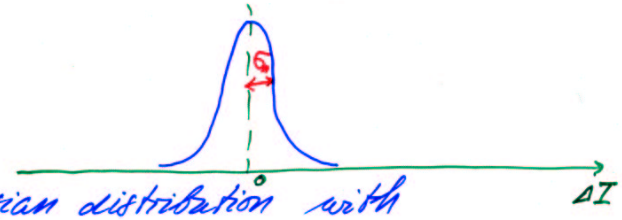
$$I_0 = \langle I \rangle = C S \tau_e q$$

τ_e - exposure time

S - area of a pixel

q - heat flux to the corona (erg/cm^2·s)

C - conversion coefficient of the instrument



Gaussian distribution with

$$\sigma_n = I_0 / \sqrt{\langle N \rangle}$$

$\langle N \rangle$ average number of the emitting hot filaments

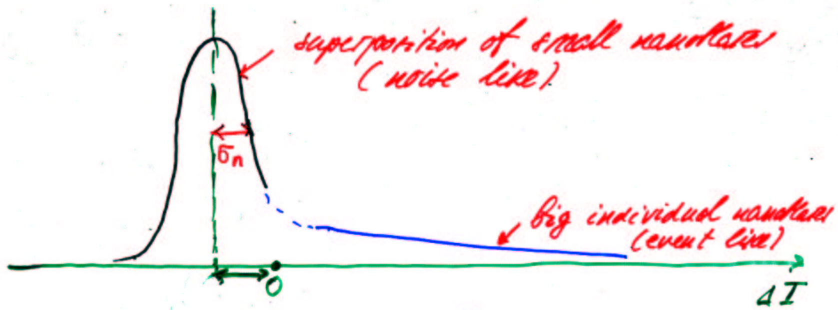
$$\langle N \rangle = \frac{q}{\Delta W} \cdot S (\Delta t)_h$$

$(\Delta t)_h$ → life-time of a hot filament

$$\boxed{\sigma_n = C^{1/2} I_0^{1/2} (\Delta W)^{1/2} \left[\tau_e / (\Delta t)_h\right]^{1/2}}$$

(13)

**x) Broad energy spectrum of nanoflares



How to derive σ_n ?

$\langle \Delta N(E)\rangle = \dot{N}(E)\, dE \cdot S (\Delta t)_h$ – average number of hot filaments within the energy interval $(E,\ E+dE)$

$$\delta(\Delta N(E)) = \sqrt{\langle \Delta N(E)\rangle}$$

$$\Delta\sigma_n^2(E) = \left[C\tau_e \frac{E\cdot\delta(\Delta N(E))}{(\Delta t)_h}\right]^2 = \frac{C^2\tau_e^2 E^2}{(\Delta t)_h}\dot{N}(E)\, dE\cdot S$$

$$\sigma_n = \sqrt{\int \Delta\sigma_n^2(E)} = \frac{C\tau_e S^{1/2}}{(\Delta t)_h^{1/2}}\left[\int_{(\Delta W)_{min}}^{(\Delta W)_{max}} E^2 \dot{N}(E)\, dE\right]^{1/2}$$

Power-law spectrum: $\dot{N}(E) \propto E^{-\alpha}$

i) $\alpha > 3$!! $\sigma_n = C^{1/2} I_0^{1/2} (\Delta W)_{eff}^{1/2} \left[\tau_e/(\Delta t)_h\right]^{1/2}$

$$(\Delta W)_{eff} = \frac{(\alpha-2)}{(\alpha-3)}(\Delta W)_{min}$$

i) $\alpha < 3$ – Big events dominate in fluctuations

no Gaussian noise-like part

(14)

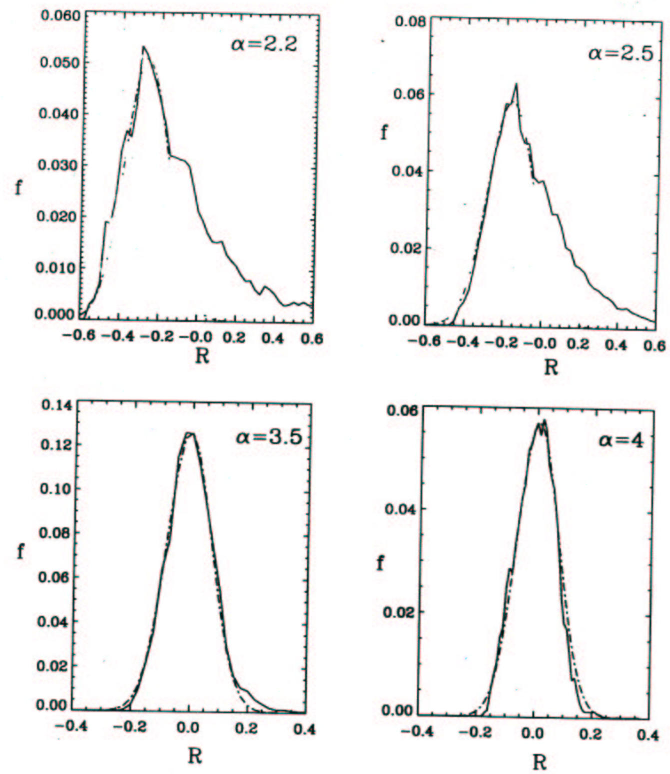


Figure 2. The fraction of events f versus the ratio of deviation dI of the mean intensity I_o to I_o $(R = \frac{dI}{I_o})$ (see the text) for four different values of α. The dot-dashed lines are the Gaussian best-fit to the core parts.

Numerical simulation of the X-ray intensity histogram

15

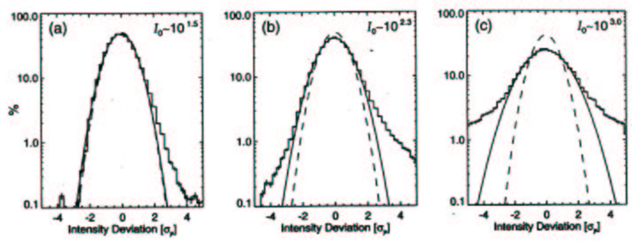


FIG. 2.—Histogram of the X-ray intensity fluctuation around the mean intensity I_0 for three intensity levels: (*a*) $I_0 \simeq 10^{1.5}$, (*b*) $I_0 \simeq 10^{2.3}$, a[nd] $I_0 \simeq 10^{3.0}$. The unit of the horizontal axis is σ_p, the standard deviation due to the photon noise. The vertical axis is the number of data points expresse[d in] percentage. The solid curves are the Gaussian best fitted to the core parts. The photon noise distributions are shown by dashed curves (see text).

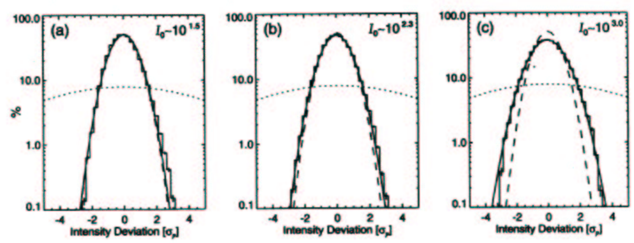


FIG. 3.—Histogram of the X-ray intensity fluctuation around the mean intensity I_0 after removing the wing component (see text). The solid curves a[re] Gaussian best fitted to the histograms. The photon noise distributions (*dashed curves*) and the distribution functions for $\sigma_s/\sigma_p = 5$ (*dotted curves*; see te[xt]) shown for comparison.

Histograms of the X-ray intensity for different SXT pixels (Katsukawa & Tsuneta, 2001)

16

Estimate of the nanoflare energy from the KT data.

σ_p (photon noise) $\approx (1.5 \pm 0.3)\, I_0^{1/2}$

$\sigma_n > \sigma_p$ for $I_0 \gtrsim 5\times10^2 \Rightarrow \sigma_n \approx (0.08 \pm 0.03)\, I_0$

$\boxed{I_0 \approx 10^3 \rightarrow \sigma_n \approx 10^2}$

$$(\Delta W)_{eff} \approx \frac{\sigma_n^2}{C\, I_0}\, \frac{(\Delta t)_h}{\tau_e}$$

$\tau_e \approx 0.7\,s$; $C \approx 10^{-20}$; $(\Delta t)_h \approx 3 \div 5\,\text{min} \approx 2\times10^2\,s$ (as seen from the X-ray variability)

$$\boxed{(\Delta W_{eff}) \approx (1 \div 3)\times10^{23}\,erg}$$

Number of nanoflares and filaments per pixel

$I_0 = C S \tau_e q \approx 10^3 \Rightarrow q \approx 5\times10^6\, erg/cm^2 s$

$\dot{N} = \frac{q \times S}{(\Delta W)} \approx 1\,s^{-1}$; $N \approx \dot{N} (\Delta t)_h \approx 300$

Nanoflare occurrence rate for the whole active region

$S \approx 10^{20}\,cm^2 \Rightarrow \dot{N} \sim 5\times10^3$ nanoflares/sec