SOLAR CORONAL HEATING: A HUNT FOR NANOFLARES

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OUTLINE

1. What is the solar corona?
2. The problem of solar coronal heating
3. The role of magnetic field and magnetic reconnection
4. Solar flares and “nanoflares”
5. Probing nanoflares with fluctuations of the coronal X-ray and EUV emission (in collaboration with S Tsuneta and Y Sakamoto, National Astronomical Observatory of Japan)

1999 eclipse, Turkey

A bit of history

1868 – helium spectral line discovered on the Sun

1869 – unknown green coronal emission line

→ a new element, "coronium" suggested

1895 – helium identified in laboratory

1939 – "coronium" spectral line identified as optical transition in the 13 times ionized iron

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corona is very hot !

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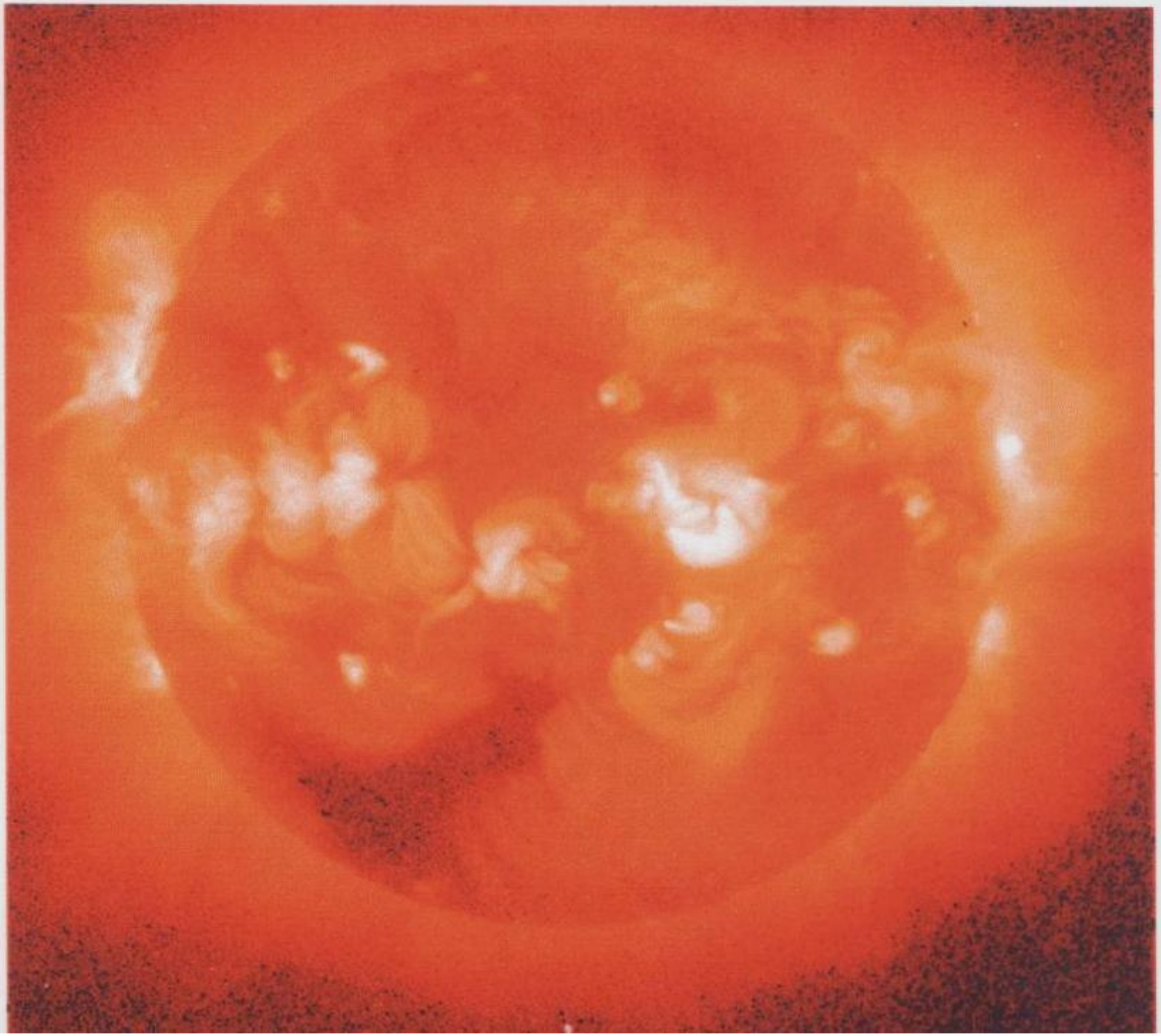
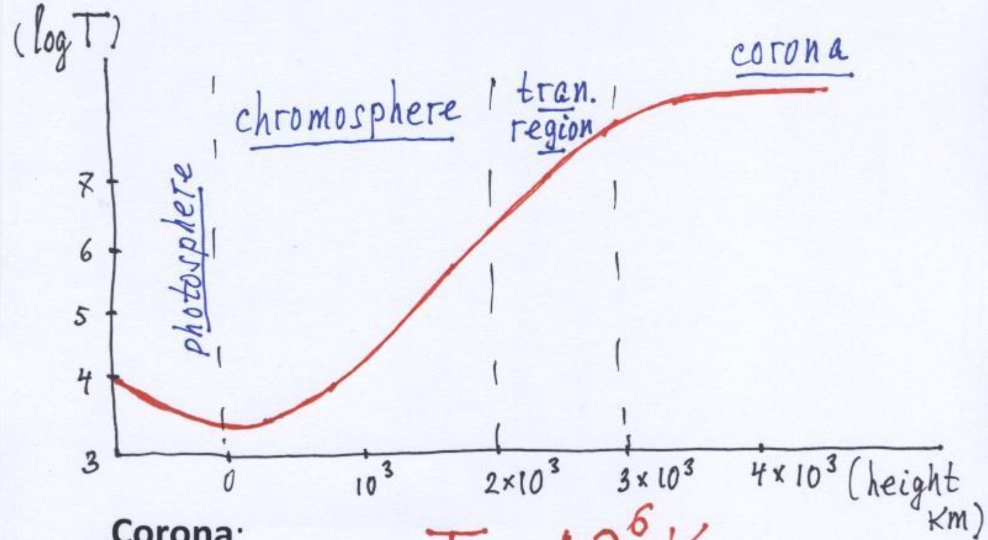
$T_e > 10^6 K$!!





Corona:

$T_c \sim 10^6 K$

$n_c \sim (10^8 \div 10^9) cm^{-3}$

quiet Sun — active regions

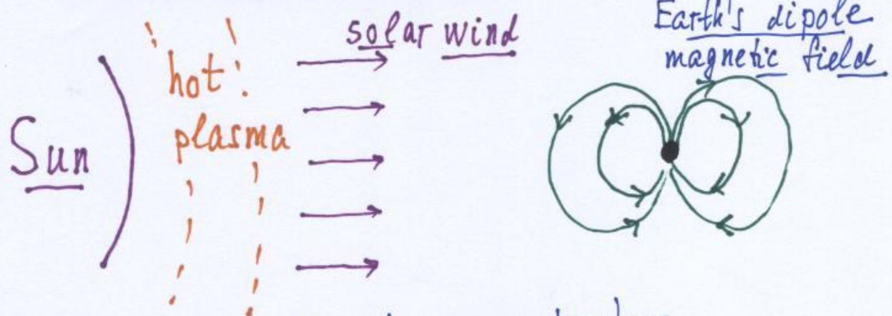
Energy supply required

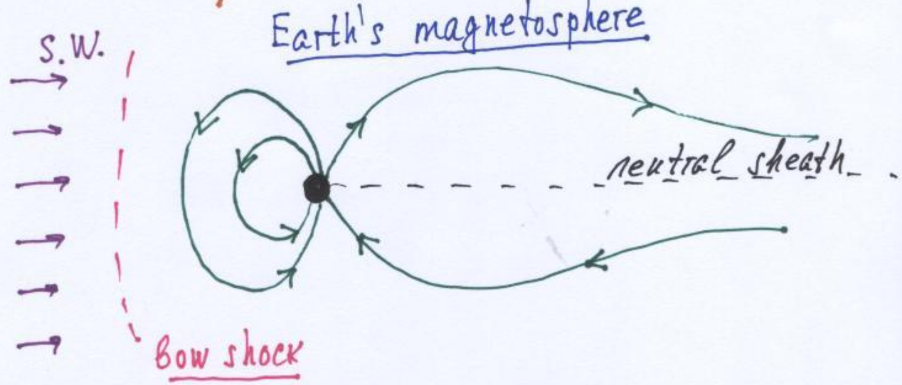
q_c (erg/cm²·s) → $\sim 3 \times 10^5$ (quiet Sun), $\sim 10^7$ (active regions)

Total solar luminosity:

$$q_{\odot} \approx 6.3 \times 10^{10} erg/cm^2 \cdot s$$

Coronal impact on Earth



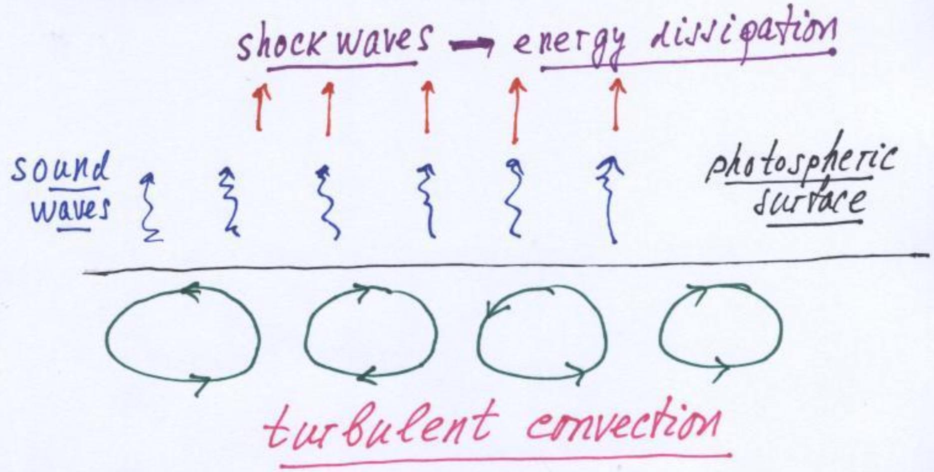


Variations in SW → **Magnetospheric pulsations**

(solar flares, coronal mass ejections, etc...) → (magnetic storms, aurora, etc...)

SPACE WEATHER

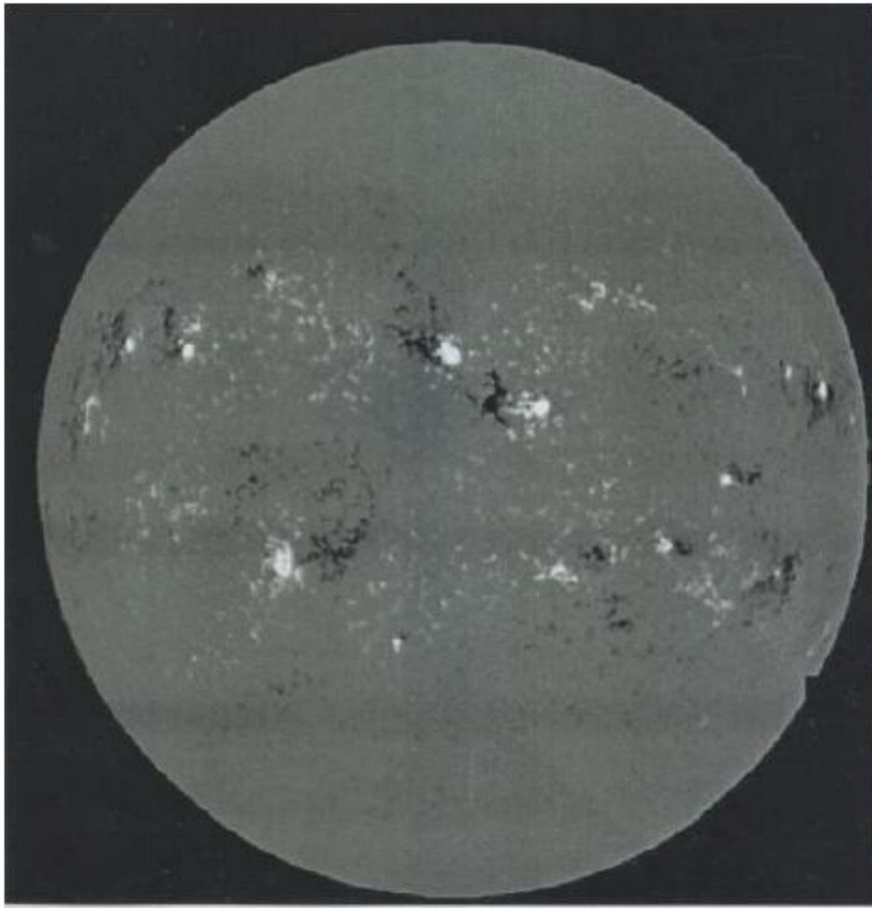
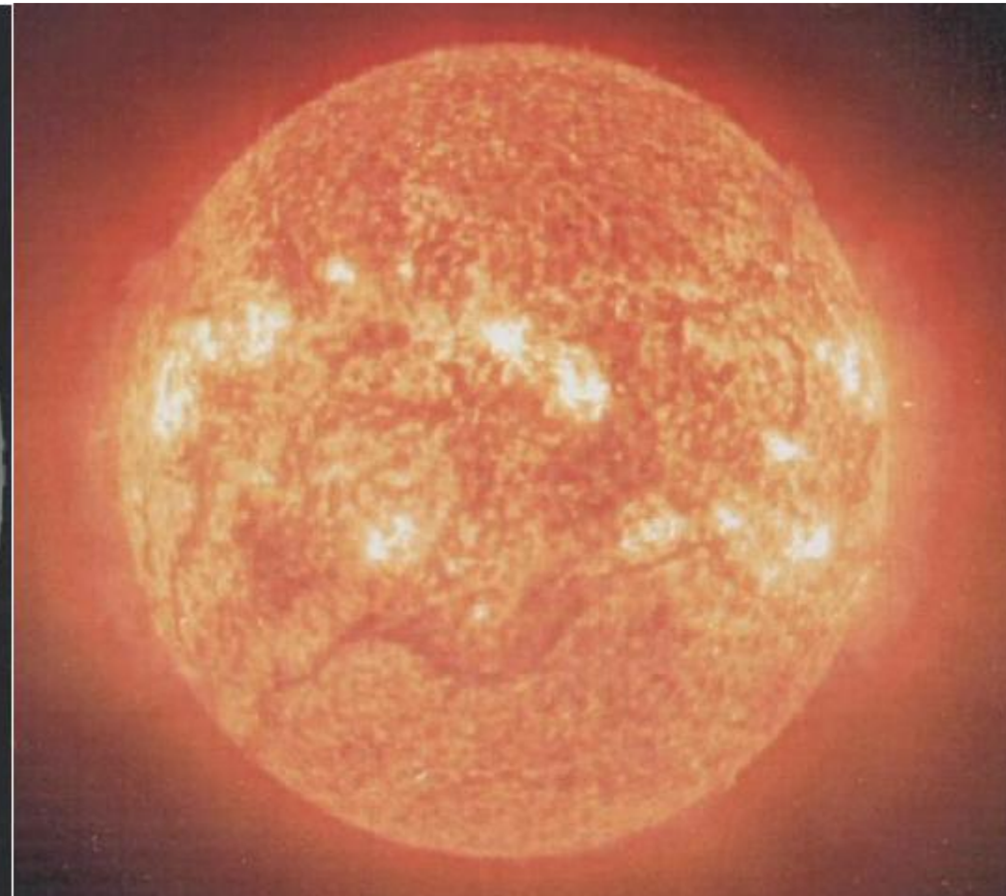
"Old" theory of coronal heating: acoustic heating



Main drawbacks

i) Observed acoustic energy flux is too small
ii) Strong correlation between the X-ray activity in the corona and the coronal magnetic field

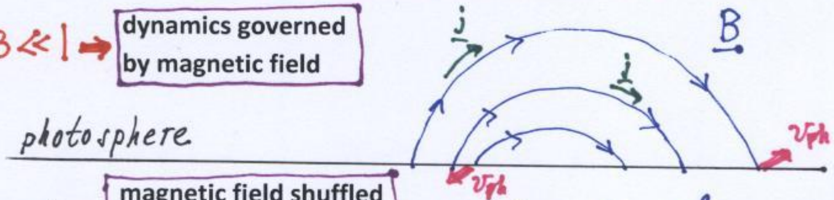
Magnetic nature of the solar coronal heating

Magnetic coronal heating: how does it work?

i) active region magnetic loop

$\beta \ll 1 \Rightarrow$ dynamics governed by magnetic field



$\beta \gg 1 \Rightarrow$ magnetic field shuffled by convective motions

$B \sim 10^2$ G, $L \sim 10^9$ cm

$V_A \sim 10^3$ km/s $\rightarrow \tau_A \sim \frac{L}{v_A} \sim 10$ s

$v_{ph} \sim 1$ km/s, $l_{ph} \sim 10^3$ km $\Rightarrow$

$\tau_{ph} \sim l_p/v_p \sim 10^3$ s $\gg \tau_A \Rightarrow$

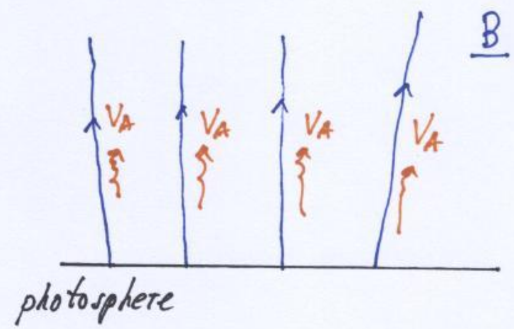
Quasistatic evolution $\Rightarrow$ force-free magnetic field : $\underline{j} \parallel \underline{B}$

ii) open magnetic region (coronal hole)

Generation of MHD waves

⬇

Supporting SW



Magnetic energy: a viable energy source

Injected power (Poynting flux)

$$P \sim v_{ph} \cdot B^2/4\pi$$

$$P_{max} \sim 10^8 \, erg/cm^2 \cdot s \gg q_c$$

Major problem: extremely high electric conductivity of the coronal plasma

$$\sigma = \frac{n e^2 \tau_e}{m_e} \propto T_e^{3/2}$$

Resistivity $\eta = \frac{1}{\mu_0 \sigma} \propto T_e^{-3/2}$

Global Ohmic energy dissipation is completely irrelevant

$$\tau_\eta \sim L^2/\eta \equiv S \, \tau_A$$

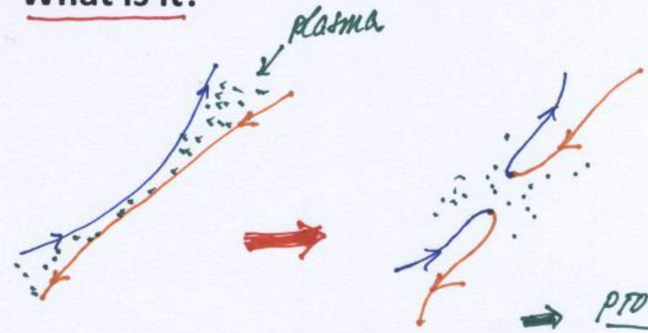
$$S \equiv \tau_\eta/\tau_A = \frac{L \cdot v_A}{\eta}$$ – Lundquist number

$S \sim 10^{12}$ for the corona $\Rightarrow$ $\tau_\eta \sim 10^6$ years!!

Possible way out → magnetic energy release via **magnetic reconnection**

MAGNETIC RECONNECTION

What is it?



→ prohibited in ideal MHD

What is it for?

Magnetic energy release via reconnection is by far more effective that with the global Ohmic heating

$$\tau_r = \tau_A \cdot S^{\alpha}, \quad 0 < \alpha < 1$$

$\alpha = \frac{1}{2} \Rightarrow$ classical Sweet-Parker reconnection model

$\alpha \to 0 \Rightarrow$ fast reconnection model

⇓

$$\tau_r \sim 10^2 \tau_A$$

Reconnection events in the solar corona

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Solar flares

Energy range: $(10^{29} \div 10^{33})\,erg$ →

Not frequent enough for maintaining the hot corona

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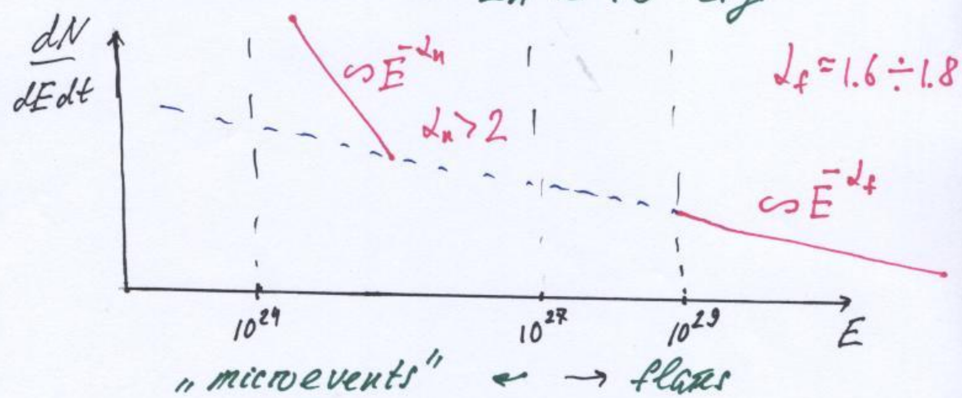
NANOFLARE concept (Parker, 1988) →

Corona is heated by numerous small flare-like reconnection events with $E_n \lesssim 10^{24}\,erg$



the outcome is very sensitive to assumptions on the structure of emitting plasma as well as on the events selection procedure

How to test the nanoflare heating scenario

without being able to resolve individual nanoflares observationally ?

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Forward modeling of the nanoflare-heated solar corona

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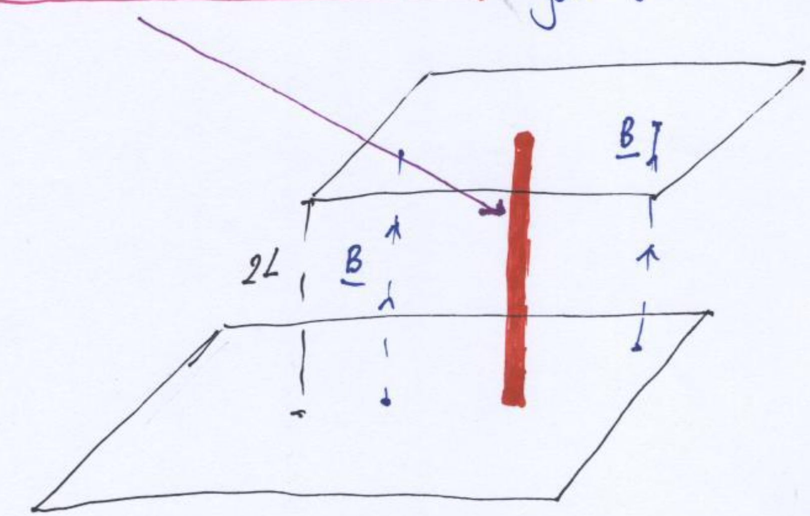
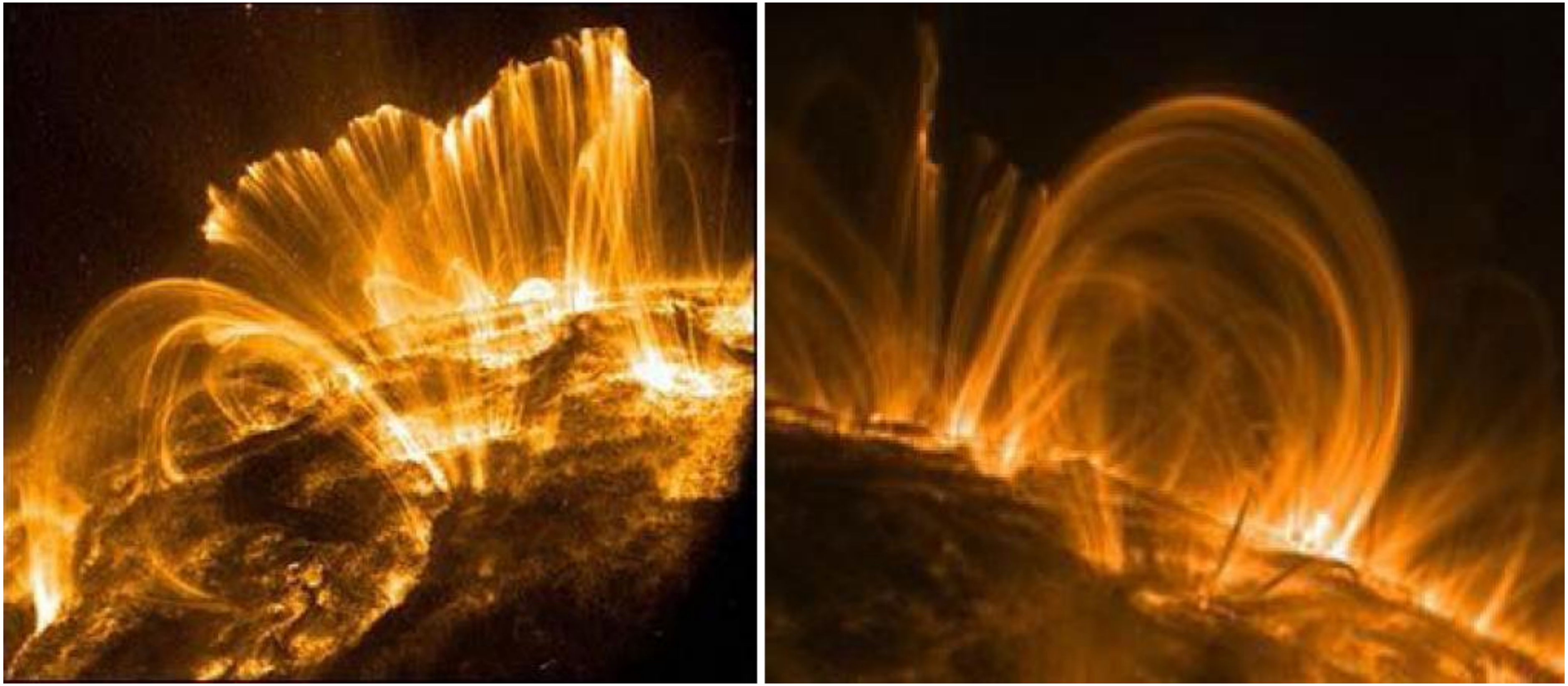
Observable signature of the nanoflare heating

Each nanoflare →

A single hot coronal filament with $\beta \sim 1$





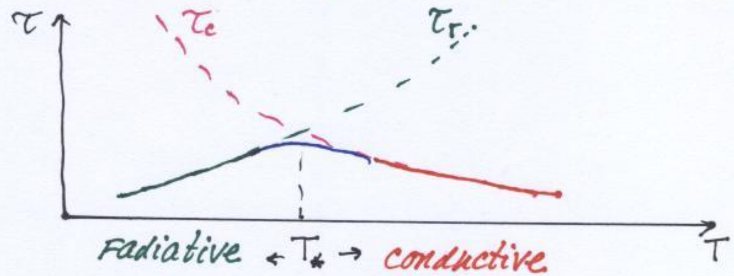
Cooling of the hot coronal filament

Heat conduction

$\tau_c \approx 4 \times 10^{-10}\, n\, L^2 / T^{5/2}$

Radiation

$\tau_r = 2 \times 10^{-3}\, T^{3/2} / n$



Two-stage cooling process →

Conductive phase → **Radiation phase**

$T_* \approx 4 \times 10^{2}\, B^{2/3} L^{1/3}$

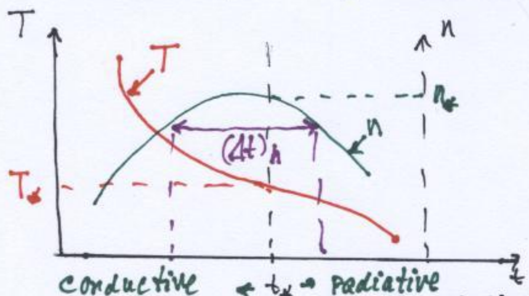
$n_* \approx 3.5 \times 10^{11}\, B^{4/3} L^{-1/3}$

$(\Delta t)_n \approx t_* \approx 10^{-4}\, L^{5/6} B^{-1/3}$

$B = 30\ G;\ L = 10^{9}\ cm$

$T_* \approx 4 \times 10^{6}\ K;\ n_* \approx 3 \times 10^{10}\ cm^{-3}$

$(\Delta t)_n \approx 10^{3}\ s$

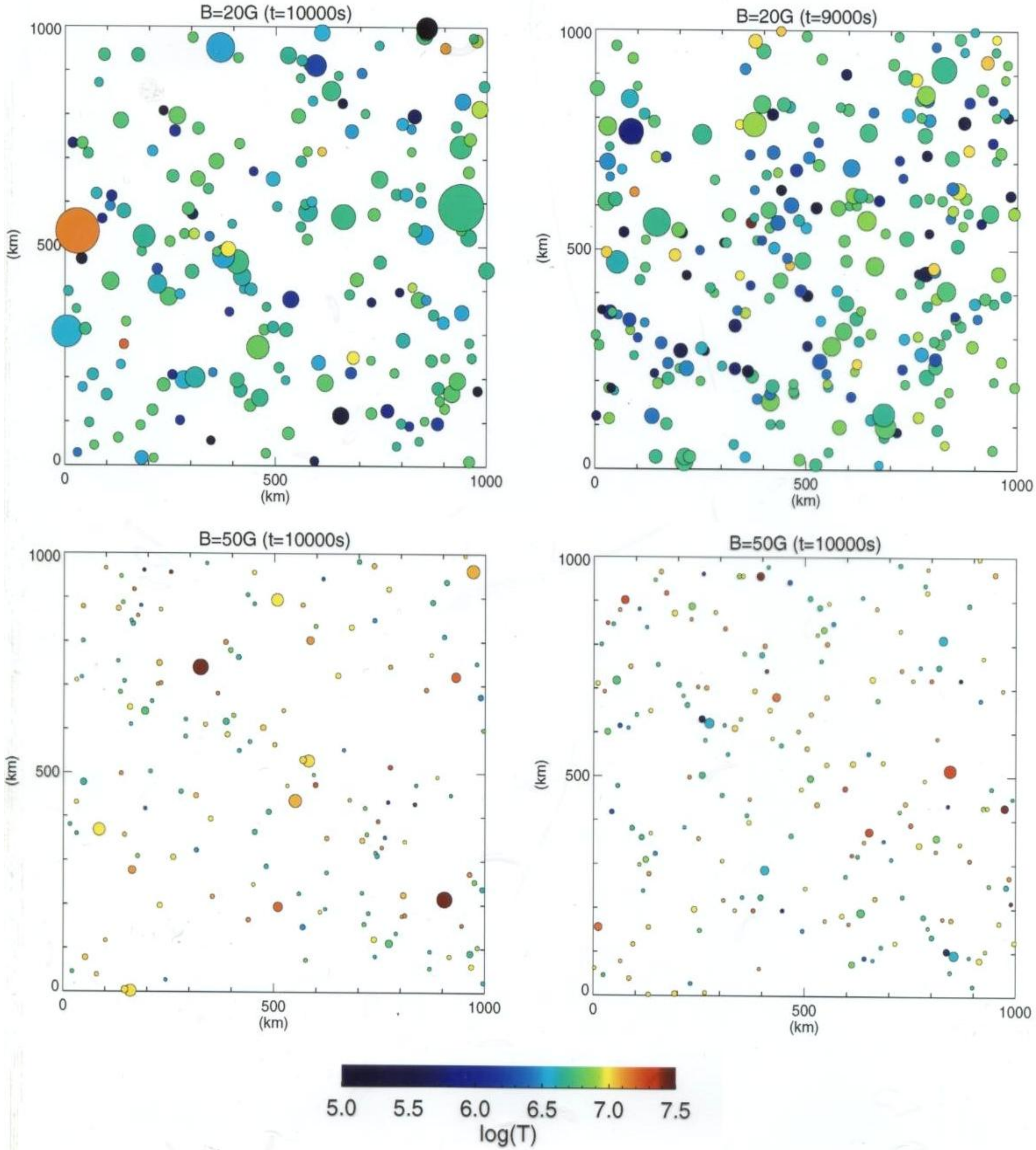


chromospheric evaporation

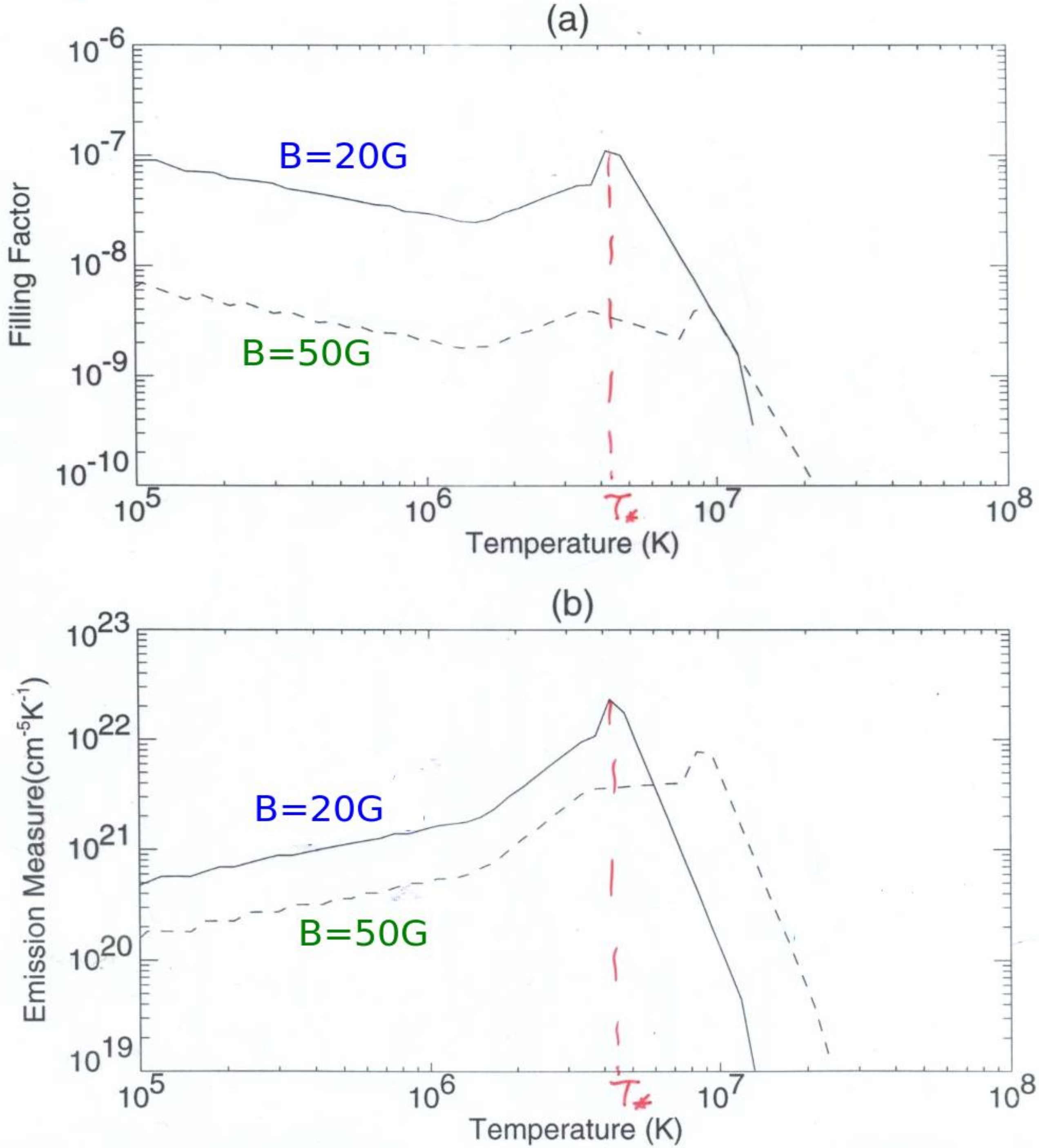
statistical steady state

$t \gg (\Delta t)_n$

- broad temperature and density distribution of filaments
- continuous replenishment of the coronal plasma



B=20G (t=10000s)
B=20G (t=9000s)
B=50G (t=10000s)
B=50G (t=10000s)
(km)
0
500
1000
5.0
5.5
6.0
6.5
7.0
7.5
log(T)



(a)
Filling Factor
B=20G
B=50G
T_*
Temperature (K)
(b)
Emission Measure(cm^{-5}K^{-1})
B=20G
B=50G
T_*
Temperature (K)

Nanoflare-heating scaling laws

- Predicted DEM distribution
- Temperature detected by a broad-band X-ray telescope (Yohkoh SXT):

$$T \approx T_* \approx 4\times10^{-2} B^{2/3} L^{1/3}$$

$$B \approx (30 \div 50)\, G \Rightarrow T_* \approx (4 \div 6)\times10^{6} K$$

- Coronal filling factor (fraction of volume filled with hot X-ray emitting plasma)

$$f \approx 2\times10^{-3} q / B^{7/3} L^{1/6}$$

$$f \approx (10^{-1} \div 10^{-2}) \ll 1$$

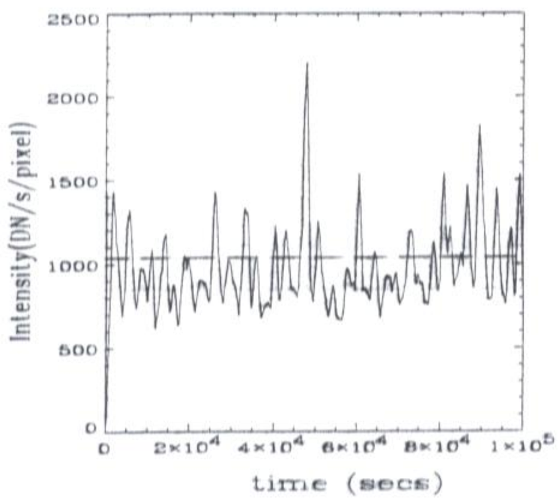
Can be obtained observationally

$$f = \langle n \rangle^2 / n_{act}^2$$

$n_{act} \rightarrow$ actual density of emitting plasma

$\langle n \rangle \rightarrow$ average density $\Rightarrow$ from emission measure

Numerical simulations of the coronal X-ray emission would be detected by Yohkoh/SXT



a bigger energy of nanoflares

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less frequent heating events

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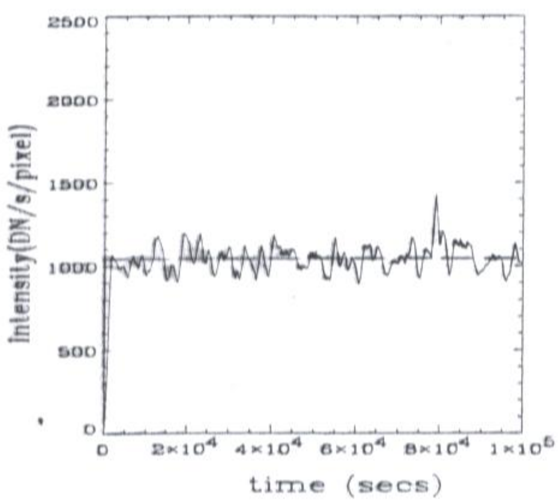
larger fluctuations



smaller nanoflares

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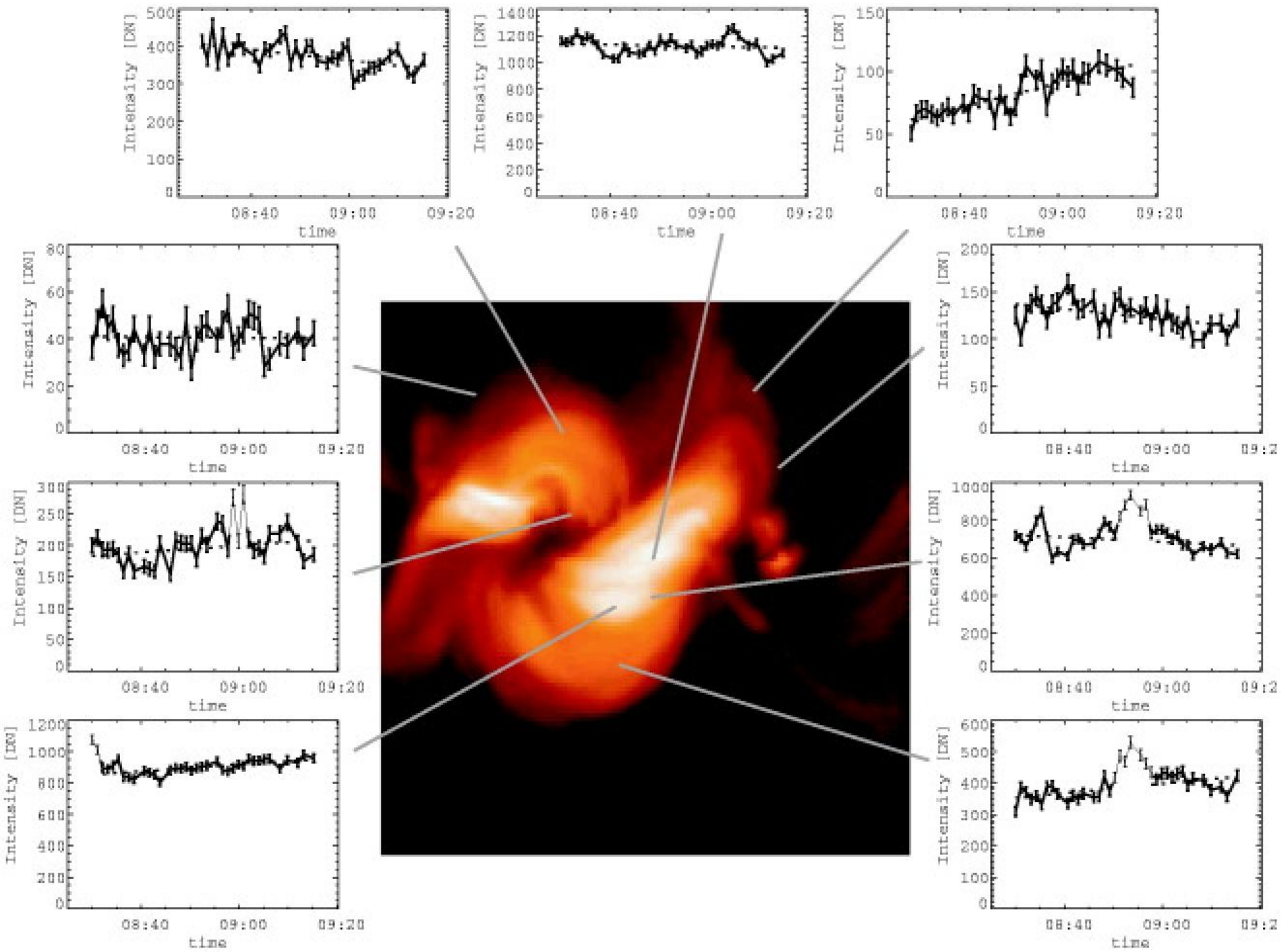
much lower fluctuations for the same mean intensity



X-ray intensity of individual pixels from SXT *(Katsukawa & Tsuneta, 2001, ApJ)*

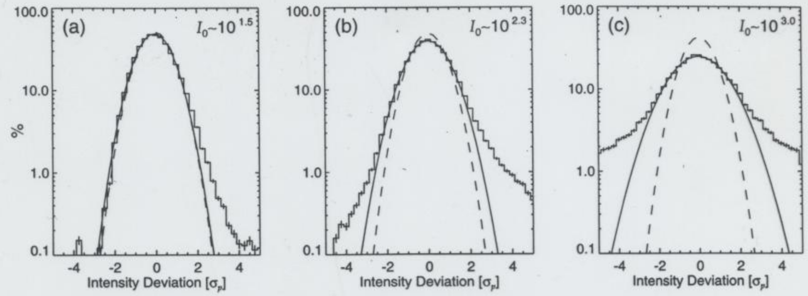


FIG. 2.—Histogram of the X-ray intensity fluctuation around the mean intensity I_0 for three intensity levels: (*a*) $I_0 \simeq 10^{1.5}$, (*b*) $I_0 \simeq 10^{2.3}$, a $I_0 \simeq 10^{3.0}$. The unit of the horizontal axis is σ_p, the standard deviation due to the photon noise. The vertical axis is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

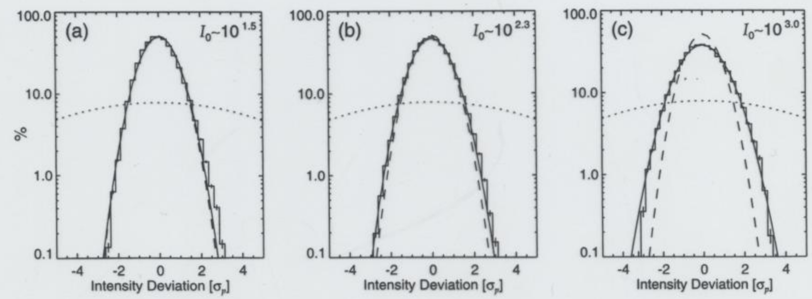
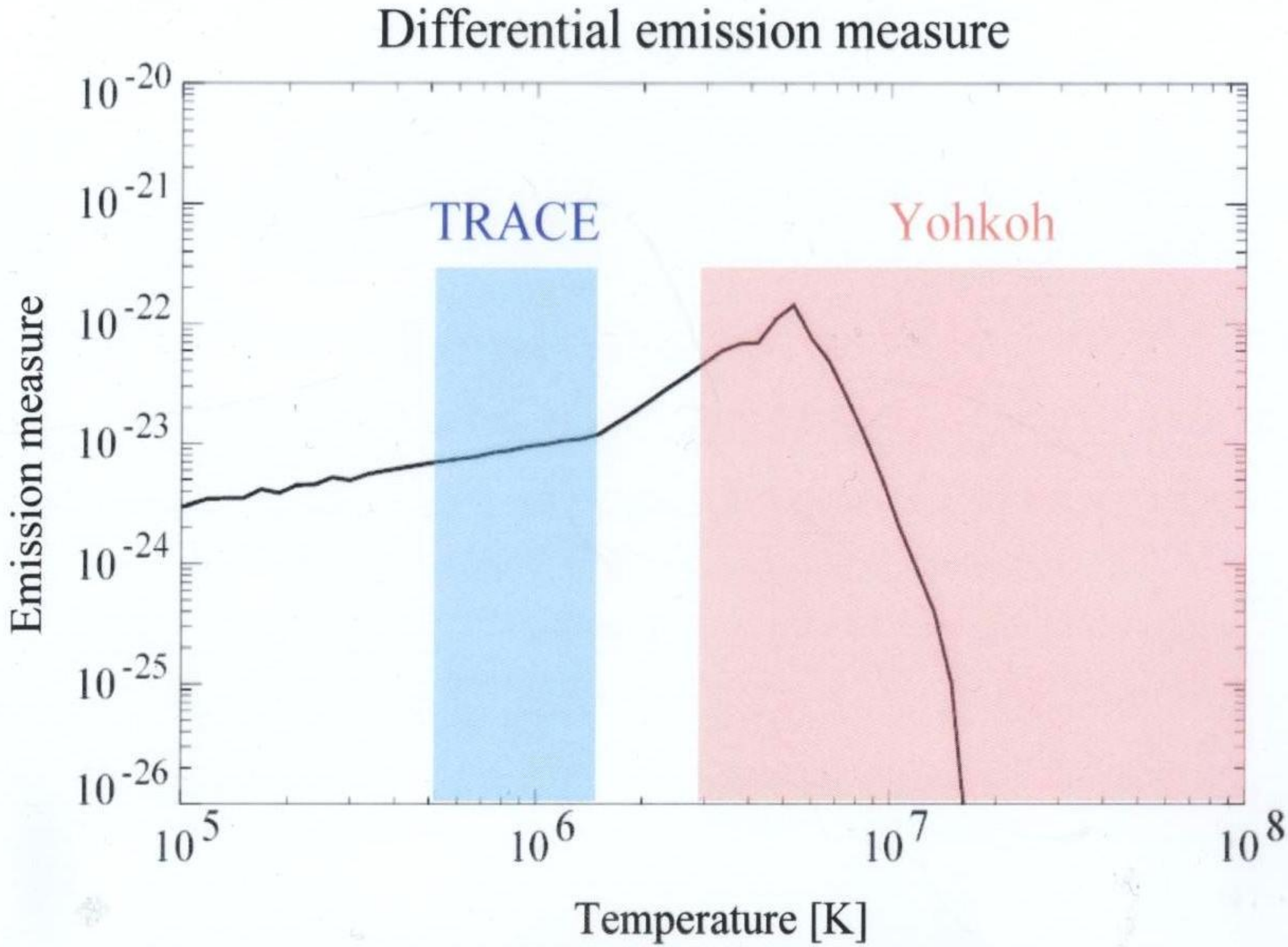


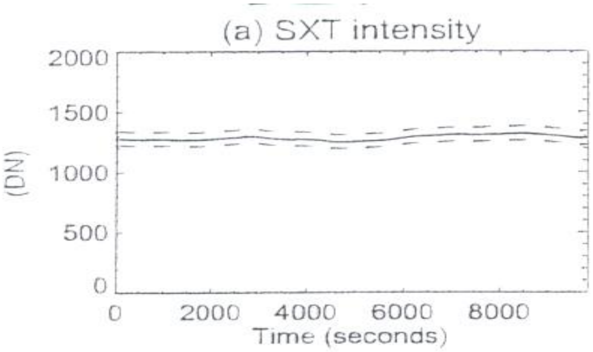
FIG. 3.—Histogram of the X-ray intensity fluctuation around the mean intensity I_0 after removing the wing component (see text). The solid curves a Gaussian best fitted to the histograms. The photon noise distributions (*dashed curves*) and the distribution functions for $\sigma_I/\sigma_p = 5$ (*dotted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

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

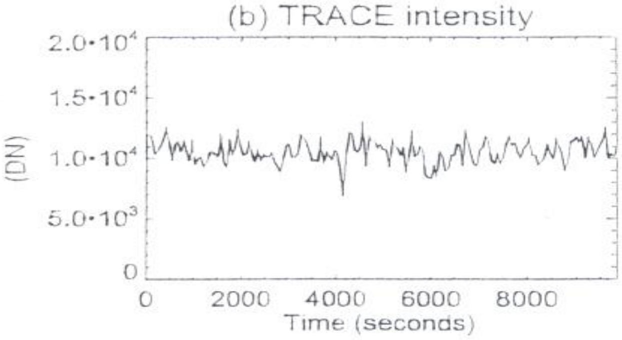

Differential emission measure
Emission measure
Temperature [K]
TRACE
Yohkoh
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^{5}
10^{6}
10^{7}
10^{8}

Simulated intensity variations

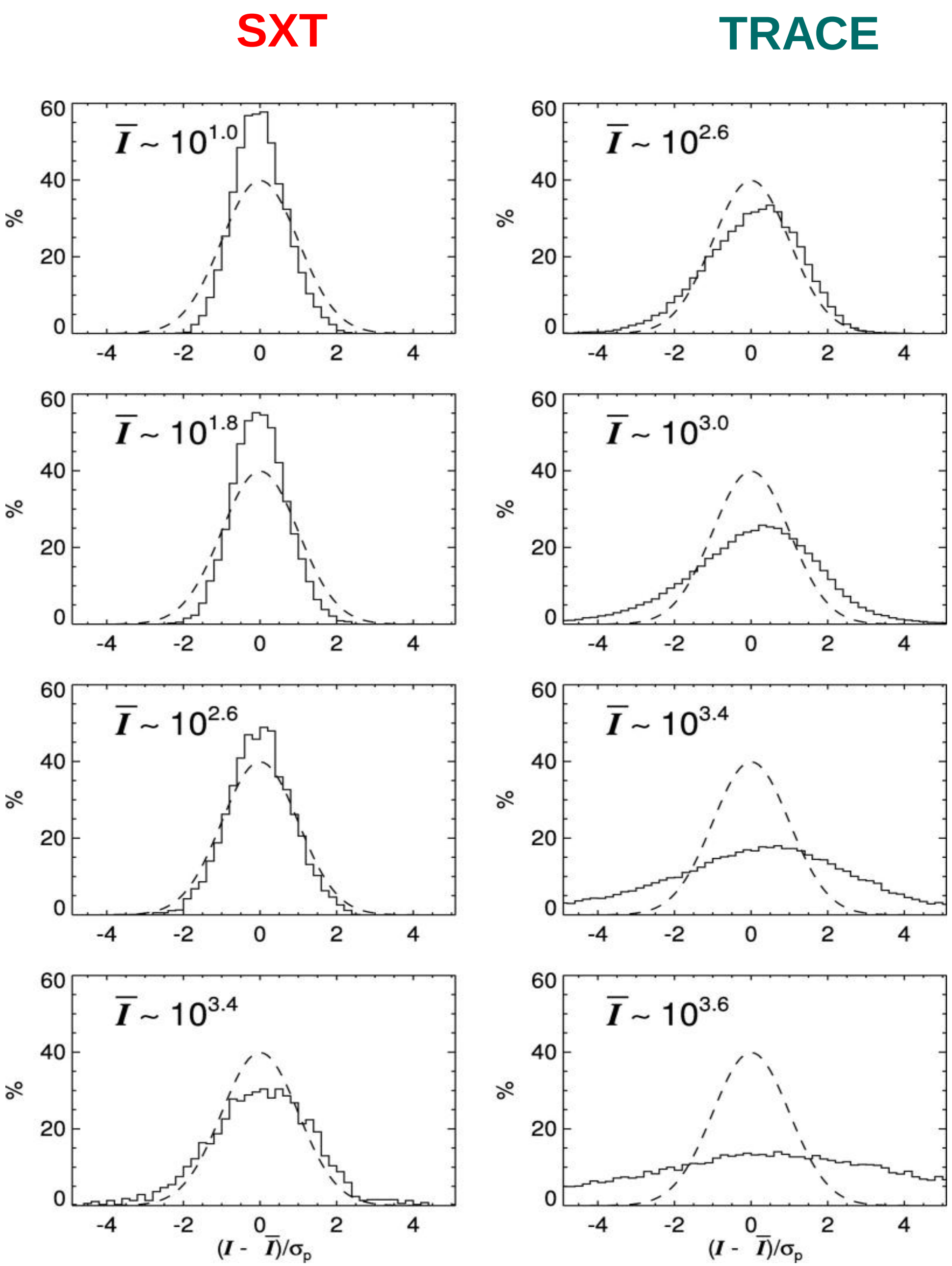
SXT



TRACE



Observed intensity variations



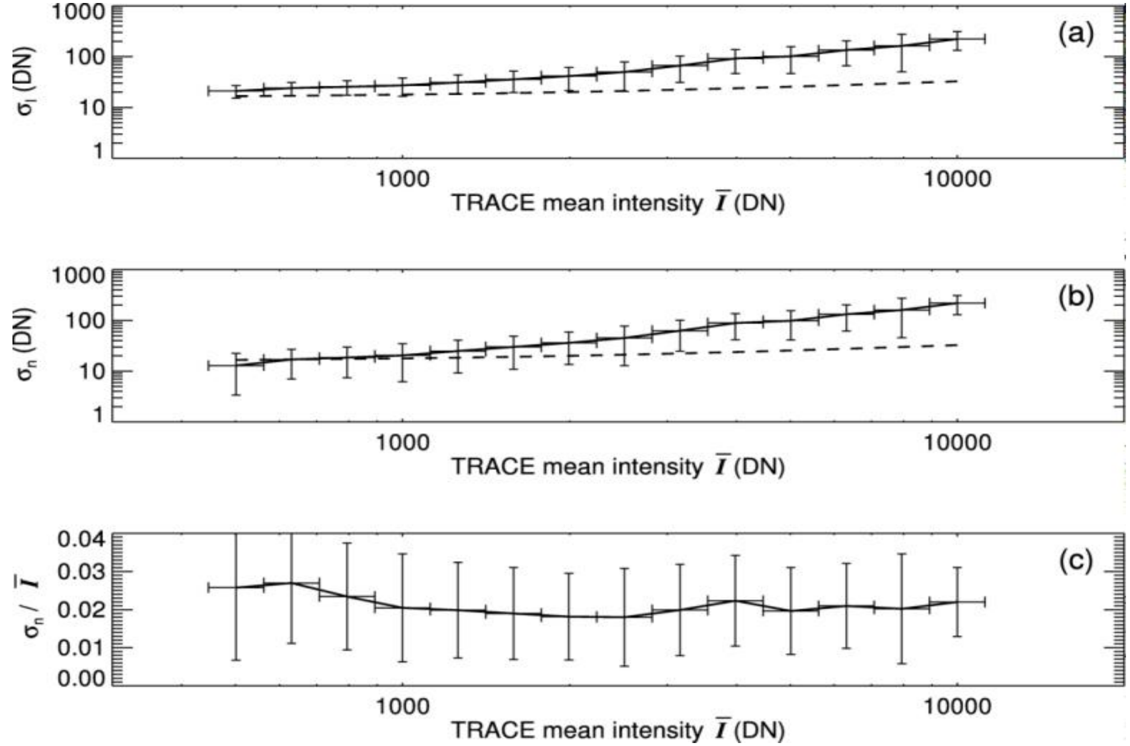
TRACE:

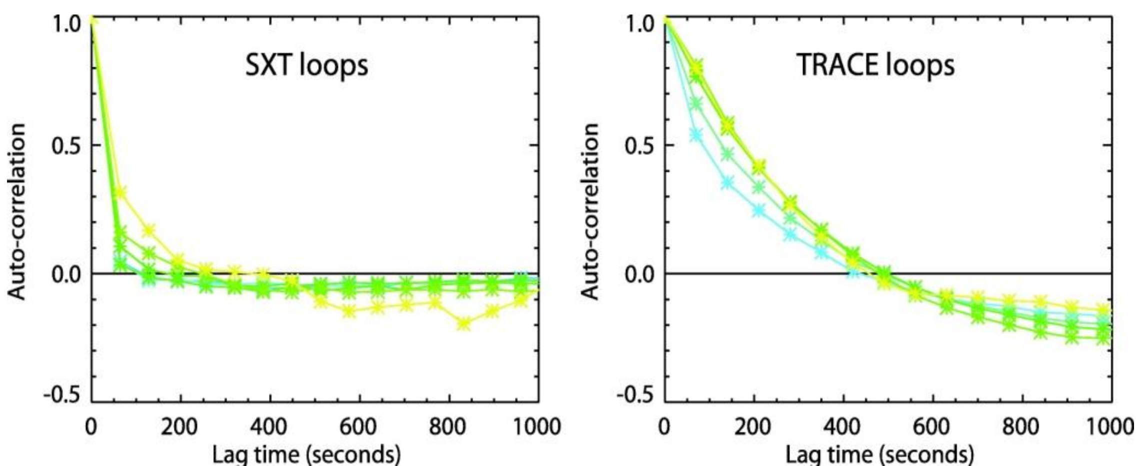
detected fluctuations are well above the estimated photon noise

(unlike Yohkoh/SXT)

Intensity fluctuations detected by TRACE

2 major characteristics:

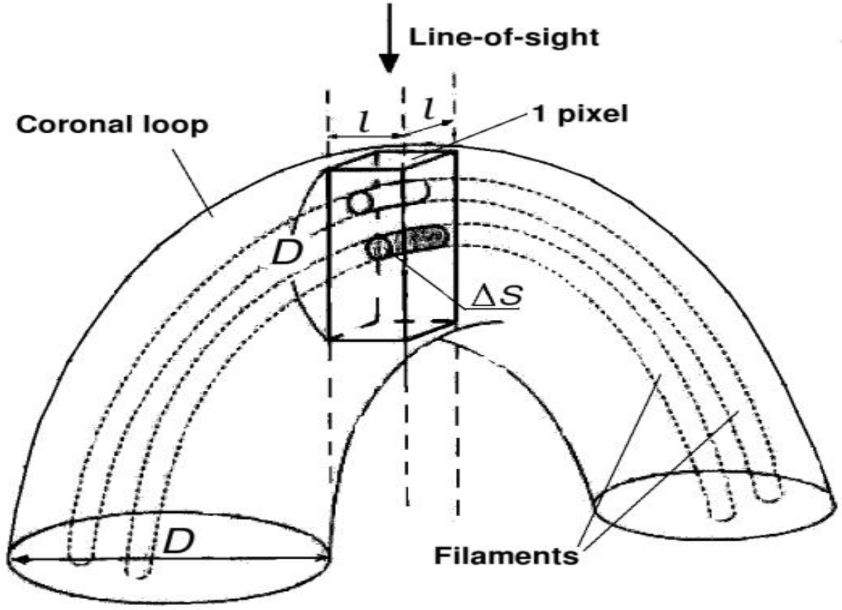




Gaussian width:

$\sigma_{TR}= 0.02 <I>$

Time-scale of fluctuations: $(\Delta t)_{TR}=500s$



Schematic diagram:

L = 10^{10}cm

D = 3 10^9cm

l = 1.8 10^8cm

(TRACE 5x5 micropixels)

Exposure time τ_e=27.6s is much shorter than $(\Delta t)_{TR}$=500s → Snapshot of the instantly present strands → $\sigma = \langle I \rangle / \langle N \rangle^{1/2}$ → $\sigma = 2\ 10^{-2} \langle I \rangle$

<N> - mean number of strands contributing to the detected intensity

$\langle N \rangle = 3\ 10^3$

Birth-rate of nanoflares:

$$\langle N \rangle = \frac{dN}{dt\, dS} (\Delta t)_{TR}\, D\, l$$

$$\frac{dN}{dt\, dS} = 10^{-17}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

Forward modelling

(Δt) is determined by the cooling time of relevant strands

$(\Delta t)_{TR}$=500s

Radiative cooling of a plasma with $T_{TR}=10^6K$ and n_{TR}= 4 10^9cm^{-3}

(*another way* of deriving the *actual density* of *individual strands*)

"Overdense" strands: n_{RTV}= 3 10^8cm^{-3}

signature of impulsive coronal heating

The *size of strands* detected by TRACE and their *filling factor*:

$$\langle I\rangle = R_{TR} \langle N\rangle \, n_{TR}^2 \, (\Delta S) \;\; \tau_e \;\; \ell$$

TRACE response coefficient (R_{TR})

cross-section area of a strand ((ΔS))

Bright TRACE pixels: $\langle I\rangle_{TR}=10^4$ → (ΔS) = 4 10^{12}cm^2 → d = 20km across

Filling factor: $f_{TR} = \dfrac{\langle N\rangle_{TR} \, (\Delta S)}{\ell D} = 2 \; 10^{-2}$

Energetics of nanoflares

TRACE strand: $E_{TR} = 3\, n_{TR}\, k\, T_{TR}\, (\Delta S)\quad 2L = 10^{23} erg$

is less than the initial energy deposition of a nanoflare E_n: TRACE plasma is in the stage of radiative cooling

How to derive En: *simultaneous* SXT data

Plasma temperature detected by SXT: $T_{SXT} = 5\ 10^6$K

↓

It relates to the peak of the DEM

↓

$n_{SXT} = n_{RTV} = 7\ 10^9 cm^{-3}$

Radiative cooling from $T_{SXT} = 5\ 10^6 K$ to $T_{TR} = 10^6 K$

Plasma draining from $n_{SXT} = 7\ 10^9 cm^{-3}$ to $n_{TR} = 4\ 10^9 cm^{-3}$

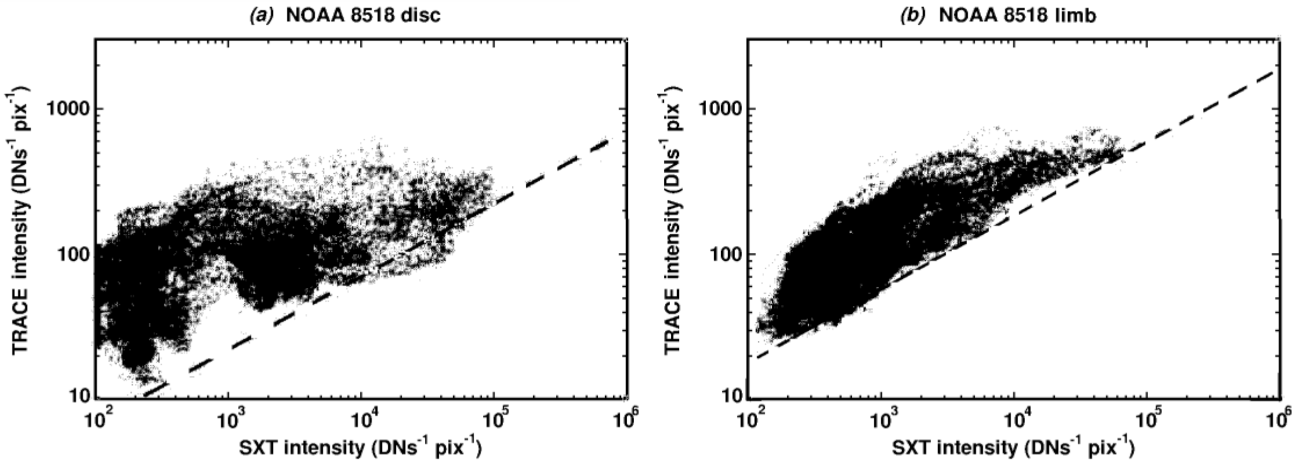
$n \sim T^{0.35}$ - very close to 1D simulations

Nanoflare energy $E_n = 5\ n_{SXT}\ kT_{SXT}\ (\Delta S)\ 2L = 2\ 10^{24} erg$

Overall energy budgett $G = En \dfrac{dN}{dt\ dS} = 2\ 10^7 erg\ cm^{-2}\ s^{-1}$

Observational support

Correlation between TRACE and SXT data



Do the numbers match?

Bright TRACE pixels: $\langle I\rangle_{TR} = 10^4 \rightarrow \langle I'\rangle_{TR} = 360$

The respective SXT pixels: $\langle I\rangle_{SXT} = 3\ 10^3 \ldots 10^4\ (\tau_e = 0.95s)$

On the other hands $\langle \Delta t\rangle_{SXT} = 3\ 10^6 s = 6\ \langle \Delta t\rangle_{TR}$

$f_{SXT} = 6\ f_{TR} \approx 0.1$

$\langle I\rangle_{SXT} = R_{SXT}\ \ n_{SXT}^2\ \ \ell^2\ D\ f_{SXT}\ \ \tau_e = 2\ 10^3$

… pretty consistent with the observed X-ray emission