Emission measure distribution of nanoflare-heated coronal loops

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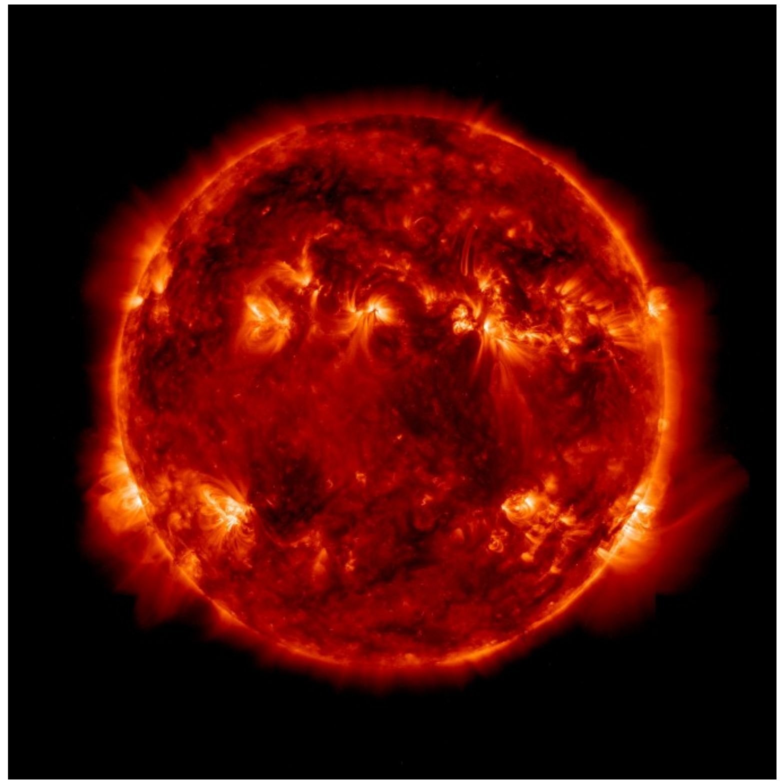
1. Introduction

The origin of the heating of the solar corona continues to be one of the most persistent problems of Solar Physics.

Any theory proposed to explain coronal heating must be consistent with a broad, and sometimes apparently contradictory, set of coronal observations.

Some of the theories that received special attention from researchers in recent years are those based on nanoflare heating.



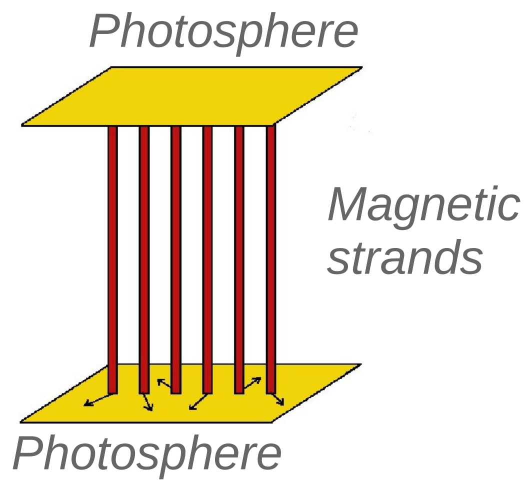
Here, we compare the results of a cellular automaton model of nanoflare heating with observed properties of coronal loops, such as the evolution of intensity in different wavelengths and the emission measure (EM) distribution of the plasma.

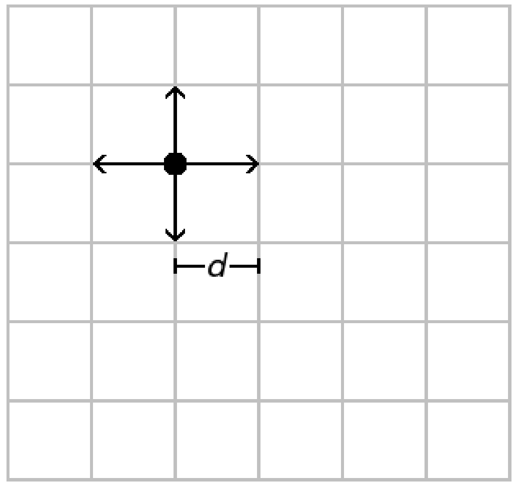
The model is based on Parker's (1988) idea that nanoflares are produced by reconnection between elementary magnetic strands that are stressed by the continuous displacement of their photospheric footpoints.

2. Model

2.1 Driving mechanism:

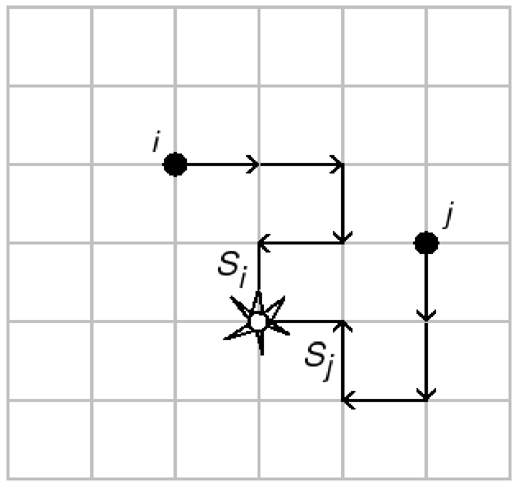
We simulate the classical representation of straight magnetic strands with a uniform distribution of points in a 2D grid





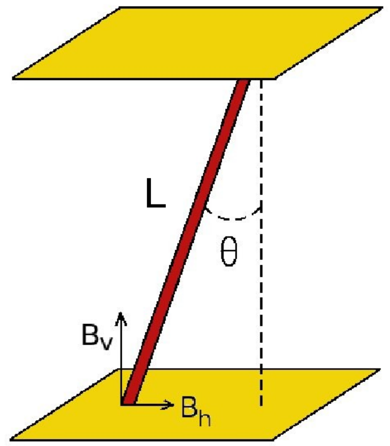
On each time step the points move to random neighbor positions, simulating photospheric displacements

The "strand-points" travel through the grid increasing their paths (S_i and S_j)



As the system evolves the "horizontal" component of the strand magnetic field increases

$$\boxed{\delta B_h = \frac{B_v d}{L}}$$



L = strand length
d = horizontal displacement

2.2 Critical condition:

When two strands occupy the same grid position a critical condition is tested:

$$\boxed{B_c = B_v \tan\theta_c}$$

θ_c = critical angle
$\tan\theta_c = 0.25$

The strands are critical when:

$$\boxed{\frac{B_v}{L}(S_i + S_j) > B_c}$$

2.3 Energy release:

When the strands are critical, S_i and S_j are transformed according to the expressions below and energy E_{ij} is released.

$$\boxed{\Delta E_{ij} = \frac{B_v^2}{8\pi L^2}\left[\left(S_i'^2 + S_j'^2\right) - \left(S_i^2 + S_j^2\right)\right]}$$

Where:

$$\boxed{\begin{aligned} S_i' &= \alpha(S_i - d) + (1-\alpha)(S_j - d) \\ S_j' &= (1-\alpha)(S_i - d) + \alpha(S_j - d) \end{aligned}}$$

and $0 < \alpha < 1$

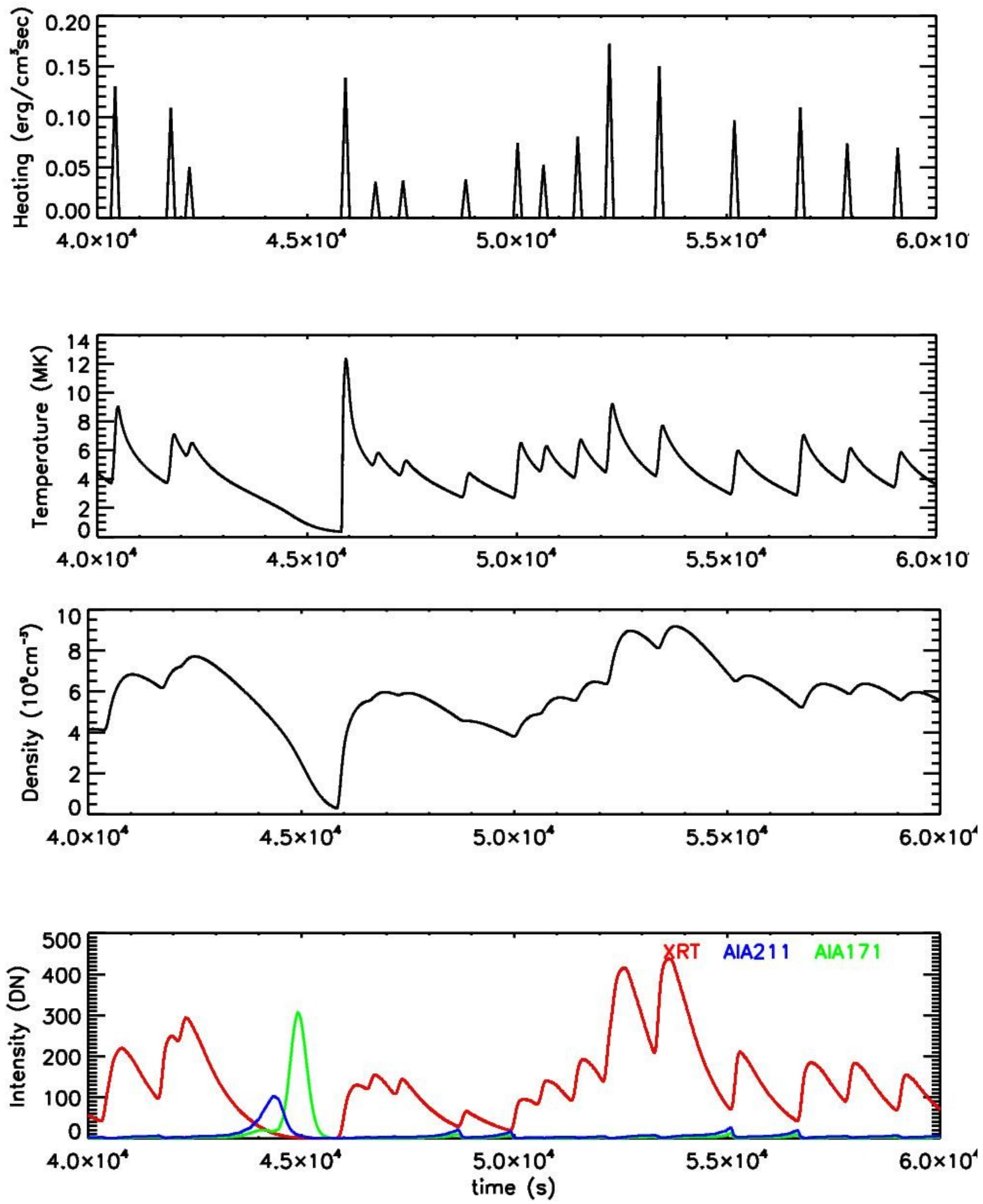
2.4 Plasma response:

We model the nanoflares with 200 s triangular heating functions. We use the EBTEL code to simulate the plasma response on each strand (Klimchuk et al. 2008)

From *n* and *T* we compute the strand emission using the known XRT and AIA instrument responses.

We add the intensity contribution from all strands in the model and obtain synthetic lightcurves that we compare with XRT and AIA observations.

We model and add the photon noise contribution from known instrument calibrations (Narukage et al. 2011, Boerner et al. 2012)

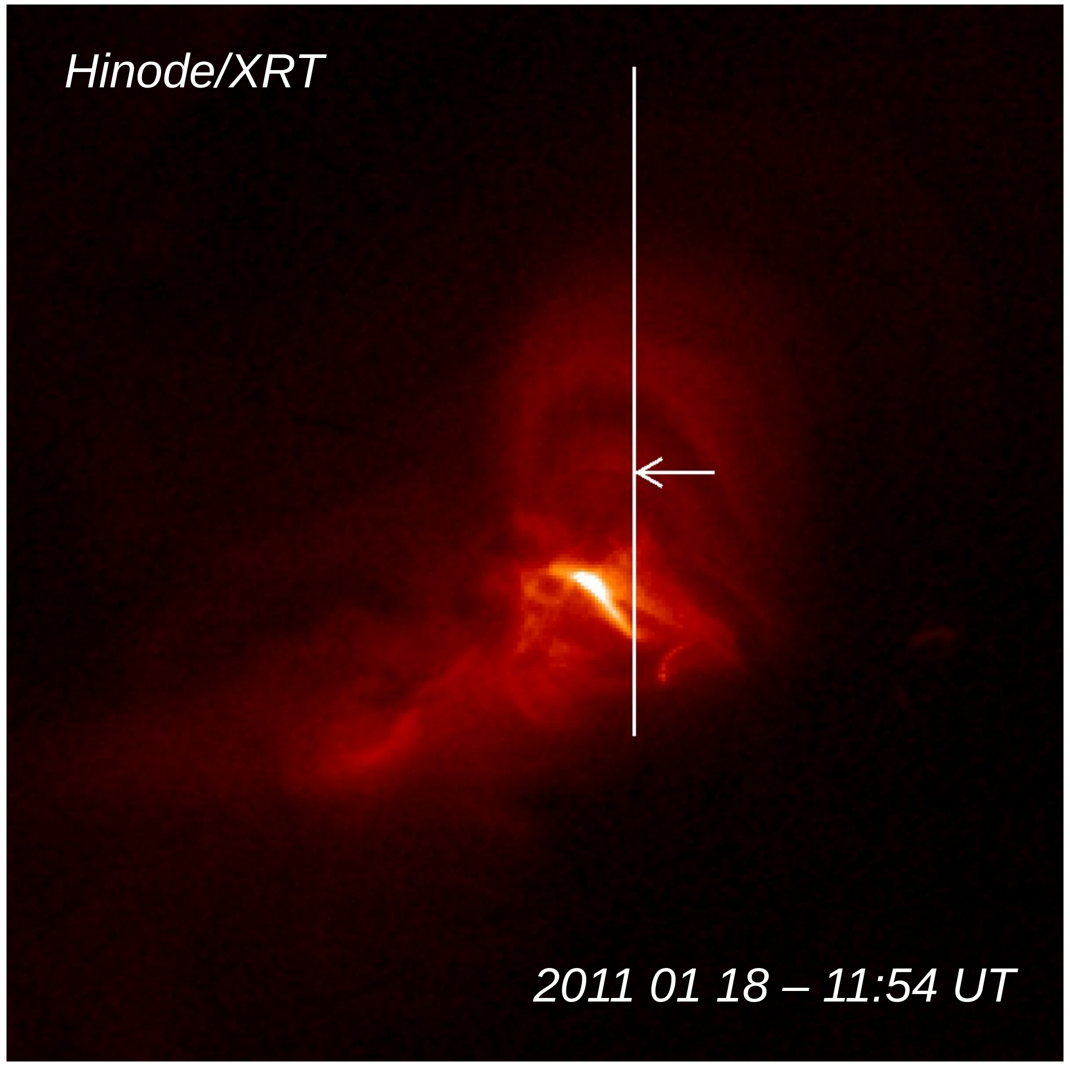


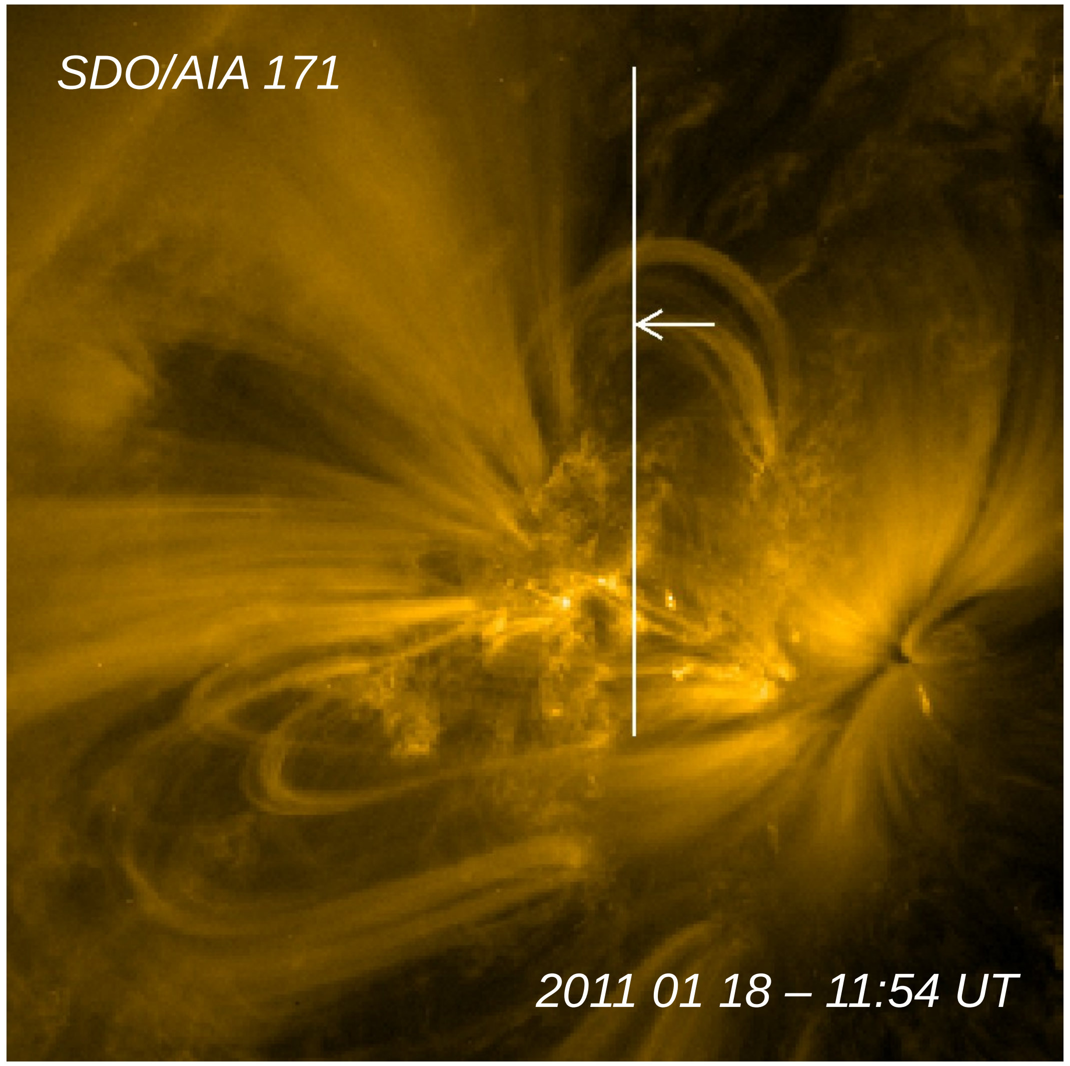
3. Observations

We study XRT and AIA observations of active region NOAA 11147.

Observation date: January 18 2011
XRT filter: Al_poly, *AIA filter:* 171
Time span: ~8000 s
Cadence: ~10 s

Examples of images from the studied datasets.



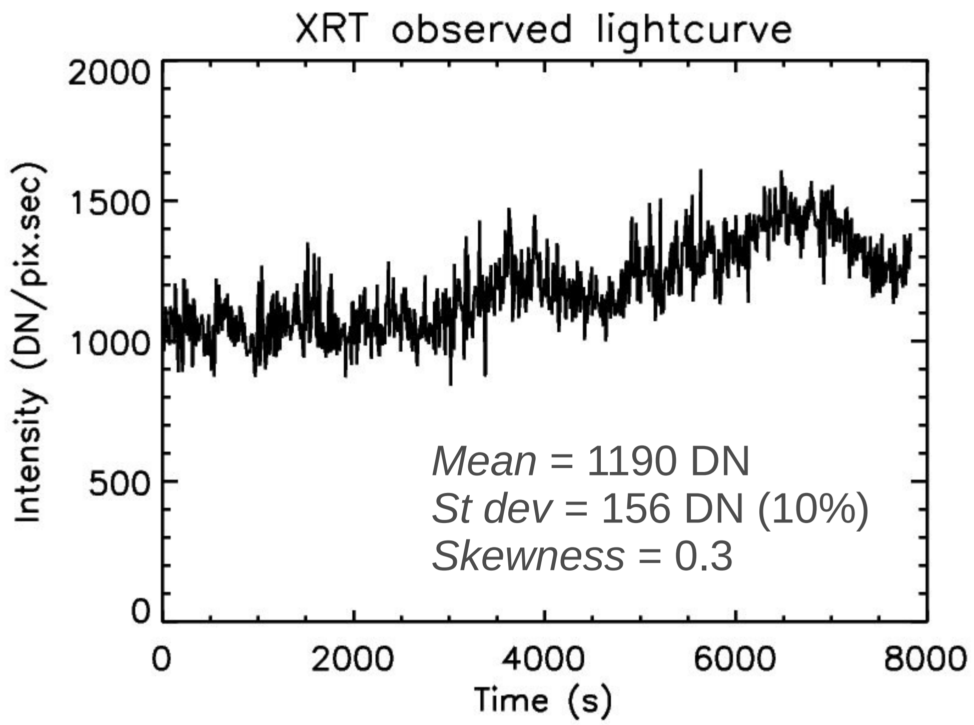


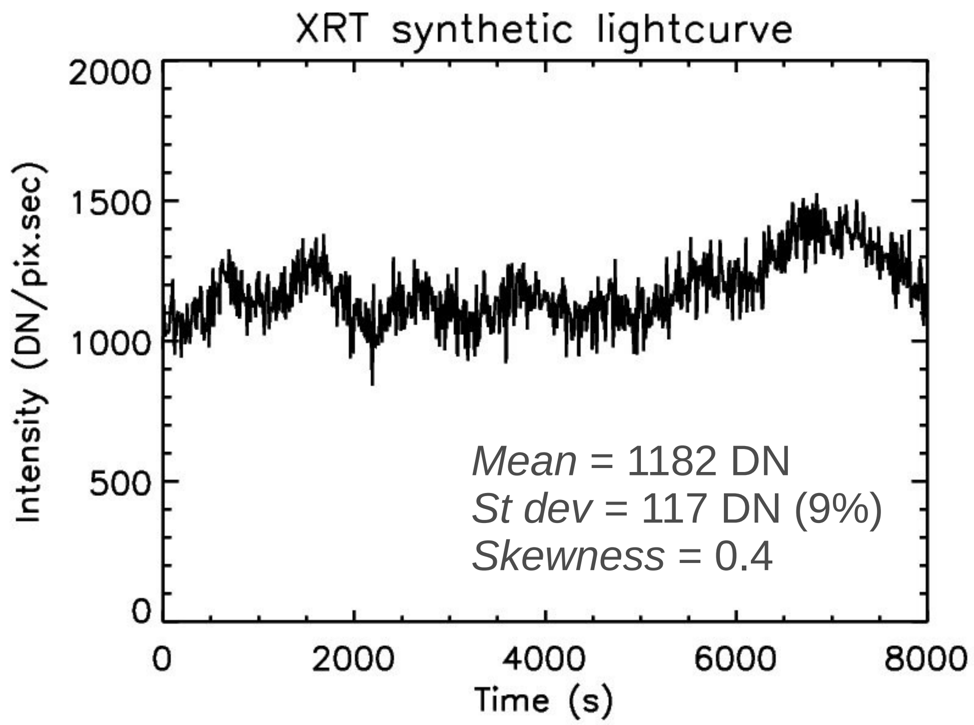
To obtain lightcurves from coronal loop pixels we select vertical segments in both datasets (indicated with white lines in the above panels) and study the intensity evolution of selected pixels along these segments.

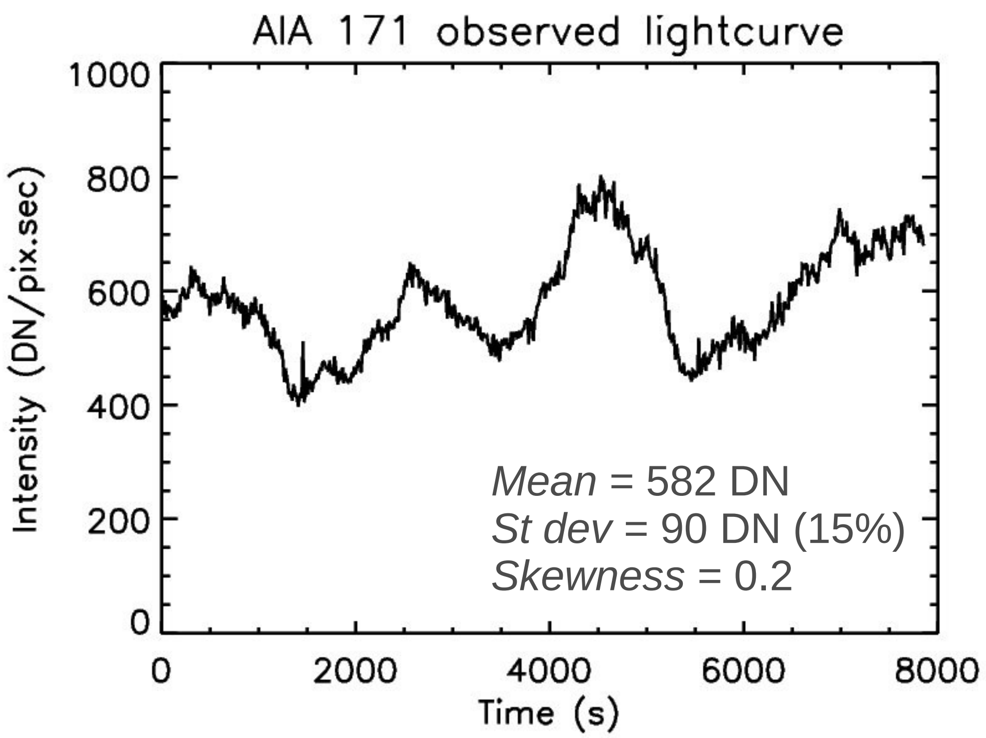
4. Observed and synthetic lightcurves

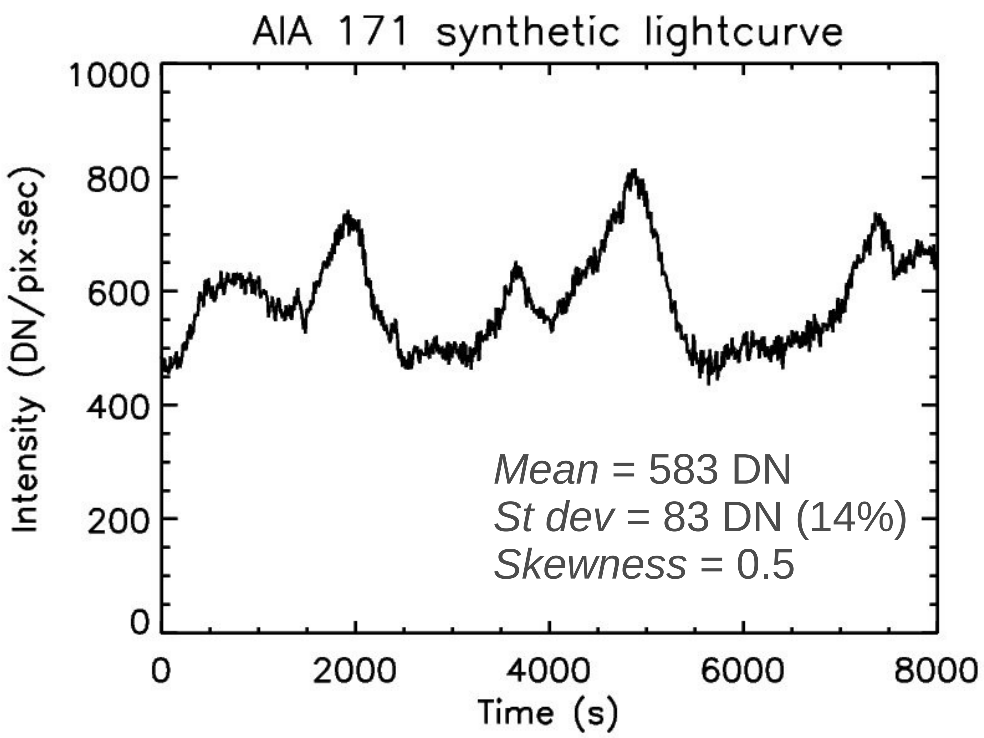
Using typical solar parameters we obtain synthetic lightcurves with the same statistical properties as the observed cases.

Model parameters:
Loop length = 88 Mm
Number of strands = 121









These ligthtcurves correspond to the positions indicated with arrows in the images shown.

Model parameters:
Loop length = 85 Mm
Number of strands = 49

Our results show that using reasonable solar parameters, the model reproduces the main observed statistical properties (mean intensity and fluctuations size) of the coronal emission.

The positive sign of the skewness indicates that the fluctuations distribution is consistent with the widespread presence of cooling processes (see Terzo et al. 2011).

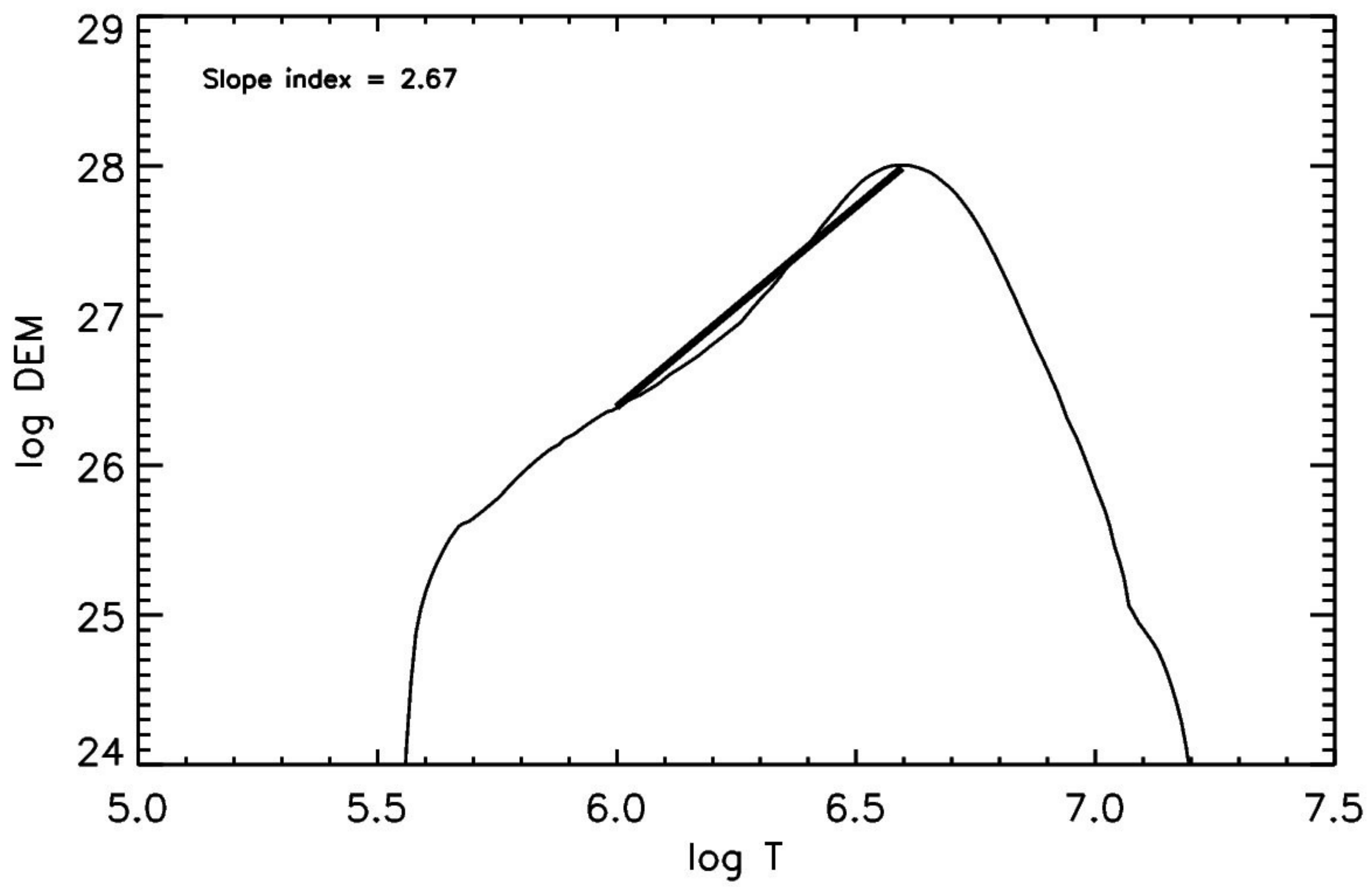
5. Emission measure distribution

The slope of the EM distribution can be used to infer the relative amount of plasma that reaches low temperatures. Then, it can be used as an indicator of the proportion of the contribution of low versus high frequency nanoflare heating (see e.g., Bradshaw et al. 2012, Schmelz & Pathak 2012, Warren et al. 2012).

Here, we analyze the differential EM (DEM) distribution obtained with the model.

The model distribution shown in the Figure corresponds to a single strand of length 100 Mm.

The slope (thick line) is computed between 1 MK and the peak temperature (~4 MK).



To compare with the EM distribution slopes from other authors we add 1 to our DEM slopes.

We compute the slopes for different model parameters and obtain values that are consistent with the ranges observed (see works cited above).

L(Mm)	40	60	80	100	120	140
EM slope indexes	2.68	2.9	3.30	3.46	3.78	4.13

6. Conclusions

We compare coronal observations from Hinode/XRT and SDO/AIA with synthetic data created using a cellular automaton model in combination with the EBTEL code.

We found that both the model and the observations present fluctuations of 10 to 15%. This is also consistent with observations reported by other authors (see e.g., Warren et al. 2010). The typical duration of the fluctuations is around 1000 s (associated to the model driving time). Similar durations have been reported recently from observations by Ugarte-Urra & Warren (2014).

The positive skewness found in observed and synthetic lightcurves indicates that the right “tail” of the fluctuations distributions is more spread and less bulky than the left one. This has been previously associated with the widespread presence of impulsive heating processes (Terzo et al. 2011).

We obtain the differential emission measure (DEM) distribution from the model. The range of slopes from the log(EM) versus log(T) distributions obtained with different model parameters is consistent with the observational results from other authors.

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