[Paper]

[Press release]

Inferring impulsive heating of quiet solar corona using machine learning

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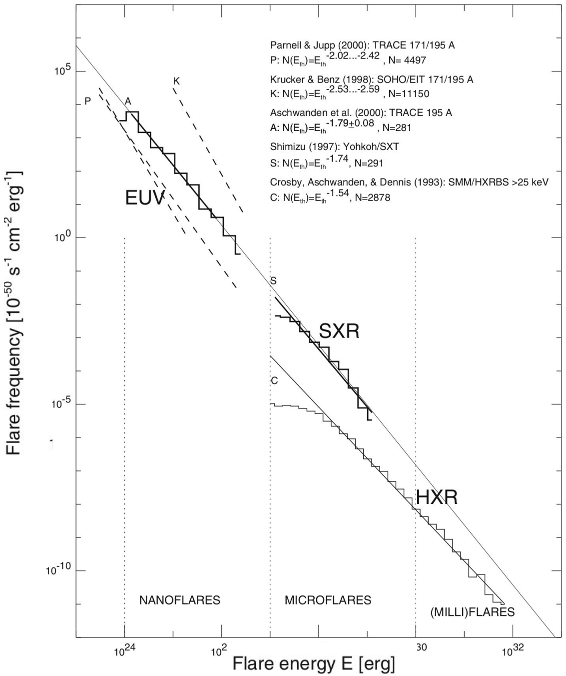
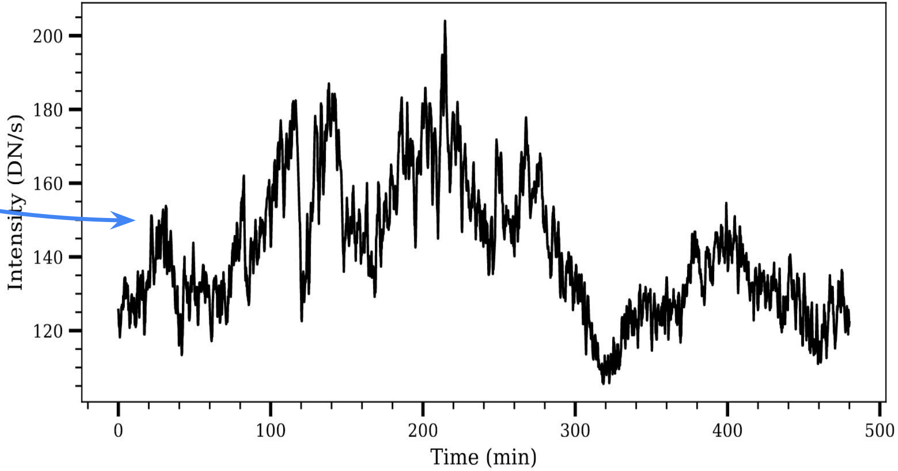
Problem: Estimate the viability of impulsive events in maintaining the quiescent solar corona (QS) at a million degree.



Count individual events: Distribution of impulsive events (Aschwanden 2019).

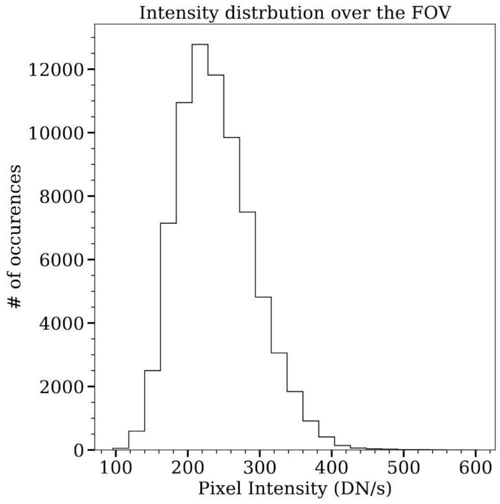
Counter: How many events here?

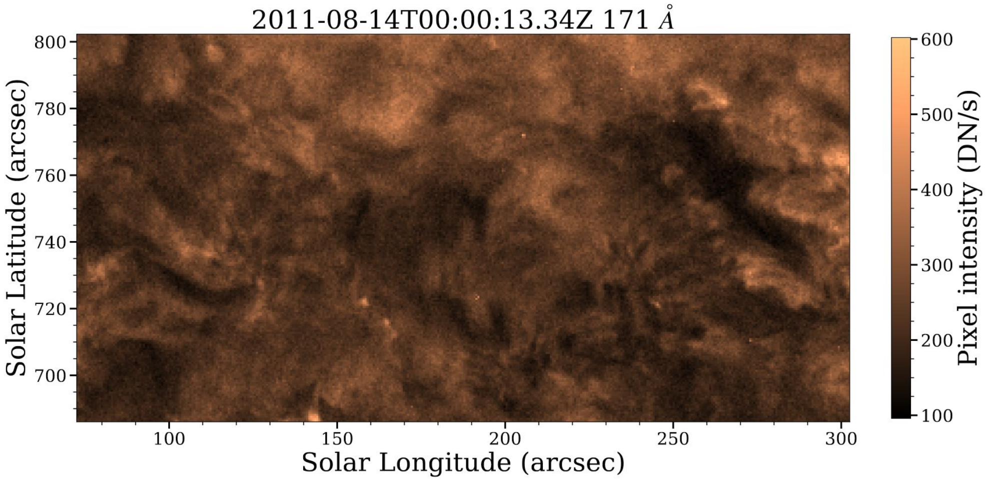
$$\frac{dN}{dE} \propto E^{-\alpha}$$



Unresolved nature of nanoflare impulsive events: inferring the heating properties is difficult.

Idea: Use impulsive models incorporating statistical QS properties





- Statistical properties of QS:
  - Intensity distribution: Lognormal — spatially and temporally (Pauluhn and Solanki 2001).
  - Markovian process in play (Gorobets+ 2016).
- Multitude of impulsive events give rise to QS intensities.
- Don't care about exact intensity locations, but only frequency of occurrence.

Forward model: Pauluhn and Solanki (2007) (PSM)

Decay+Rise time scale of flare: τ
E-folding time scale; fixed for a pixel

Probability of flare: flaring frequency p_f
Exponentially distributed waiting times

Peak flare energy: α, y_{max}, y_{min}
Peaks sampled from a power law distribution with slope α, and bounds $[y_{min}, y_{max}]$.

Power law event distribution

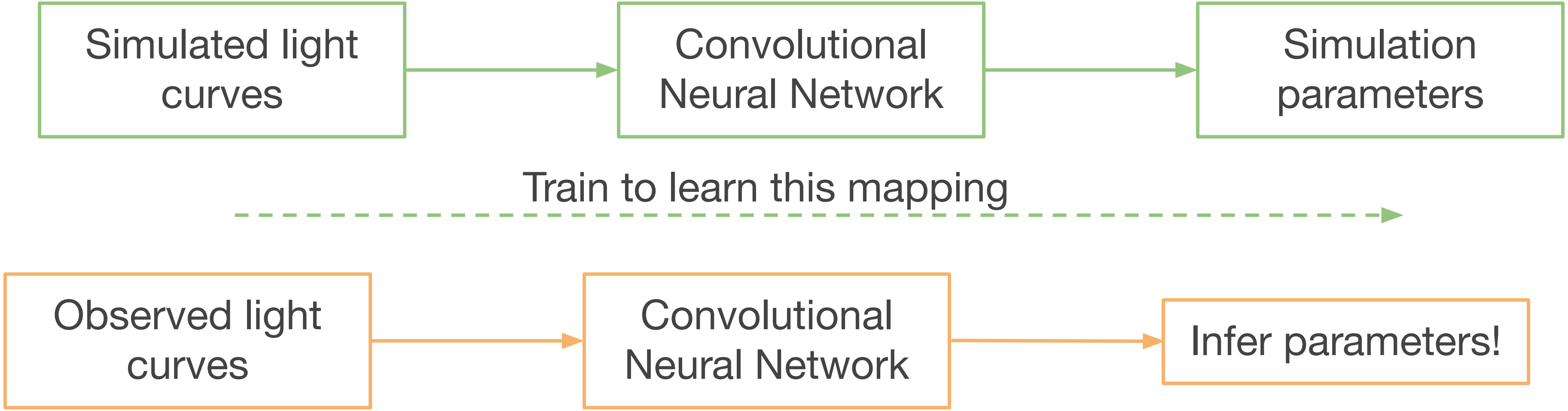
Markovian process
$\mathbf{I_m} = k_{m-1}\mathbf{I_{m-1}}$

Lognormal Intensity distribution

Stochasticity

Inversion recipe: Convolutional Neural Network (CNN)

- Statistical model: No point-by-point comparison.
- Qualitative comparison: Histogram and Power spectrum.
- **Quantify: Using Convolutional Neural Networks** (Szegedy et al. 2015)



Feed the data!

Observation dataset

Identifier	DS1	DS2
Start time	2011-08-14 T00:00:00	2019-05-02 T00:00:00
End time	2011-08-14 T08:00:00	2019-05-02 T08:00:00
Reference time	2011-08-14 T00:00:00	2019-05-02 T00:00:00
Xcen, Ycen	192″, 749″	19.0″, 211.5″
FOVx, FOVy	230″, 116″	346.0″, 269.0″
Instrument	AIA	AIA
Passband	171,193, 211	171, 193, 211
Exposure normalize	True	True
Cadence	12 s	12 s

~300,000 light curves, 3 passbands

Parameter	p_f	α	τ	y_{max}	y_{min}
Range	[0.05,0.95)	[1.1,3.0)	[1,100)	0.3	0.03
Step size	0.05	0.1	2.0	-	-

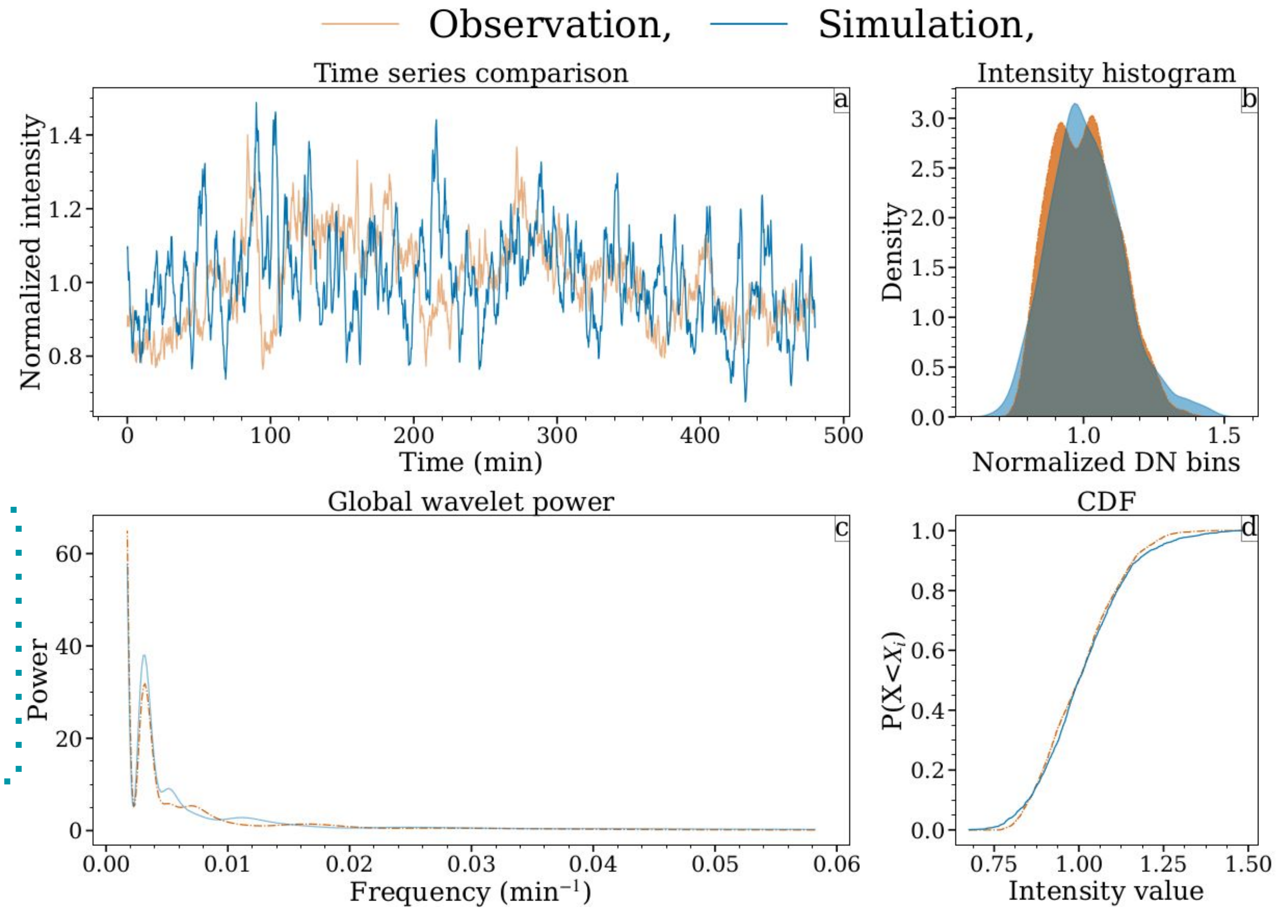
Simulation grid

Results #1: Inversion of example light curves

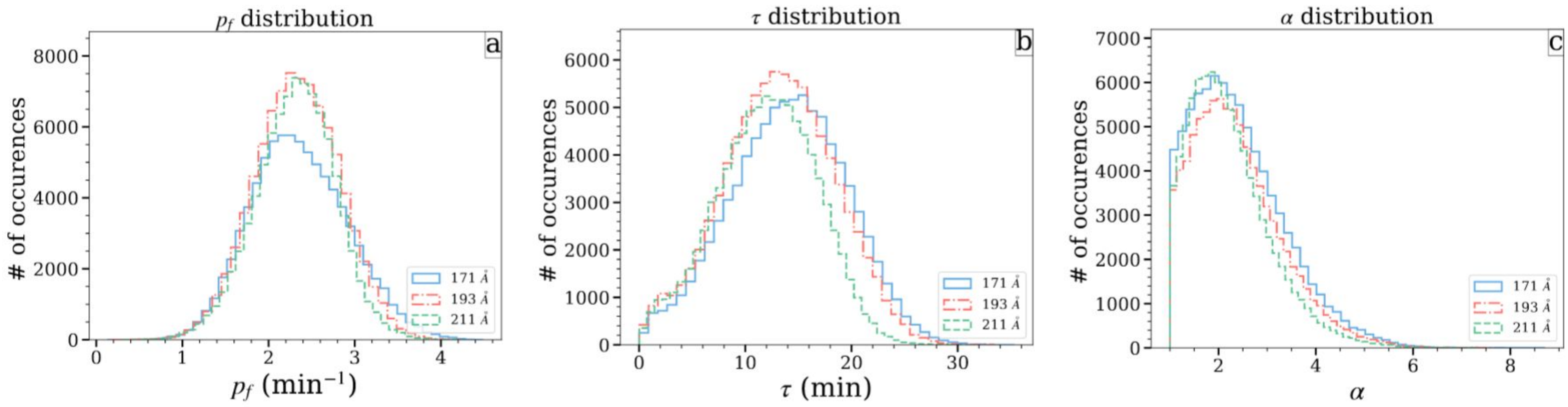
$\alpha = 2.32 \pm 0.37,\ p_f = 2.40 \pm 0.14,$
$\tau = 11.33 \pm 0.52$

τ: in minutes
p_f: in min^{-1}

Epistemic uncertainty:
Fitting uncertainties &
deviations from PSM
(Kendall & Gal 2017).



Results #2: Parameter distributions



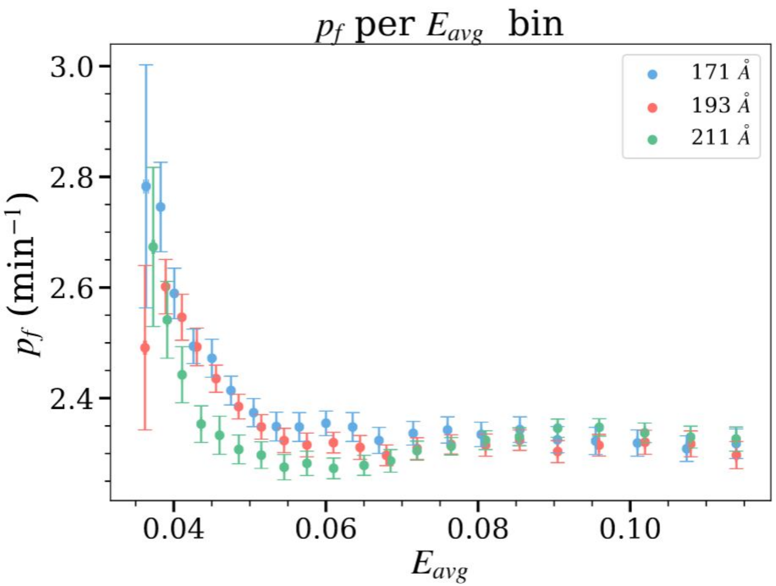
Frequency: Mean waiting time is 30 sec.

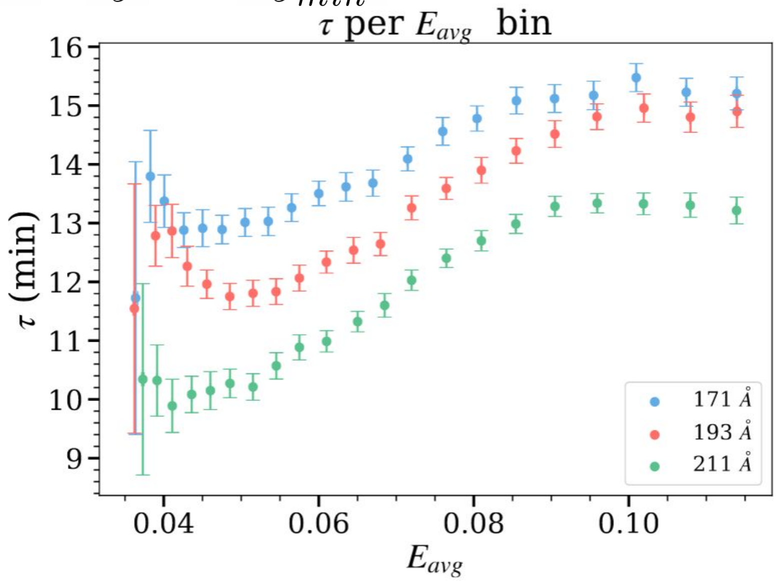
Cooling times: 600 sec.

Impulsive events: Viable source of heating in the Quiet corona.

Results #2: Energetics

$$E_{avg} := \frac{1+\alpha}{2+\alpha}\frac{y_{max}^{2+\alpha} - y_{min}^{2+\alpha}}{y_{max}^{1+\alpha} - y_{min}^{1+\alpha}}.$$





Waiting time - Peak flux: Hudson 2020

Model input: Cargill 2014.

Existence of energy reservoir

Weak correlation in flares :

Veronig+ 2002

$\tau_c \propto n_e \propto \sqrt{DN}$

Conduction dominated cooling

Salient takeaways

1. QS intensities: Can be explained using an empirical impulsive heating model.
2. Average waiting time: 30 sec.
3. Average cooling time: 600 sec.
4. The average nanoflare intensity dependence on flaring frequency points to the existence of an energy reservoir.
5. The average nanoflare intensity dependence on flaring time scale can be explained if Conductive loss is dominant.
6. Caveat #1: y_{max} and y_{min} need to be fixed - model does not train well if all parameters varied.
    a. Degeneracy amongst $\mathrm{y}_{\mathrm{max}}$, $\mathrm{y}_{\mathrm{min}}$ and α.
7. Caveat #2: Energy bounds not in ergs → needs calibration for correct estimation.
8. Caveat #3: ~ 30% of light curves have $\alpha < 2$ → needs study.