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Multi-scale Observations of Thermal Nonequilibrium Cycles in Solar Coronal Loops

Colloque PNST – November 19-21, 2018

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Thermal nonequilibrium (TNE)

TNE processes are known to play an important role for **prominences** (e.g. Antiochos & Klimchuk 1991, Luna et al. 2012; Xia et al. 2014) and **coronal rain** (e.g Müller et al. 2005, Antolin et al. 2010)

Quasi-steady heating mainly concentrated at the loop footpoints

Unstable loops, no possible thermal equilibrium

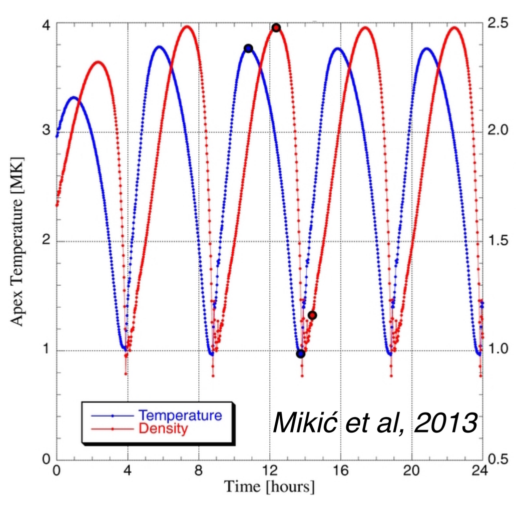
Evaporation of chromospheric plasma
Temperature ↗ Density ↗

« **Catastrophic cooling** »
Thermal Instability
thermal runaway & recombination

Condensation
the plasma falls toward the loop legs

pulsations in the temperature and in the density

A periodic evolution predicted by the simulations



Long-period EUV pulsations

- in almost every active region
- **917 events found in 13 yrs of SoHO/EIT (195 Å),** *Auchère et al. 2014*

54% Active Region (AR), 45% Quiet Sun (QS)

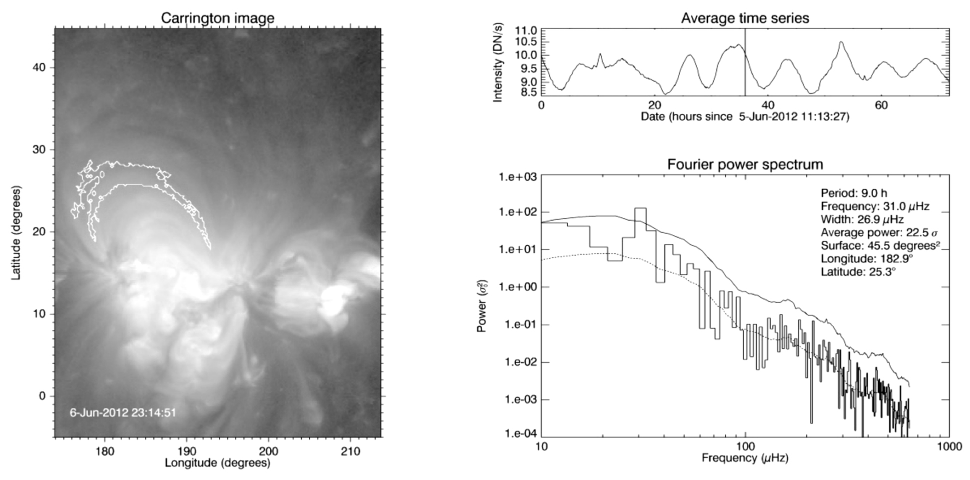
- **3181 events found in 6 yrs of AIA** *Froment 2016, PhD thesis*

67% AR, 33% QS

- **2981 events found in 7 yrs of AIA off-limb** *Froment et al., in prep*

62% AR, 38% QS

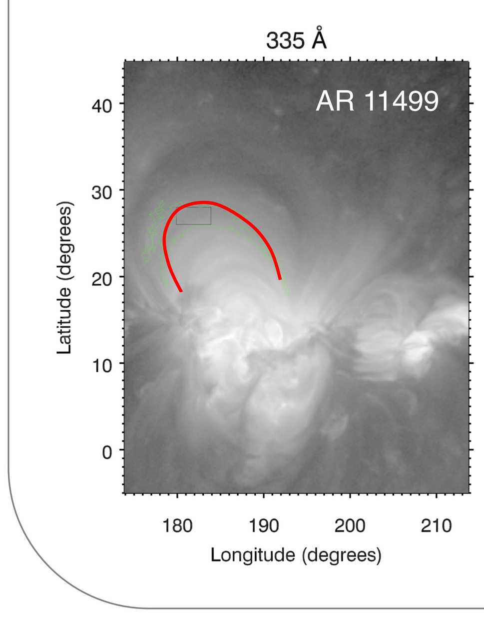
Not triggered by an other event, Not a mechanical oscillation



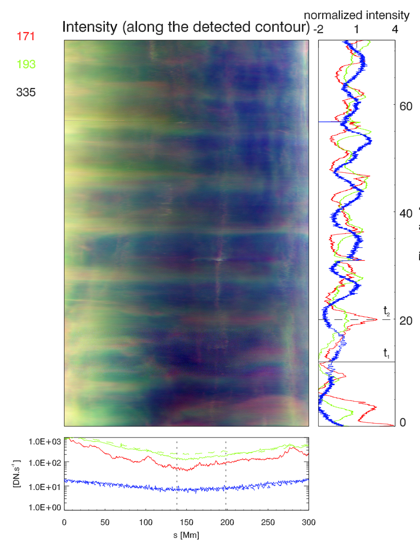
- Current explanation: **Coronal counterpart of thermal nonequilibrium cycles**
- **Implications for coronal heating: spatial location and timescale**

Evaporation/condensation cycles in loops

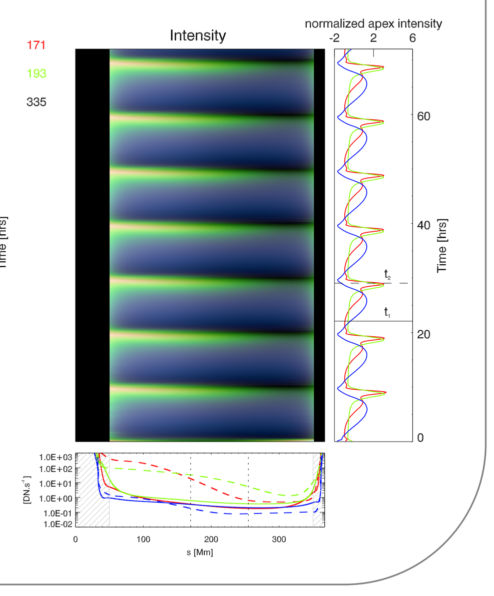
Detection with AIA
9 hr pulsations

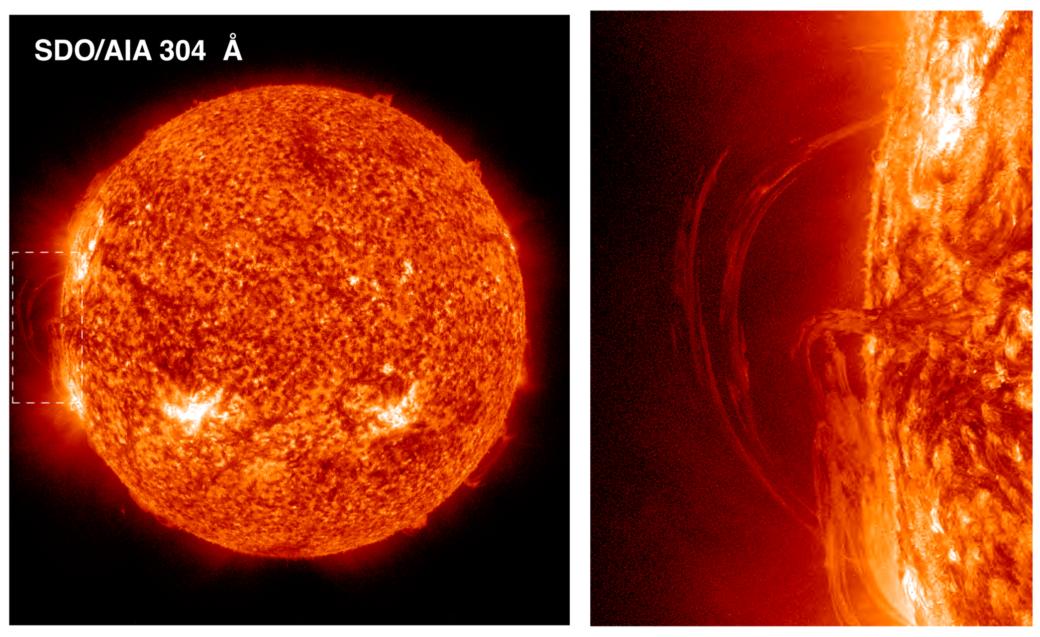


AIA observations
Froment et al. 2015



Synthetic intensities from a 1D hydrodynamic simulation
Froment et al. 2017 & 2018

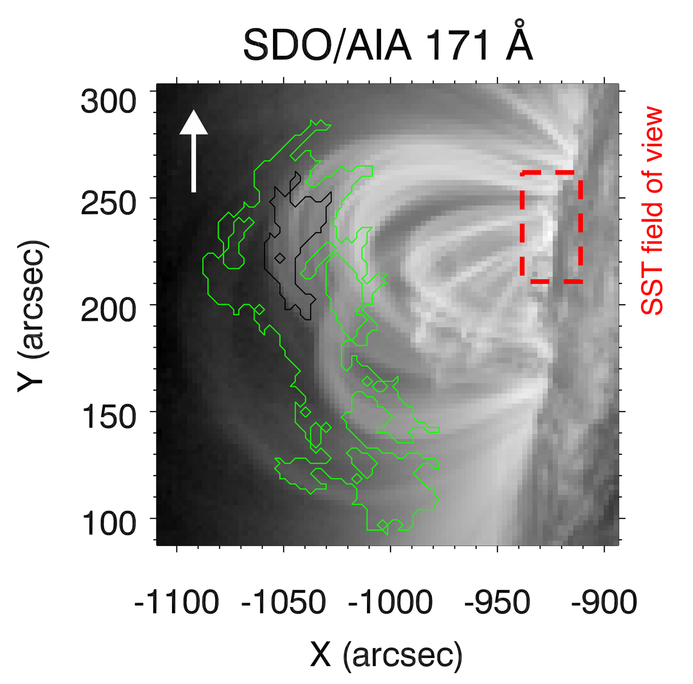




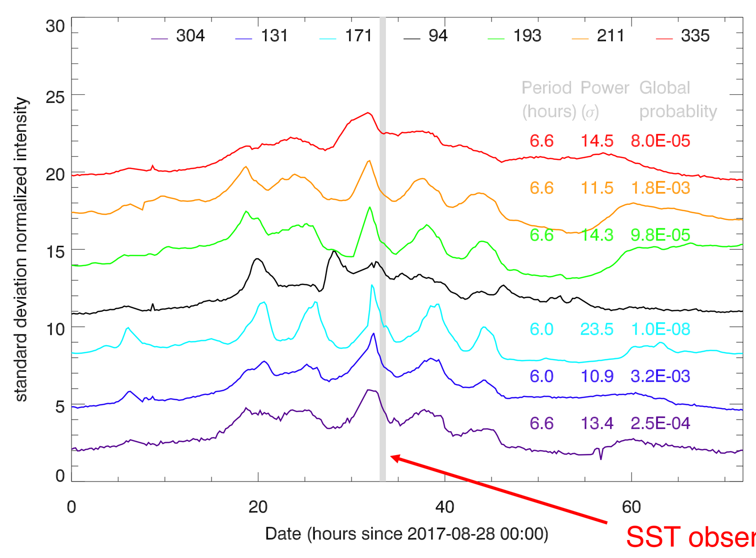
- **Coronal rain**: condensations seen in transition region and chromospheric lines

- Periodic rain event observed for the first time (with SDO/AIA, *Auchère et al. 2018*)
- **How cold can it get?**
- At least some events should show **coronal rain down to chromospheric temperatures**

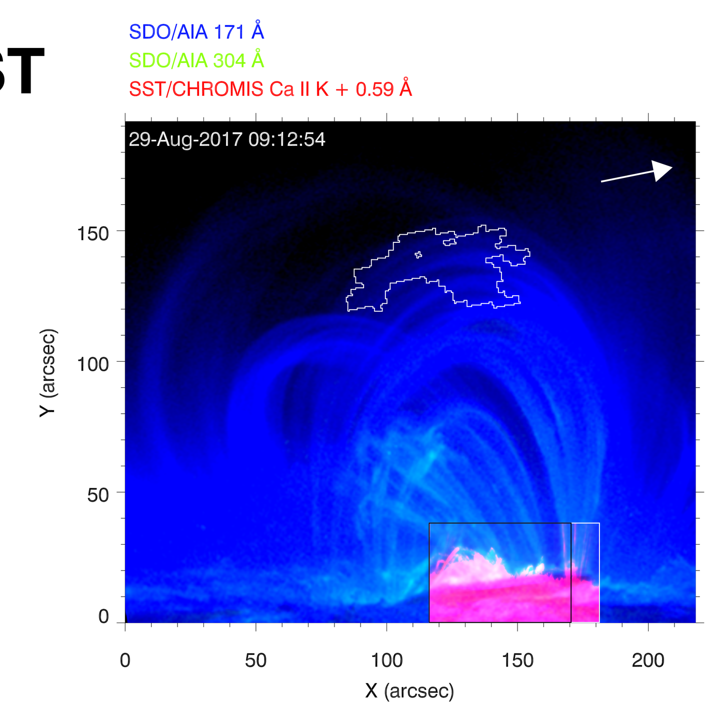
Multi-thermal analysis off-limb with the SDO and the SST



- Period of ~6.h in almost all the channels
- Swedish 1-m Solar Telescope (SST) observations at **one footpoint** during the **cooling phase of one of the cycles**



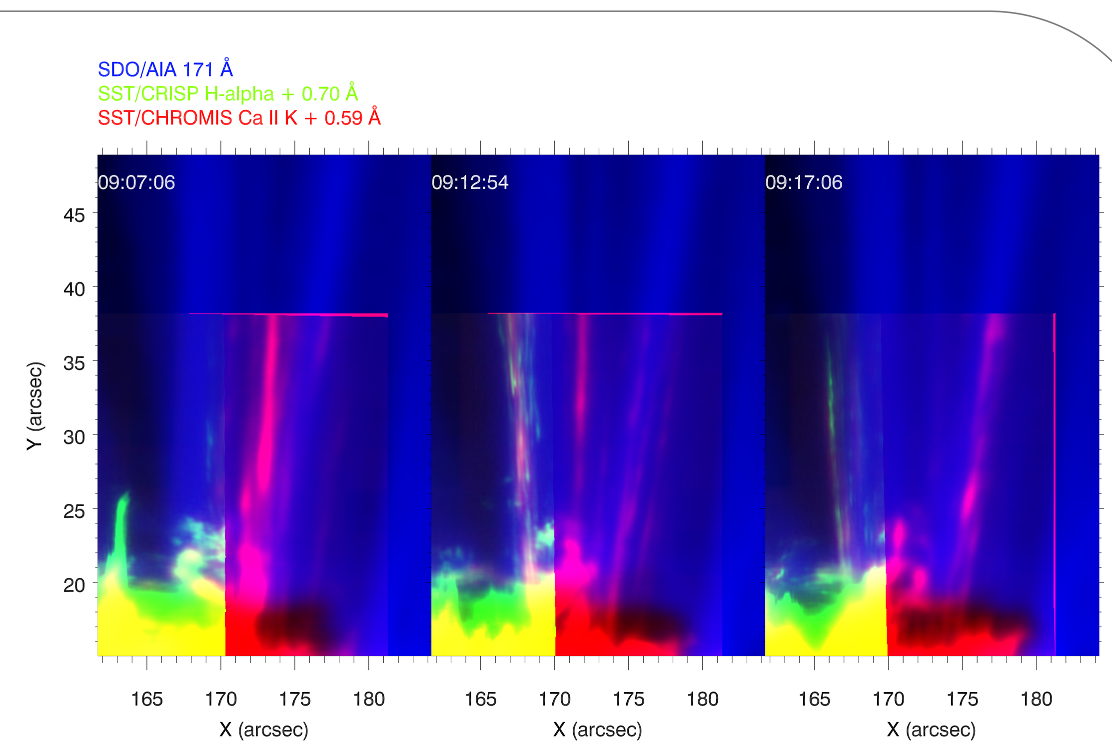
Froment, Antolin, Henriques & Rouppe van der Voort, in prep



SST data:

CRISP: Hα (6563 Å)
pixel size: 0.06”

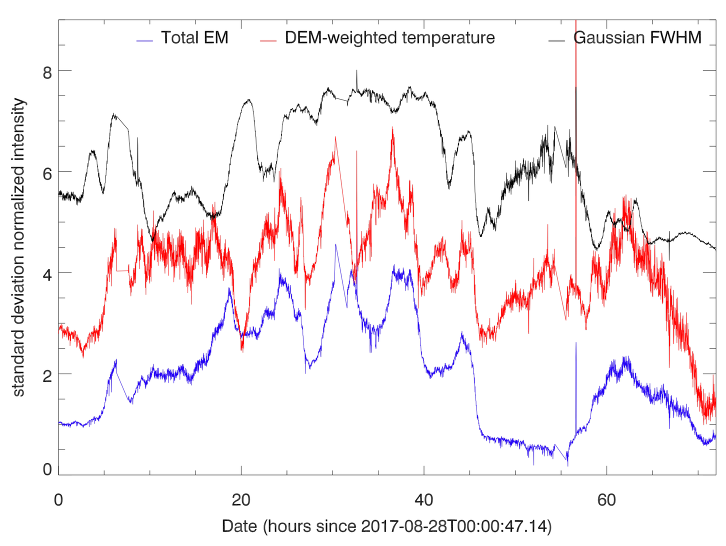
CHROMIS: Ca II K (3934 Å)
pixel size: 0.04”



- Observation of the cycle from coronal to **chromospheric temperature**
- High-resolution coronal rain observations

Evolution of the temperature and the density

Analysis of the thermal structure with AIA
Reconstruction of the Differential Emission Measure (DEM) - code from *Cheung et al, 2015*



- **Cycles** (~6h) in the DEM-weighted temperature and the total EM (proportional to square density)
- The temperature increases before the total EM
- Temperature and width anti-correlated **Thermal width increase cooling phases**
- **Same conclusions as for on-disk observations of pulsating loops**
- **Strong evidence of TNE**

Thermodynamic of the rain

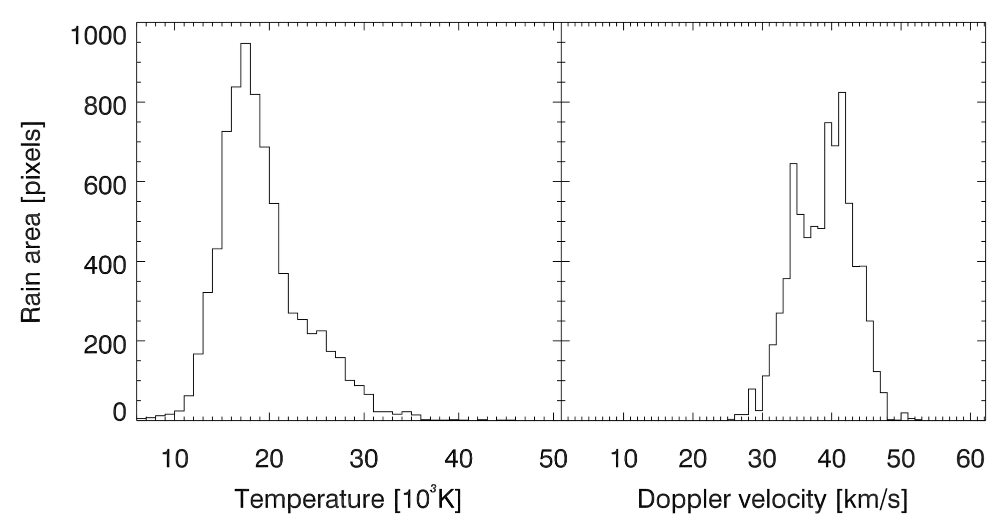
- Intensity threshold to detect rain pixels
- Stack of N slabs in time

Average temperature: ~25 000 K
Average Doppler velocity: ~39 km/s

Projected velocities ~70 km/s
Total velocity ~80 km/s

Gaussian fit of the Hα condensation profiles

$$FWHM = 2\sqrt{2\ ln2}\ \frac{\lambda_0}{c}\sqrt{\frac{2k_BT}{m_H} + \cancel{v_{nic}^2}}$$



Temperature and velocities consistent with other rain studies
(*Antolin & Rouppe Van der Voort 2011, Ahn et al. 2014, Antolin et al. 2015)*

Main takeaways

Implications for coronal heating: spatial location and timescale

- **Long-period intensity pulsations** (several hours) are **very common in coronal loops**
- **Long-period intensity pulsations** are **the coronal counterpart** of **thermal nonequilibrium cycles** and thus of **quasi-constant** and **highly stratified heating**
- The pulsating loops studied with AIA off-limb show the same thermal behaviour as for on-disk pulsating loops
- These observations allow us to **probe the bulk of the cooling phases** and emphasise that these **pulsations and coronal rain are two aspects of the same phenomenon**

Further reading

- Long-period intensity pulsations in the solar corona during activity cycle 23 Auchère et al. 2014 A&A, 508, A8
- Evidence for cycles of evaporation and incomplete condensation in warm solar coronal loops Froment et al. 2015 ApJ, 807, 158
- Long-period intensity pulsations in coronal loops explained by thermal non-equilibrium cycles Froment et al. 2017 ApJ, 835, 272
- On the occurence of thermal non-equilibrium cycles in coronal loops Froment et al. 2018 ApJ, 855,52
- The Coronal Moonson: TNE revealed by periodic coronal rain Auchère et al. 2018 ApJ, 853,176