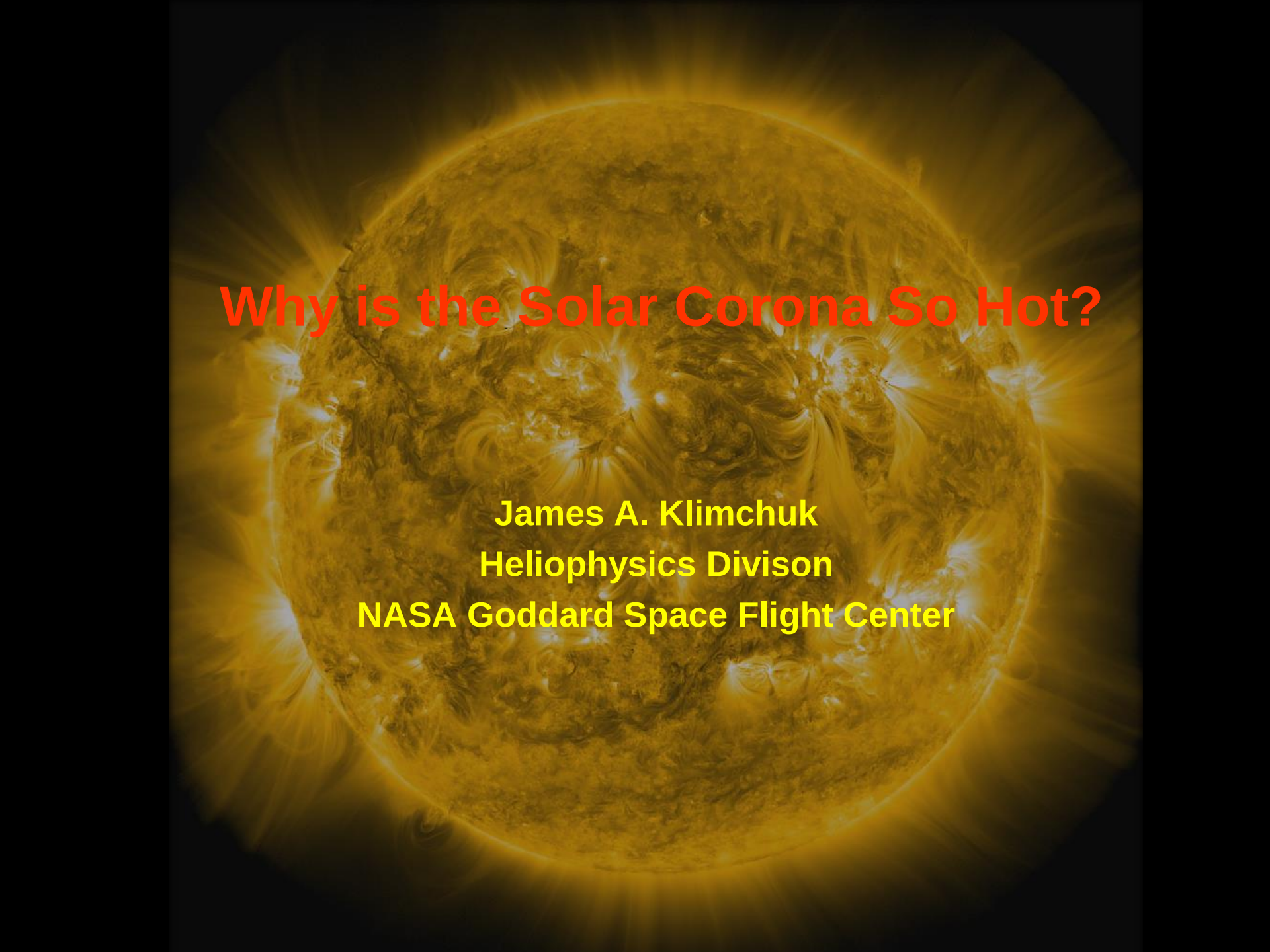
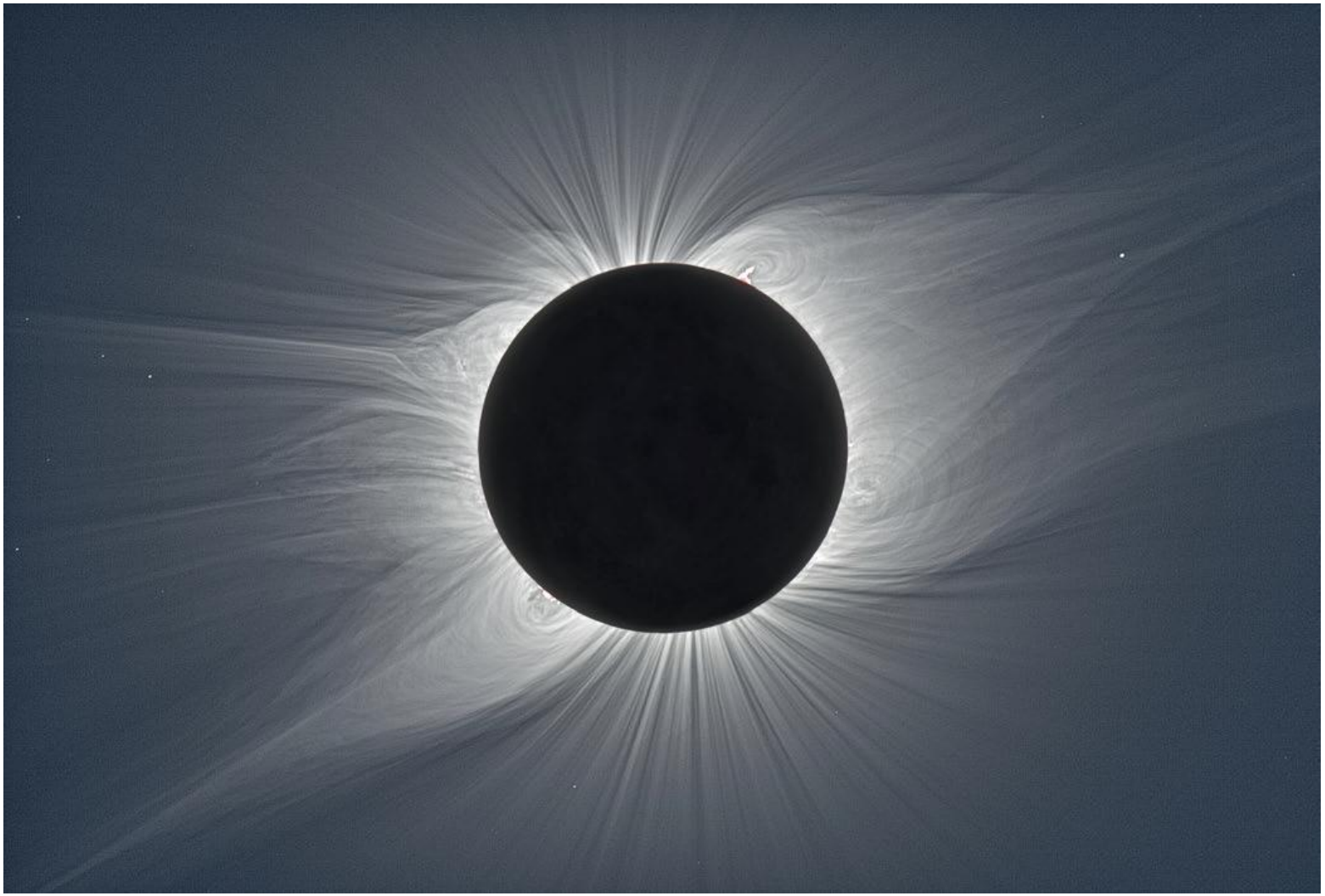


Why is the Solar Corona So Hot?

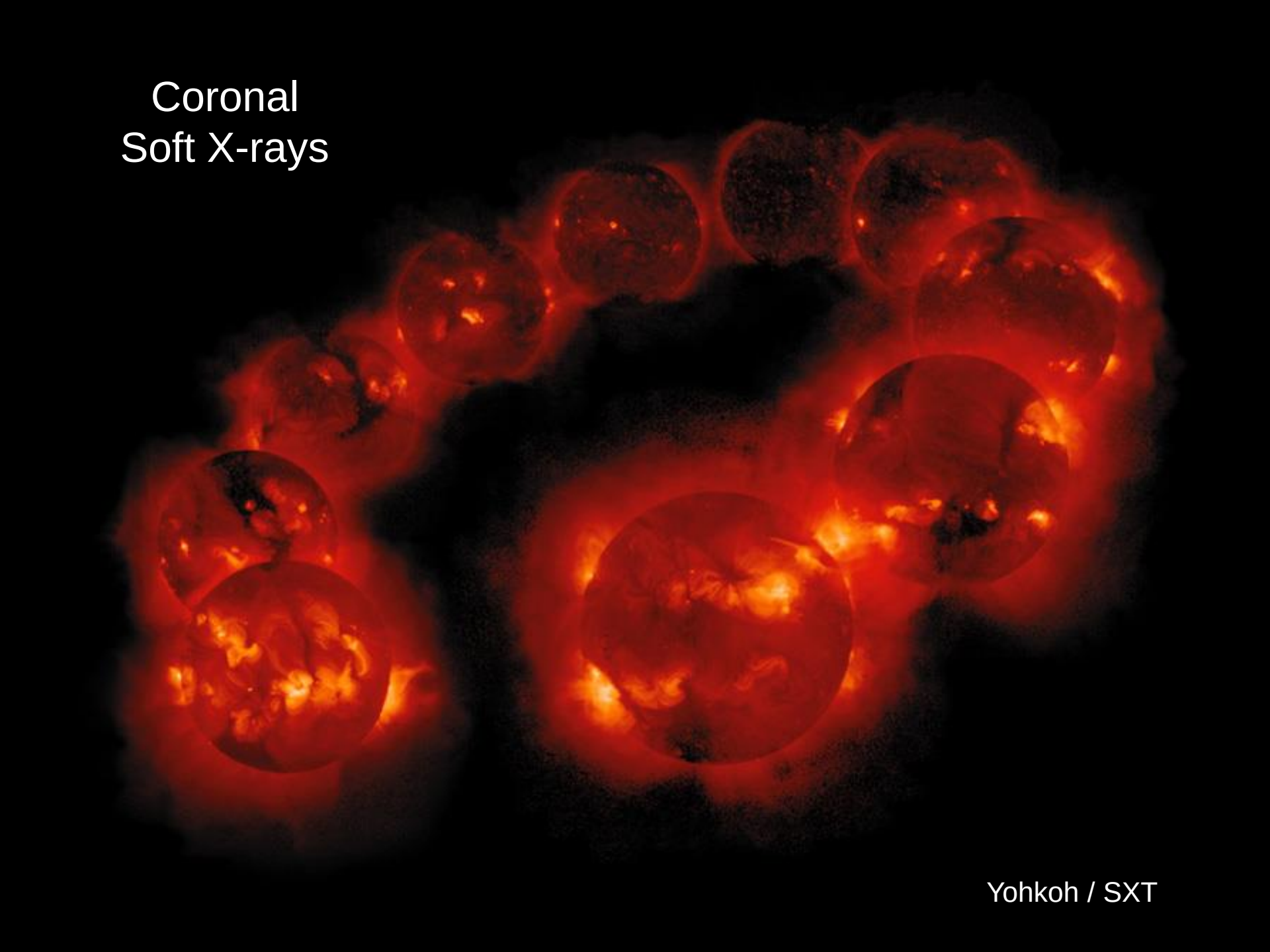
James A. Klimchuk
Heliophysics Divison
NASA Goddard Space Flight Center

Total Solar Eclipse
Aug. 1, 2008



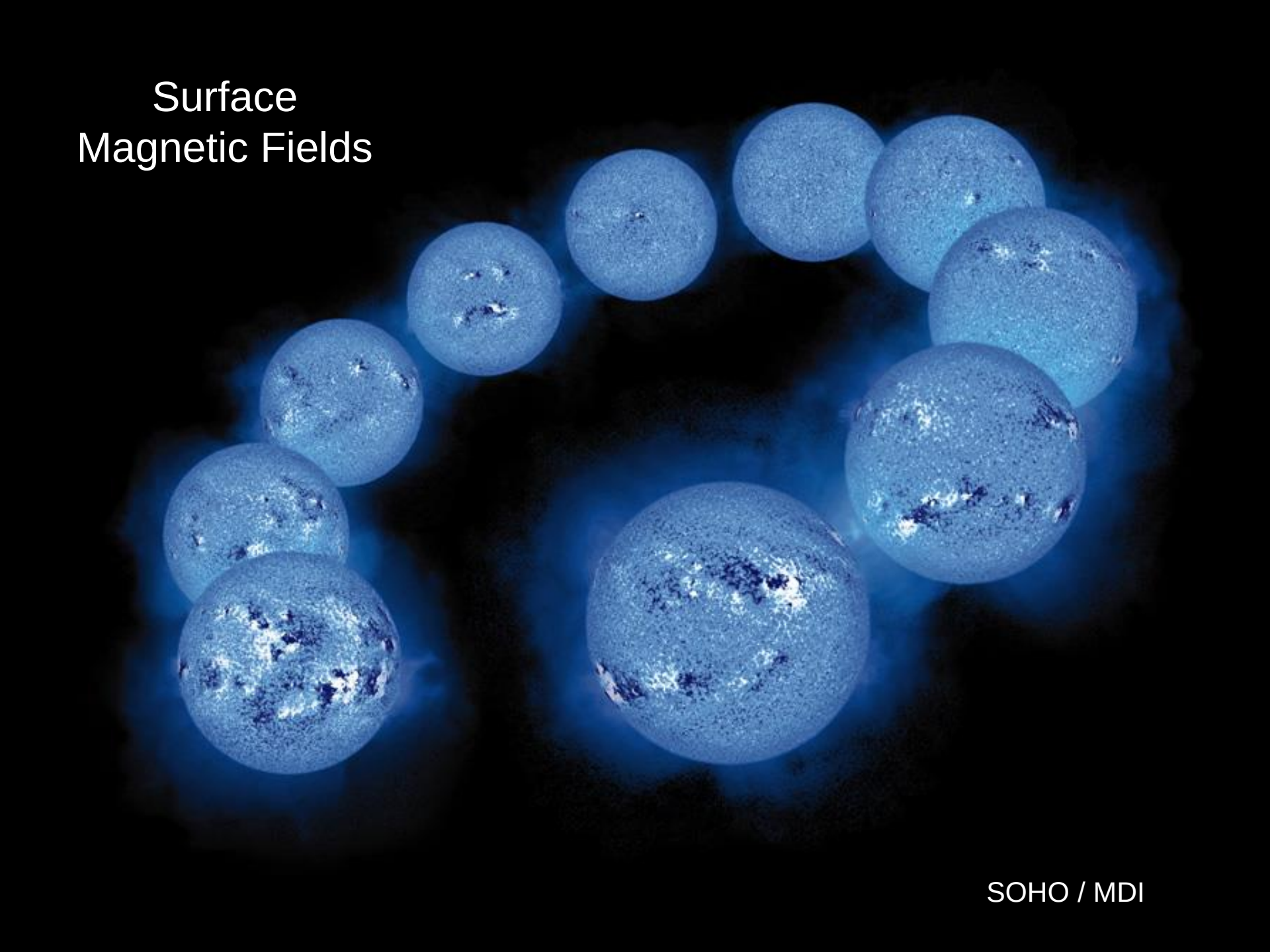
M. Druckmuller

Coronal
Soft X-rays



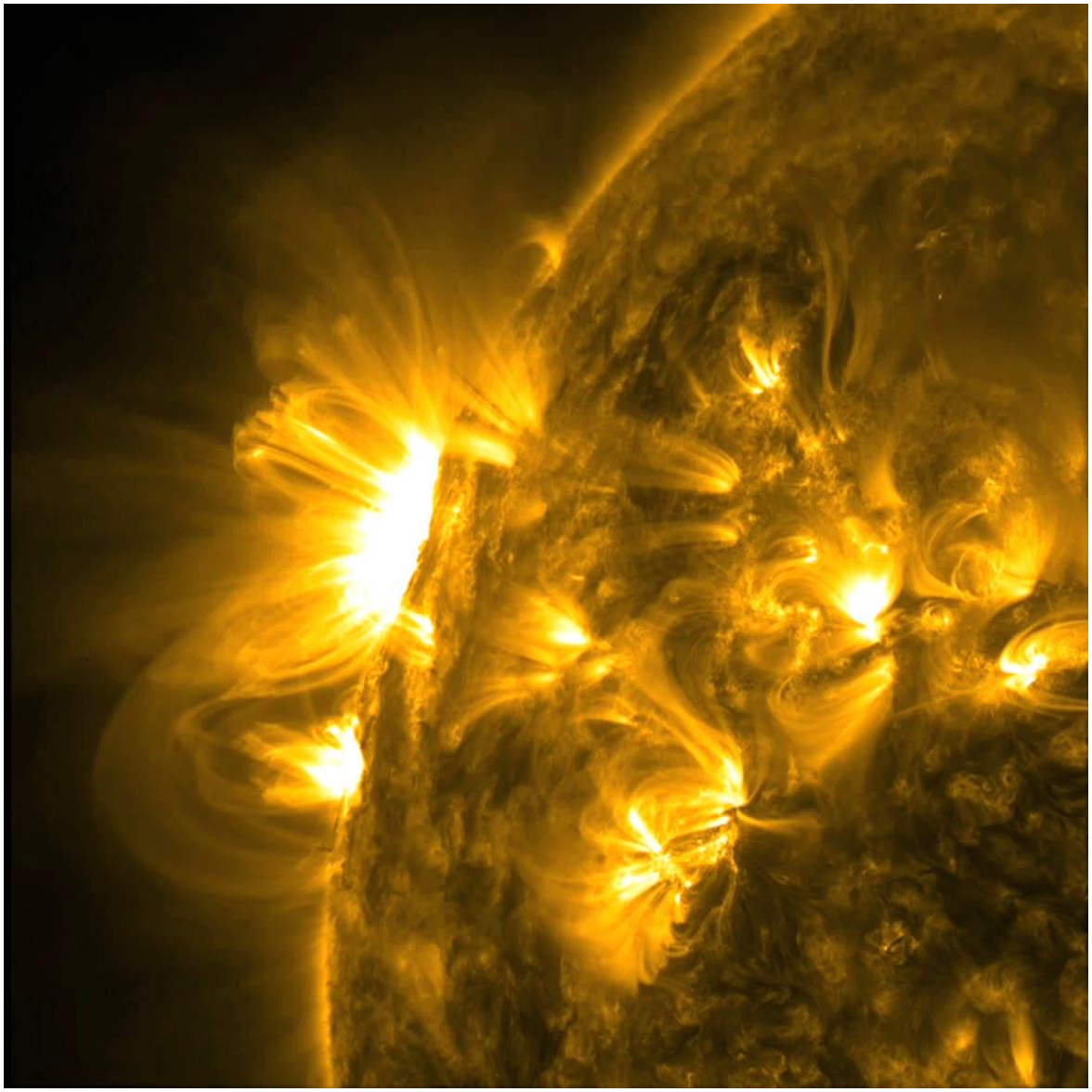
Yohkoh / SXT

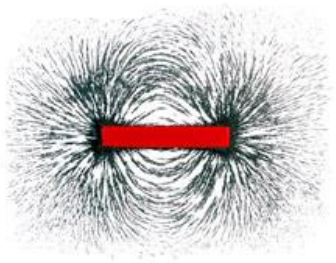
Surface Magnetic Fields

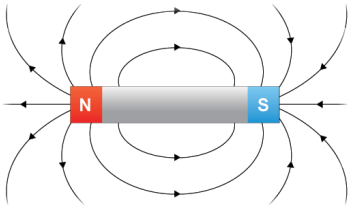


SOHO / MDI

Magnetic Fields Rule the Corona

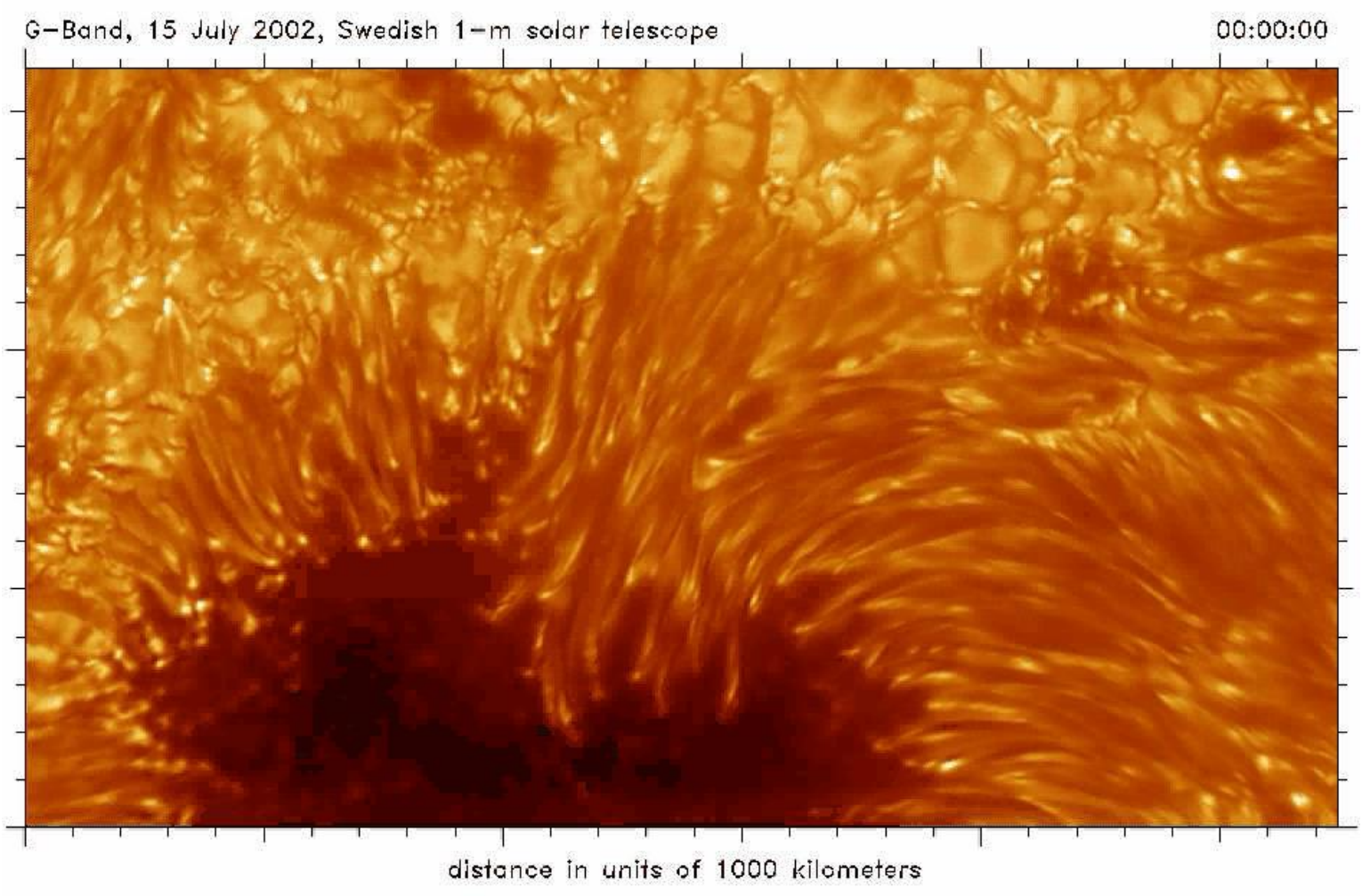






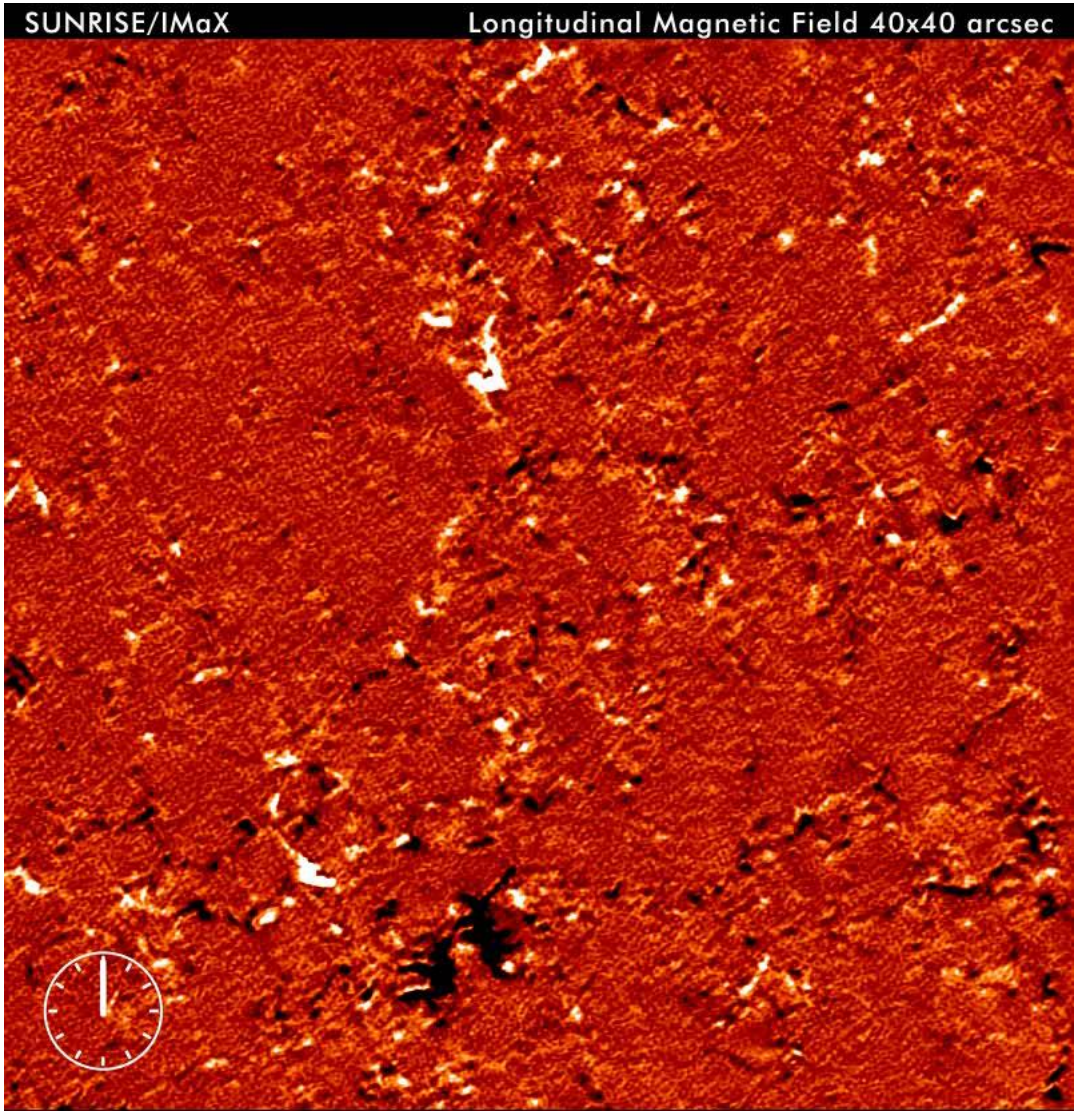
SDO / AIA 171

Plasma Rules the Photosphere (Solar Surface)



Swedish Solar Telescope

Turbulent motions “stir” the coronal magnetic field….

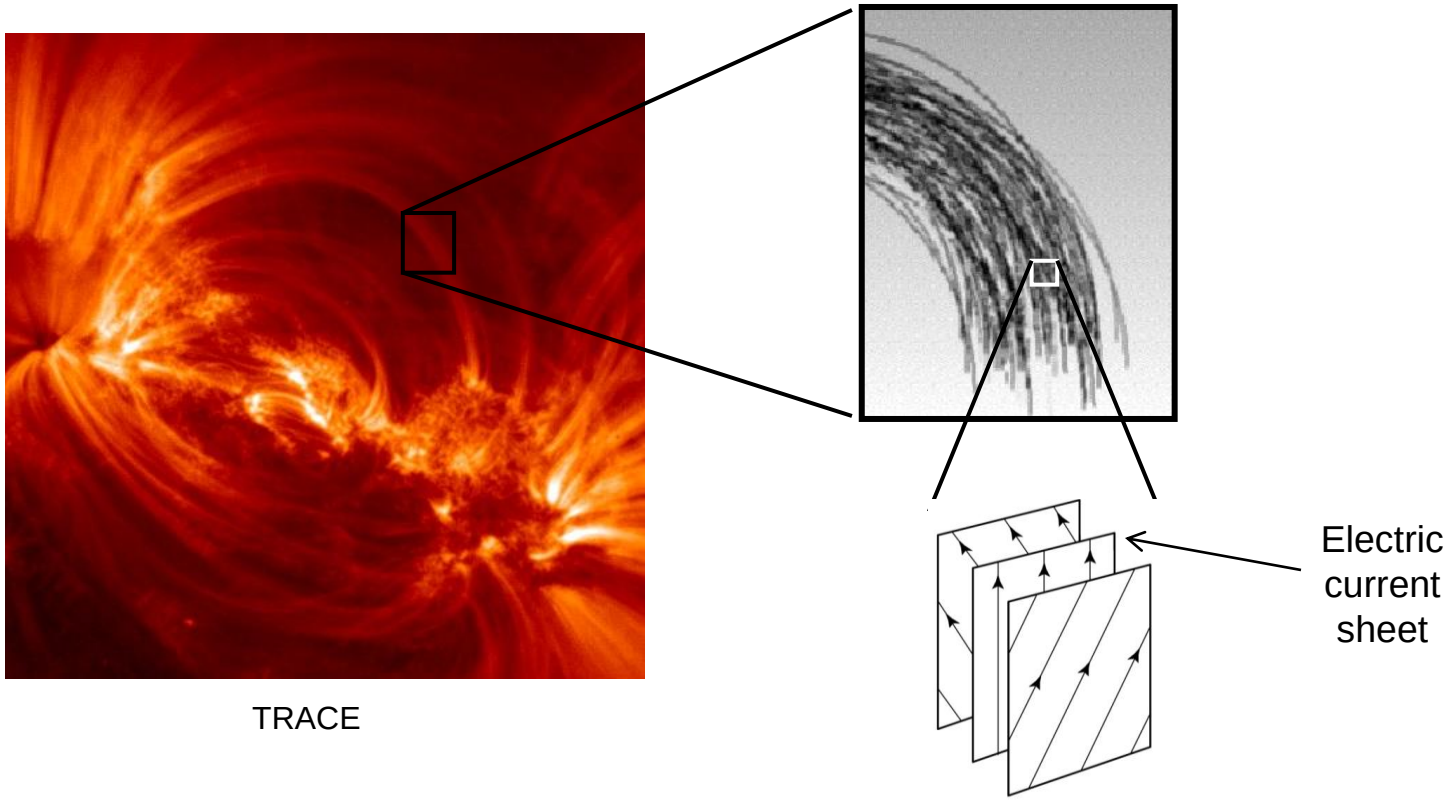


Loop cross-section

Quiet Sun

SUNRISE / IMaX

….causing it to become twisted and tangled (stressed).



TRACE

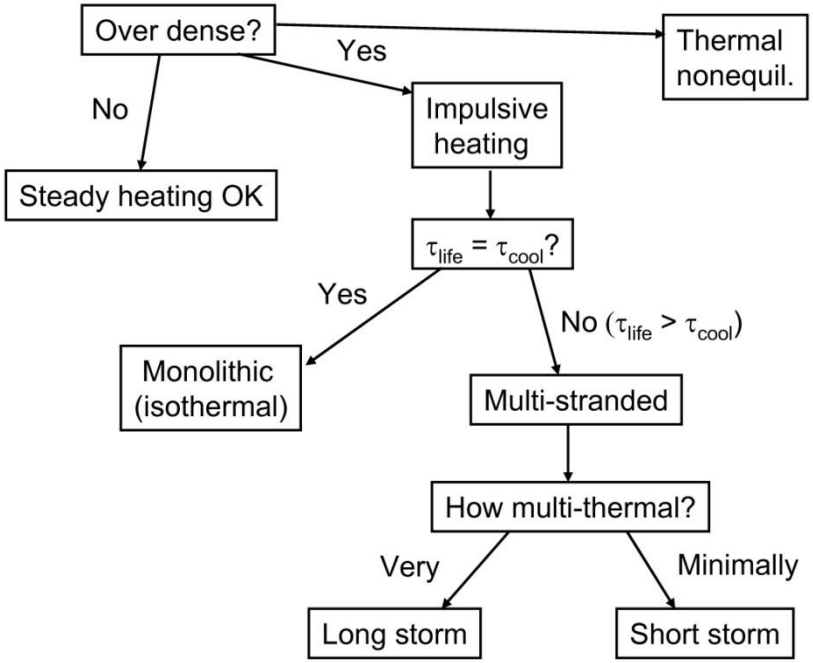
When it breaks, small bursts of energy called nanoflares heat the gas.

Millions of nanoflares occur every second across the Sun.

Parker (1983)

Observations and hydrodynamic models reveal that each coronal loop is:

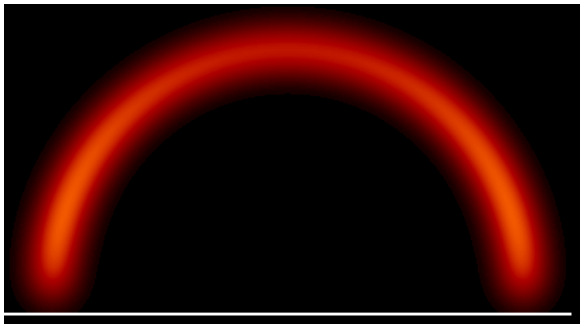
- A bundle of thin strands
- Heated by a “storm” of nanoflares



Klimchuk (2009)

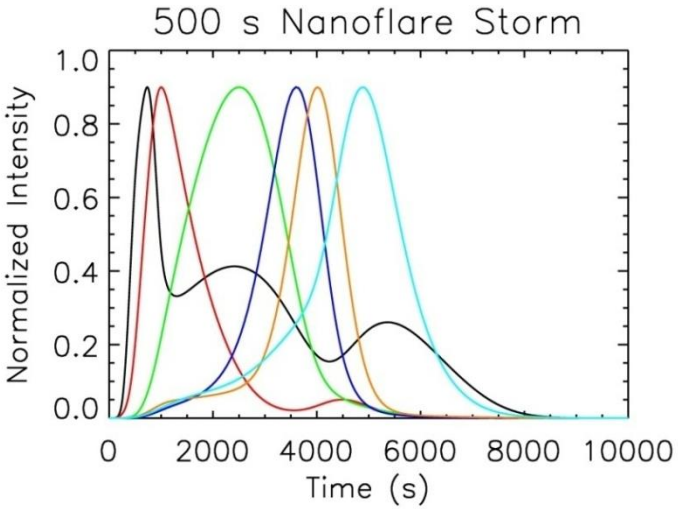
Simulated Loop Observations

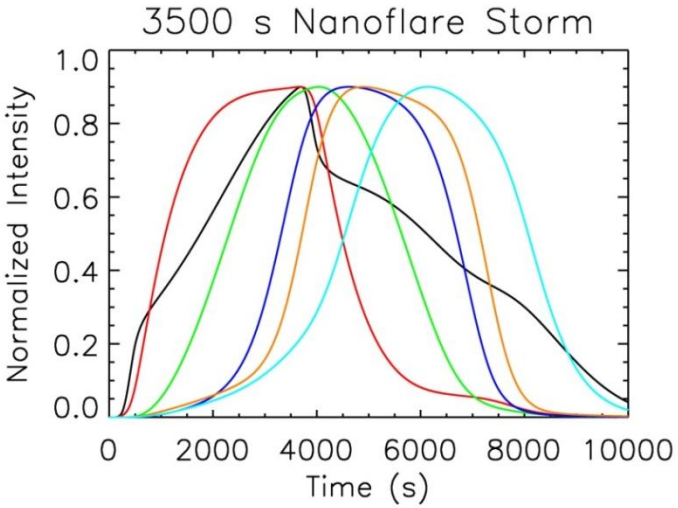
One strand of a multi-stranded loop



3 MK

SDO / AIA light curves





AIA Channels

131 Hot
94
335
211
193
171 Cool

Viall & Klimchuk (2011)

Simulated Loop Observations

One strand of a multi-stranded loop

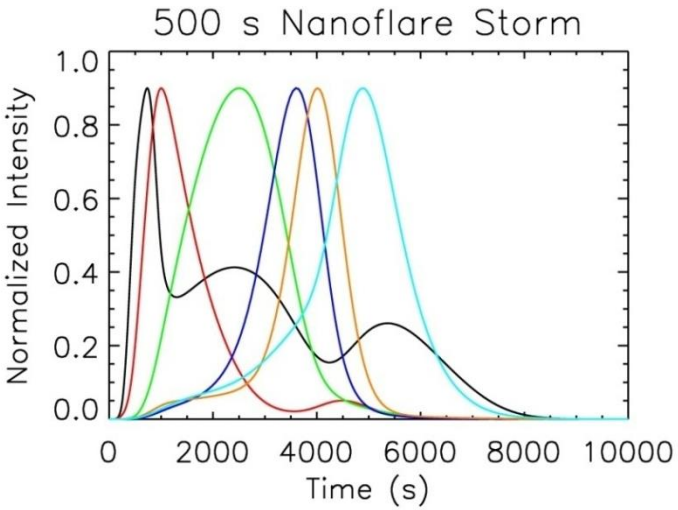
3 MK

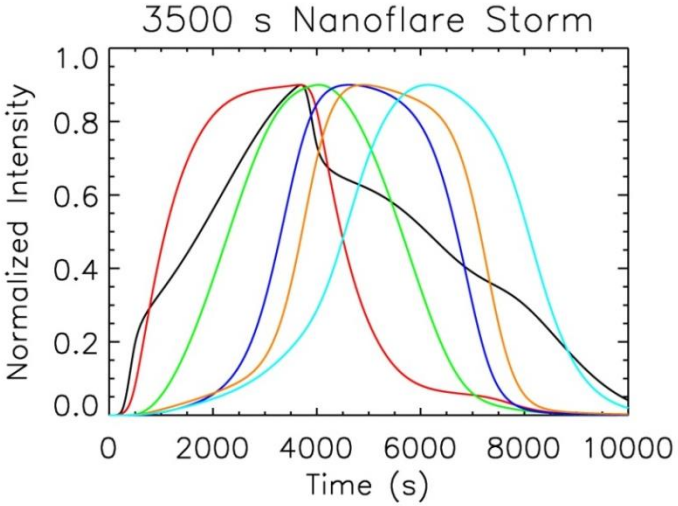
1 MK

AIA Channels

131 Hot
94
335
211
193
171 Cool

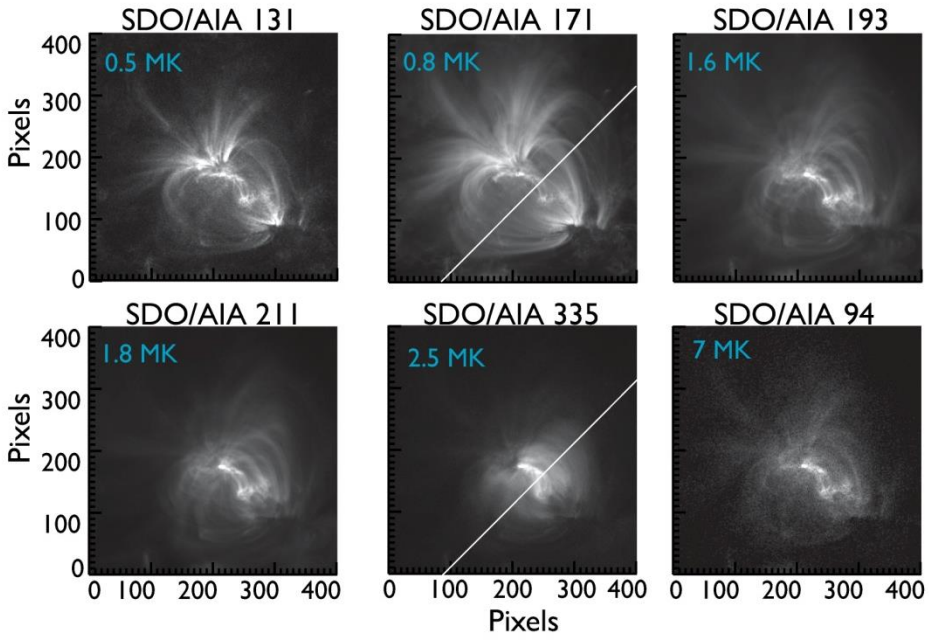
SDO / AIA light curves

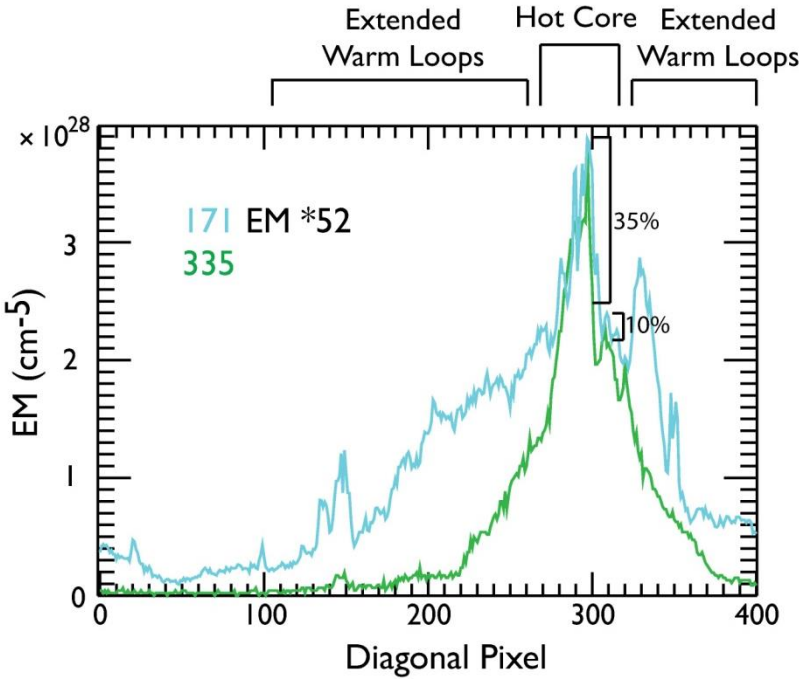




Viall & Klimchuk (2011)

Diffuse Emission Between Loops





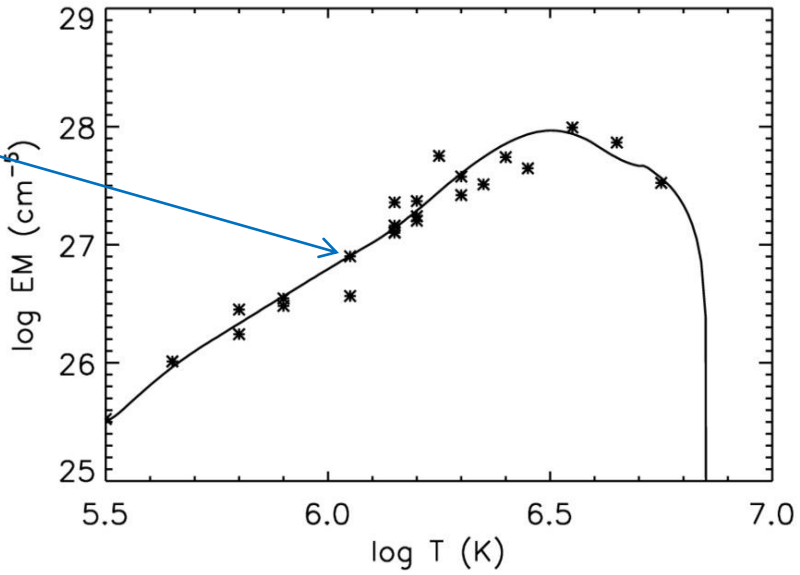
Distinct loops account for a minor fraction of the total emission.

Viall & Klimchuk (2011)

Diffuse Corona also Heated by Nanoflares?

Emission Measure Distribution
(thermal distribution of the plasma)

Slope indicates whether heating is impulsive or steady



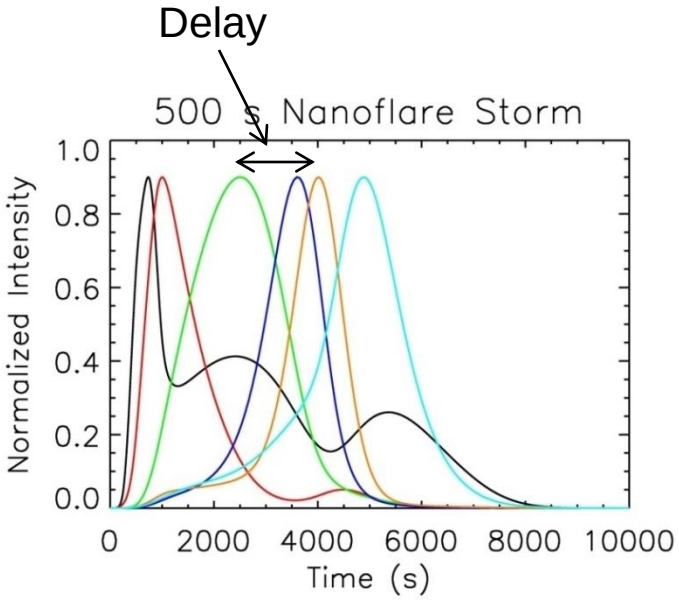
$$EM(T) = n^2 \frac{dV}{d\log T}$$

points – data; line – nanoflare model

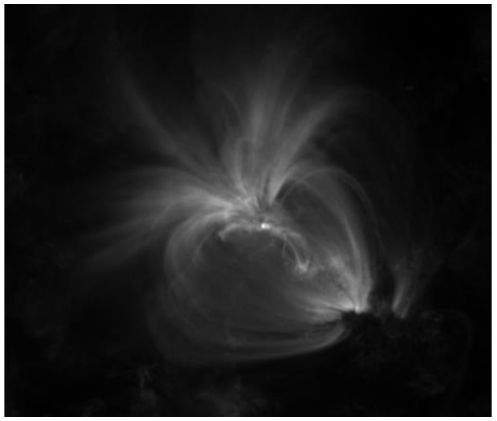
Yes in places,
no in places,
mostly ambiguous

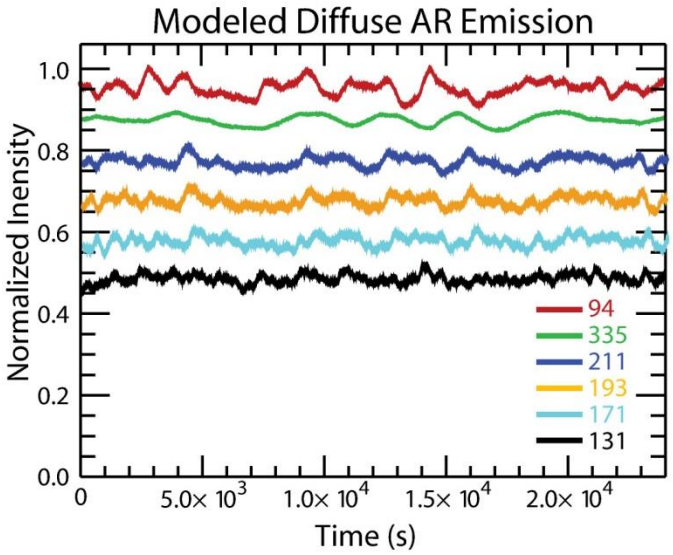
Tripathi, Klimchuk, & Mason (2011)
Bradshaw, Klimchuk, & Reep (2012)
Guennou, Klimchuk, et al. (2013)

Time Lag Analysis

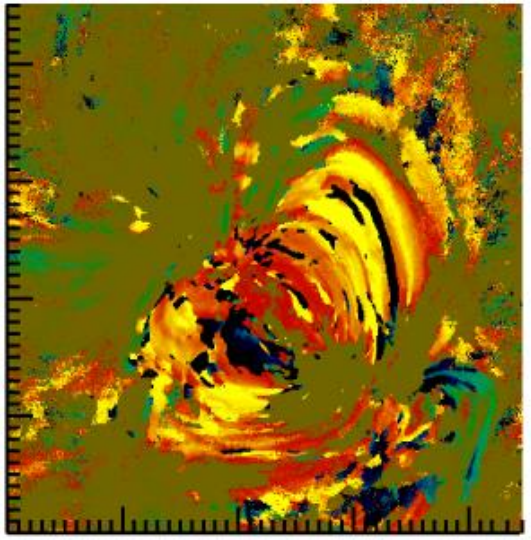


Intensity





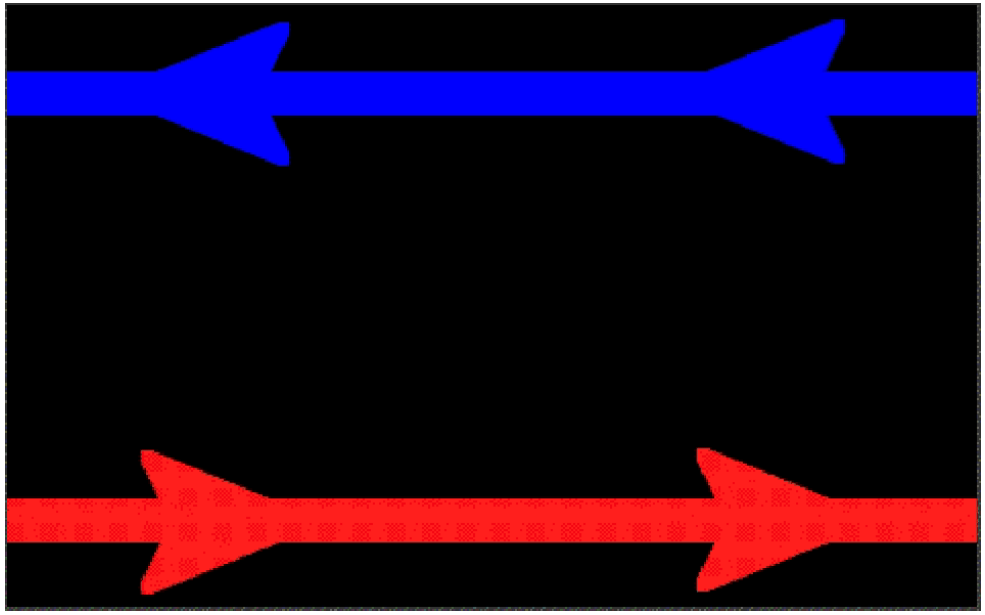
Hot – Cool Time Delay

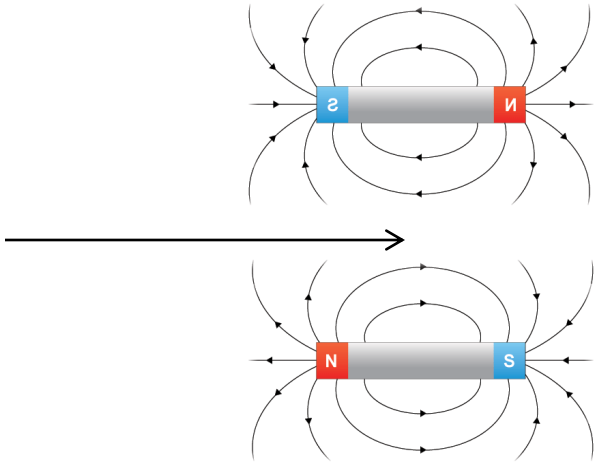


Viall & Klimchuk (2012, 2013)

Magnetic Reconnection

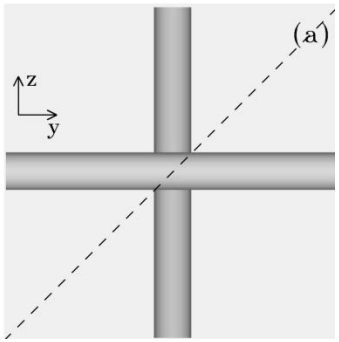
(a fundamental process throughout the universe)

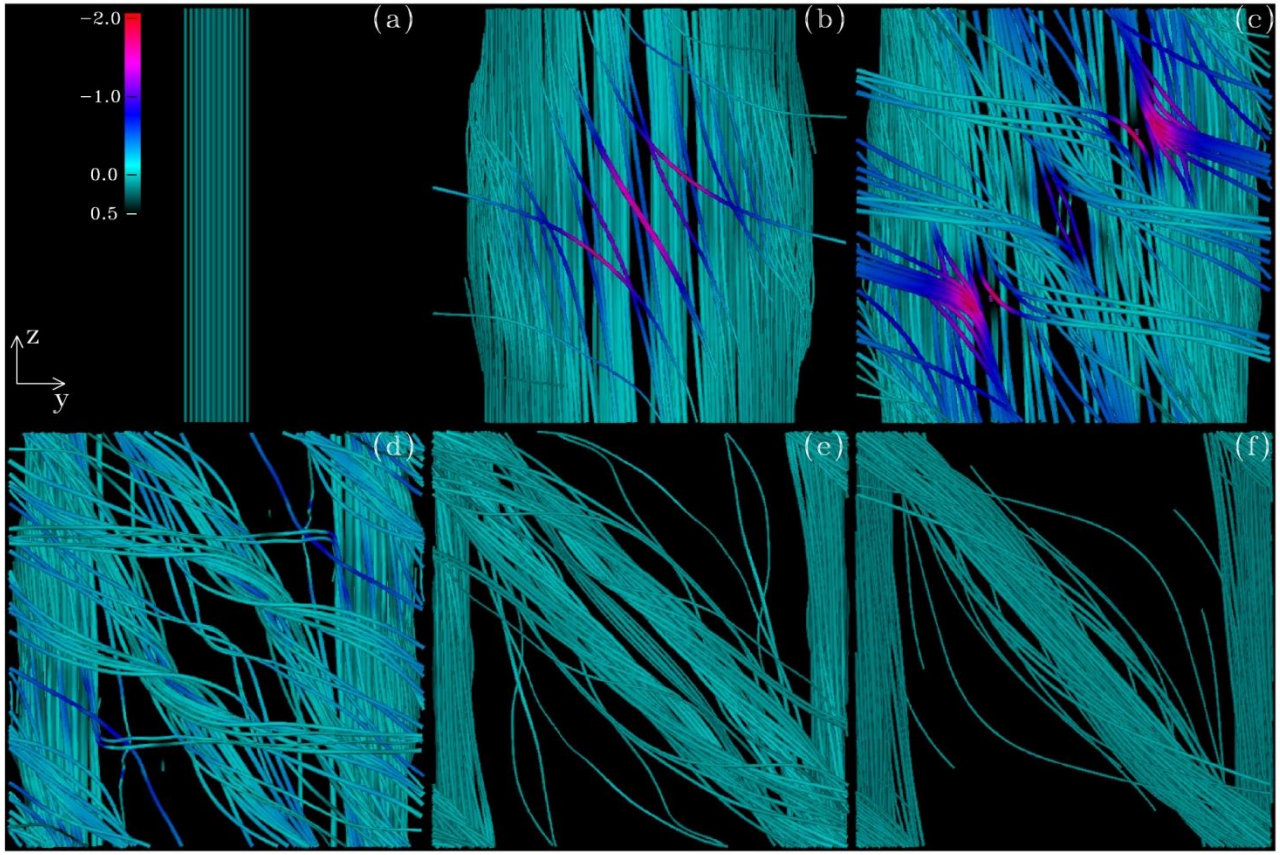




(Magnetic field lines need not be perfectly anti-parallel, simply misaligned)

Orthogonal Reconnecting Flux Tubes





Magnetic field lines (pink: regions of strong reconnection)

Linton & Priest (2003)

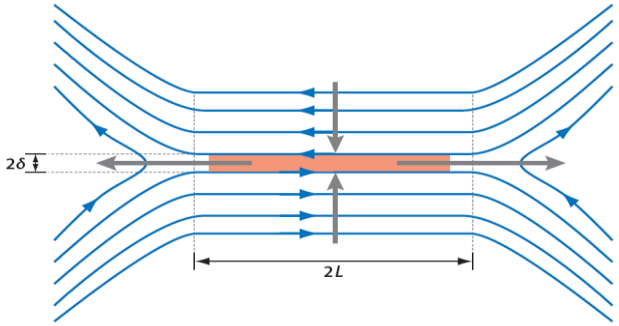
Orthogonal Reconnecting Flux Tubes

Magnetic field lines (pink: regions of strong reconnection)

Linton & Priest (2003)

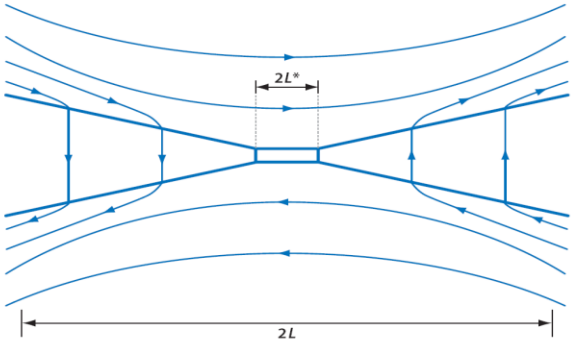
History of Magnetic Reconnection

Sweet-Parker

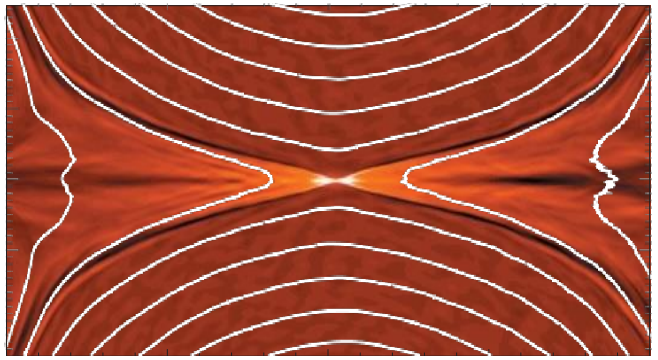


Zweibel & Yamada (2009)

Petschek

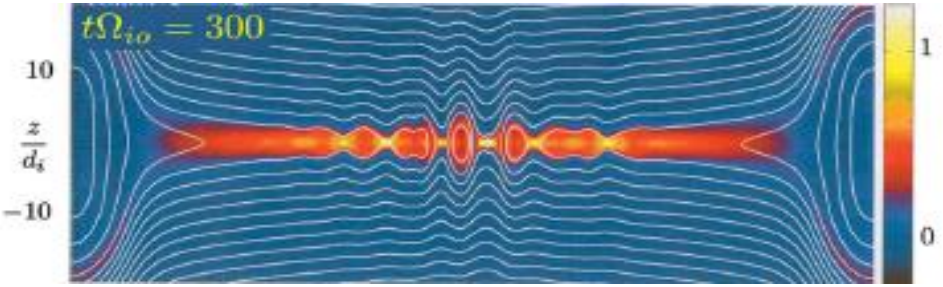


Hall



Cassak, Shay, Drake (2010)

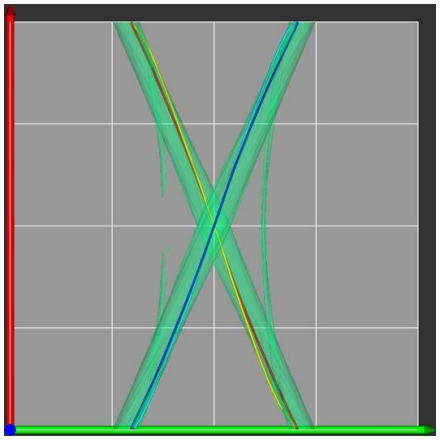
Secondary Islands



Daughton et al. (2009)

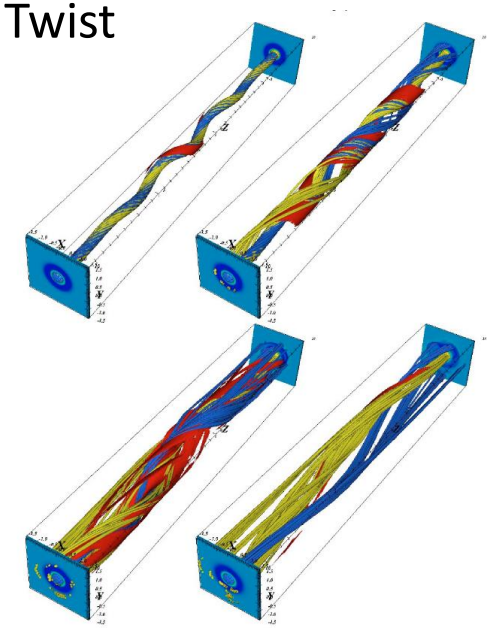
Critical Onset Conditions

Misalignment Angle



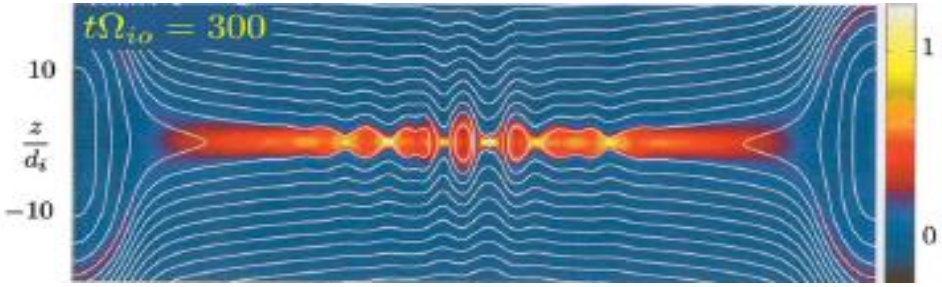
Klimchuk et al. (2007)

Twist



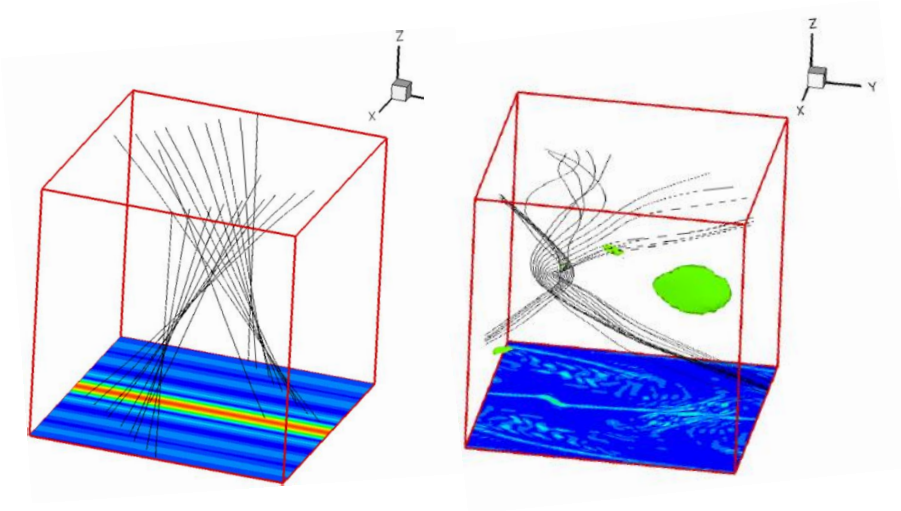
Hood et al. (2009)

Length-to-Width Ratio

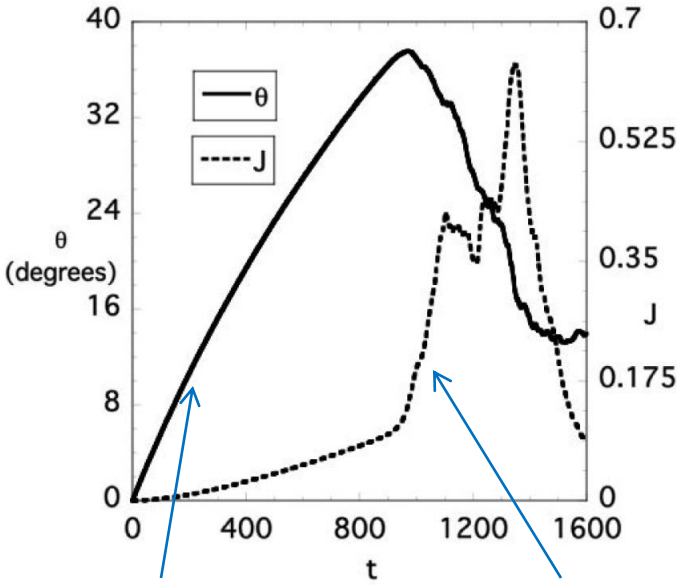


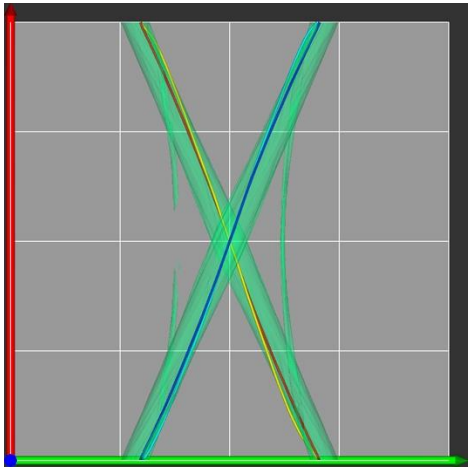
Daughton et al. (2009)

Secondary Instability



Vertical dimension “squashed” by factor 10

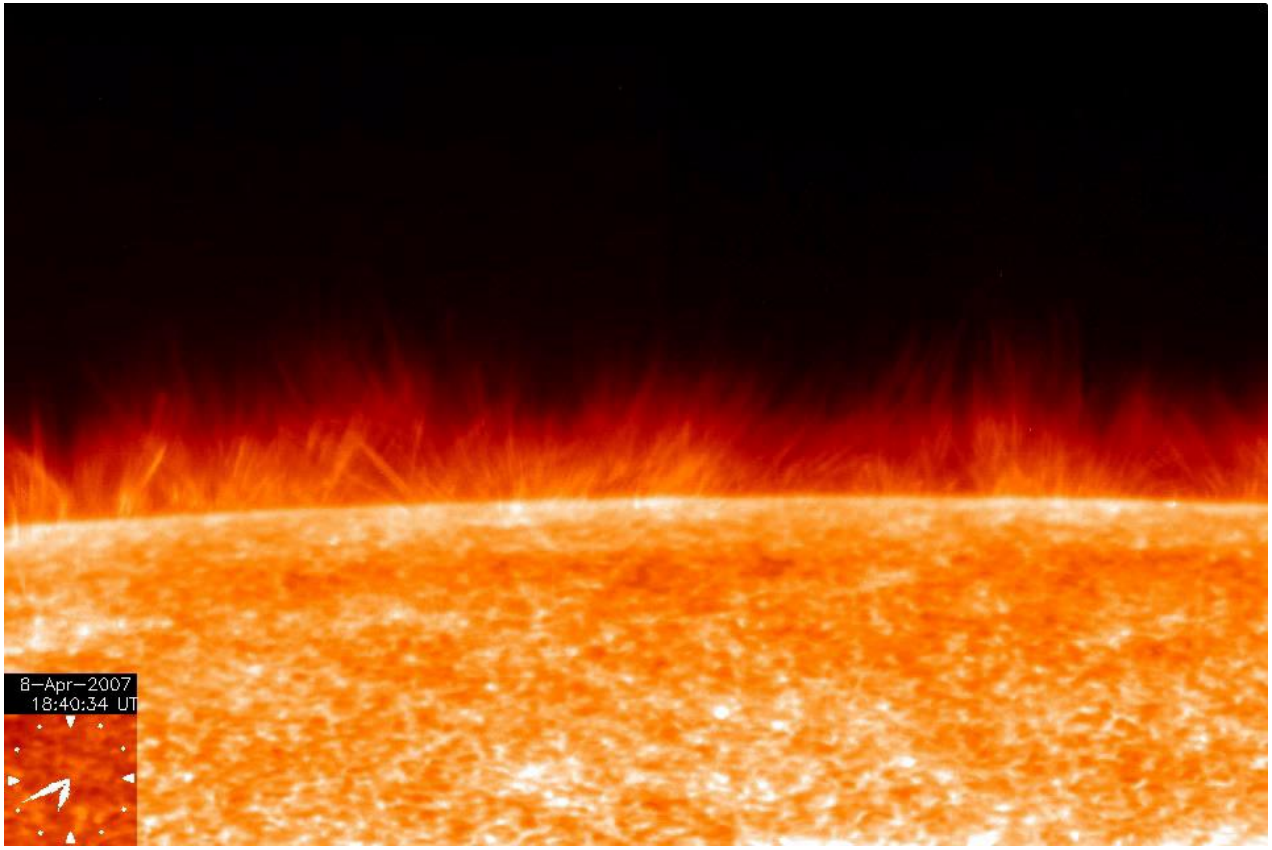




Nanoflare occurs when magnetic misalignment reaches ~35 degrees

Dahlburg, Klimchuk, & Antiochos (2003, 05, 09); Klimchuk et al. (2007)

Spicules



Hinode / SOT

Small jets of cool gas that rise and fall.

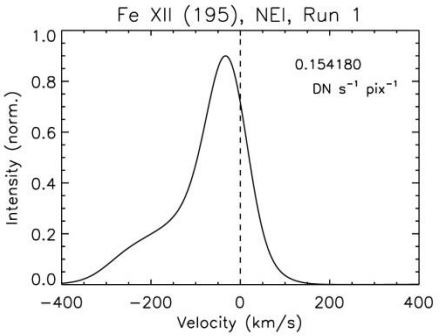
Tips of “type II” spicules are hot and continue rising.

Hypothesis: Corona is explained by hot plasma ejected at spicule tips?

3 observational tests

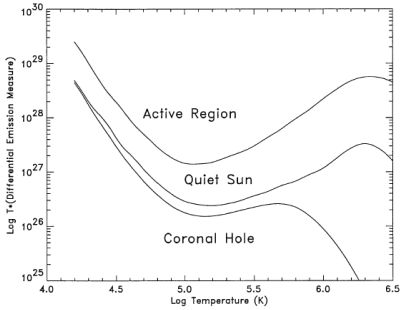
1. Blue-wing to line core intensity ratio:

$$R = \frac{I_{wing}}{I_{core}} \geq 1.5x10^{-14} \ \frac{n_c \, h_c^2 \, A}{l \, v}$$



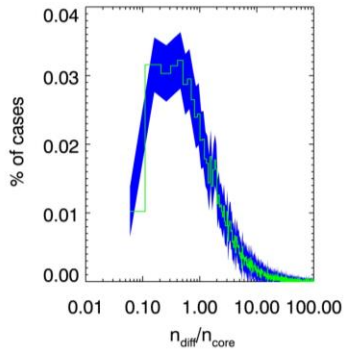
2. LTR (0.1 MK) to corona (2 MK) intensity ratio:

$$\frac{EM_{LTR}}{EM_{Cor}} = 1.5x10^{-13} \left(\frac{1-\delta}{\delta^2}\right) \frac{h_c}{h_s} \, A \, n_c \tau_{LTR}$$



3. Blue-wing to line core density ratio:

$$\frac{n_{wing}}{n_{core}} \approx \frac{h_c A}{l}$$



Hypothesis fails all 3 tests....miserably!

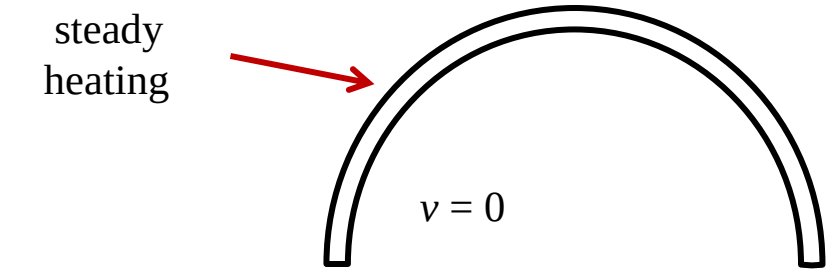
Klimchuk (2012), Tripathi & Klimchuk (2013), Patsourakos, Klimchuk, & Young (2013), Klimchuk & Bradshaw (2014)

Summary

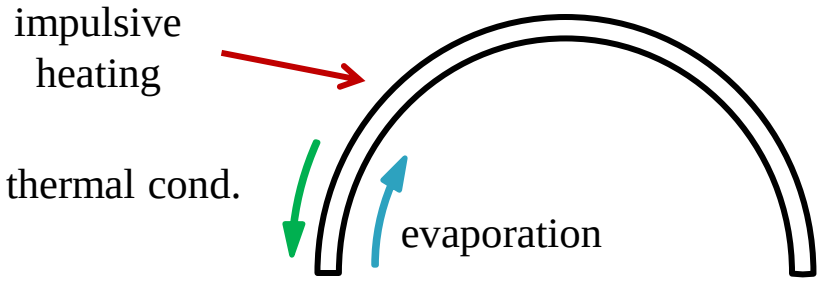
- Coronal loops are heated by storms of nanoflares.
- Some of the diffuse corona is also heated by nanoflares, but how much?
- Nanoflares are caused by reconnection of the tangled and twisted magnetic fields produced by photospheric convection. Other options?
- How exactly does reconnection work?
- What are the onset conditions for reconnection?
- Do nanoflares accelerate particles to high energy?
- Need new observations:
  - EUNIS rocket
  - FOXSI rocket
  - Solar-C mission
- Need much more Research & Analysis

Backup Slides

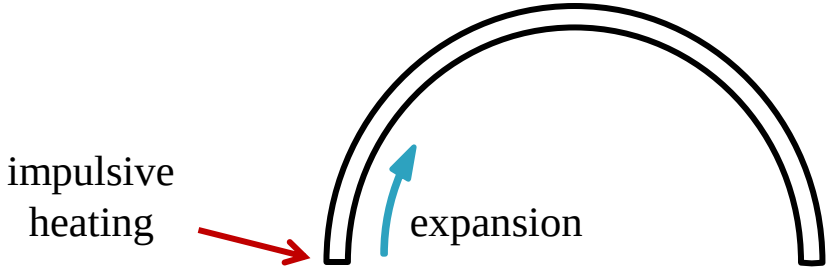
Three Basic Scenarios



"Steady"
Coronal Heating



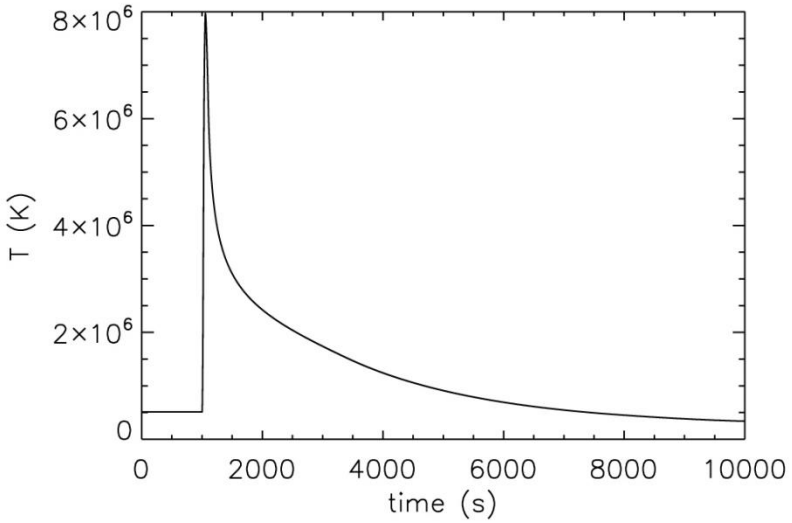
Impulsive
Coronal Heating



Impulsive
Chromospheric Heating
(incl. Type II Spicules)

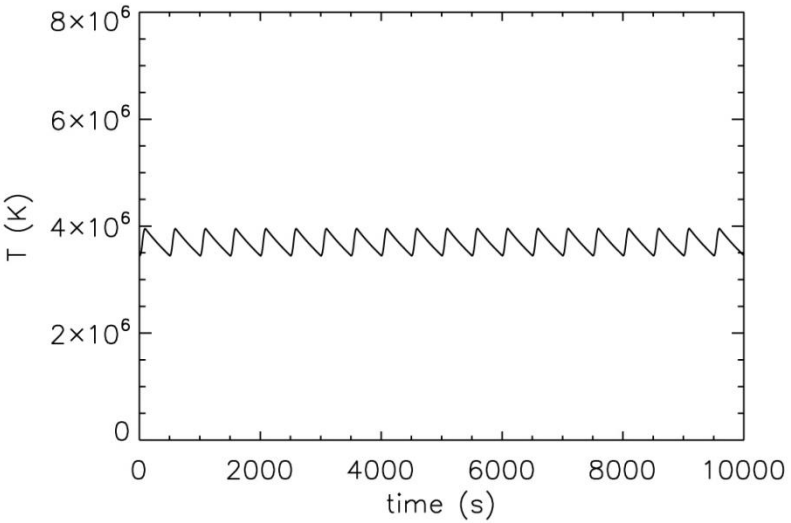
Nanoflare Frequency

Low Frequency



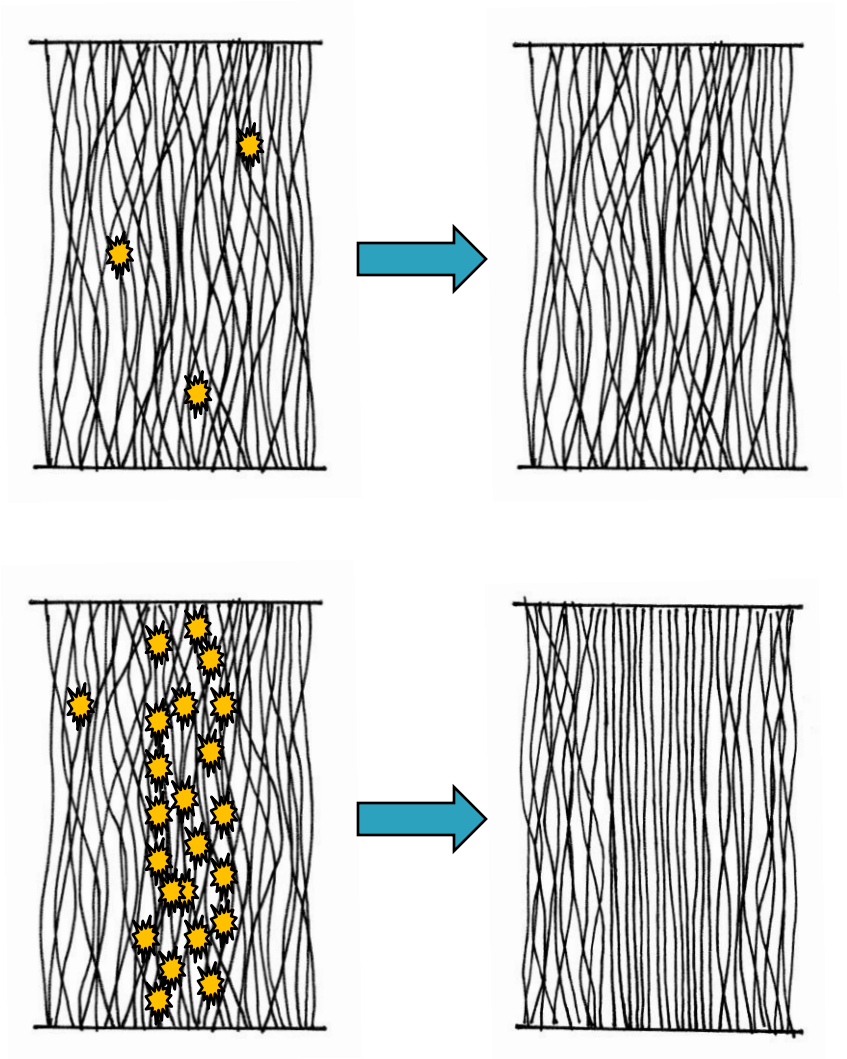
$\tau_{repeat} >> \tau_{cool}$

High Frequency



$\tau_{repeat} << \tau_{cool}$

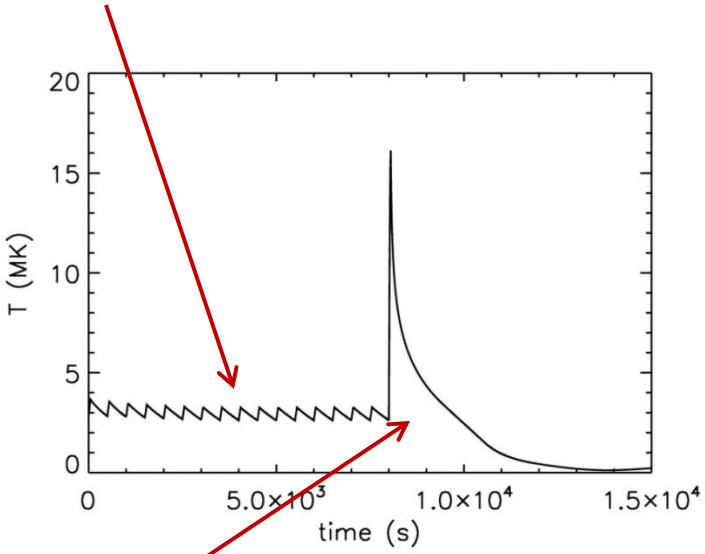
Distinct Loops from Nanoflare “Storms”



Nanoflare Storm

Needs time to “recharge”

Diffuse component
(high-freq. nanoflares)



Distinct loop
(low-freq. nanoflares)

Klimchuk (2009)

Hot Emission is Faint

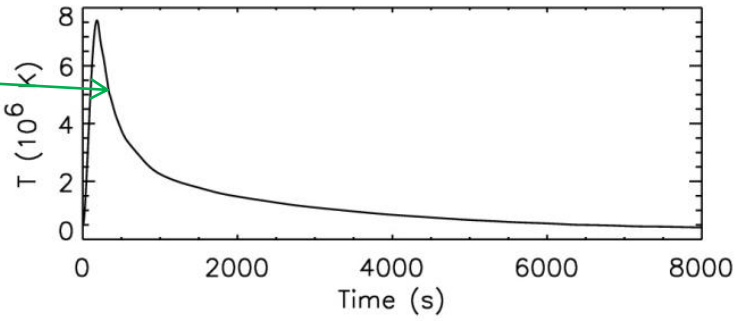
1. Hot plasma is short-lived
   Temperature is changing rapidly

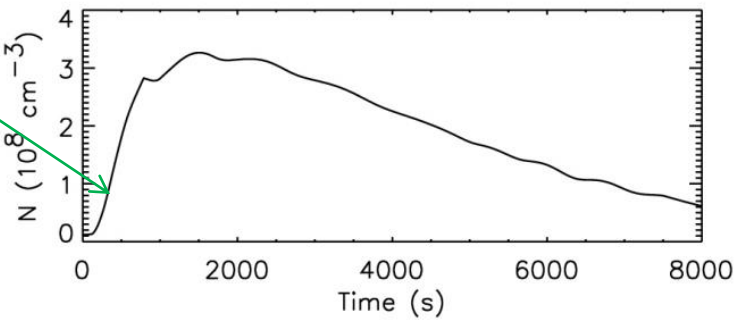
2. Density and emission measure are low

3. Greatest departure from ionization equil.

   Ionization rate is slow at low density

   Ionization cannot keep pace with the rapidly changing temperatures

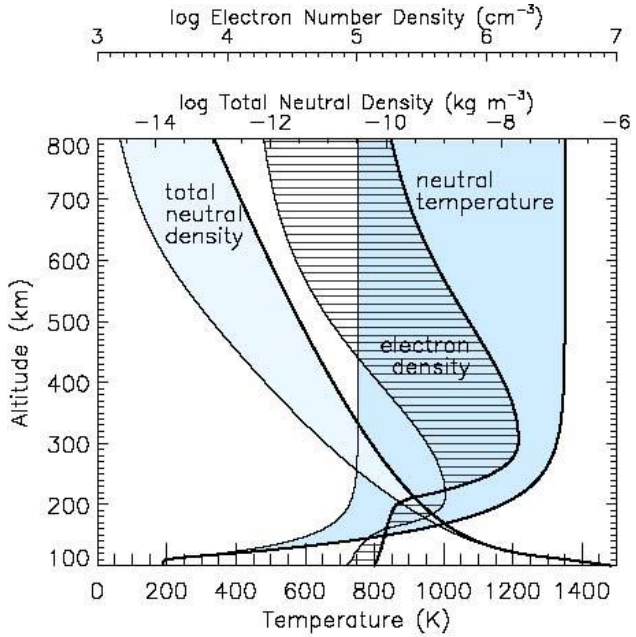


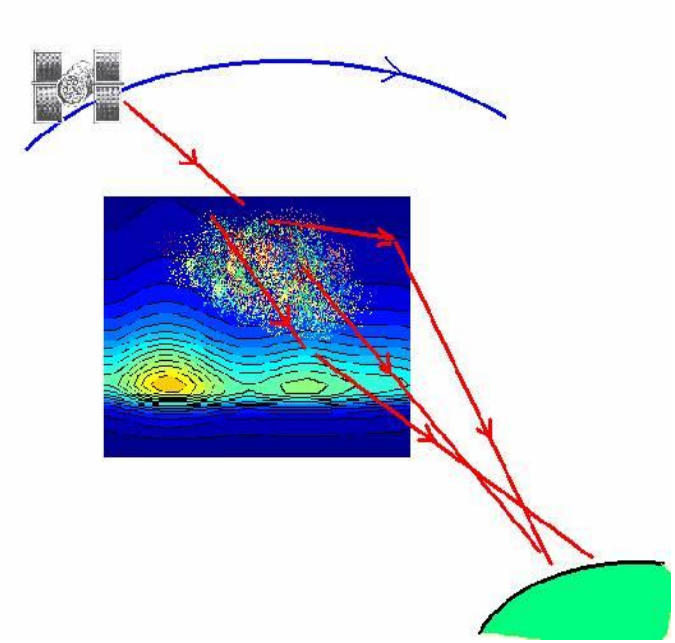


500 s nanoflare simulation

Klimchuk (2006)

Importance for Space Weather





Solar radiation produced by coronal heating controls the dynamics, chemistry, and ionization state of the Earth's upper atmosphere....

….impacting satellite drag and technologies involving radio signal propagation.