Solar Flares

(Solar Eruptive Events)

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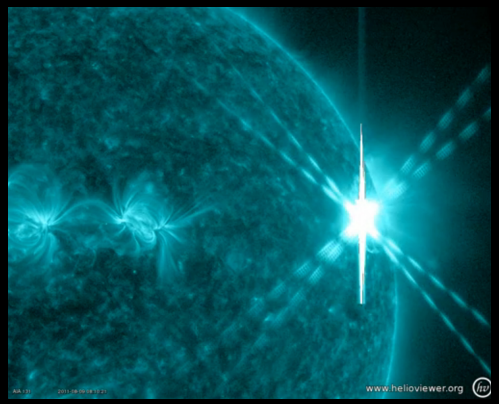
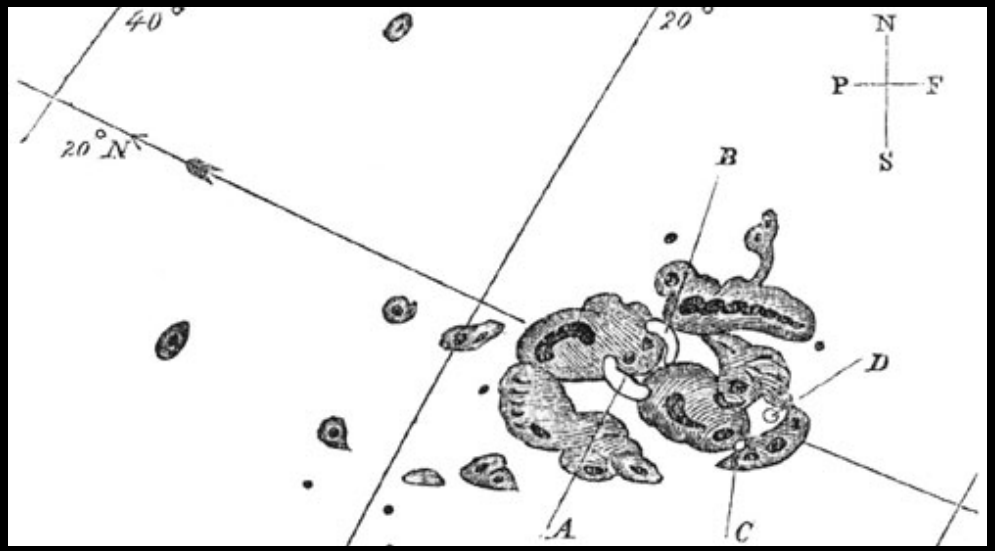
Solar Physics Laboratory
Code 671

A solar flare is a significant brightening on the sun, at any wavelength, that typically lasts from seconds to hours.



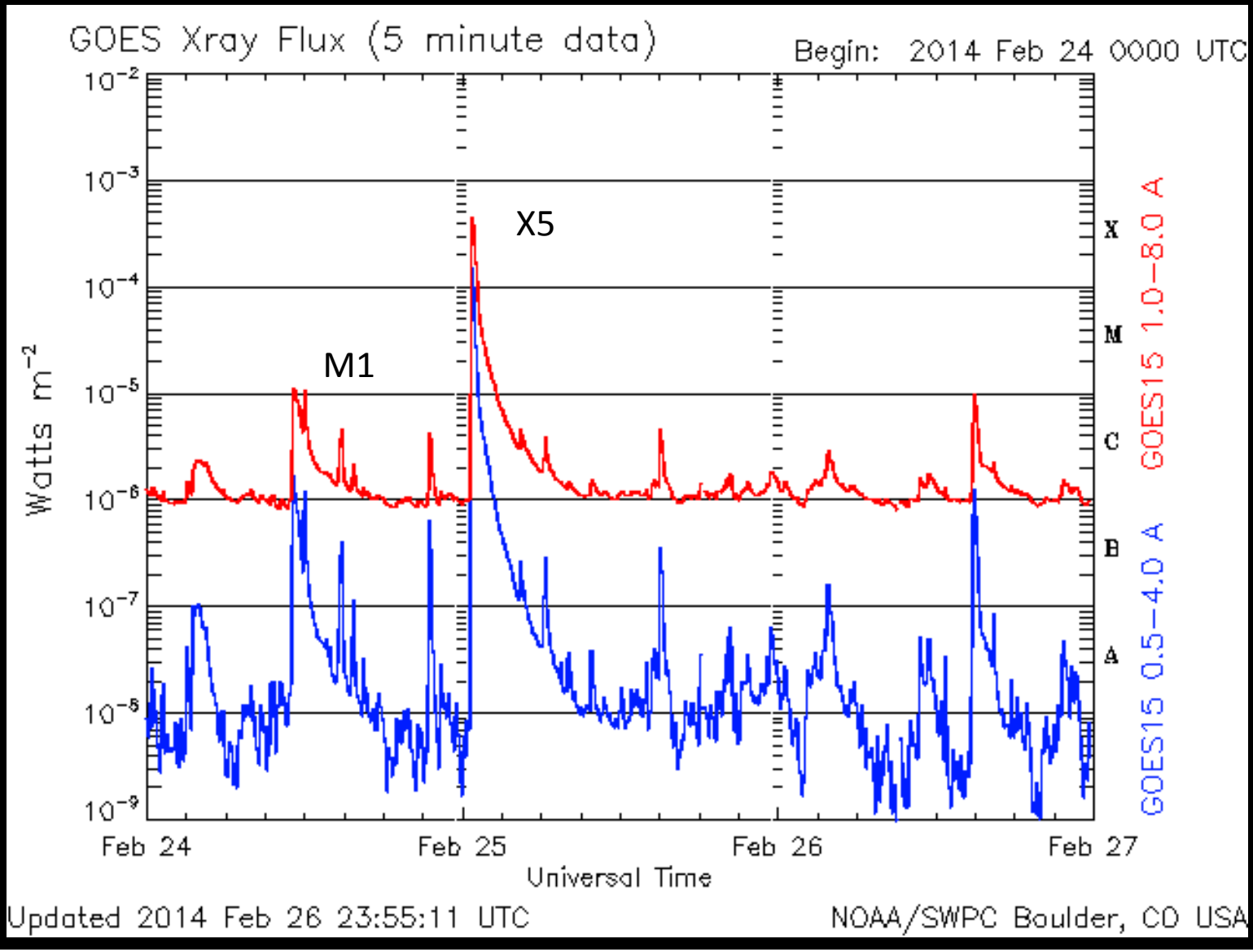
Large flares often produce electromagnetic radiation at all observable wavelengths.

Solar flare first observed on September 1, 1859, in white light



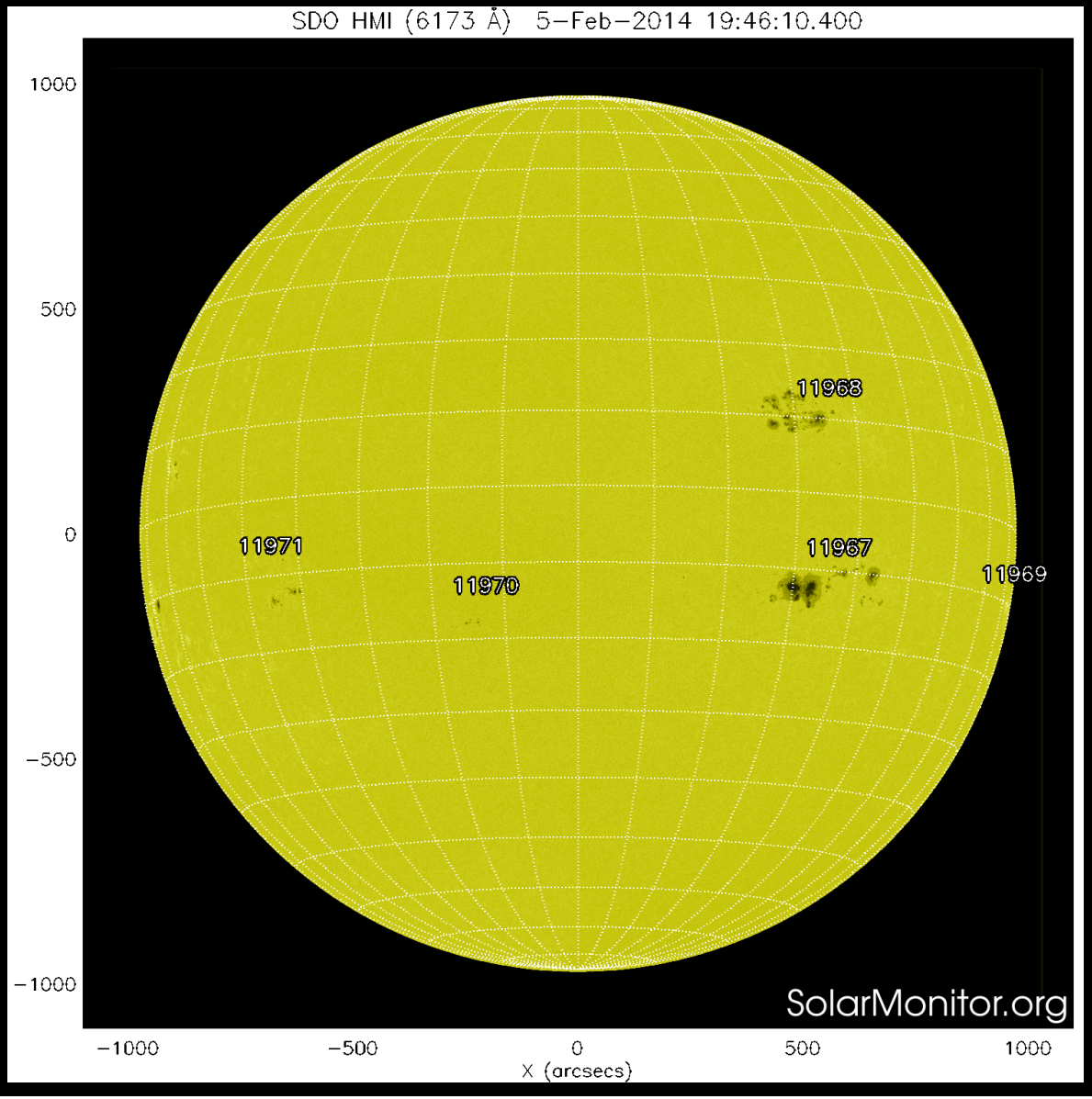
Drawing by Richard Carrington

Flare Identification with the *Geostationary Operational Environmental Satellites (GOES)*



Solar Flares Occur (Mostly) in Active Regions

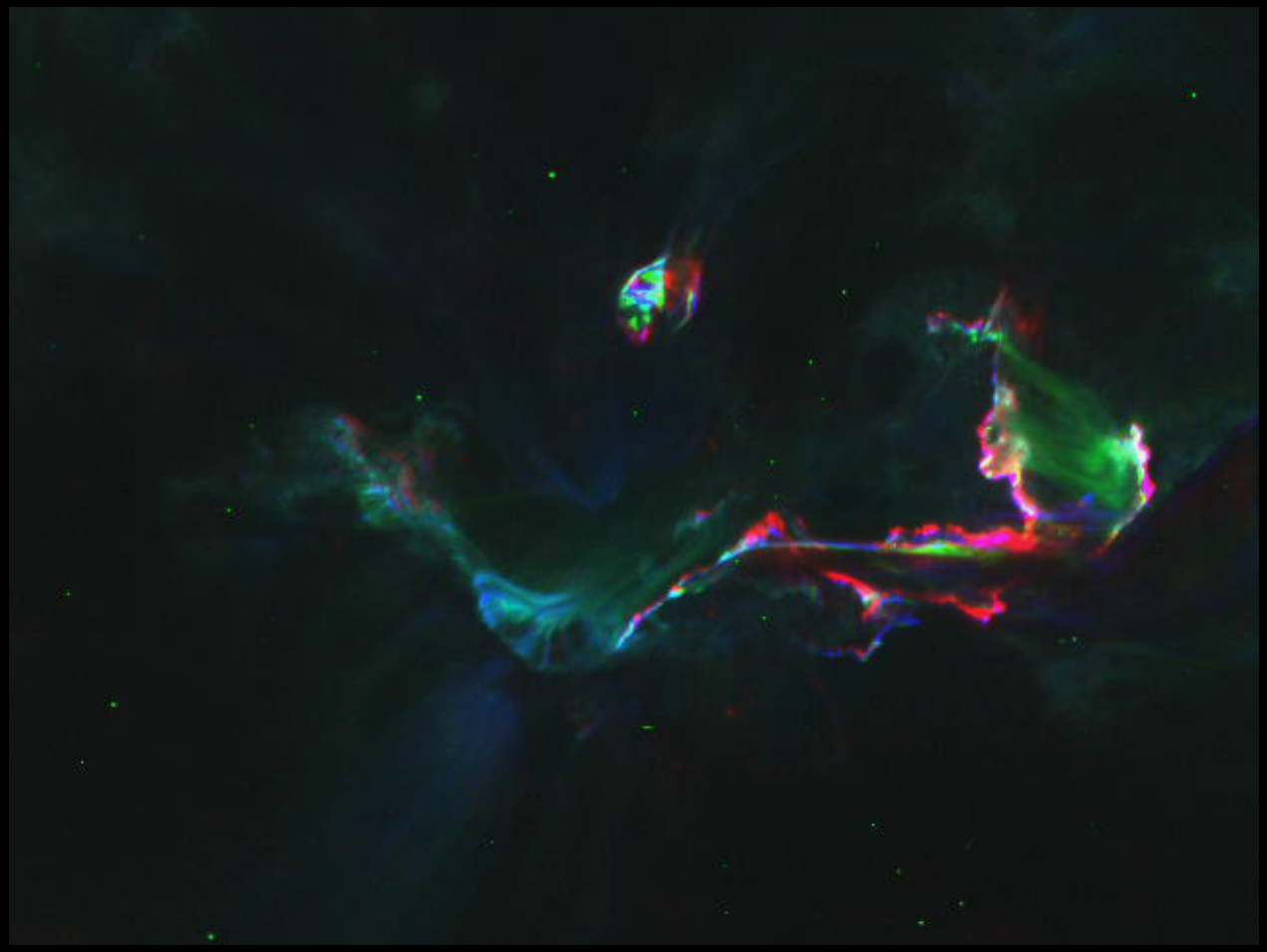
Active regions contain magnetic loops of relatively hot (MK) and dense plasma



Active regions are where sunspots are located

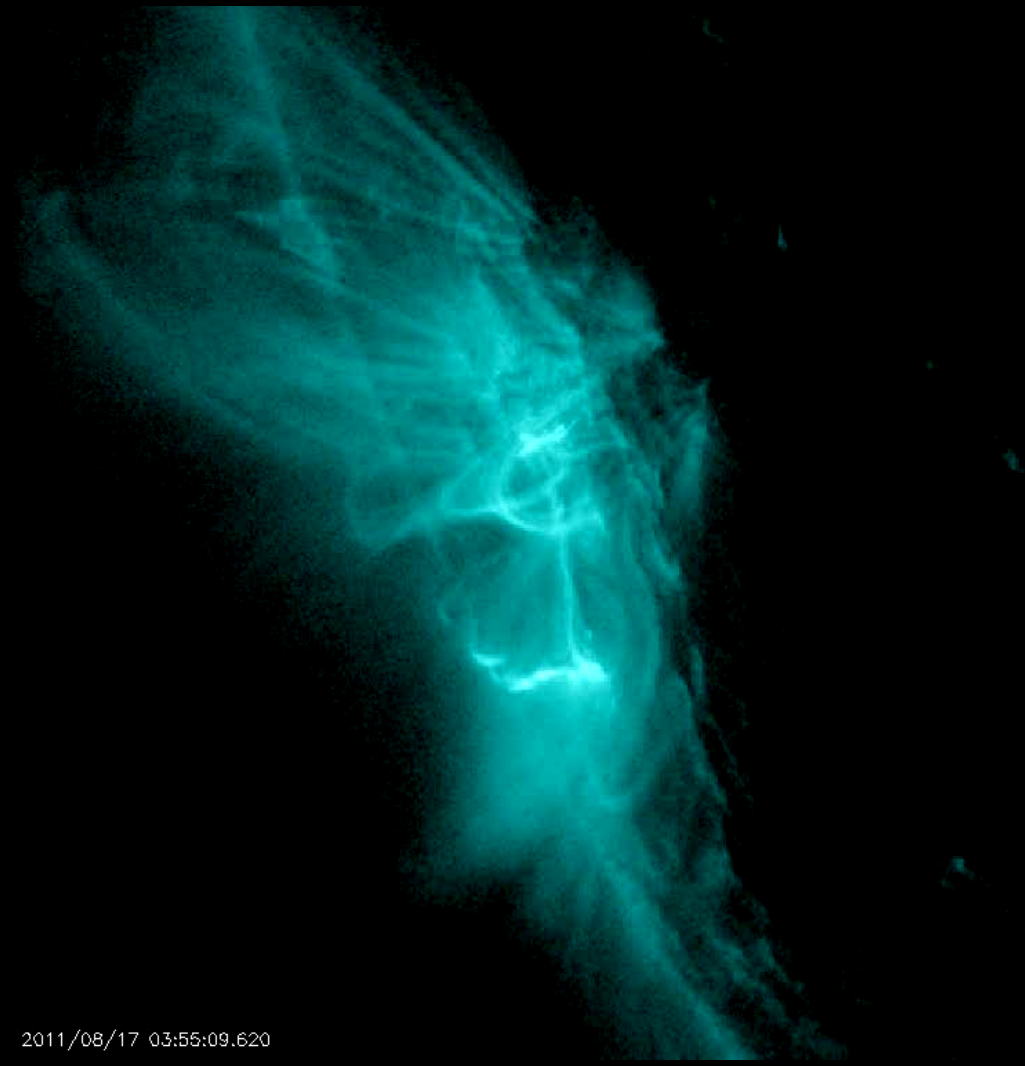
Active regions contain strong, relatively complex magnetic fields

2000 July 14 “Bastille Day” Event as observed by the *Transition Region and Coronal Explorer* (TRACE)

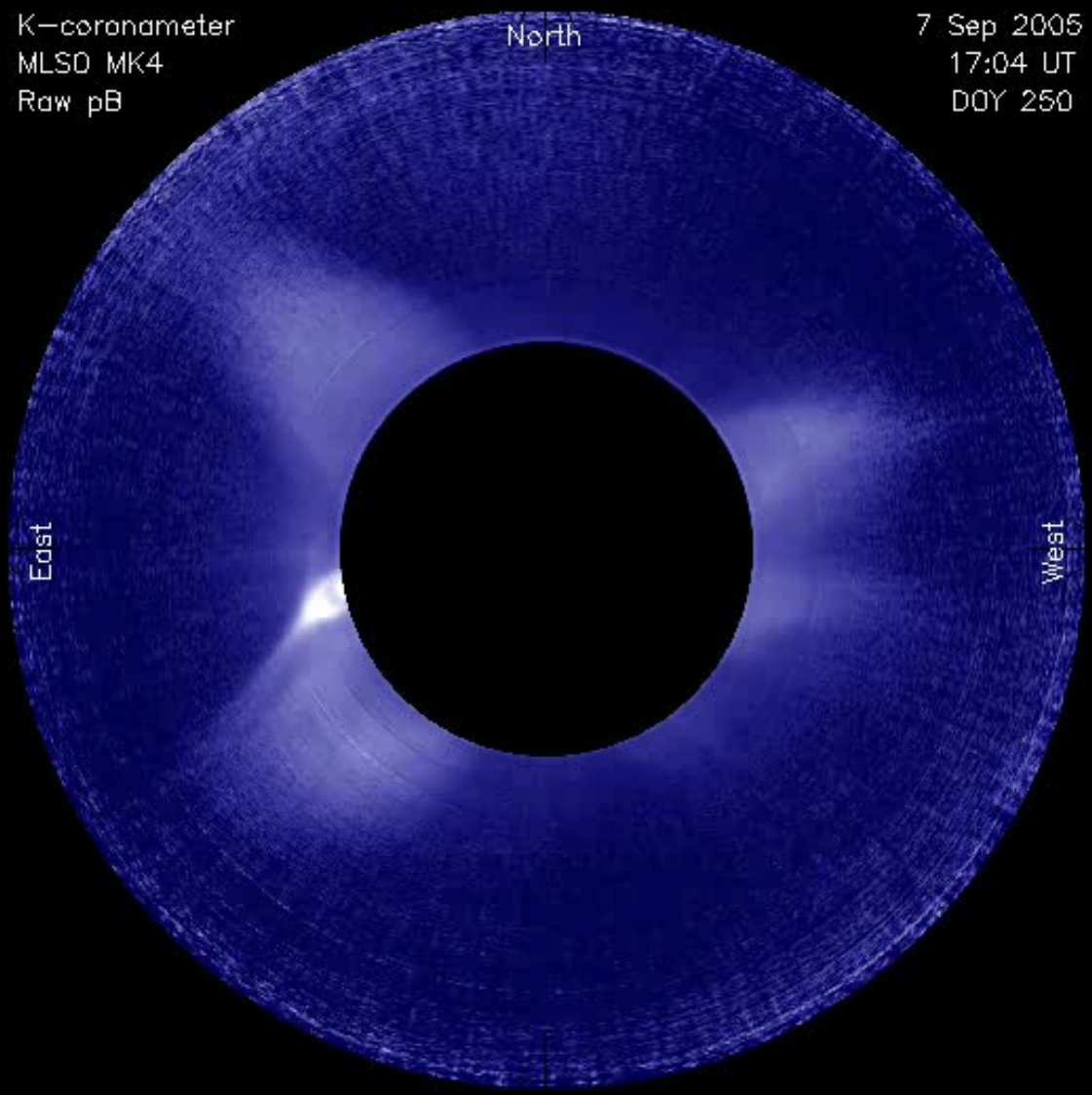


2012 July 19 Event as observed by the *Solar Dynamics Observatory* (SDO) Atmospheric Imaging Assembly (AIA)

2011 August 17 Event Observed by SDO AIA

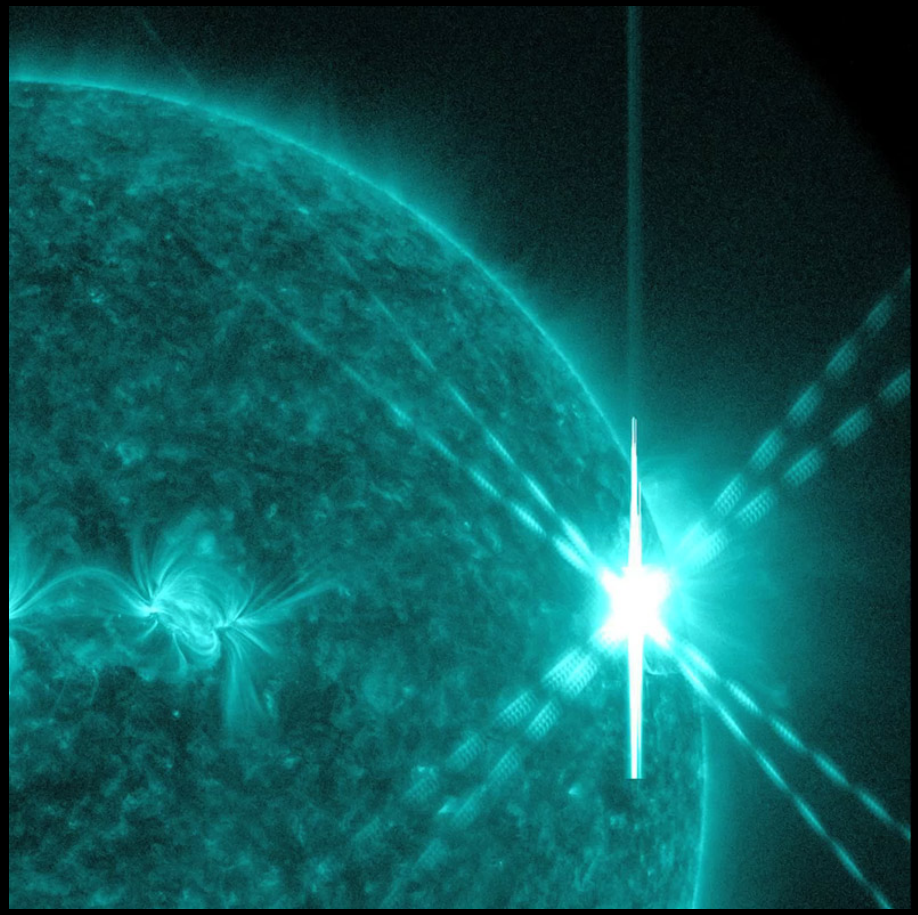


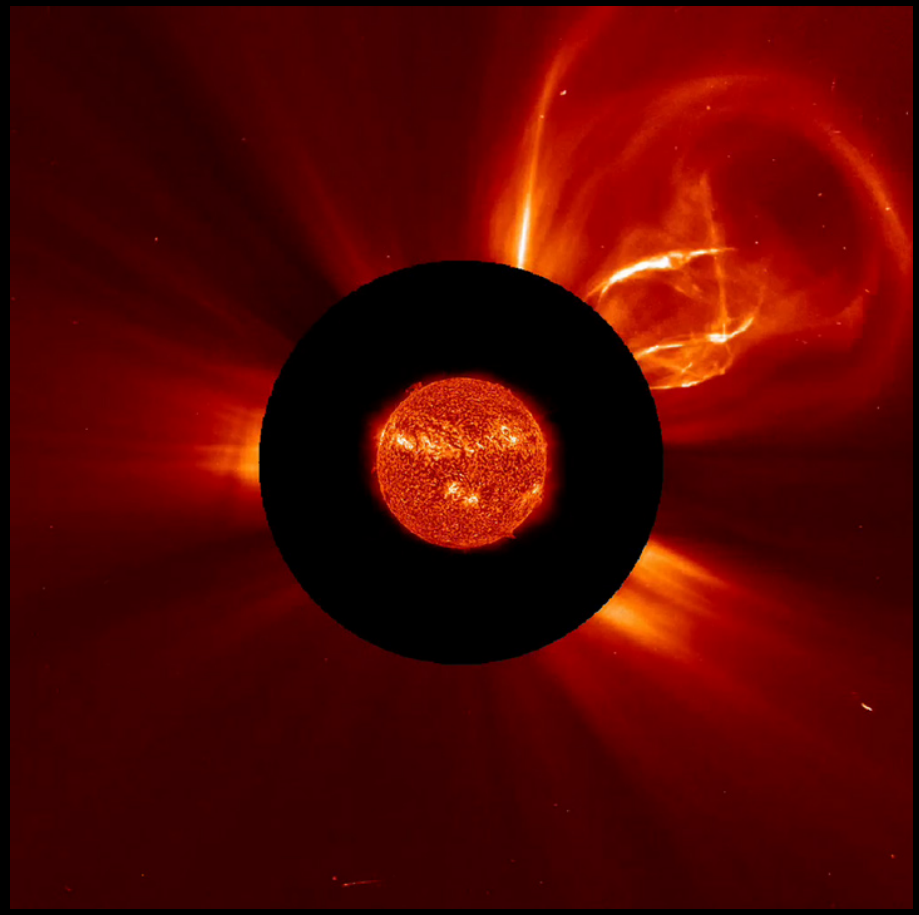
Coronal Mass Ejection (CME)



Ling, Webb, Burkepile, & Cliver 2014

What is a *Solar Eruptive Event*?





Flare + Coronal Mass Ejection (CME)

PUZZLE #1

What is the relationship between a flare and a coronal mass ejection? How are they produced together to give a solar eruptive event?

- Why are there flares without CMEs?
- Why are there CMEs without flares?

PUZZLE #2

Solar eruptive events release up to 10^{25} joules of magnetic energy on time-scales from tens of seconds to hours (up to 10^{22} watts)

- Resistive dissipation of a current in the solar atmosphere cannot accomplish this.
- This is on the order of the total magnetic energy in an active region!

How is the magnetic energy released?

PUZZLE #3

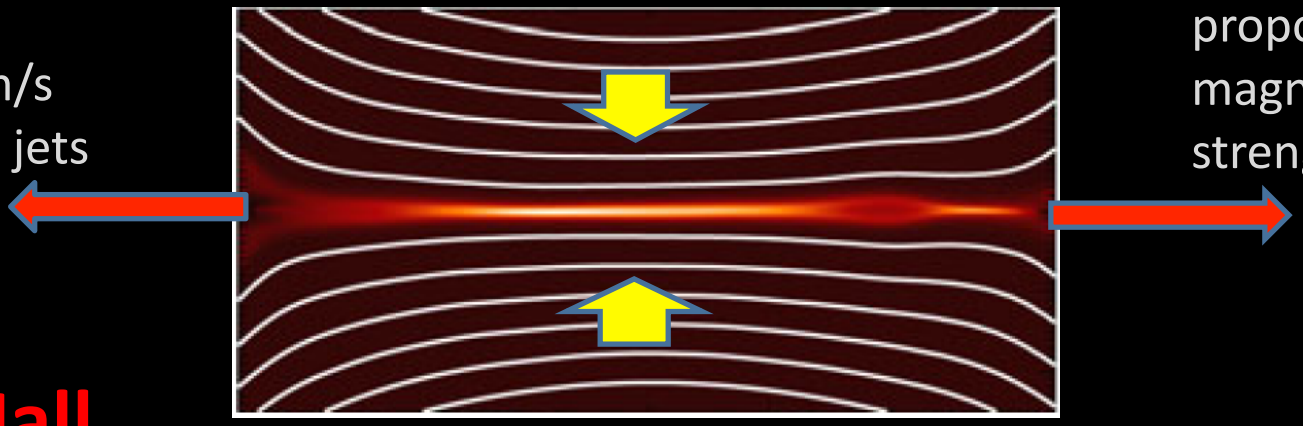
Where and how are non-thermal, energetic electrons accelerated in flares?

- The density of accelerated electrons is typically estimated to be as high as 10% of the density of thermal plasma.
- This is enough energy in accelerated electrons to heat all the flare plasma!

Magnetic Reconnection

- Sweet-Parker (slow) reconnection

~1000 km/s outflow jets

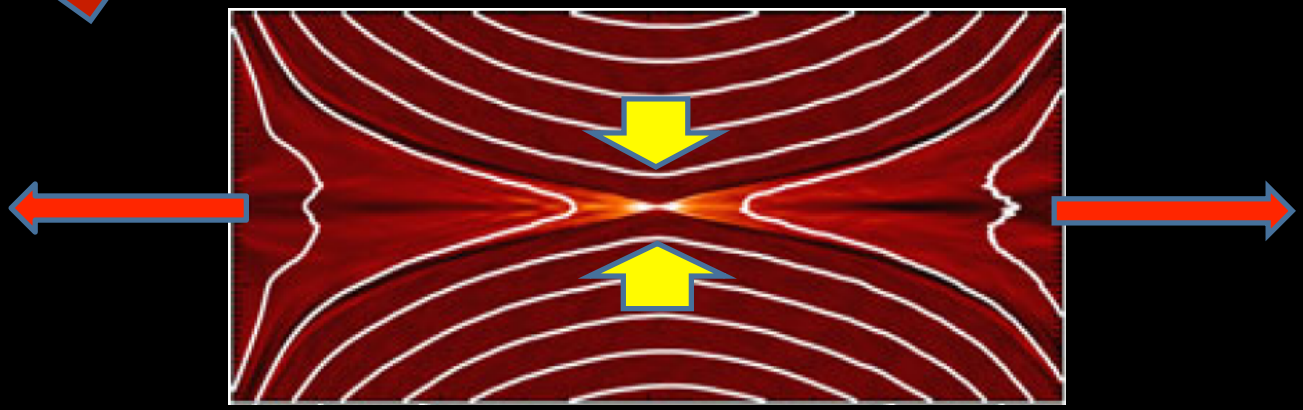


Outflow speed proportional to magnetic field strength

Hall

- Petschek (fast) reconnection

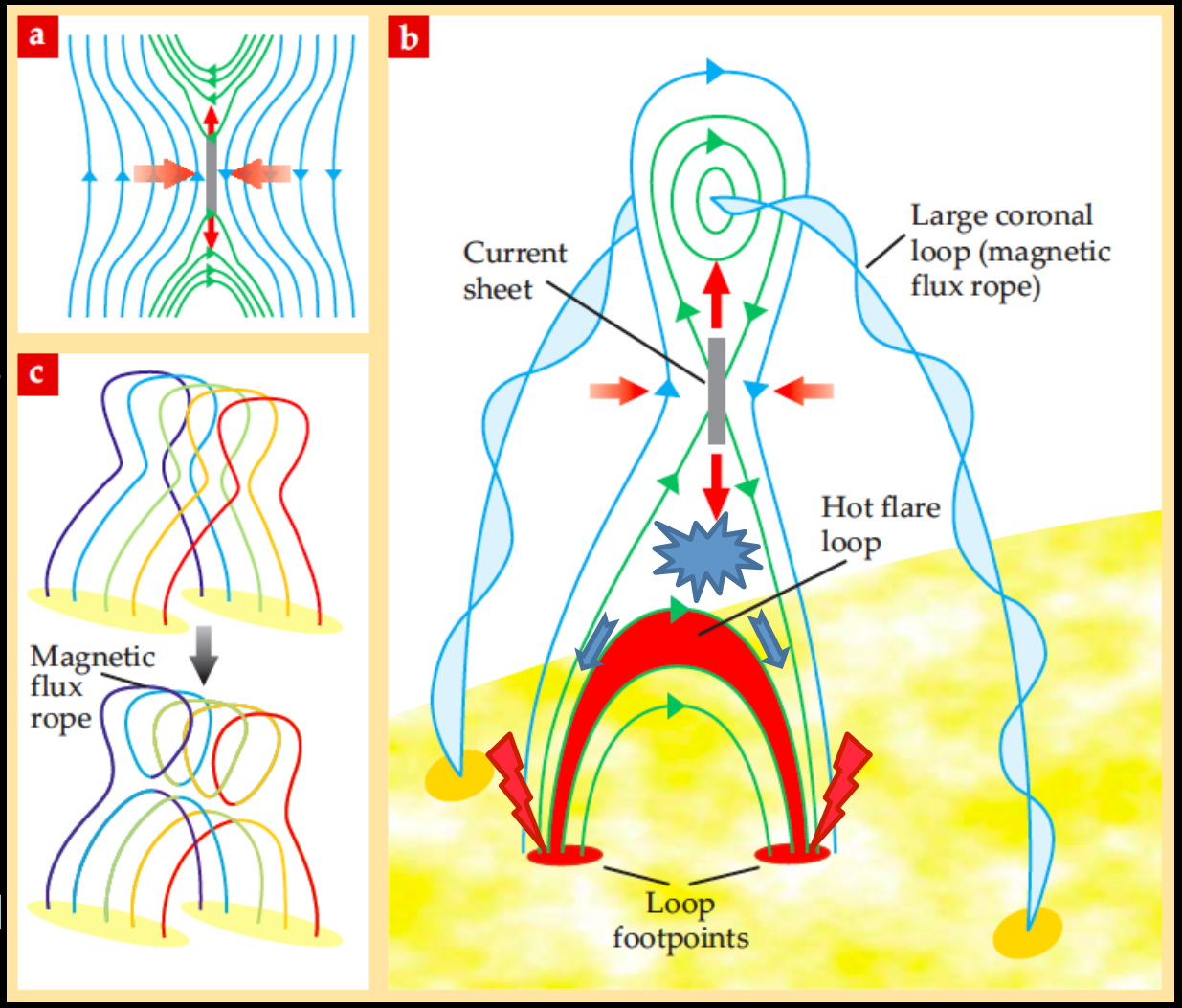
Simulations from Cassak, Shay, & Drake (2010)



The Standard Model for Solar Eruptive Events

As the ribbons are sheared

- Footpoints separate
- Loop tops expand upward
- Loops collapse inward and reconnect



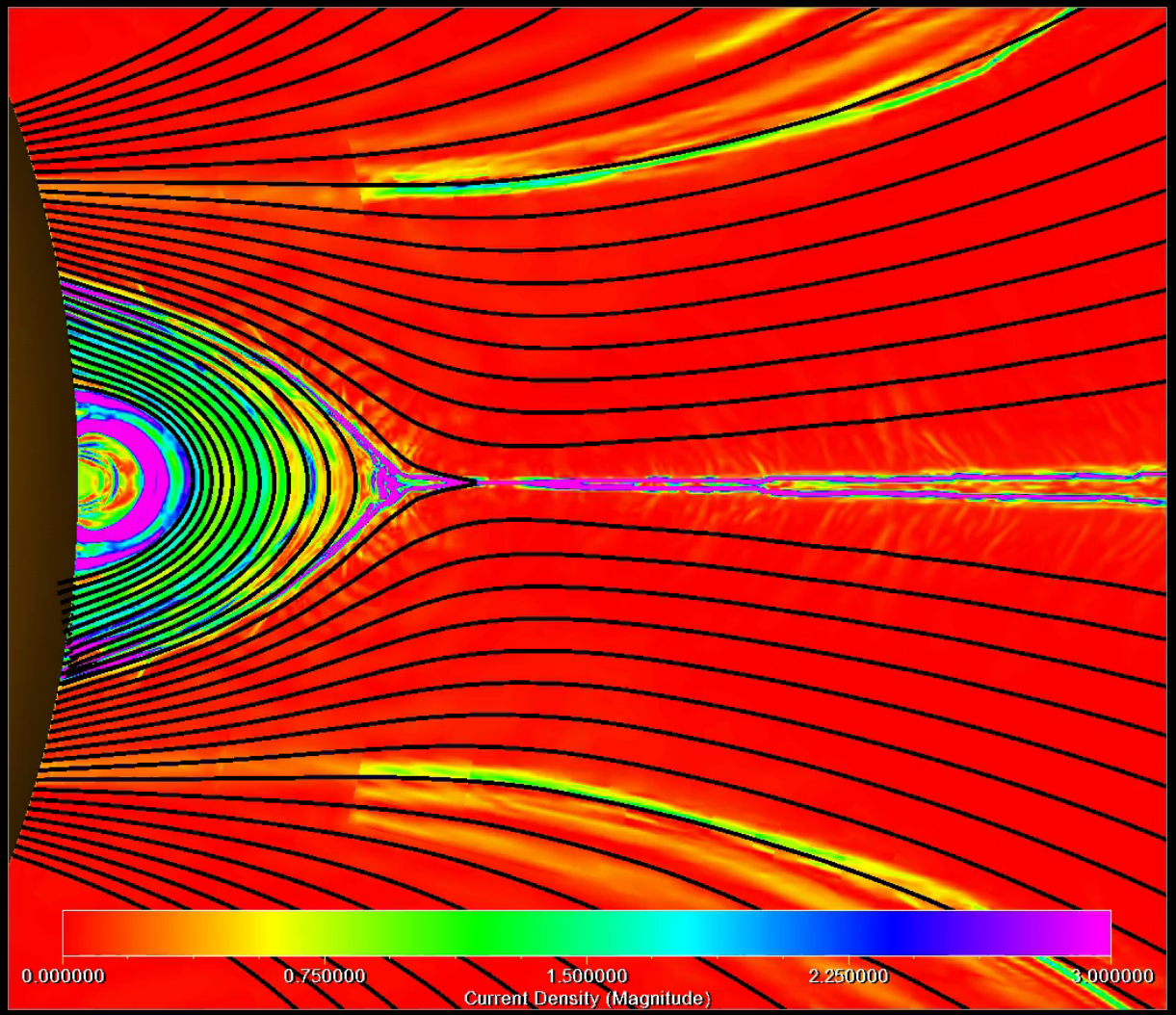
Holman, G. D. 2012, *Physics Today*, April issue

Electron Acceleration

Electron Propagation

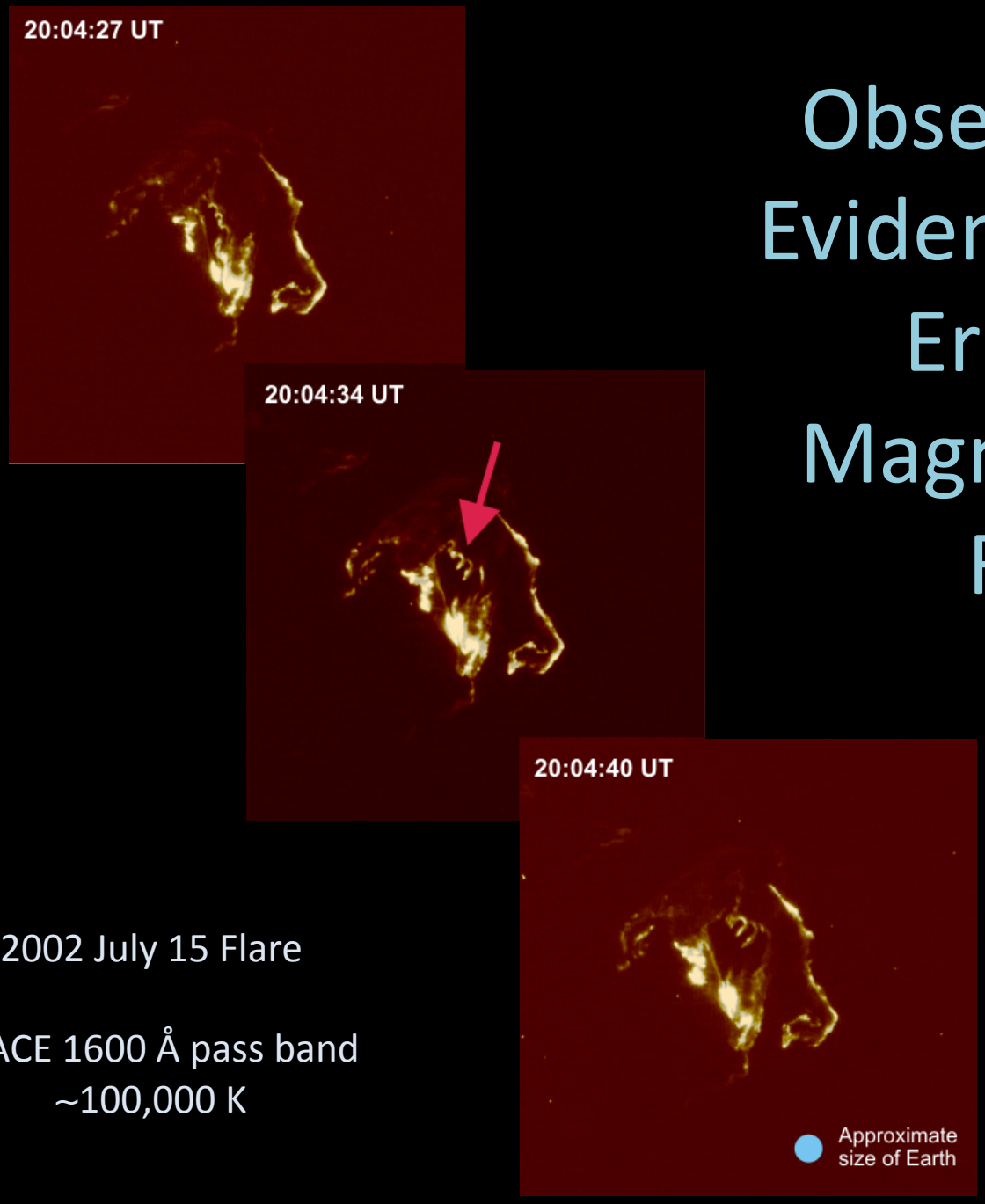
Thick-Target Brems-strahlung X-Rays

Numerical Simulation of Magnetic Reconnection in a Solar Eruptive Event



Courtesy of Silvina Guidoni, Goddard NPP Postdoc

Observational Evidence for the Erupting Magnetic Flux Rope

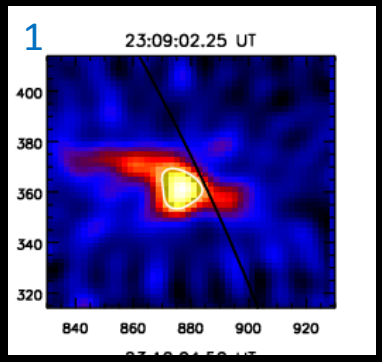


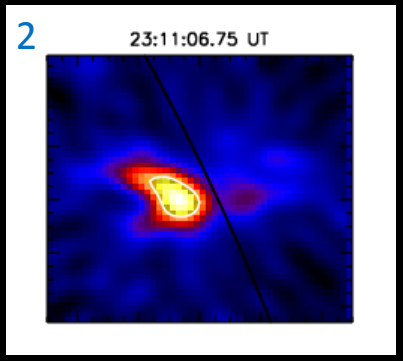
2002 July 15 Flare

TRACE 1600 Å pass band
~100,000 K

Evolution of a Solar Flare in X-Rays

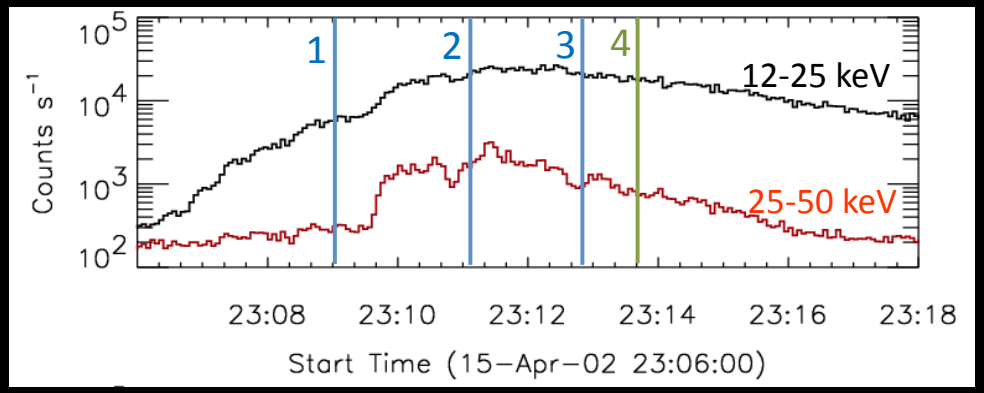
Sui & Holman 2003

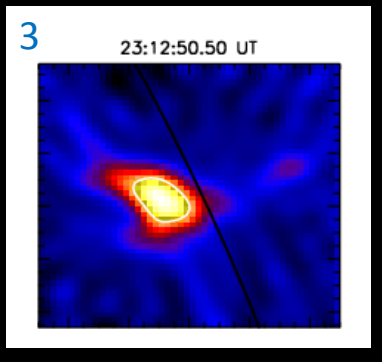


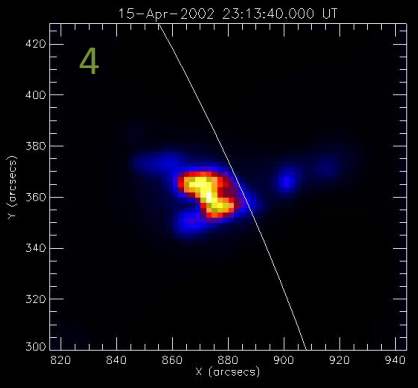


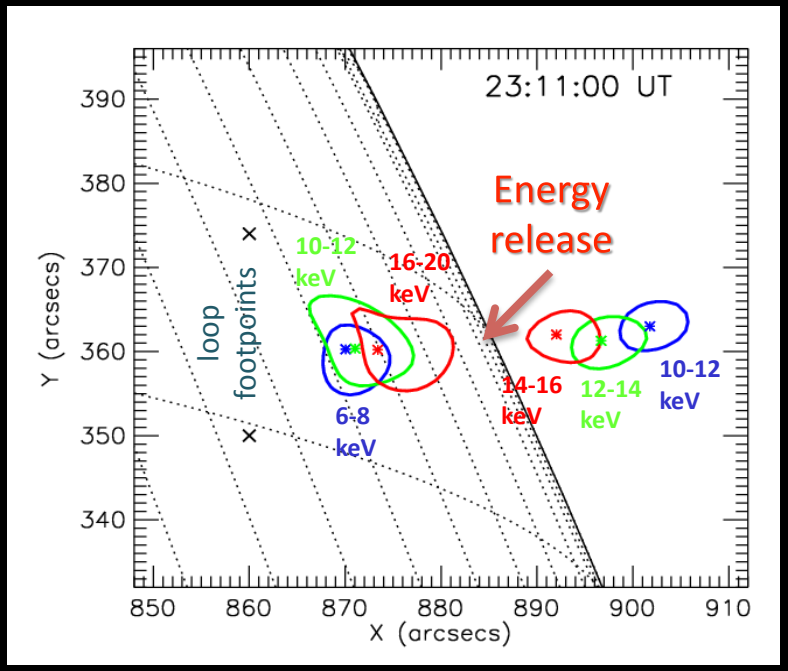
RHESSI 10-25 keV Images: Loop + Compact Coronal Source (1 – 3)

RHESSI Light Curves



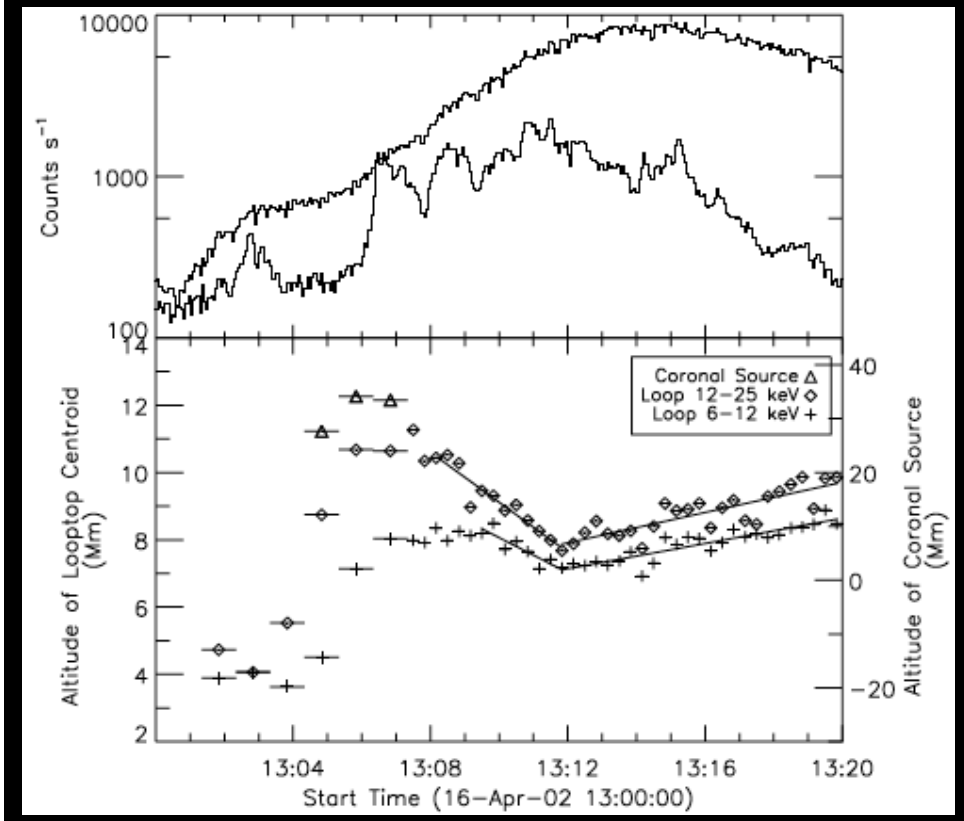


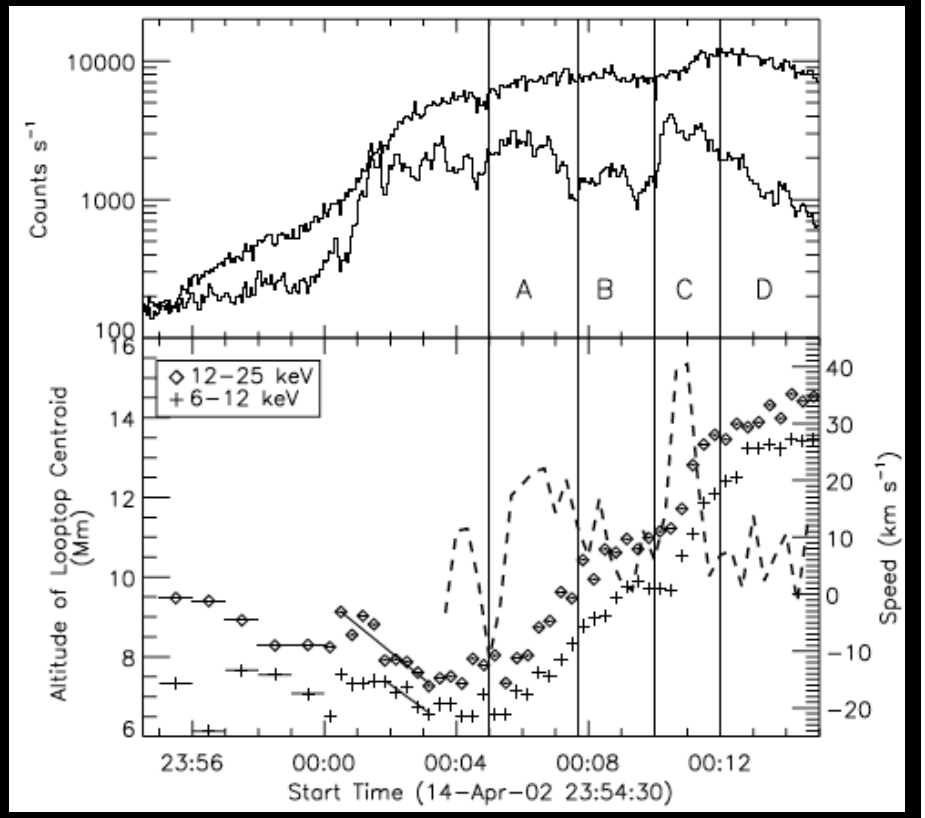




New Coronal Sources along current sheet (4)

X-Ray Loop-Top Height Time Evolution Observed by *RHESSI*

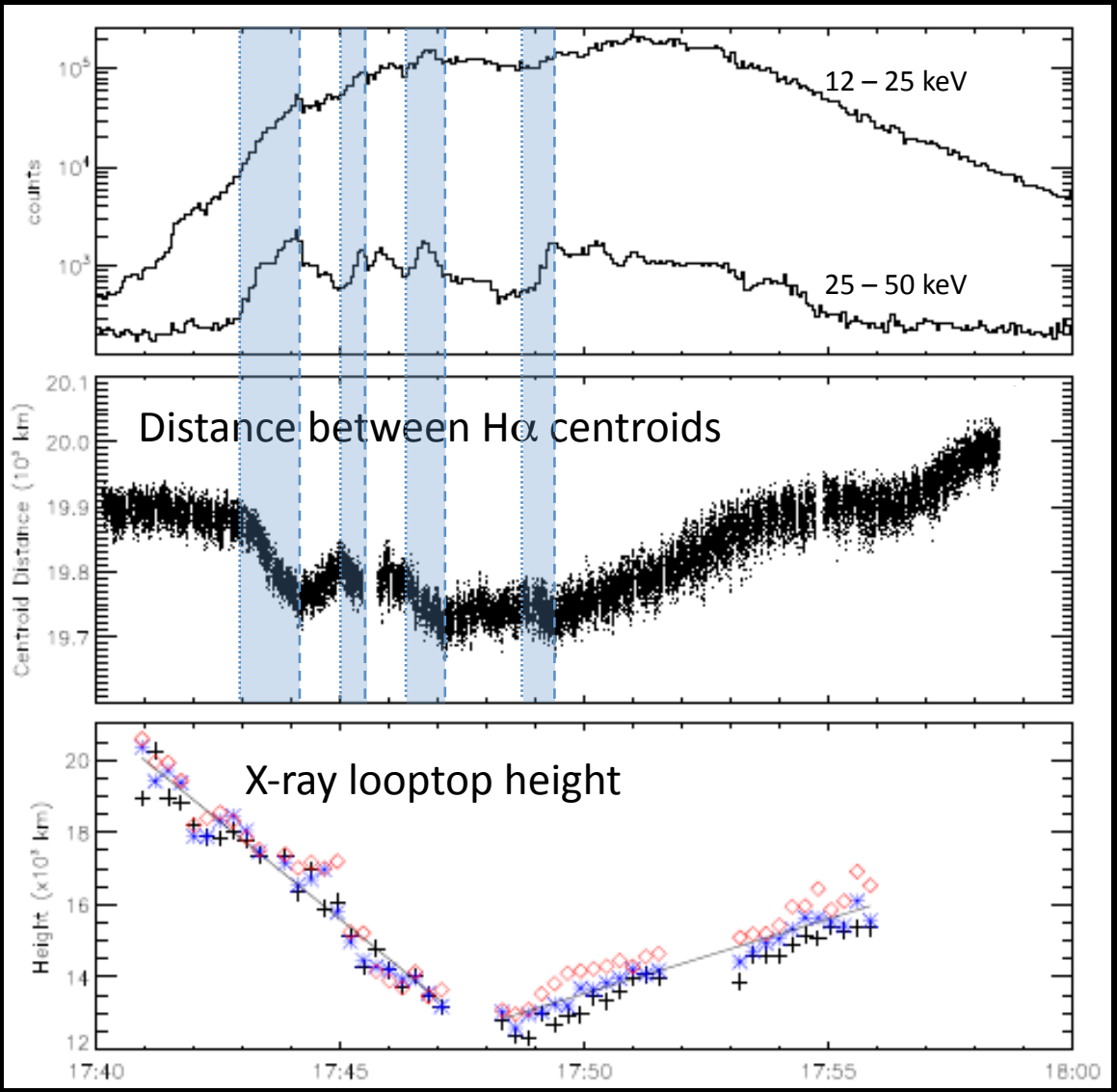




- Up – Down – Up evolution
- Plasma temperature increases with height
- Electron acceleration correlated with evolution

Sui, Holman & Dennis 2004

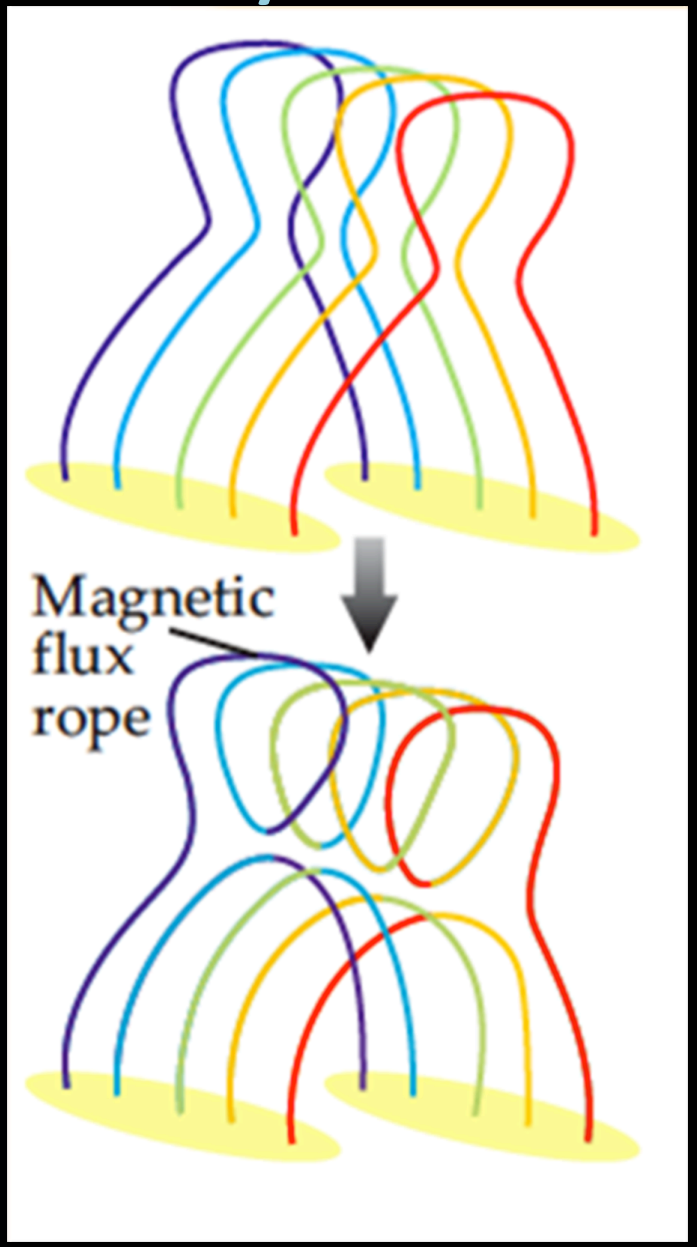
Correlation of Looptop and Footpoint Motions and X-ray Flux

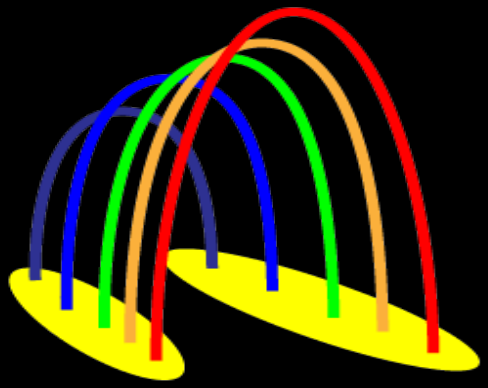


Electron acceleration rate correlates with rate at which distance between footpoints decreases

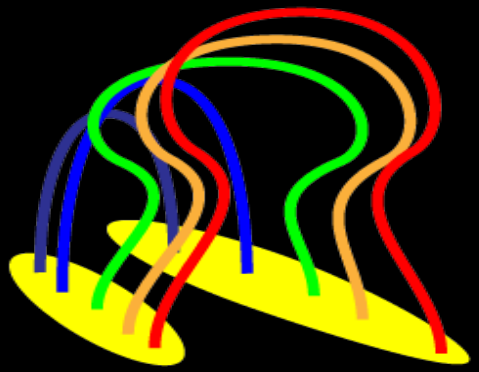
Shen, Zhou, Ji, Wang, Cao & Wang 2008

Asymmetric Arcade Reconnection



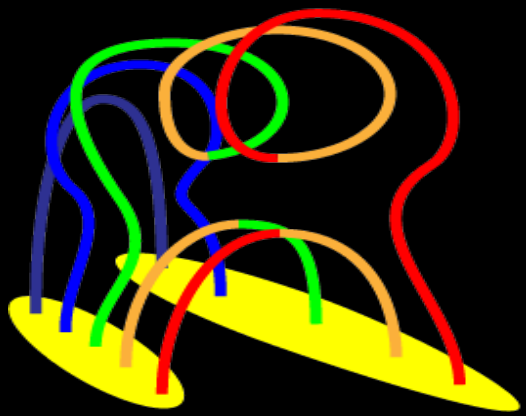


Early Upward Loop-Top Motion: Different length ribbons, loops at one end expand more



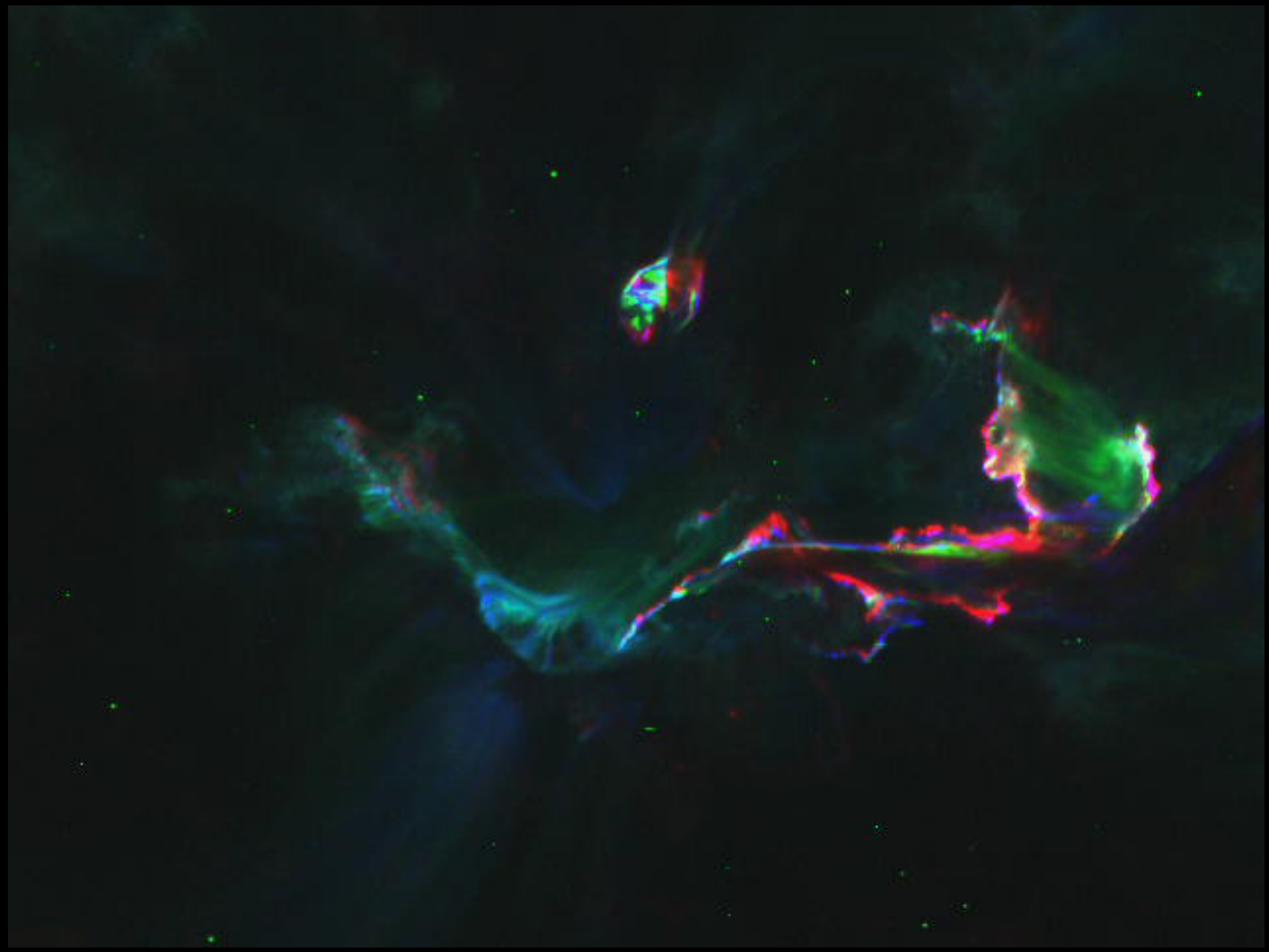
The higher, more sheared loops collapse and reconnect first

Downward Loop-Top Motion: Reconnection propagates along the arcade to the lower loops



Late Upward Loop-Top Motion: The arcade grows as reconnection continues above

2000 July 14 “Bastille Day” Event Revisited – as observed by the *Transition Region and Coronal Explorer* (TRACE)

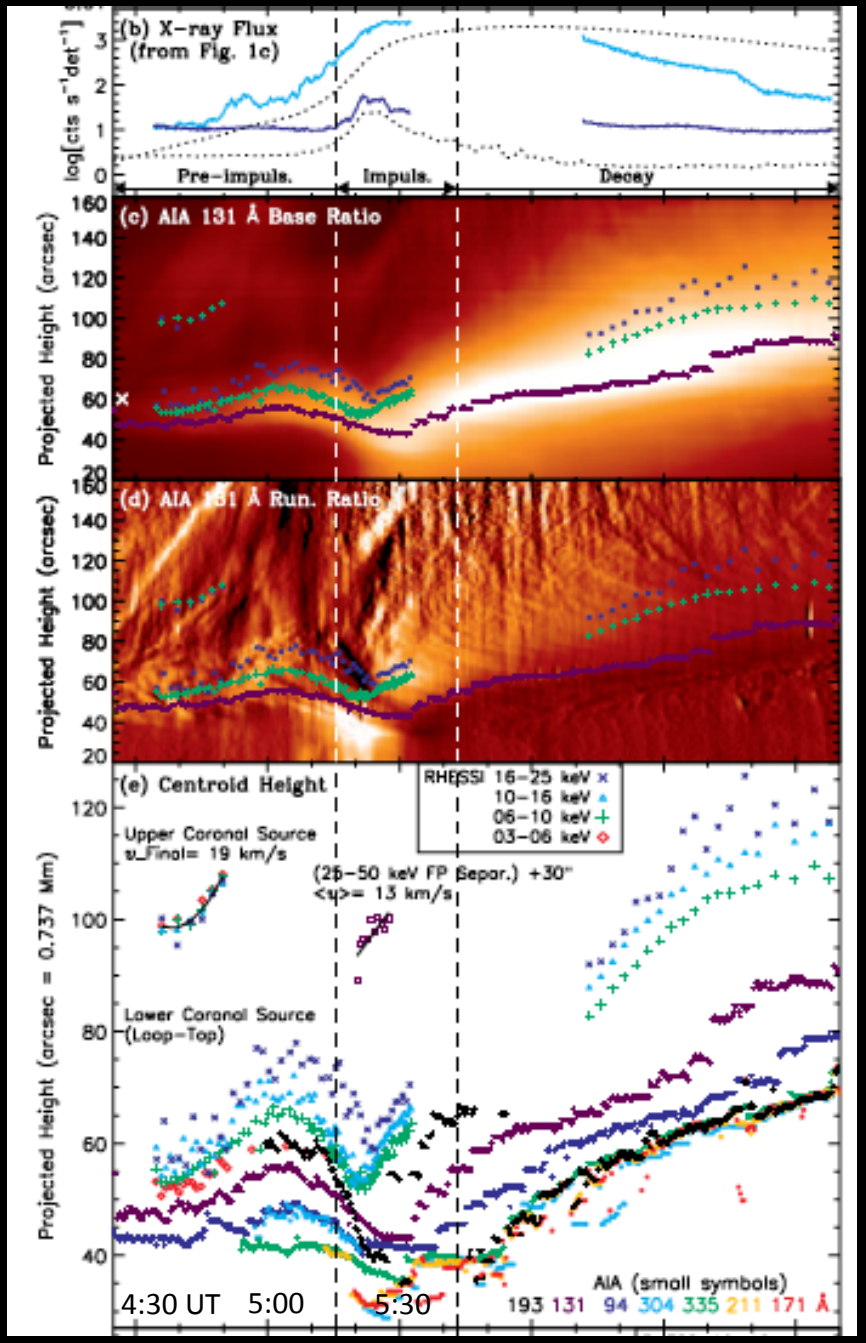


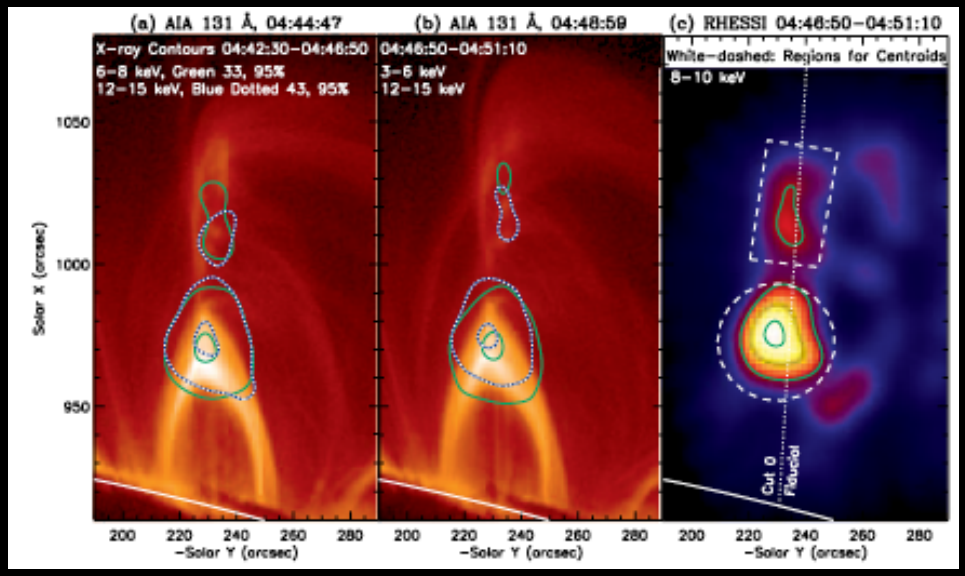
2012 July 19 Event Revisited

Below: *RHESSI* X-ray sources in the upper and lower reconnection jets

Left: Height-time plots showing the Up-Down-Up evolution of the loop-top emission from *RHESSI* and AIA

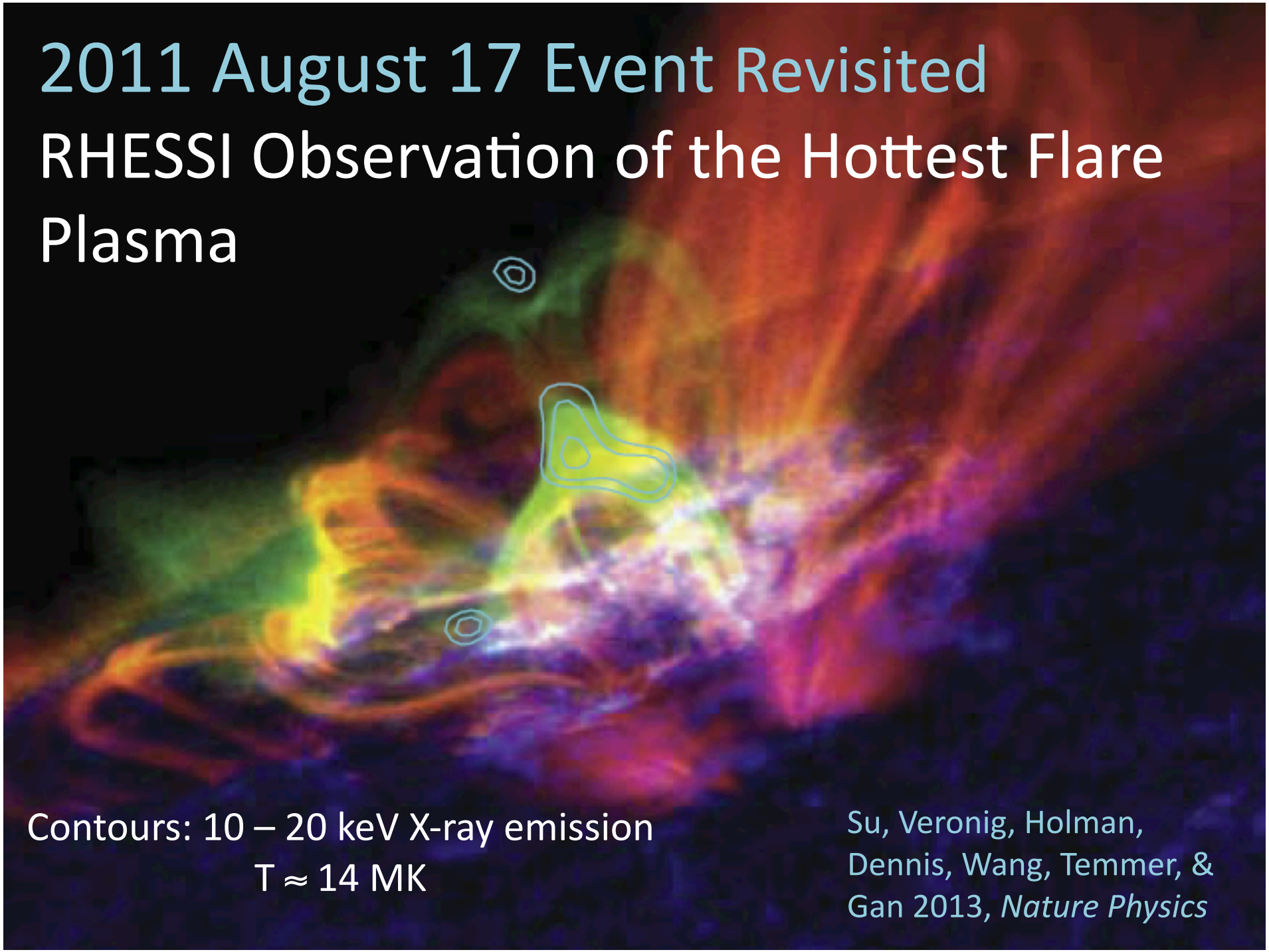
Liu, Chen & Petrosian 2013





2011 August 17 Event Revisited

RHESSI Observation of the Hottest Flare Plasma

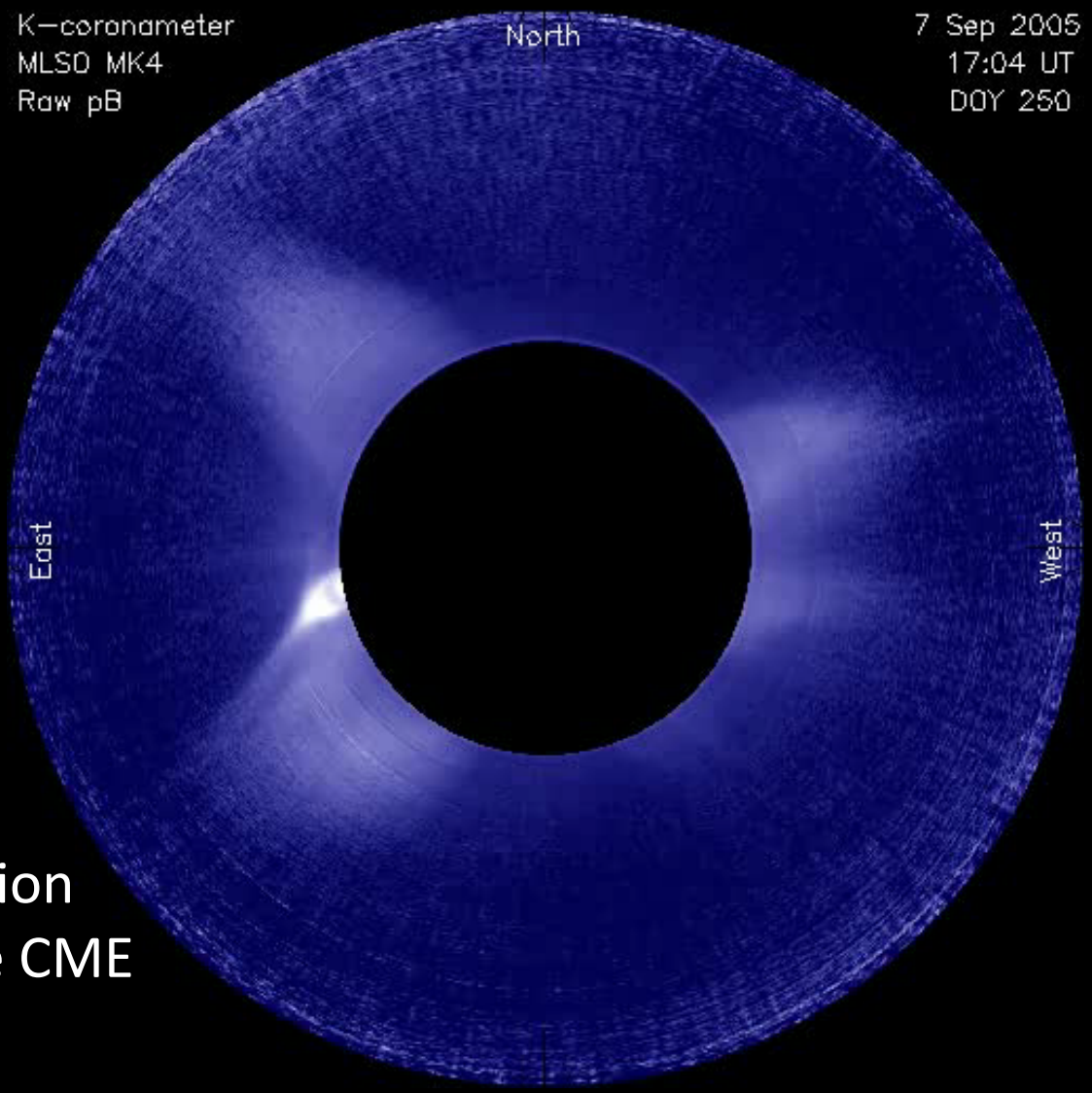


Contours: 10 – 20 keV X-ray emission
T ≈ 14 MK

Su, Veronig, Holman, Dennis, Wang, Temmer, & Gan 2013, *Nature Physics*

2011 August 17 Event: The Movie

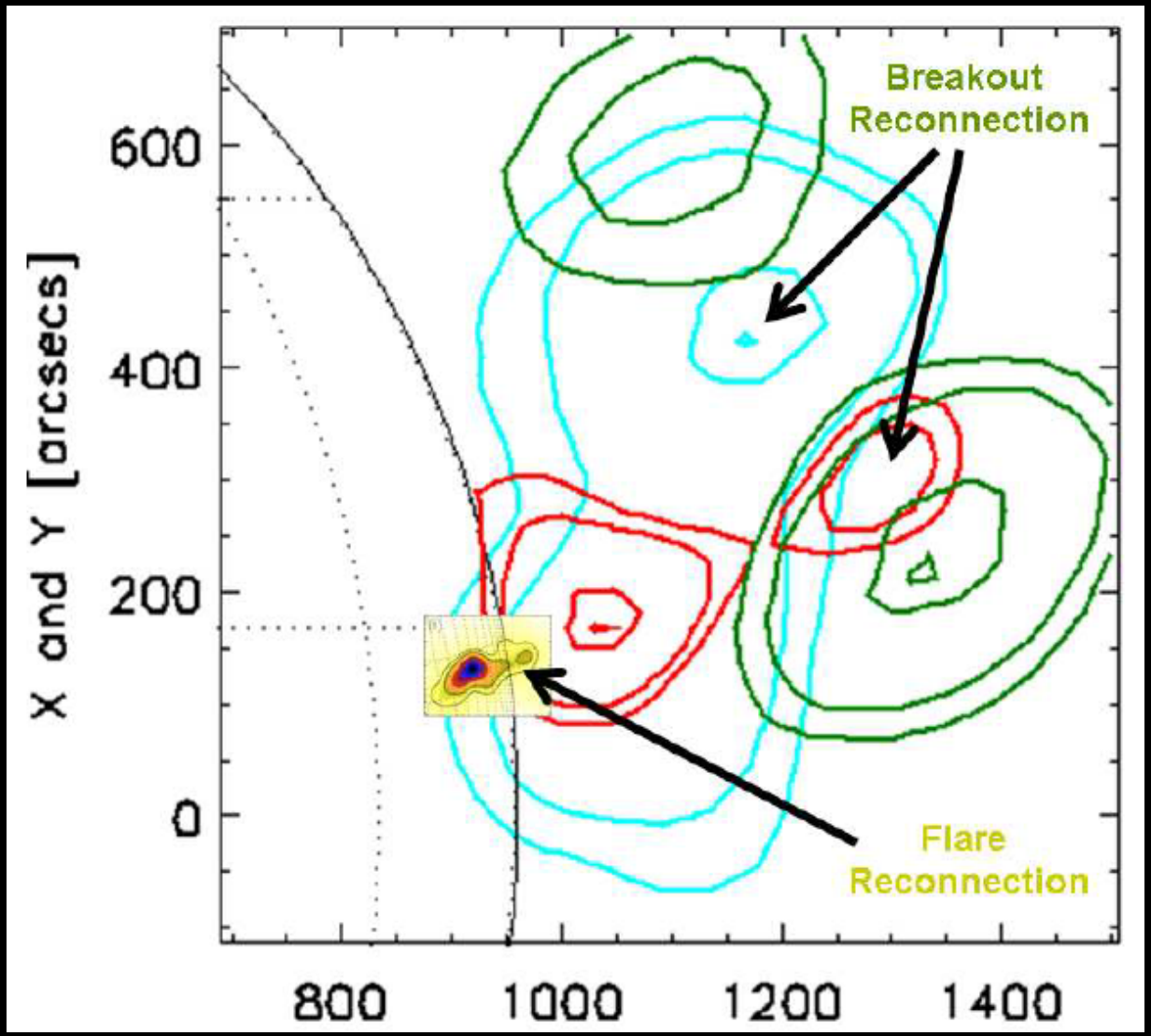
Coronal Mass Ejection (CME)



Magnetic Reconnection behind the CME

Ling, Webb, Burkepile, & Cliver 2014

Reconnection at the Top: A Solar Eruptive Event in Radio Emission

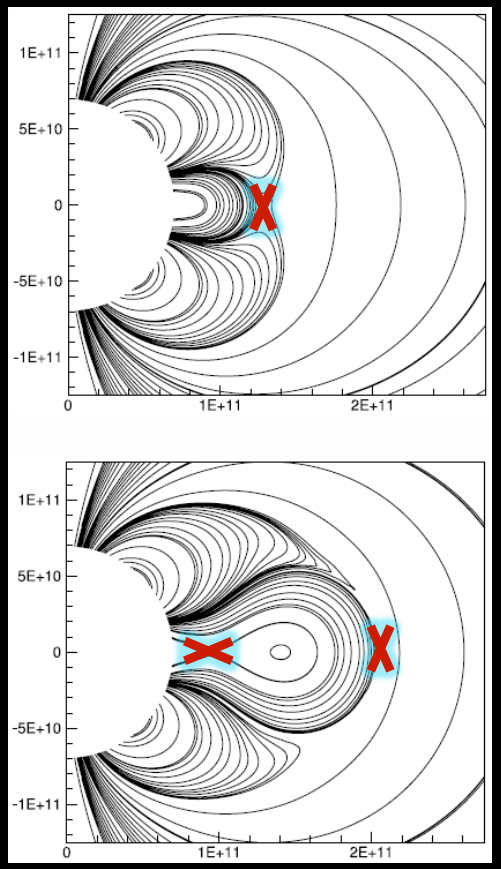


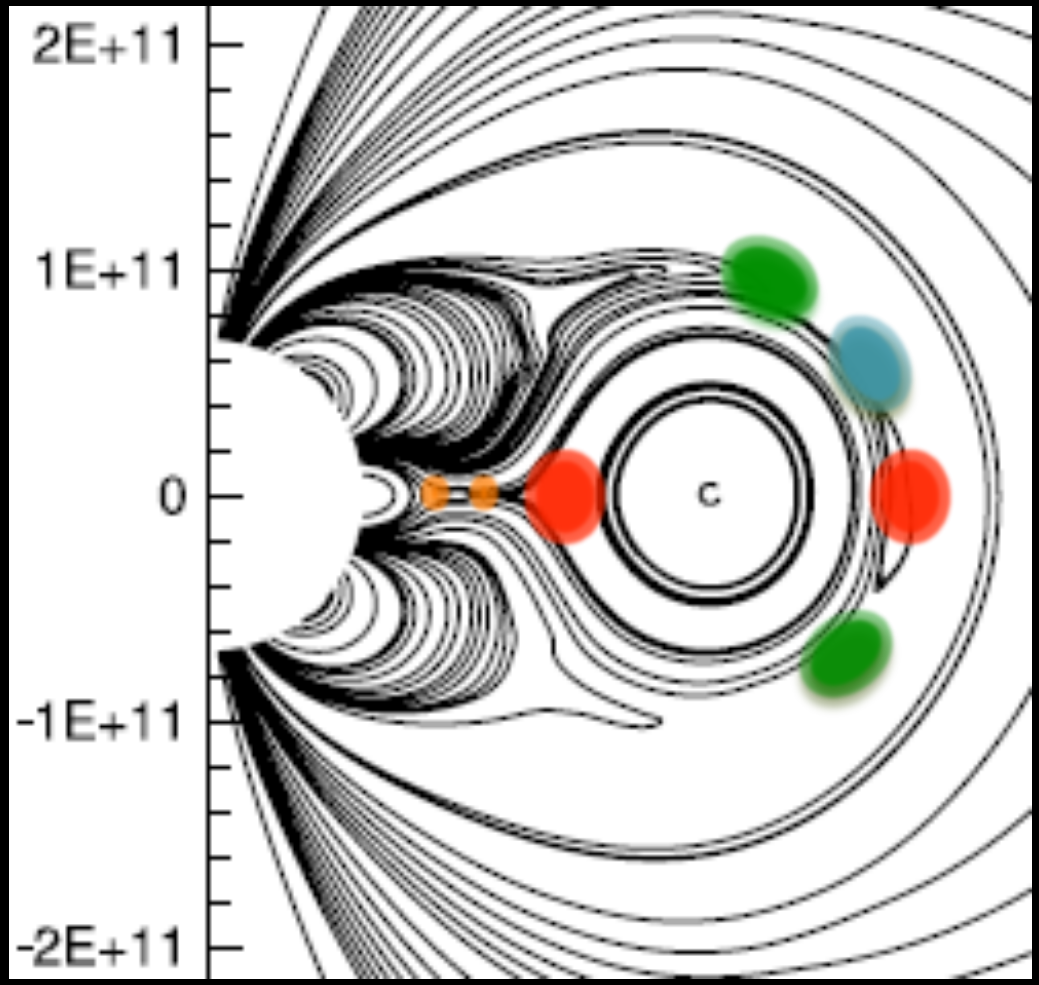
Red: 410 MHz
Cyan: 327 MHz
Green: 236 MHz

Breakout reconnection at the top of a stationary magnetic flux rope

Aurass, Holman, Braune, Mann, & Zlobec 2013

Breakout Reconnection Context

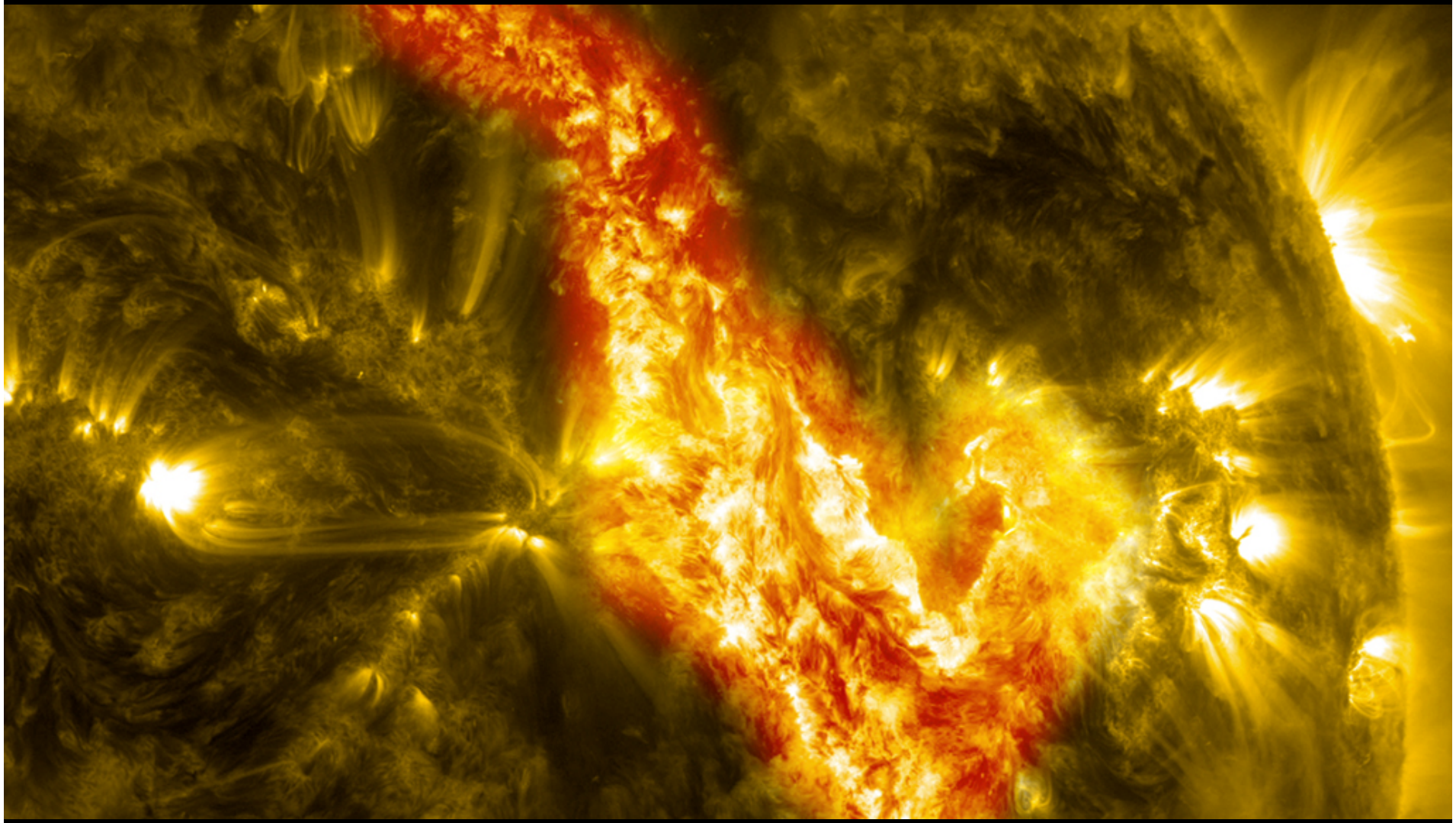




Antiochos, DeVore, & Klimchuk 1999
Simulation: MacNeice, P., et al. 2004

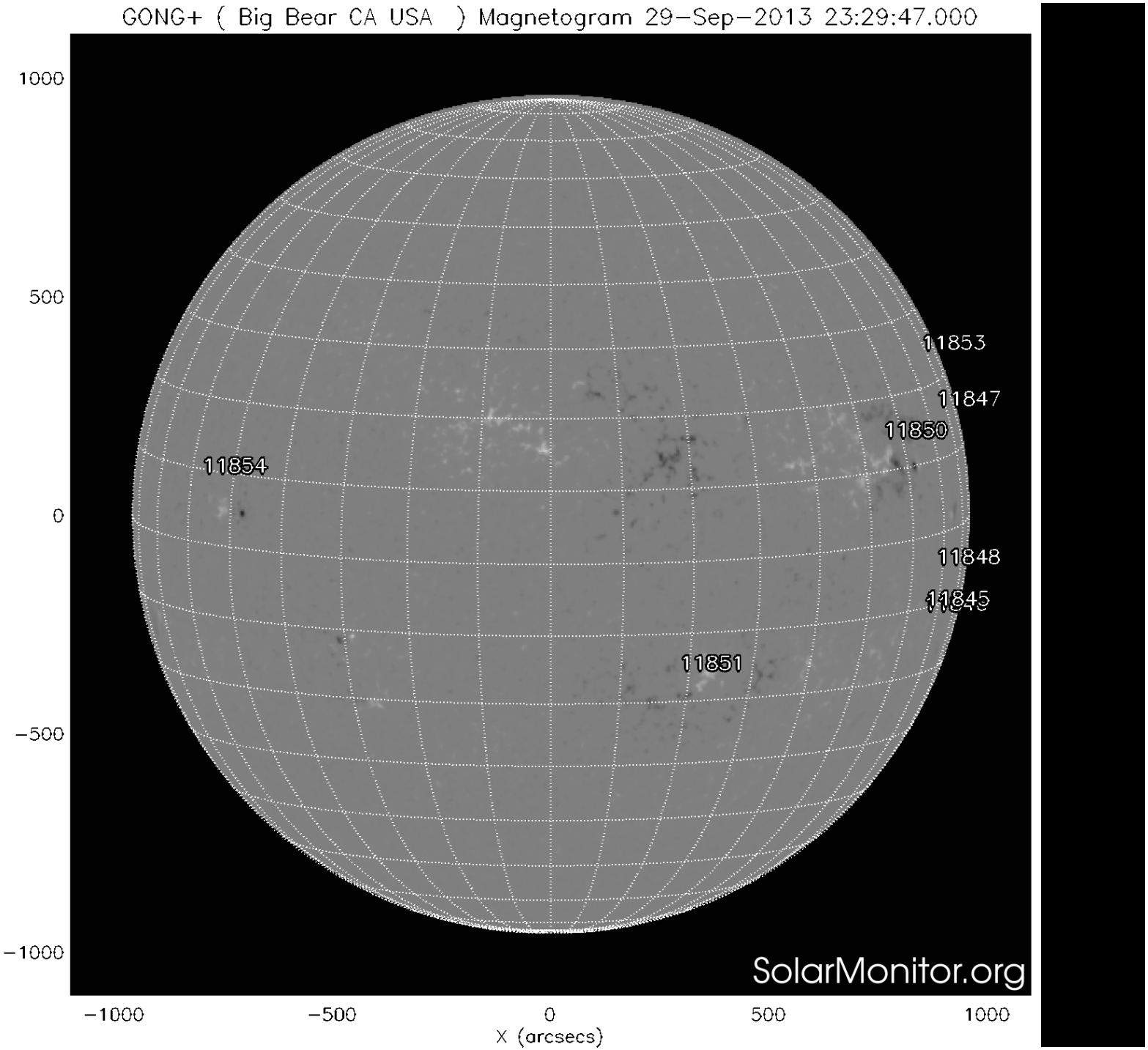
15 – 20 keV 410 MHz 327 MHz 236 MHz

2013 September 29 - 30
“Canyon of Fire” Filament Eruption

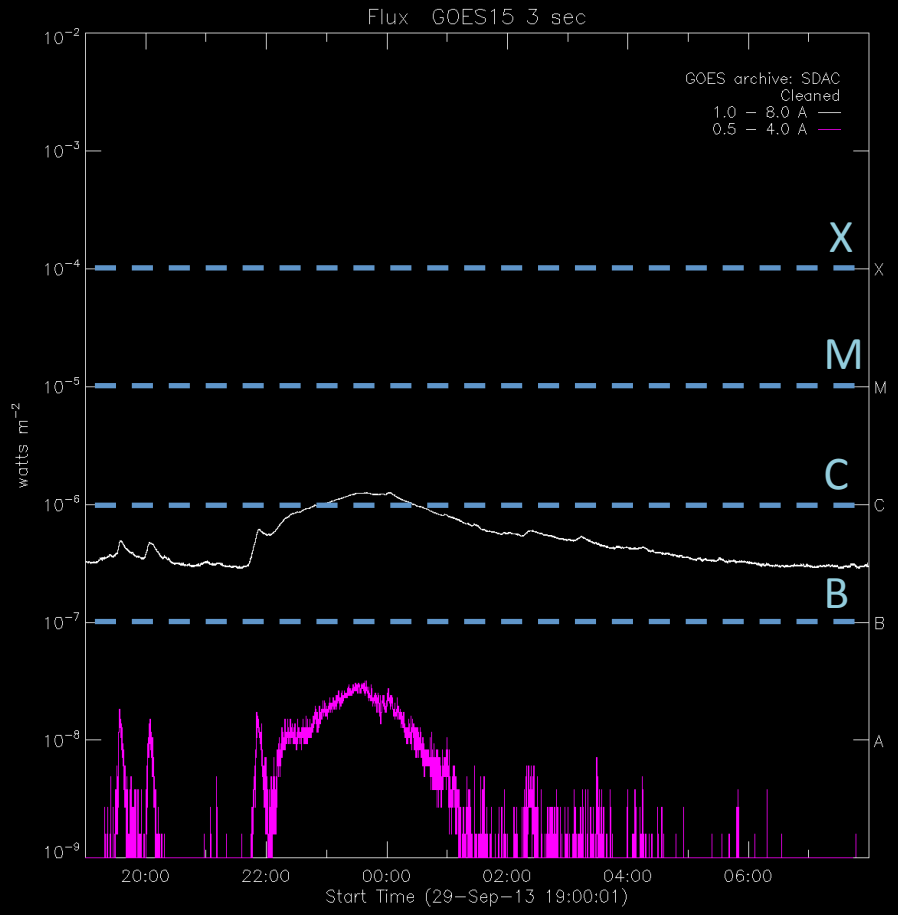


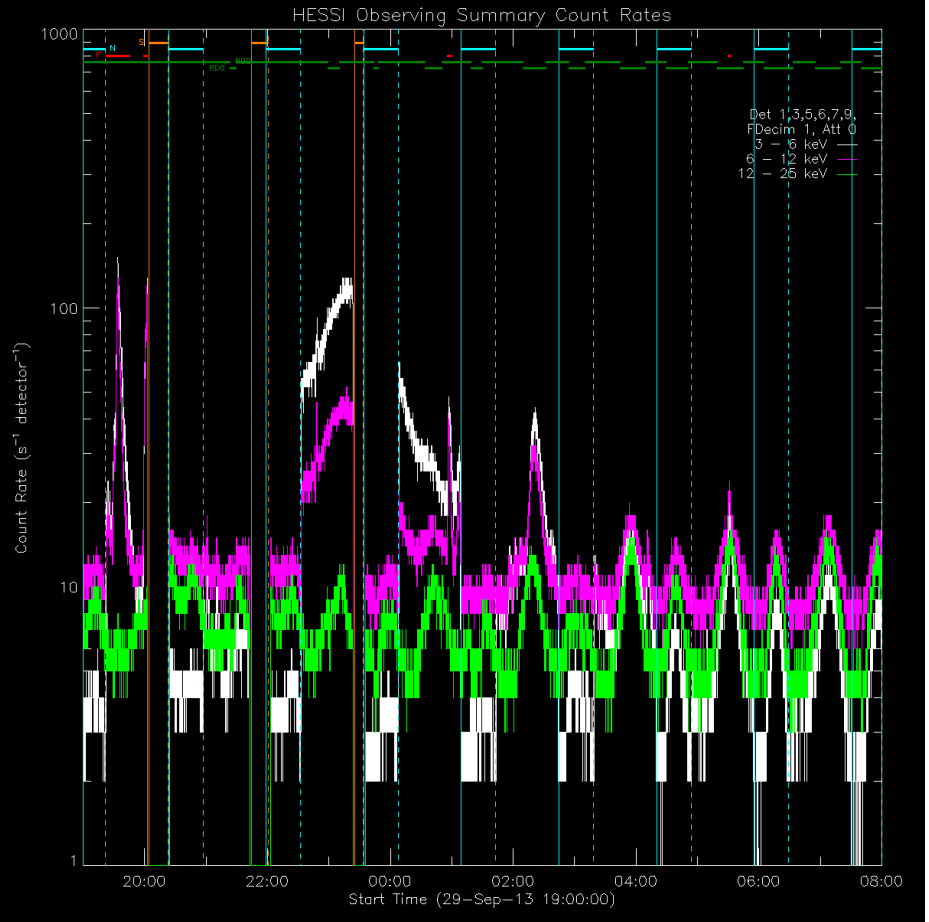
Canyon of Fire

Location on Sun



Response to the “Canyon of Fire” Filament Eruption in GOES and RHESSI





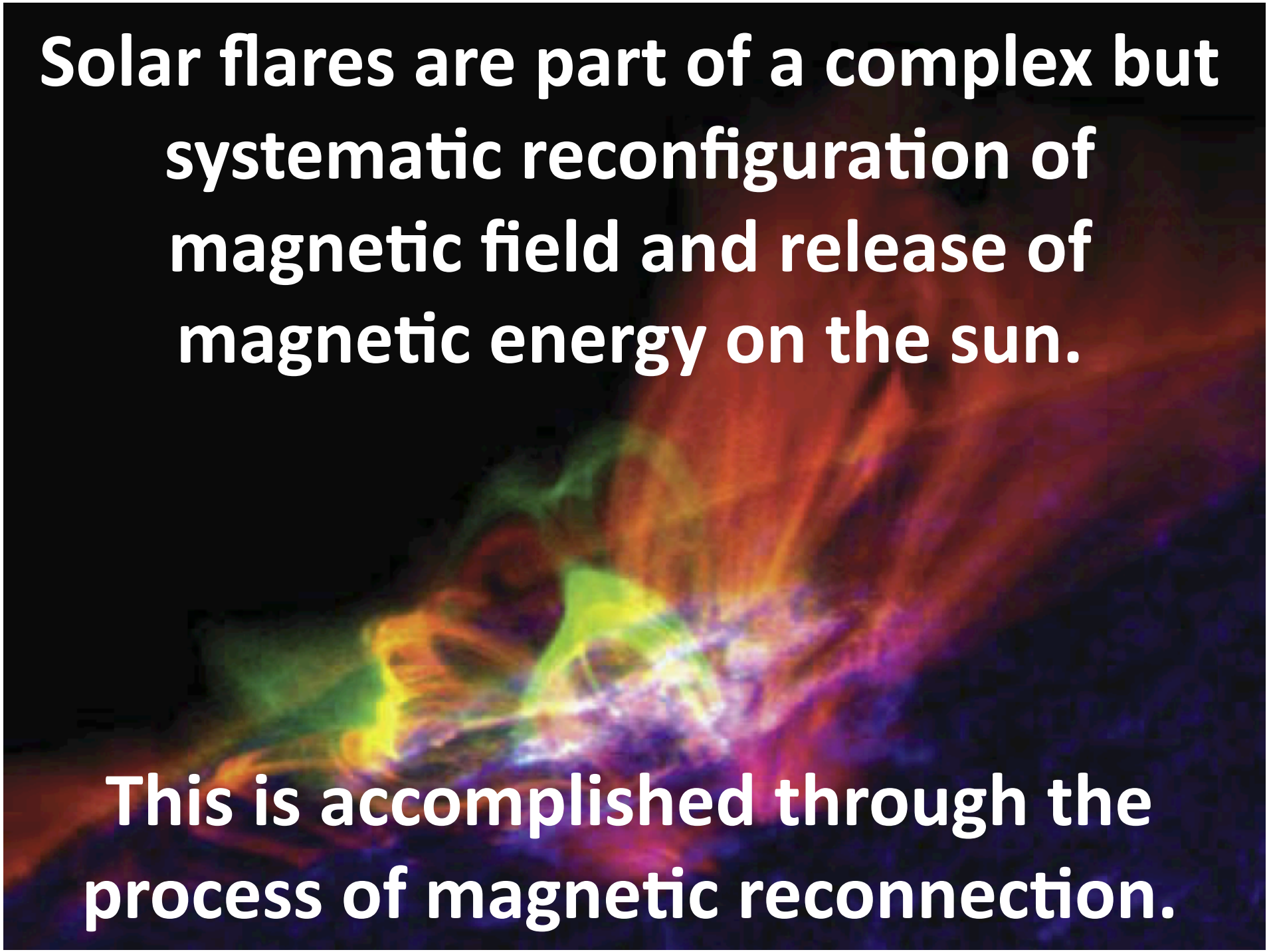
A minor flare response for such a large, impressive event!

SUMMARY (1 of 2)

- *Solar eruptive event*: combination of a flare and a coronal mass ejection (CME)
- Downward and upward ejecta (jets) from *magnetic reconnection* provide the connection between flares and CMEs (PUZZLE #1)
- *Magnetic reconnection* and its propagation along a magnetic arcade gives faster energy release and greater access to available magnetic energy (PUZZLE #2)

SUMMARY (2 of 2)

- Electron acceleration occurs primarily in the downward reconnection jet, when the acceleration region is relatively low and compact (PUZZLE #3)
- The acceleration process is most likely stochastic, with a contribution from compression (betatron and first-order Fermi acceleration)
- Much (all? – not likely) of the flare plasma is collisionally heated by the accelerated electrons


Solar flares are part of a complex but systematic reconfiguration of magnetic field and release of magnetic energy on the sun.
This is accomplished through the process of magnetic reconnection.