Introduction to Solar Flares

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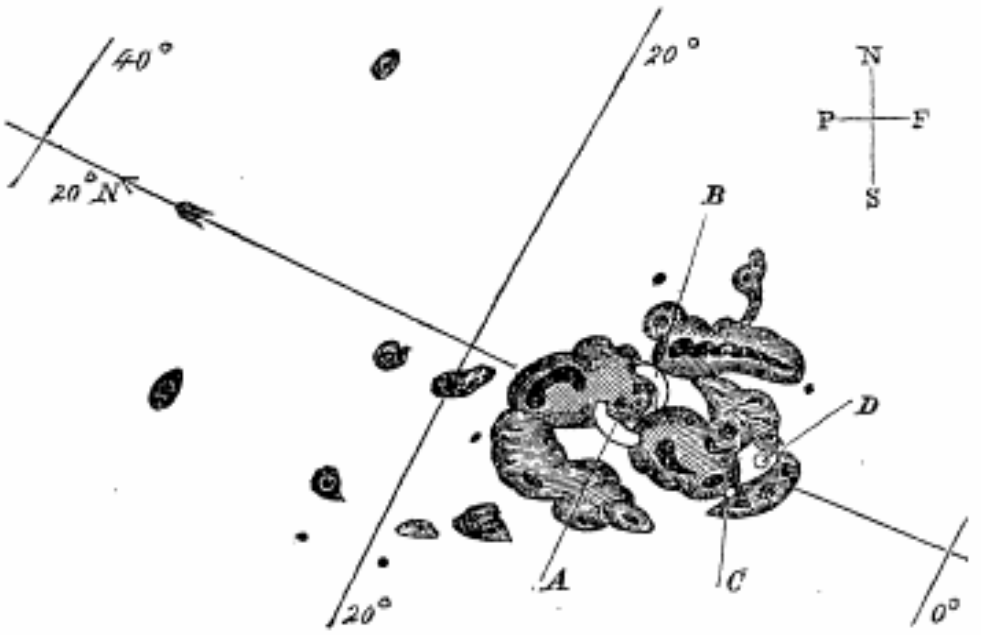
Discovery of a Solar Flare

- September 1, 1859
- Independently observed by R. C. Carrington and R. Hodgson
- Magnetic storm commenced early on September 2



Drawing by Carrington

While the contemporary occurrence [of a magnetic storm] may deserve noting, [Mr. Carrington] would not have it supposed that he even leans towards hastily connecting them. “One swallow does not make a summer.”

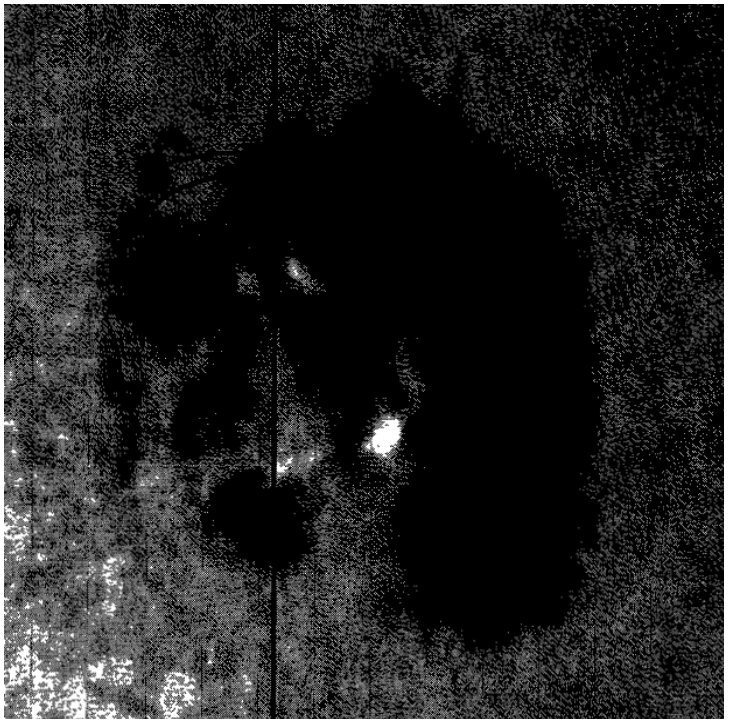
- Monthly Notices of the Royal Astronomical Society, 1860

“within the Sun there was a black spot, and black and blue and white vapors”

- 1638 December 9 Chinese Record

White Light Flares

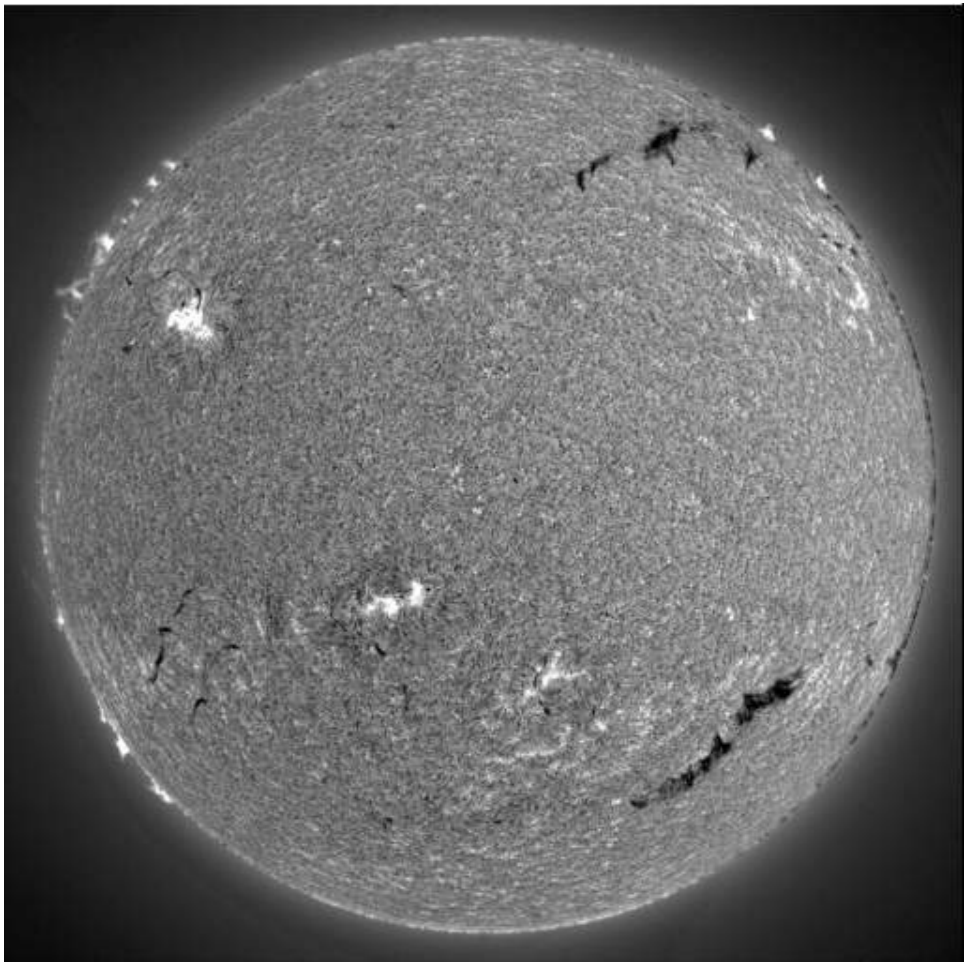
- At most 50% brighter than the solar disk
- Typical energy released in a large flare: 10^{32} erg
- Solar Luminosity: 4×10^{33} erg s^{-1}
- Exciter: nonthermal electrons and/or protons



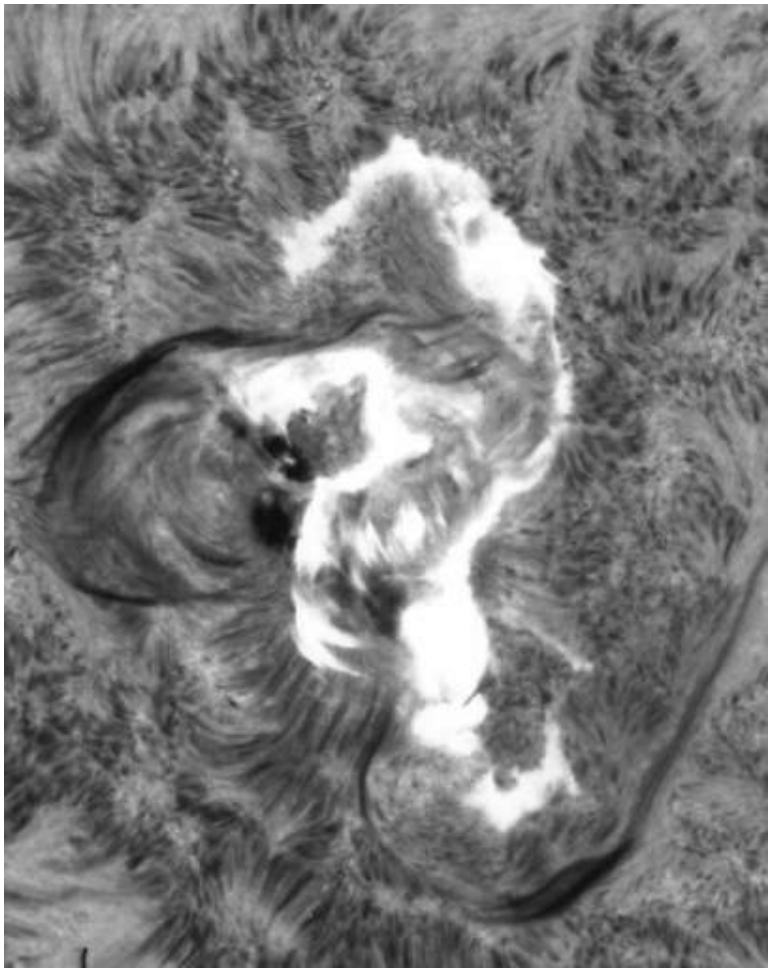
Machado & Rust, *Solar Physics*, 1974

Flares in Hα

The Sun in Hα

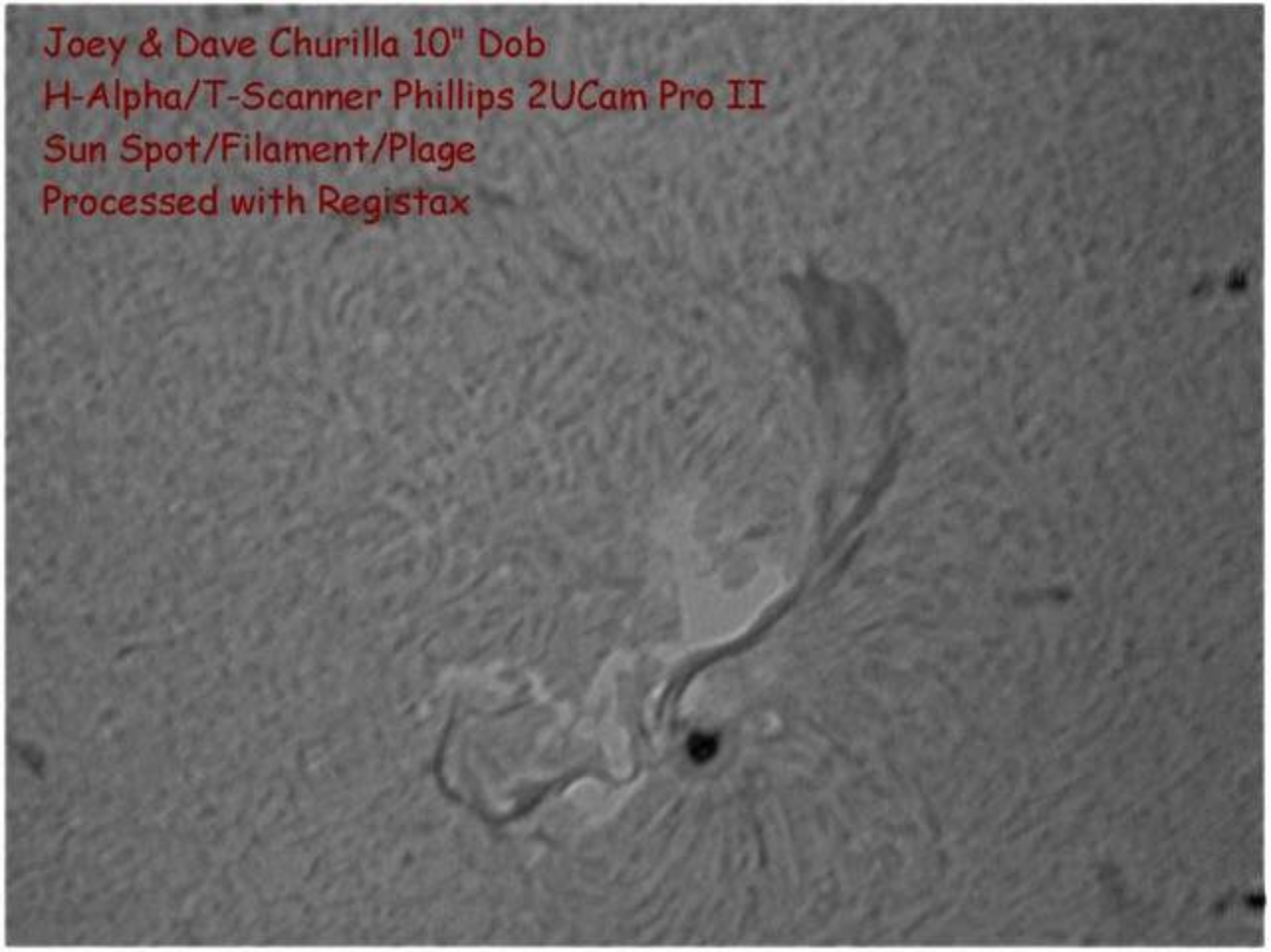


7 August 1972 Flare



Big Bear Solar Observatory

From the Prairie Astronomy Club in Lincoln, Nebraska



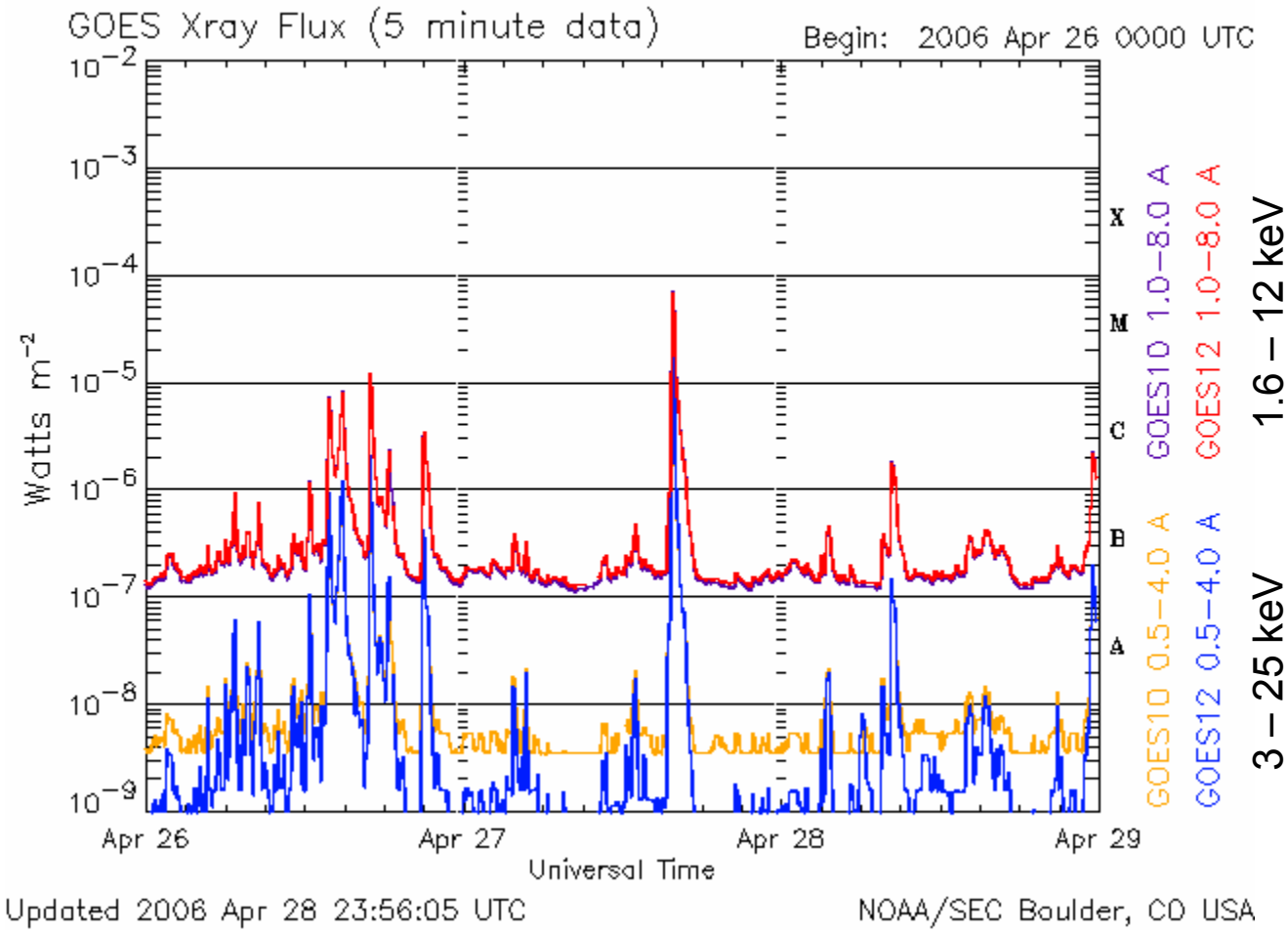
http://www.prairieastronomyclub.org/astrophotos.asp

Hα Impact (Linear) Polarization

Beam Particles	Direction of polarization
Electrons > 200 eV	⊥ to beam
Electrons < 200 eV	∥ to beam
Protons > 400 keV	⊥ to beam
Protons < 400 keV	∥ to beam

- Both ∥ and ⊥ polarization have been observed (Xu, Hénoux, Chambe, Karlický, & Fang 2005, *The Astrophysical Journal*)
- Bianda, Benz, Stenflo, Küveler, & Ramelli (2005, *Astronomy & Astrophysics*) found no Hα polarization above ~0.1% in 30 flares

Soft X-Ray Light Curves from the Geostationary Operational Environmental Satellites (GOES)



Flare Classification Schemes

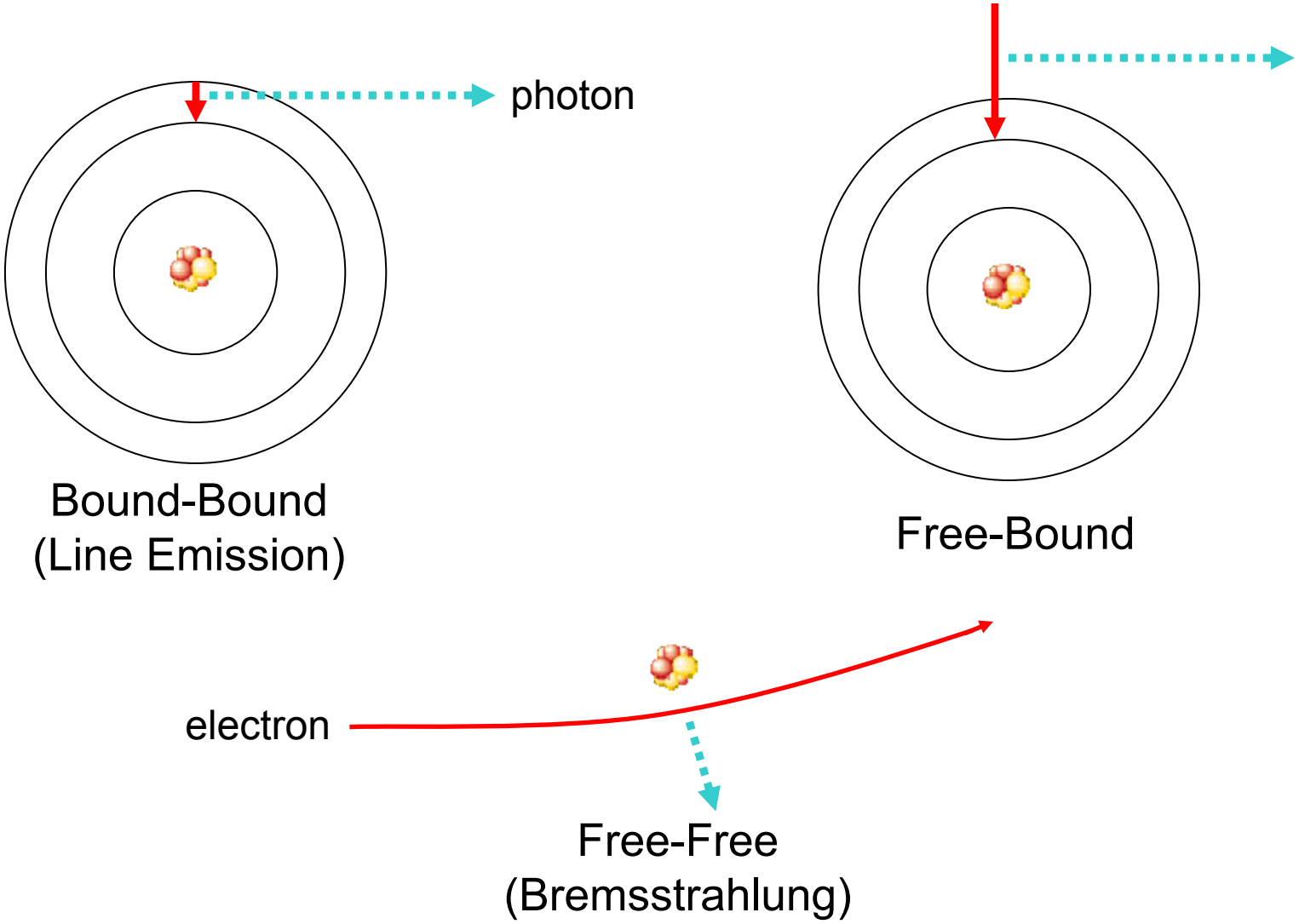
After Bhatnagar & Livingston 2005

Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m^2
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

Hα sub-classification by brightness: F – faint, N – normal, B – bright

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}

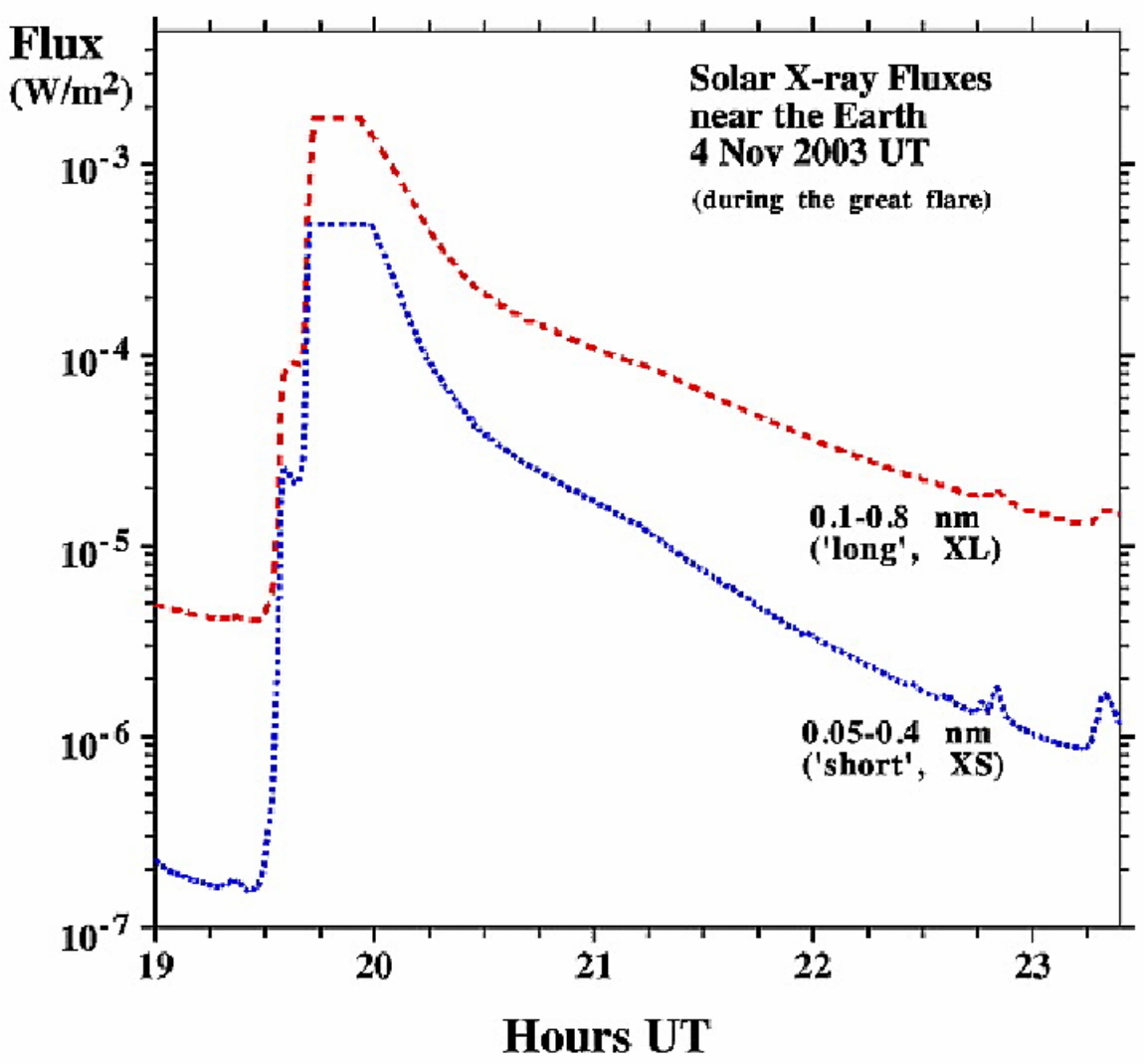
Radiation Mechanisms



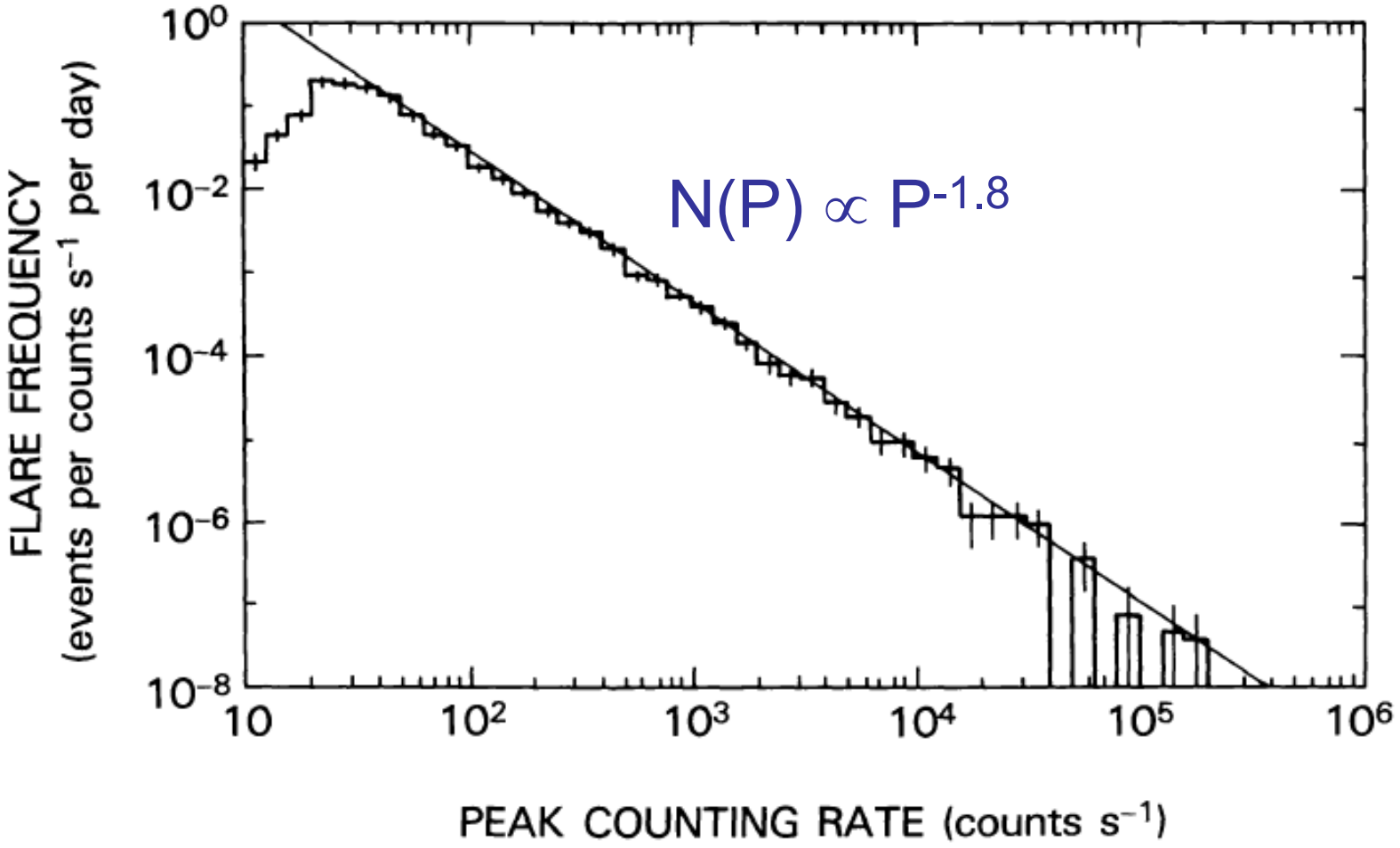
Physical Information from the GOES Light Curves

- *Assume* that the soft X-rays are radiated by a single temperature thermal plasma
- Apply knowledge of contributing radiation mechanisms and *assumed* or *inferred* element abundances
- Compute time evolution of plasma **temperature** and **emission measure**

2003 Nov 4 X18 Flare

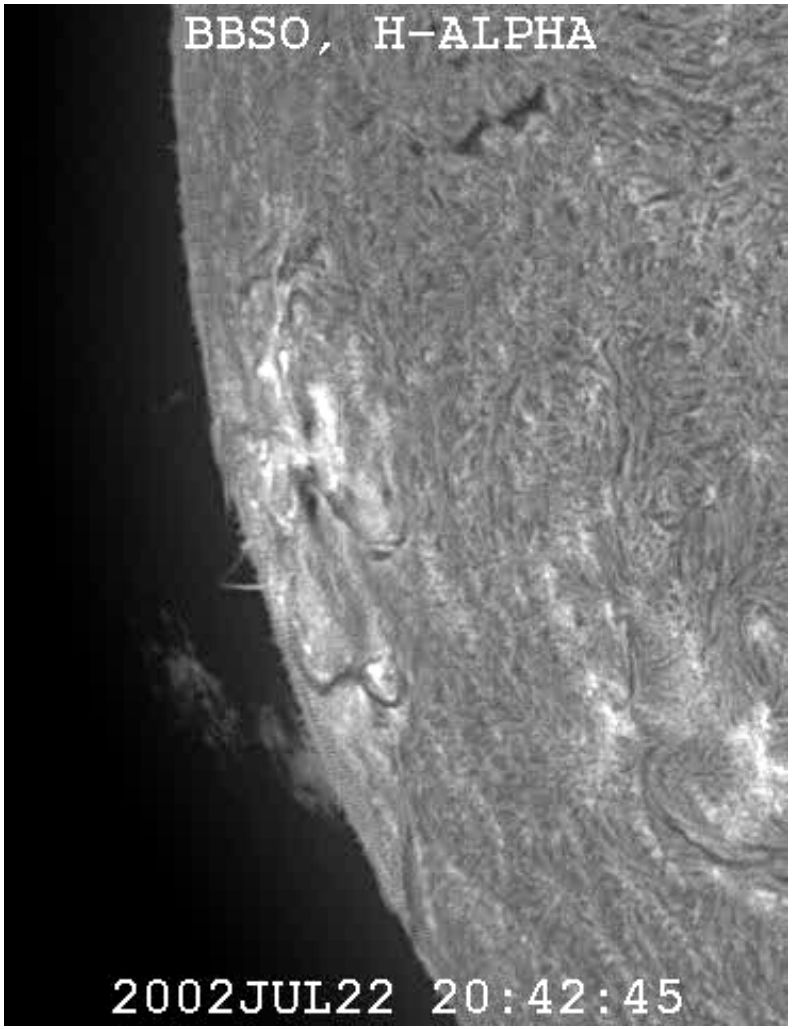


Flare Intensity Distribution



B. R. Dennis, *Solar Physics,* 1985

Flares Occur in Evolving Active Regions



Active Region Classification
(Mt. Wilson)

- ALPHA: A single dominant spot, often linked with a plage of opposite magnetic polarity.
- BETA: A pair of dominant spots of opposite polarity (Bipolar, i.e., a leader and a follower).
- GAMMA: Complex groups with irregular distribution of polarities.
- BETA-GAMMA: Bipolar groups which have more than one clear north-south polarity inversion line.
- DELTA: Umbrae of opposite polarity together in a single penumbra.

A Solar Activity Report

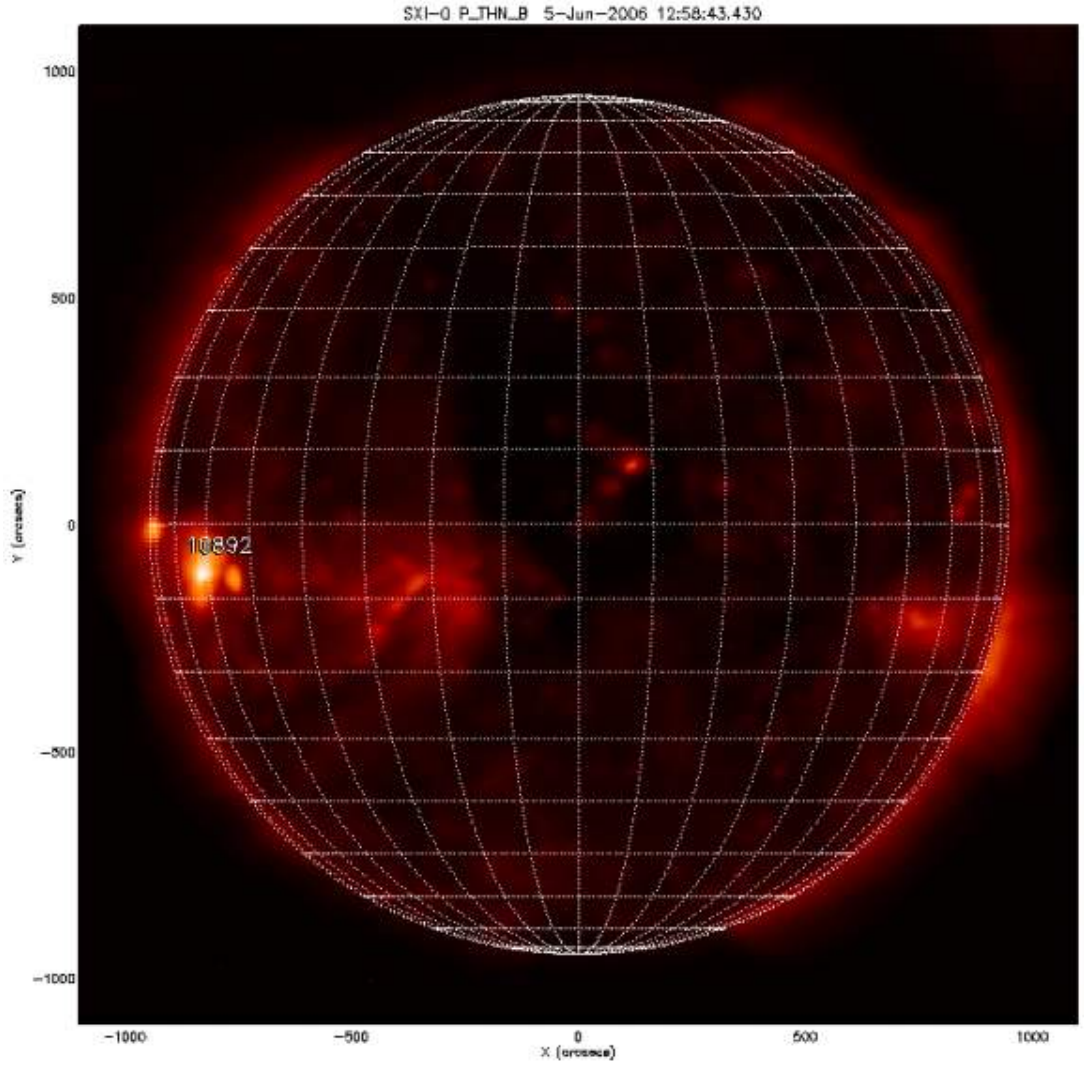
Max Millennium "Message of the Day"

(2006 June 5)

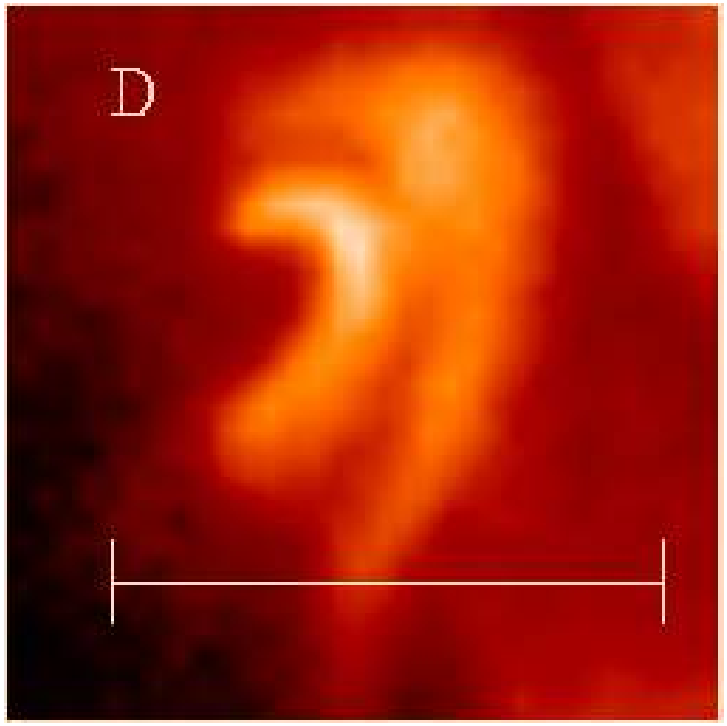
NOAA 0892 has continued in a strong growth phase developing into an E-type sunspot group. Recent GONG magnetograms from the Big Bear site indicate a possible delta magnetic configuration emerging within the leading portion.

The intermediate and trailing portions of the region are also displaying growth with bright H-alpha plage and arch-type-filaments. C-class events expected with the chance of an M-class event if development continues.

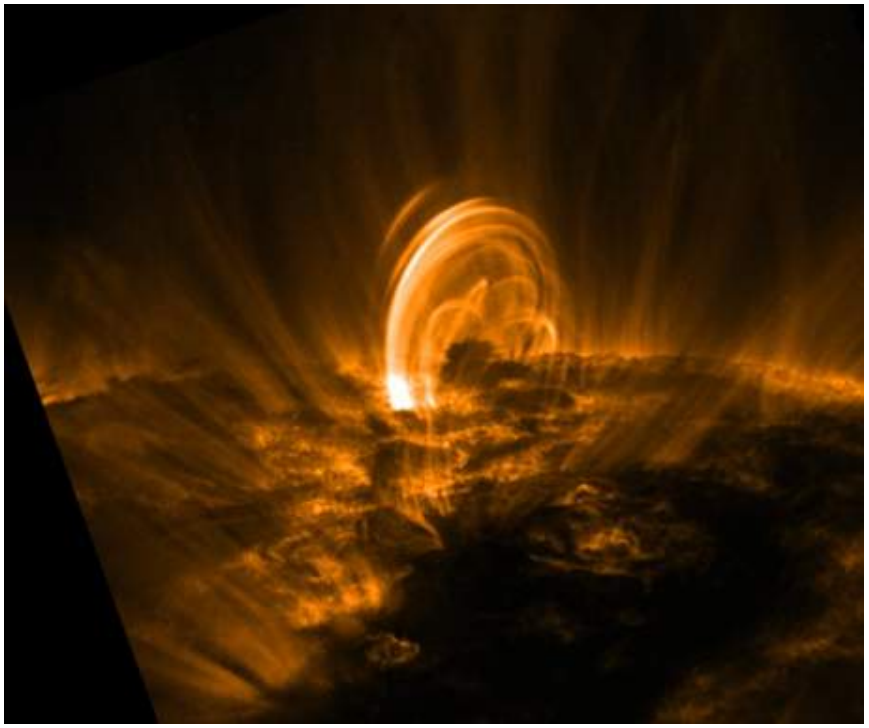
The position of NOAA 0892 on June 05 at 18:30 UT: S08E56 (Solar X = -778", Solar Y = -130")



Flare & Post-Flare **Loops**

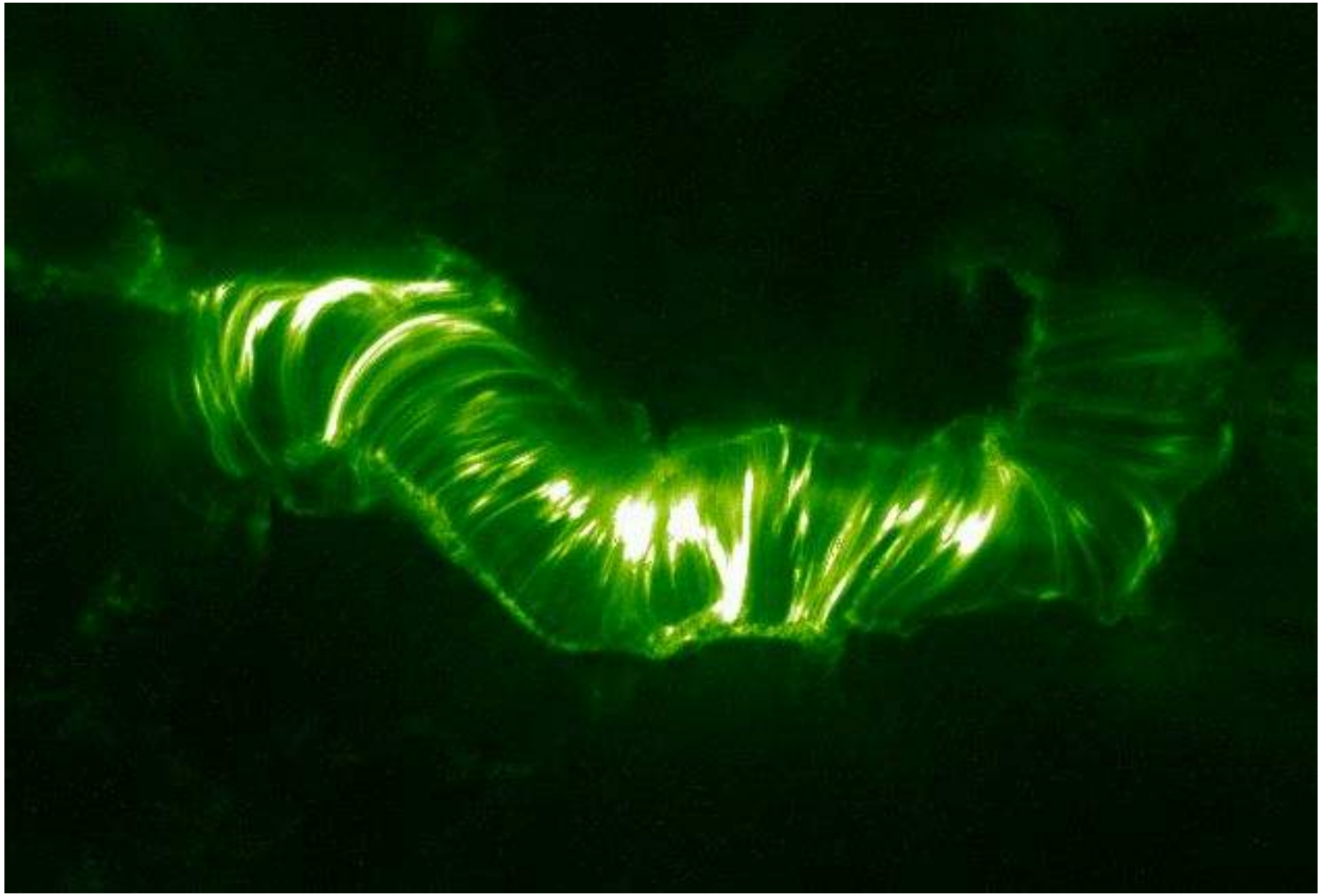


"Simple" flare loop
Yohkoh Soft X-ray Telescope (SXT)



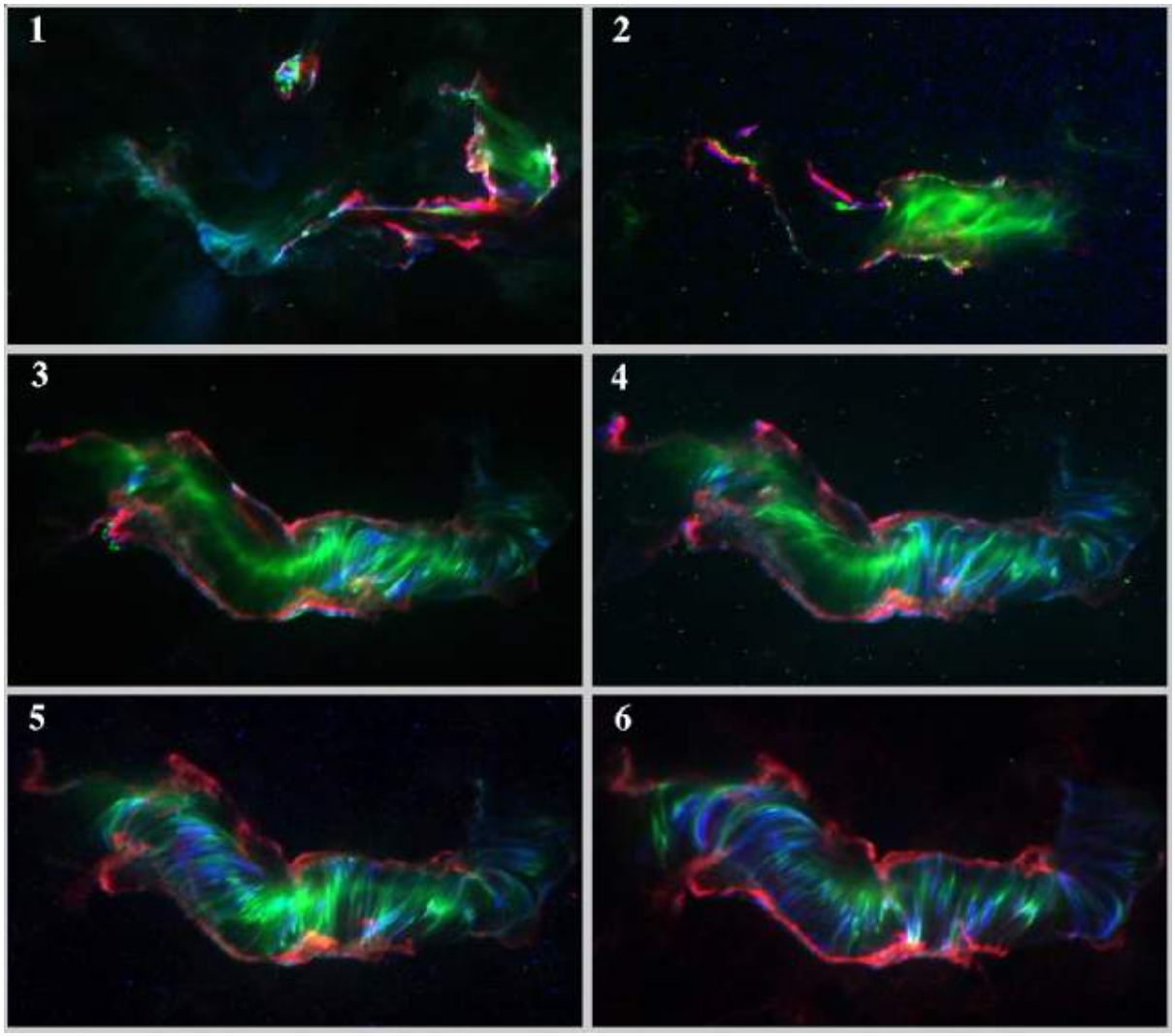
19 April 2001 post-flare loops
TRACE 171 Å band (~1 MK)

Arcade of Loops in the 14 July 2000 “Bastille Day” Flare



TRACE

14 July 2000 Flare
TRACE 3 Band Composite Images

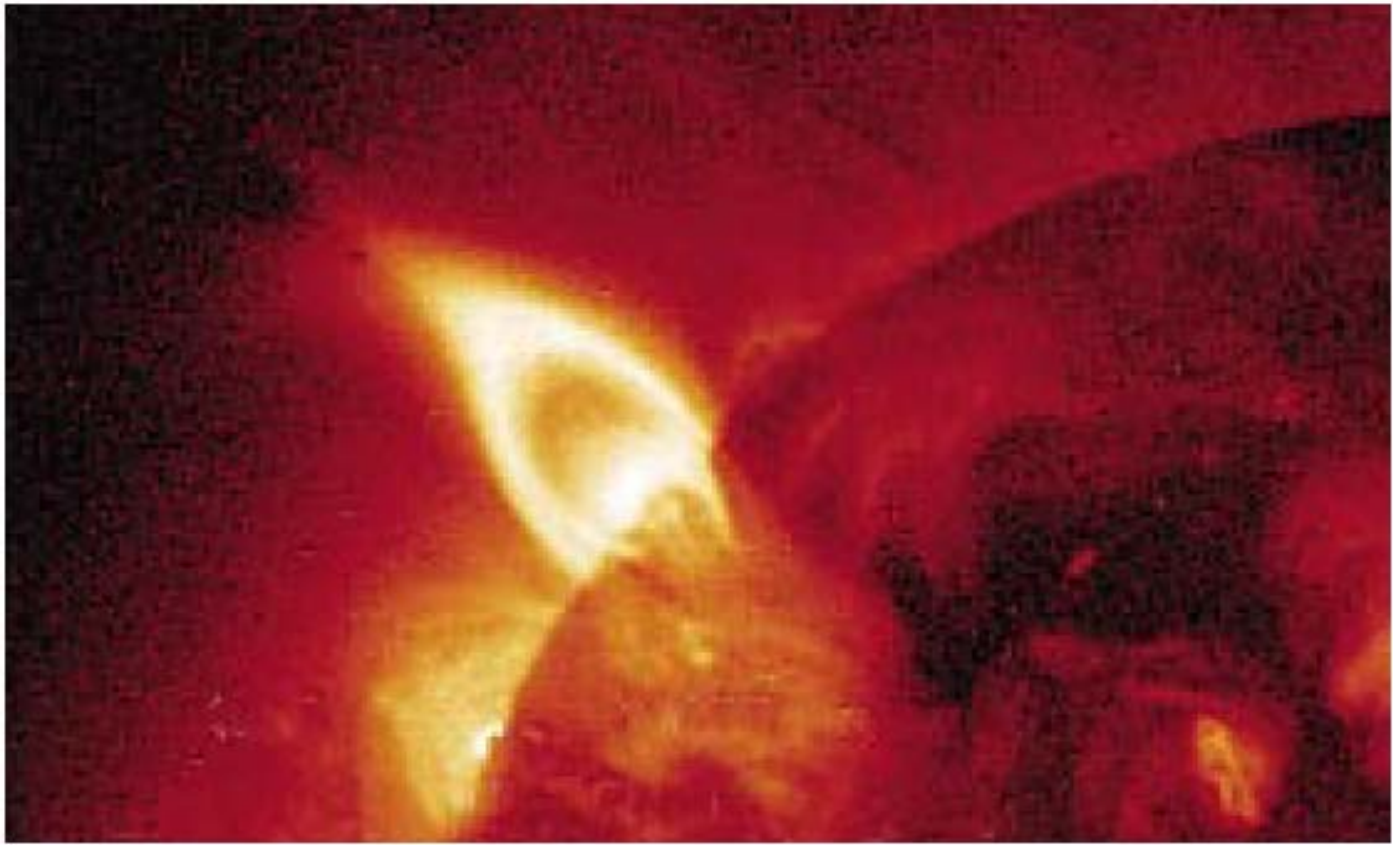


Red: UV continuum

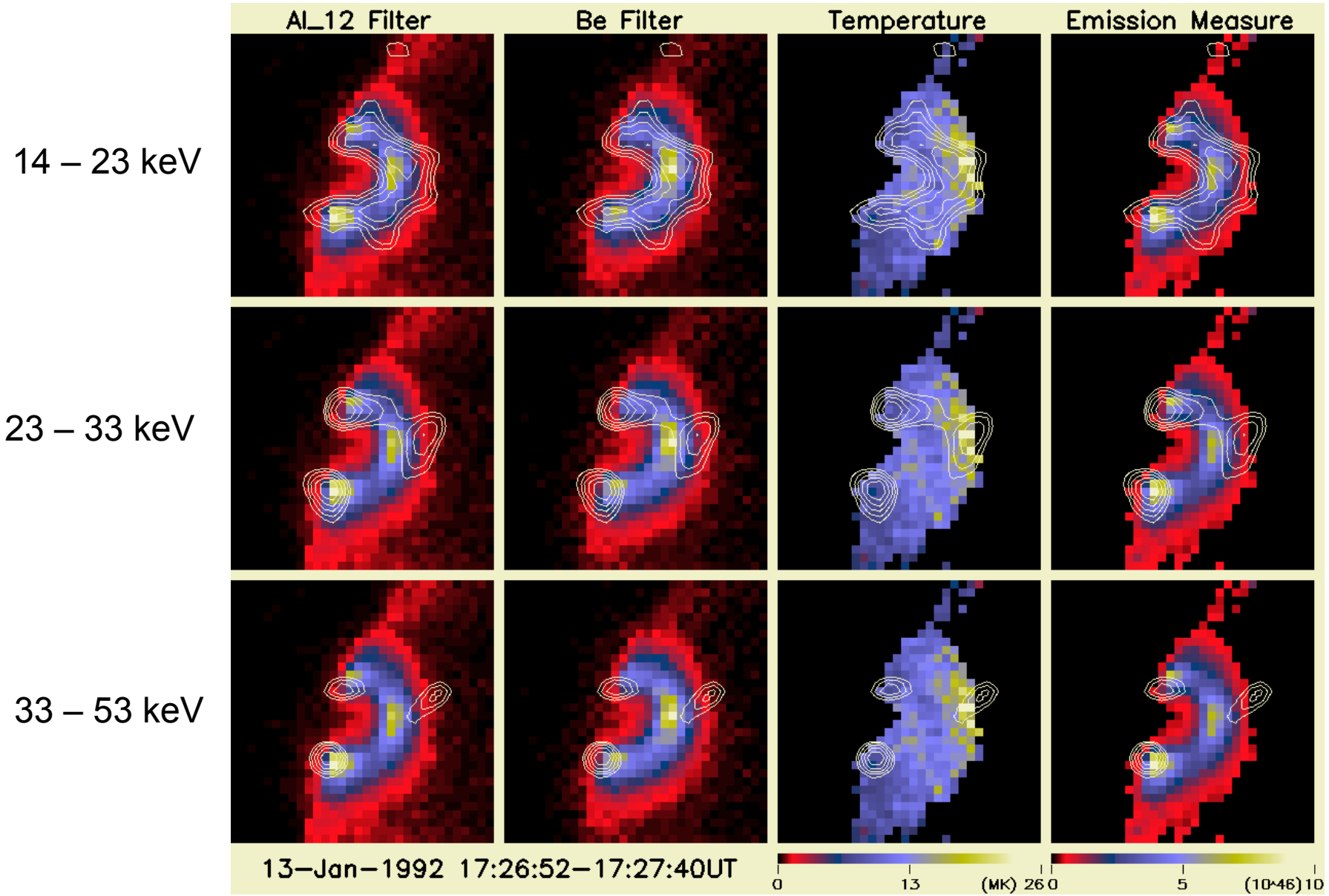
Blue: 171 Å pass band, ~1 MK

Green: 195 Å pass band, >1.5 MK

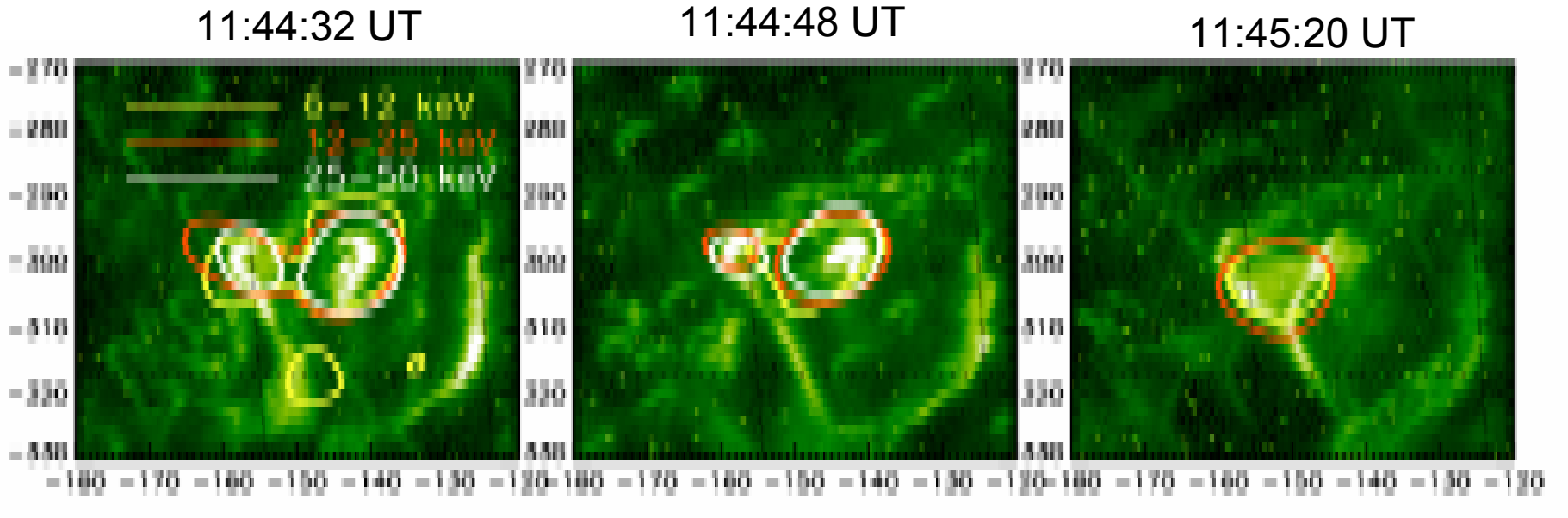
Post-Flare Loops with **Cusp** Observed with the *Yohkoh* Soft X-ray Telescope (SXT)



The “Masuda” Flare



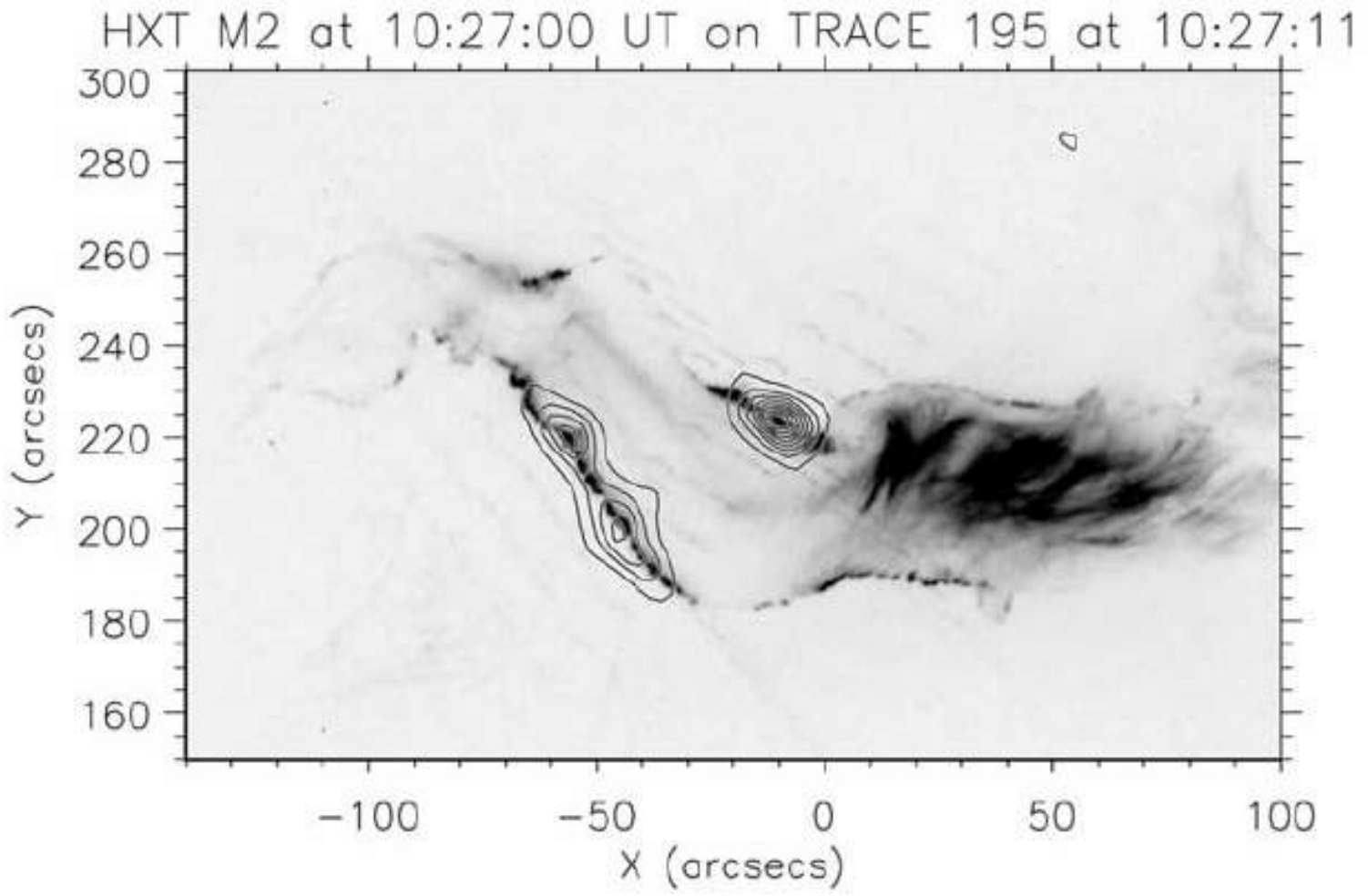
Elongated Cusp
TRACE 195 Å & RHESSI



2 June 2002 C9.4 Flare

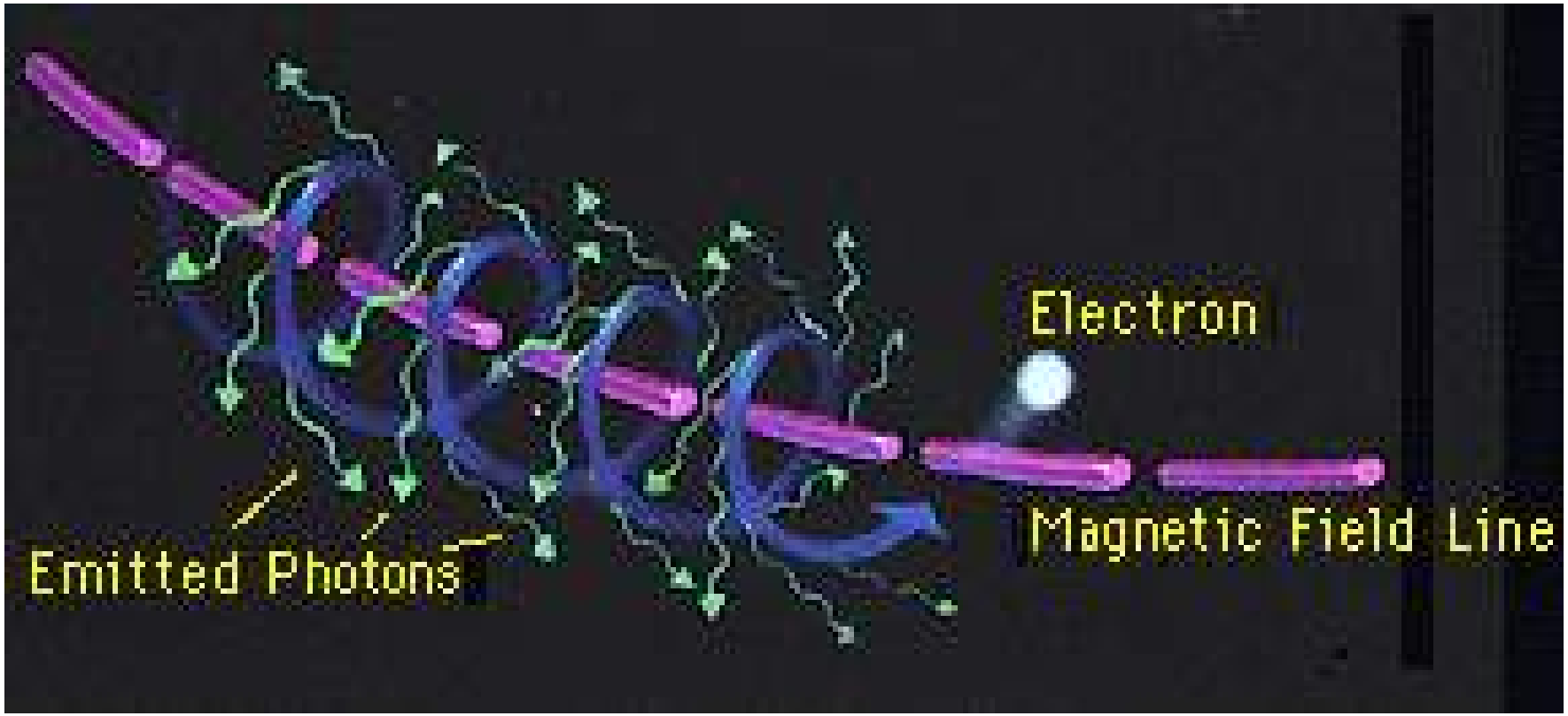
Sui, Holman, & Dennis, *The Astrophysical Journal*, 2006

“Bastille Day” Flare Ribbons and Hard X-Rays

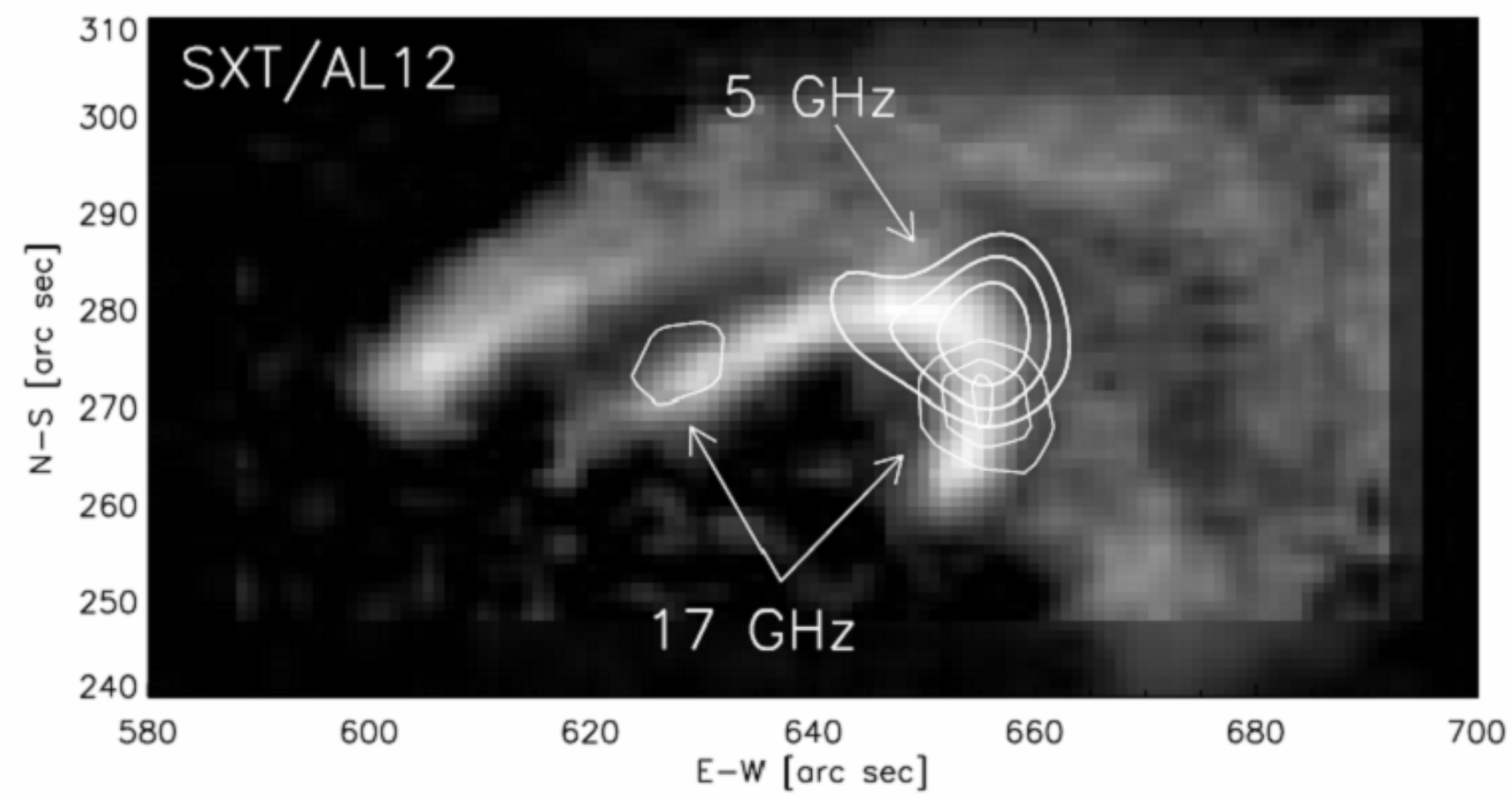


Fletcher & Hudson, Solar Physics, 2001

Gyrosynchrotron Radiation

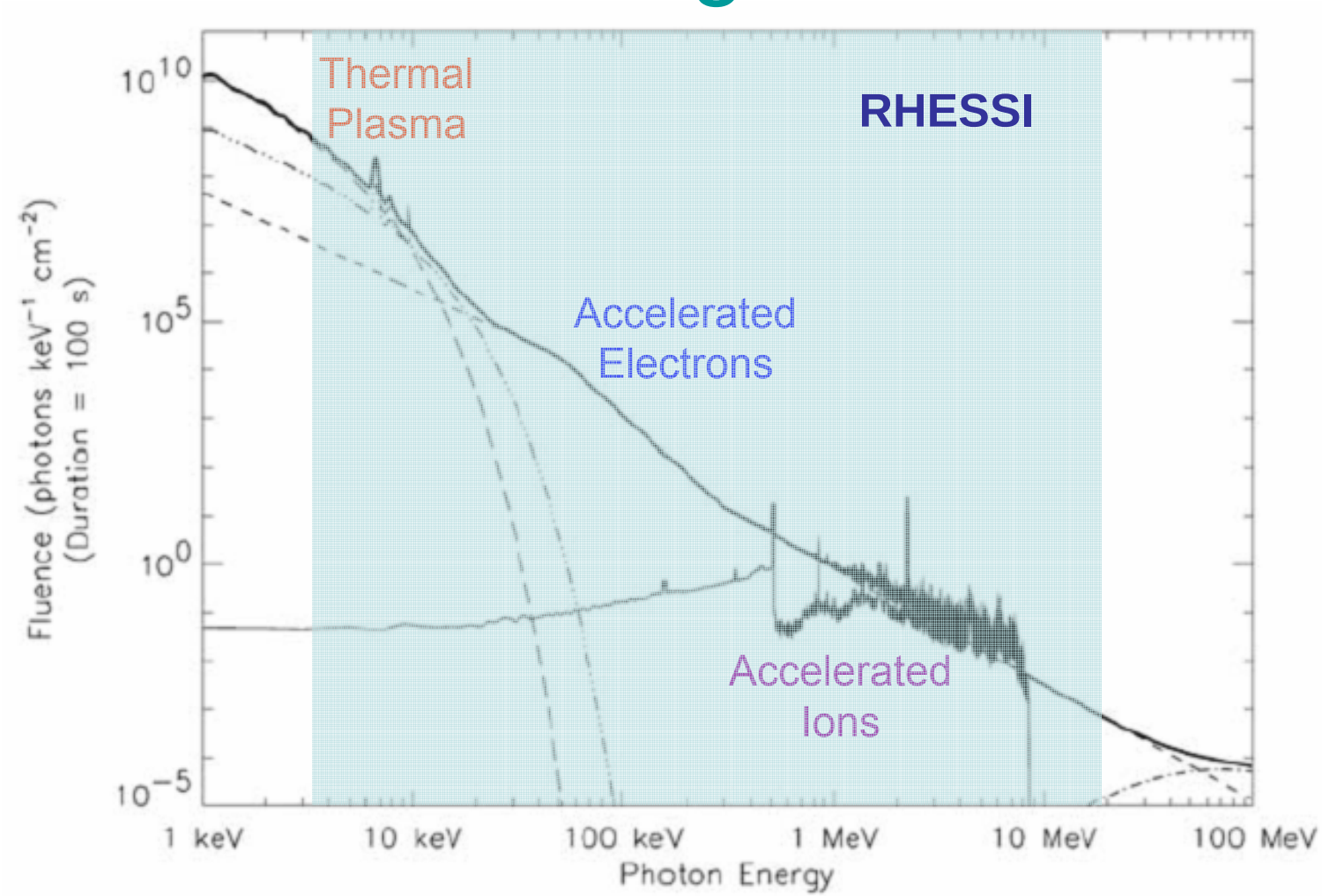


A Flare in Soft X-rays & Microwaves

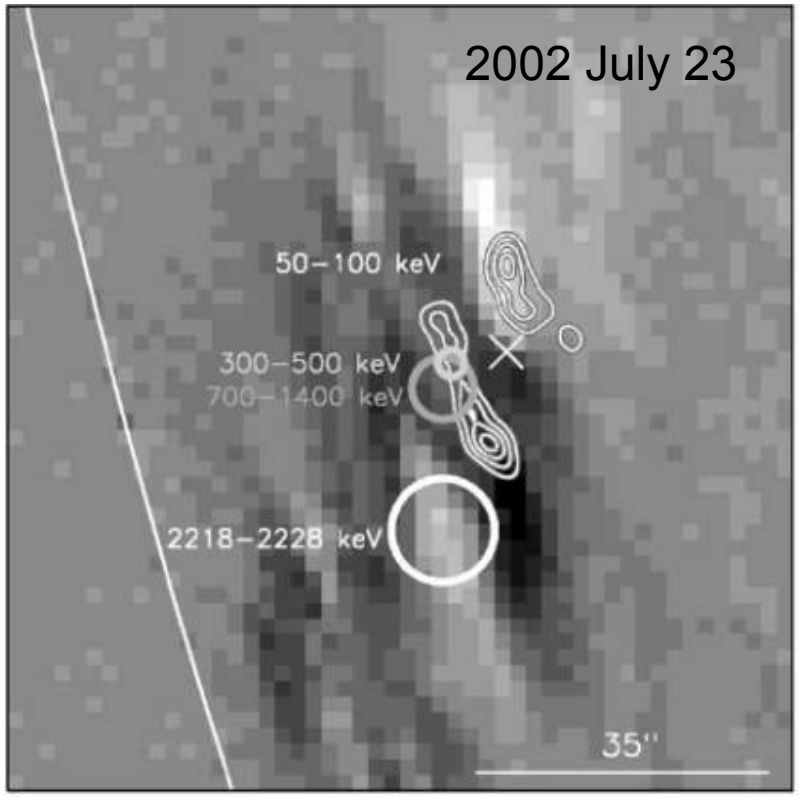


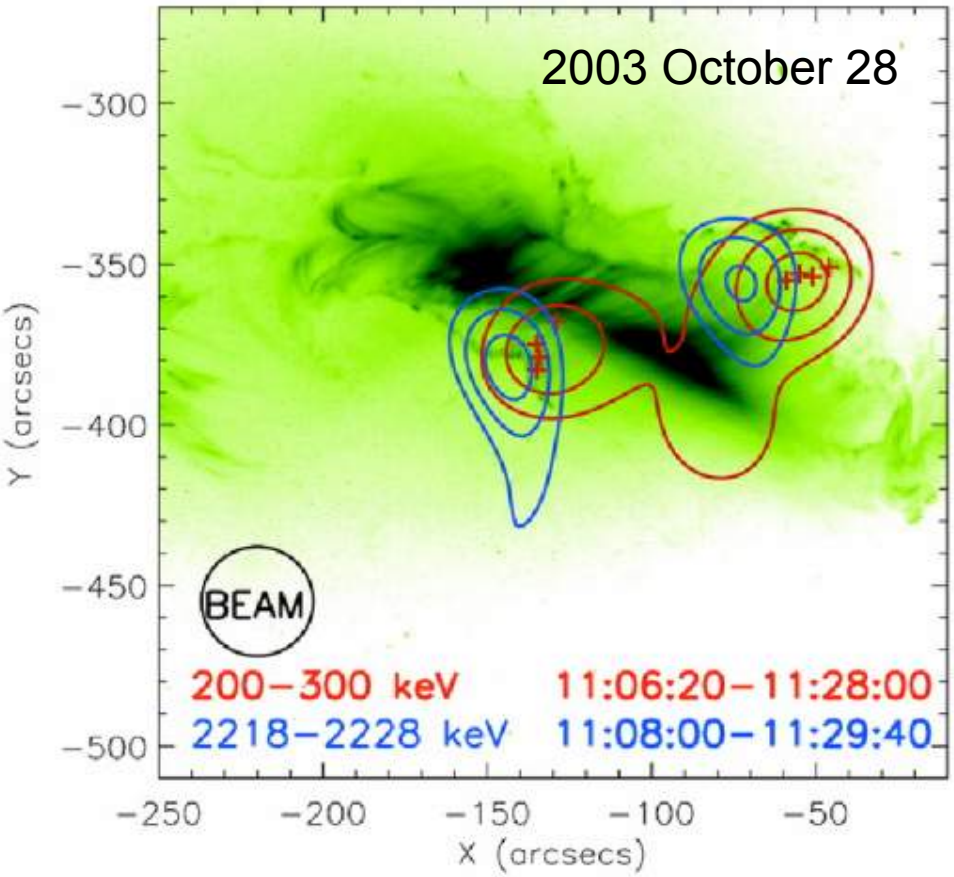
Lee & Gary, *The Astrophysical Journal*, 2000

Composite Spectrum from a Large Flare



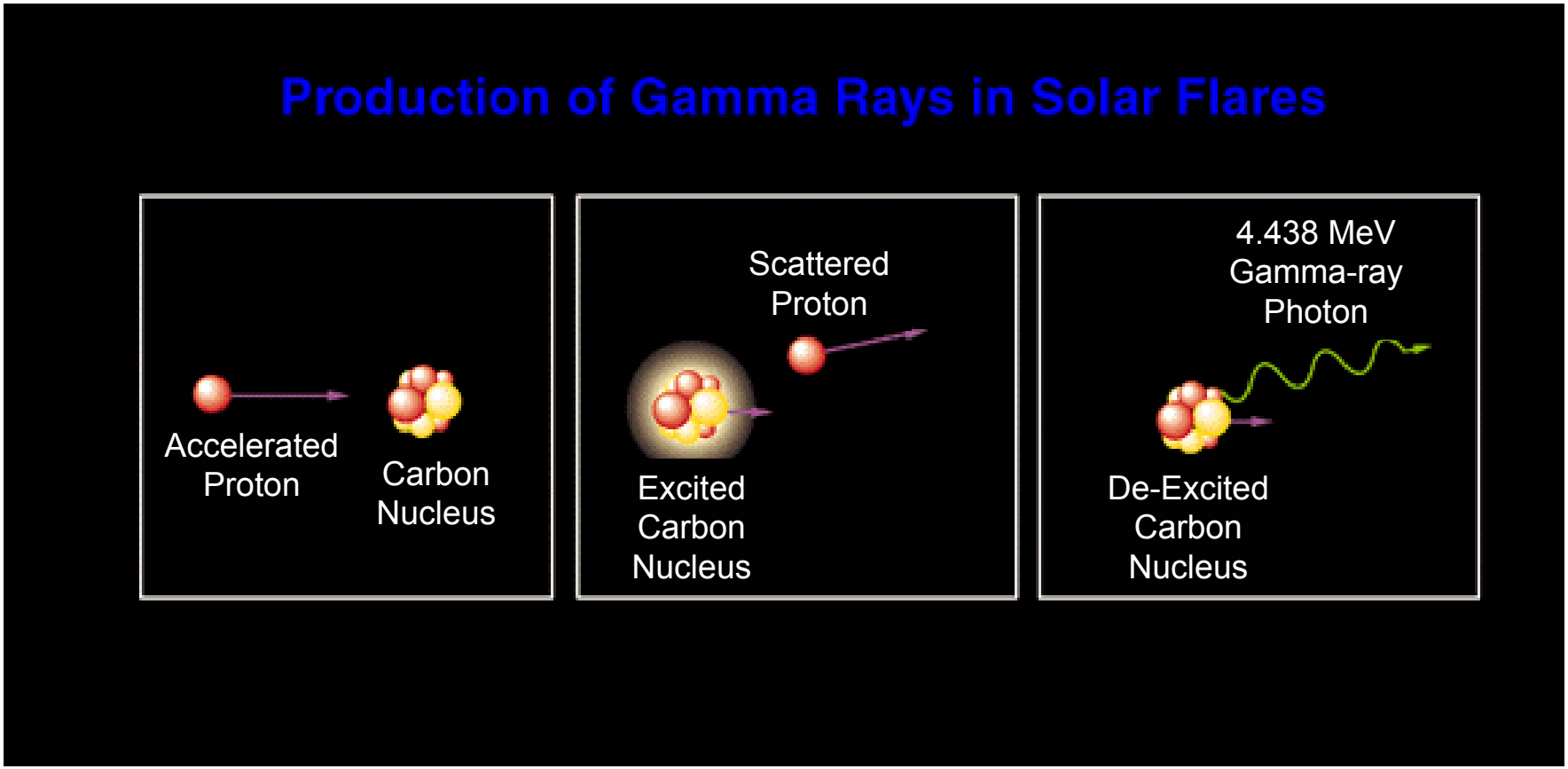
Location of Electron and Ion Footpoint Sources



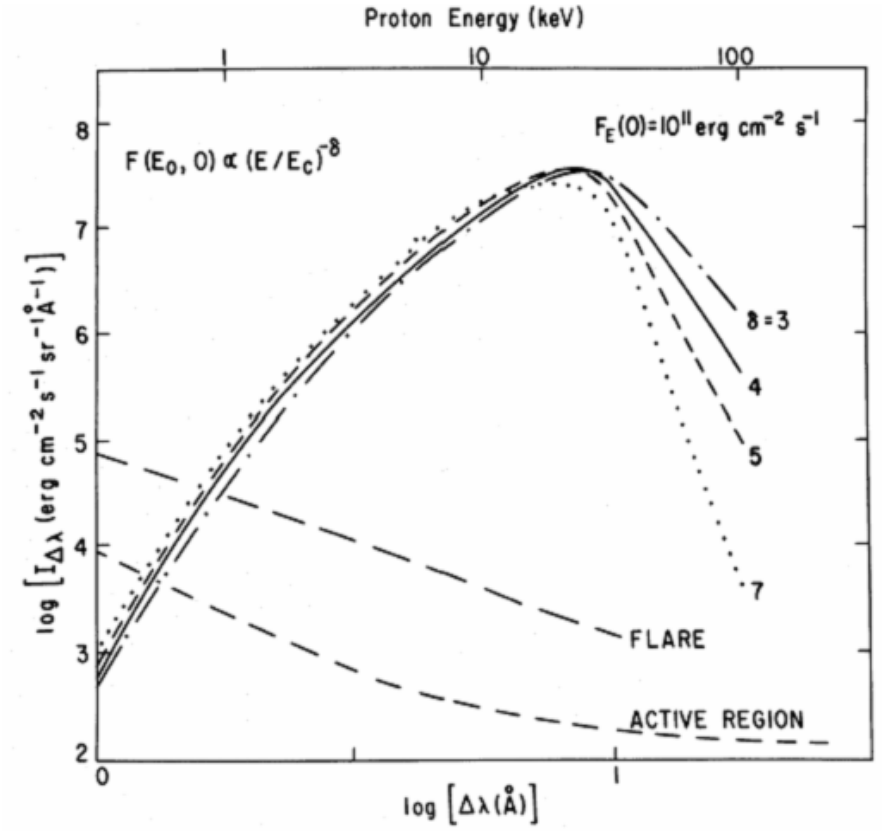


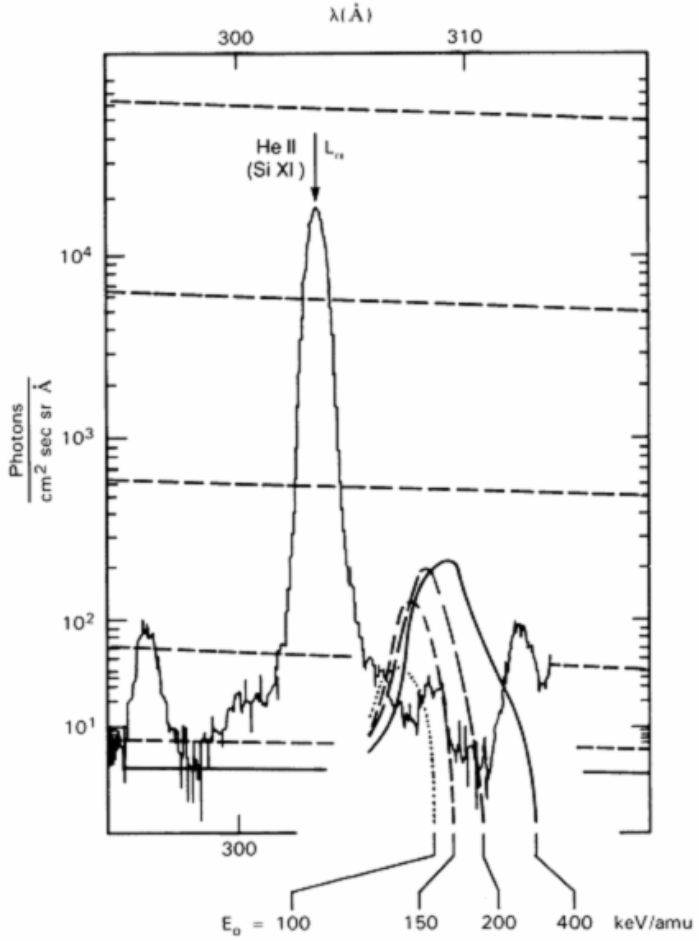
Hurford et. al., *Astrophysical Journal Letters*, 2003, 2006

Nuclear De-Excitation



A Signature of Sub-MeV Ions:
Redshifted Lyman Alpha from Charge Exchange





Hydrogen Ly-α (1216 Å)
>20 keV proton beam

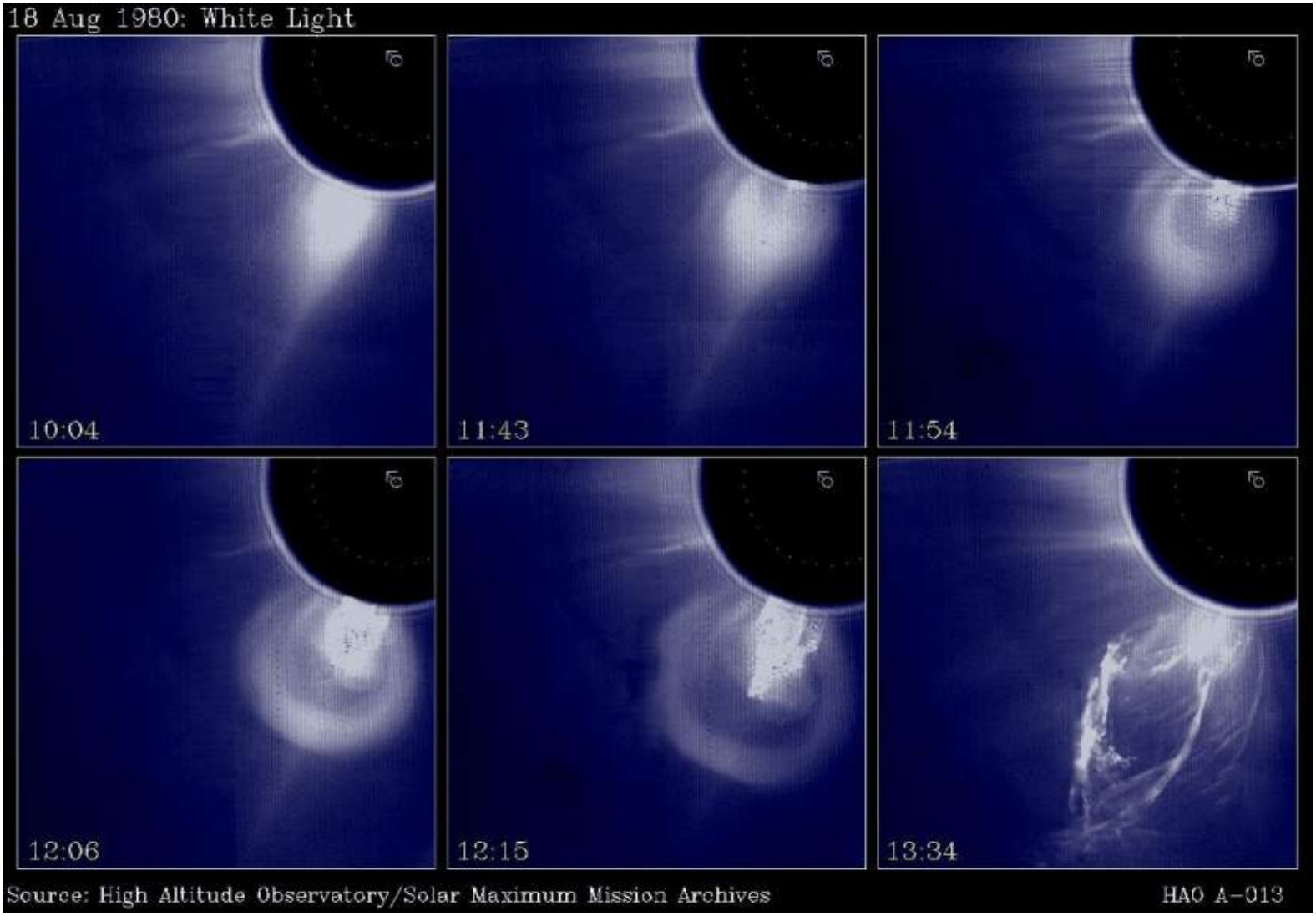
Helium Ly-α (304 Å)
>E_0 α-particle beam

Orrall & Zirker, 1976; Canfield & Chang, 1985; Peter et al., 1990; *Astrophysical Journal*

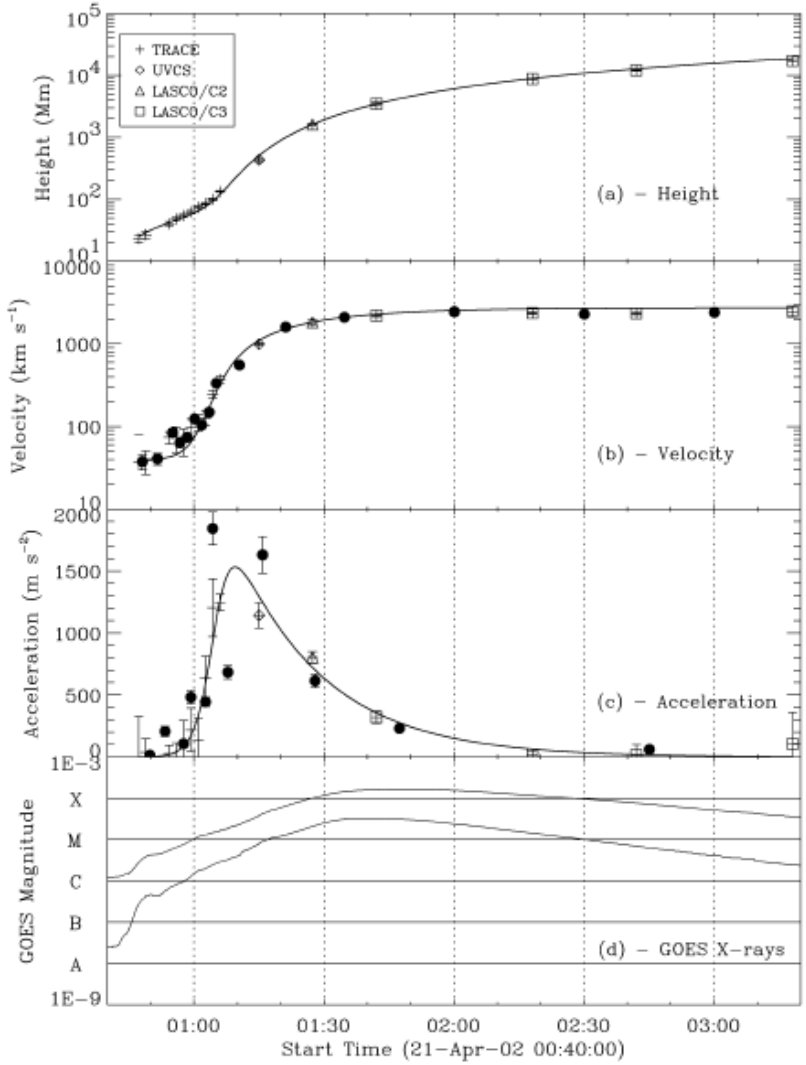
Particle Acceleration Mechanisms

- Direct Electric Field
- Stochastic (Type 2 Fermi)
- Resonant wave stochastic
- Betatron
- Shock (including Shock Drift & Type 1 Fermi)

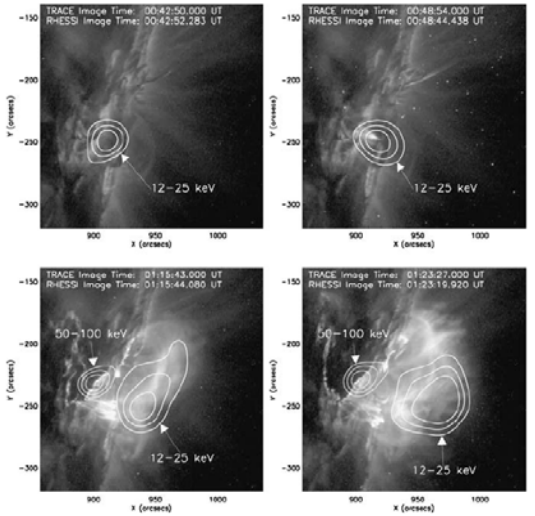
Coronal Mass Ejection (CME)

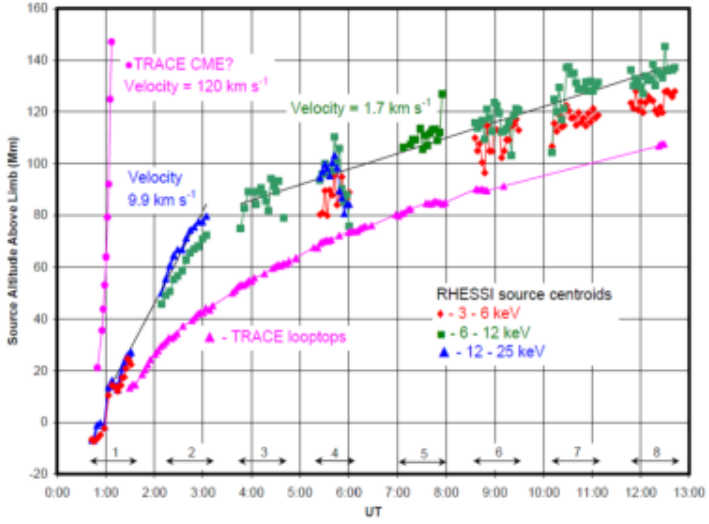


21 April 2002 X1.5 Flare



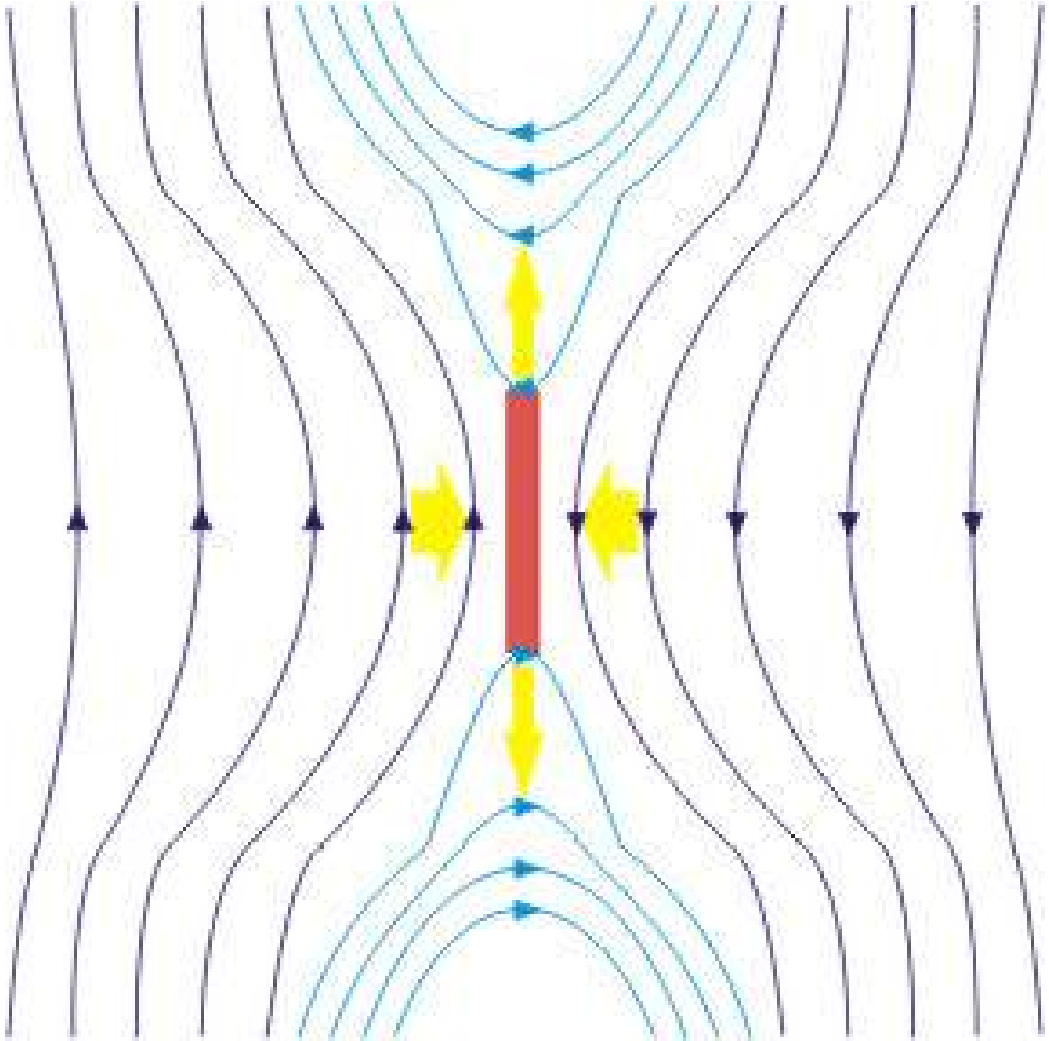
Gallagher, Lawrence, & Dennis,
The Astrophysical Journal Letters, 2003



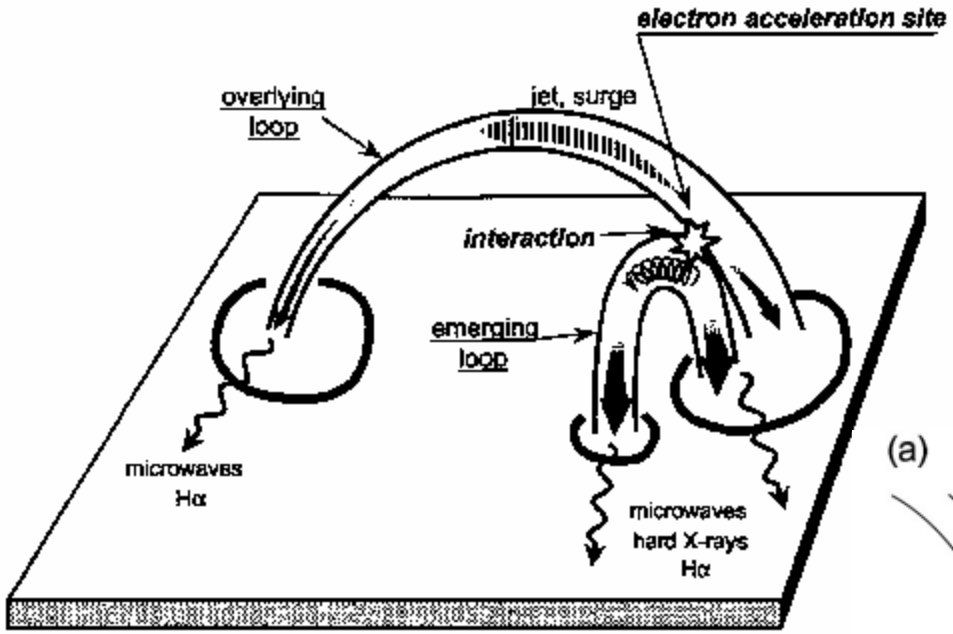


Gallagher, et. al., *Solar Physics*, 2002

Magnetic Reconnection

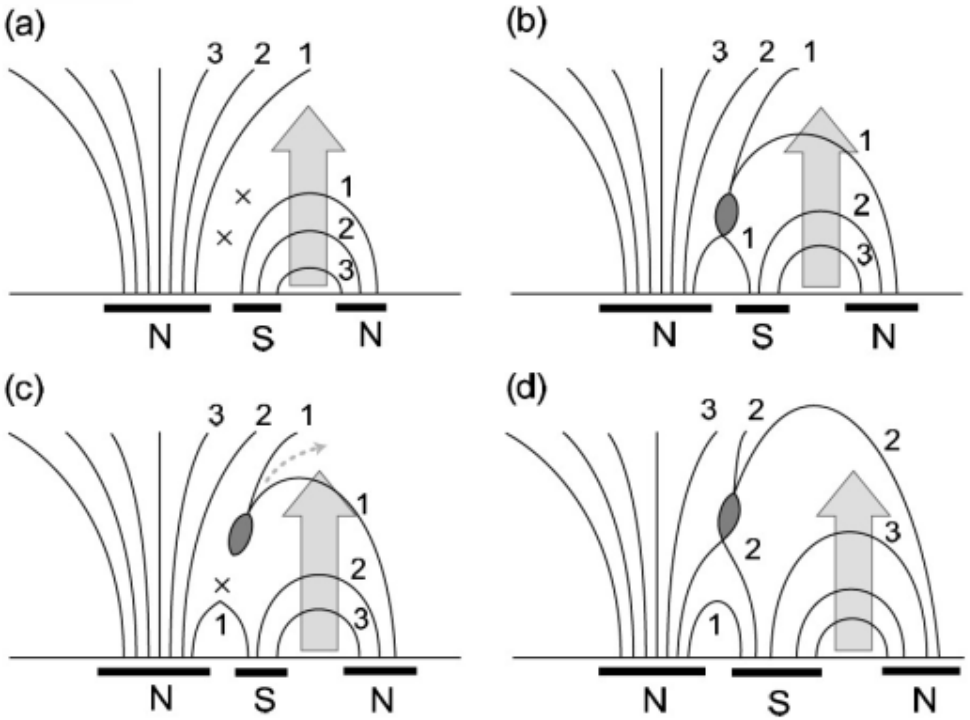


Interacting Loops

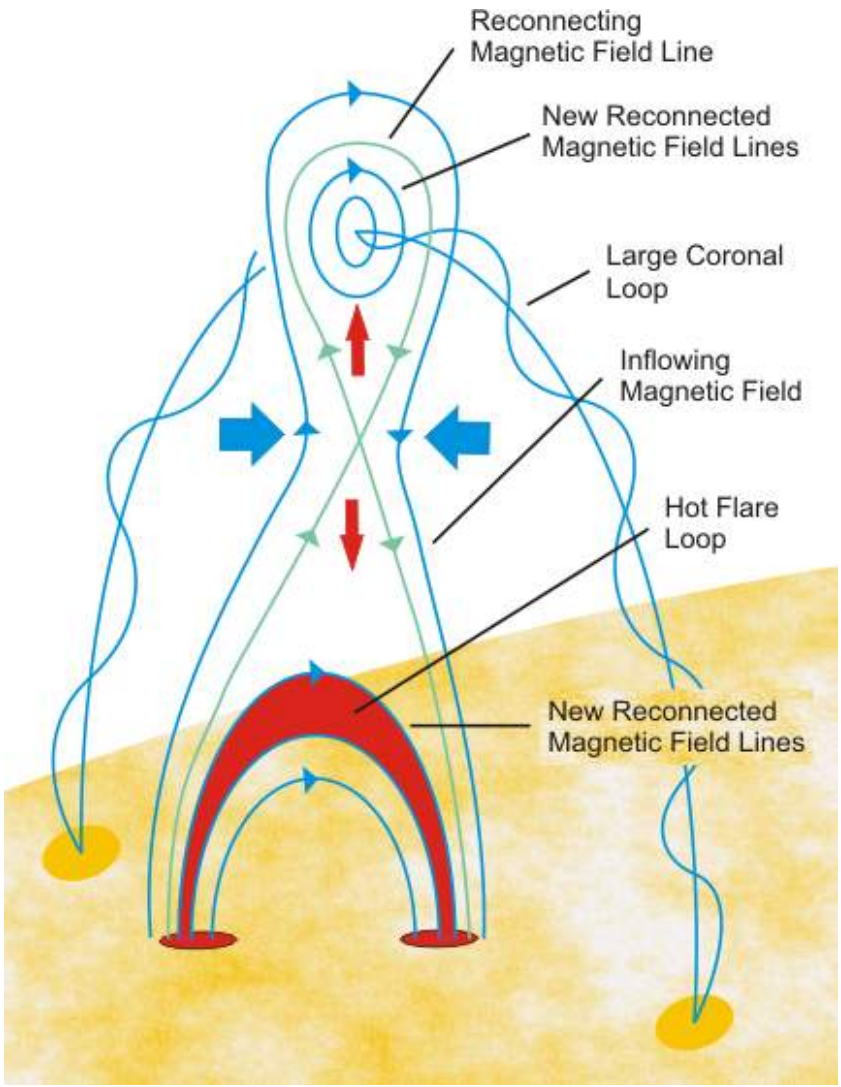


Hanaoka, *Publications of the Astronomical Society of Japan*, 1999

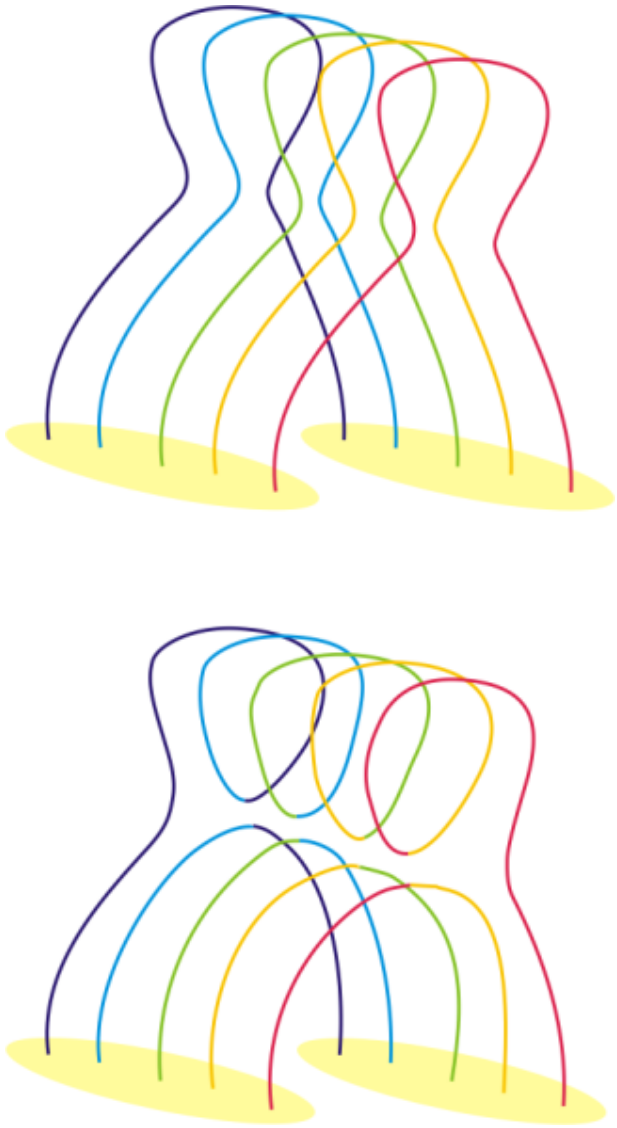
Takasaki et al., *The Astrophysical Journal*, 2004



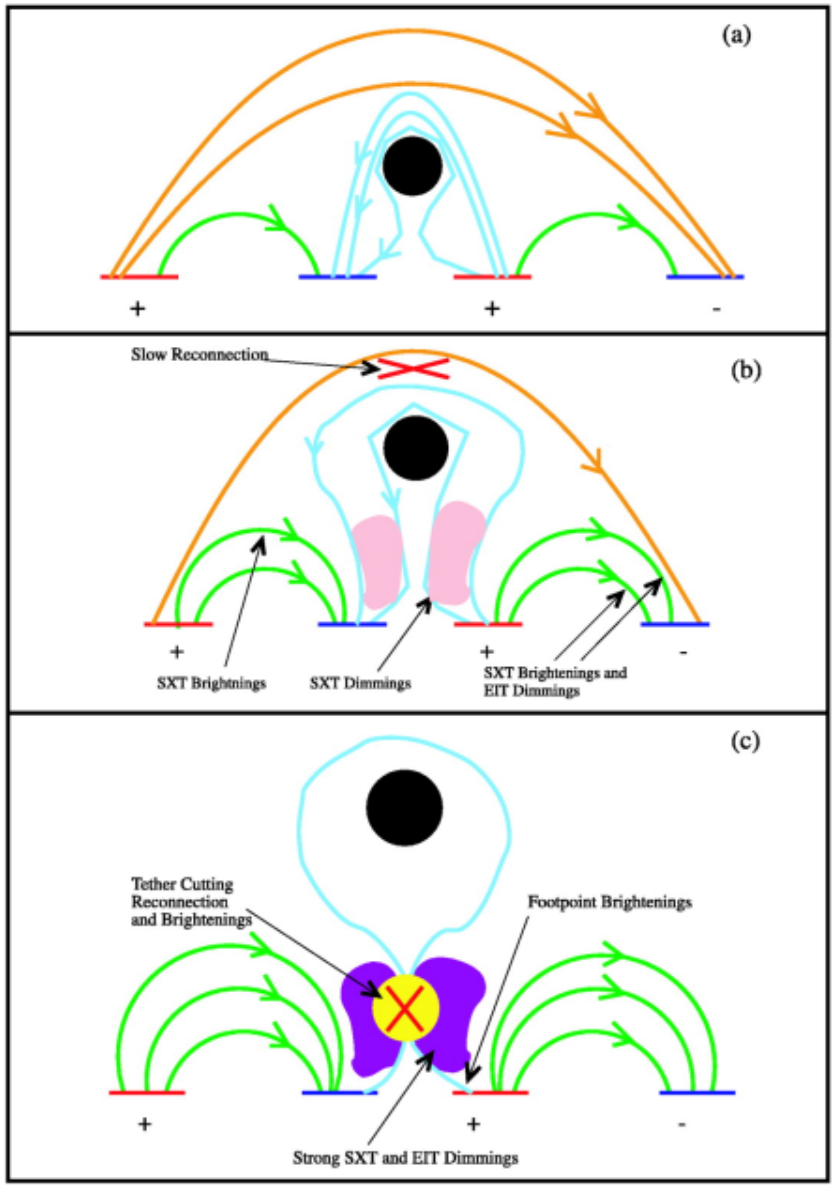
The “Standard” Model for Eruptive Flares



The Reconnection Model in 3-D

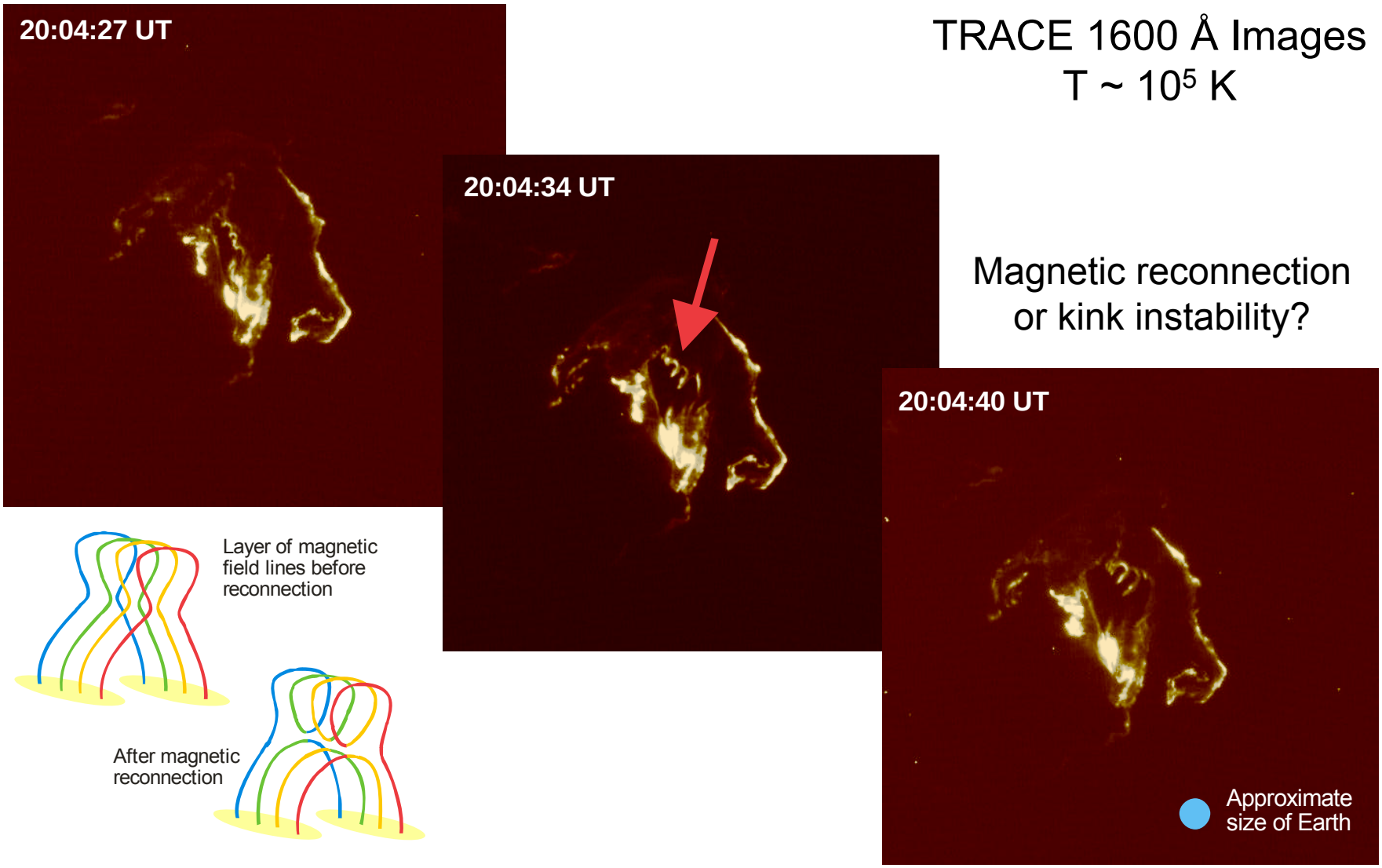


Breakout Model



Antiochos, 1999;
Sterling & Moore, 2004;
The Astrophysical Journal

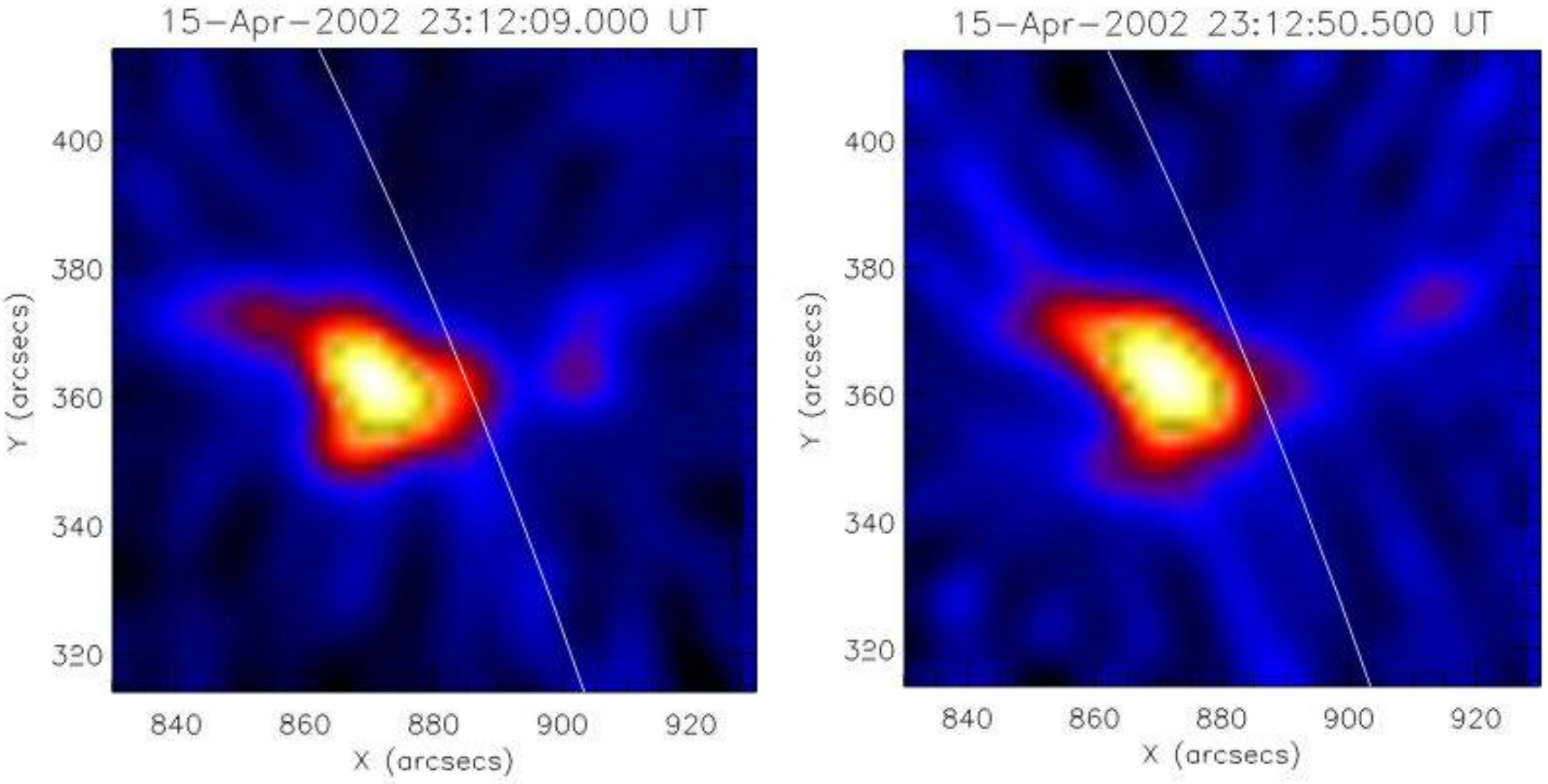
15 July 2002 Flare



TRACE 1600 Å Images
$T \sim 10^5$ K

Magnetic reconnection or kink instability?

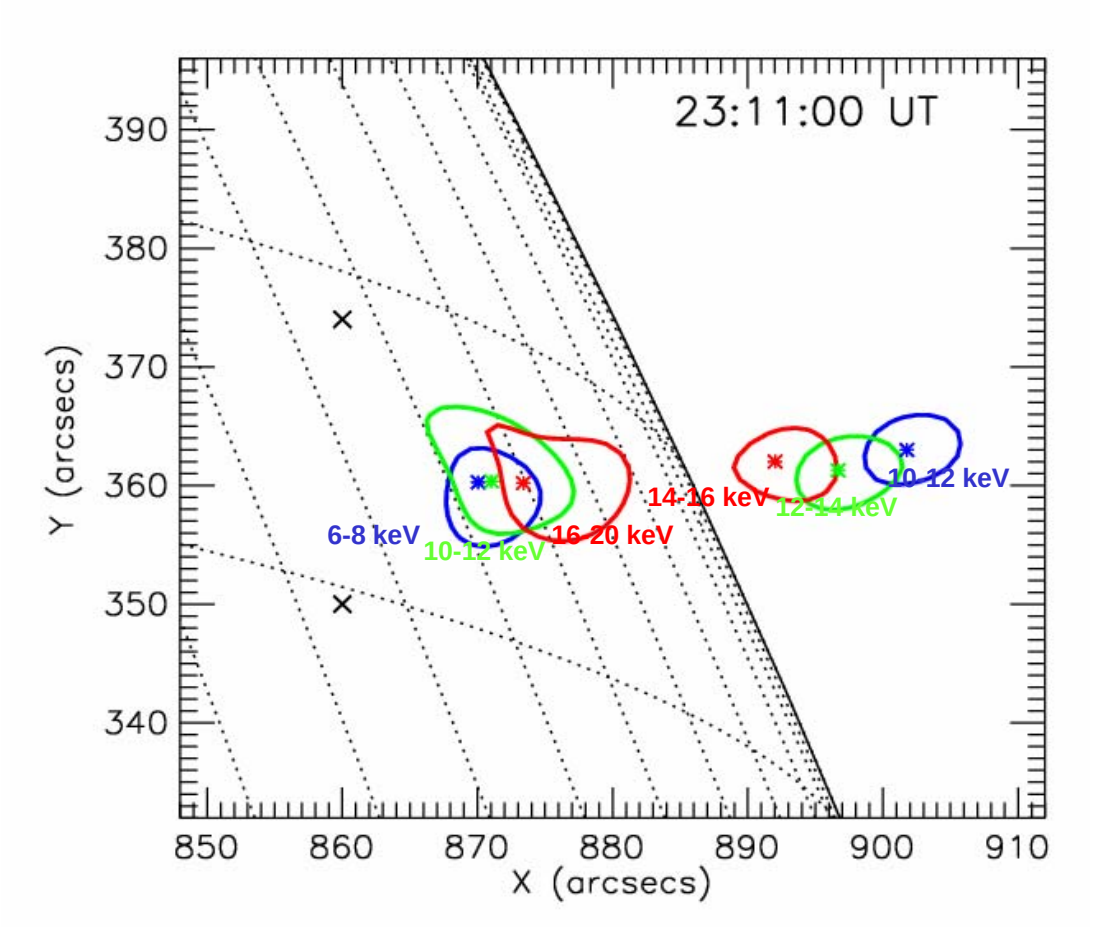
2002 April 15 M1.2 Flare



RHESSI 10 – 25 keV Images
Outward Propagation of Coronal Source

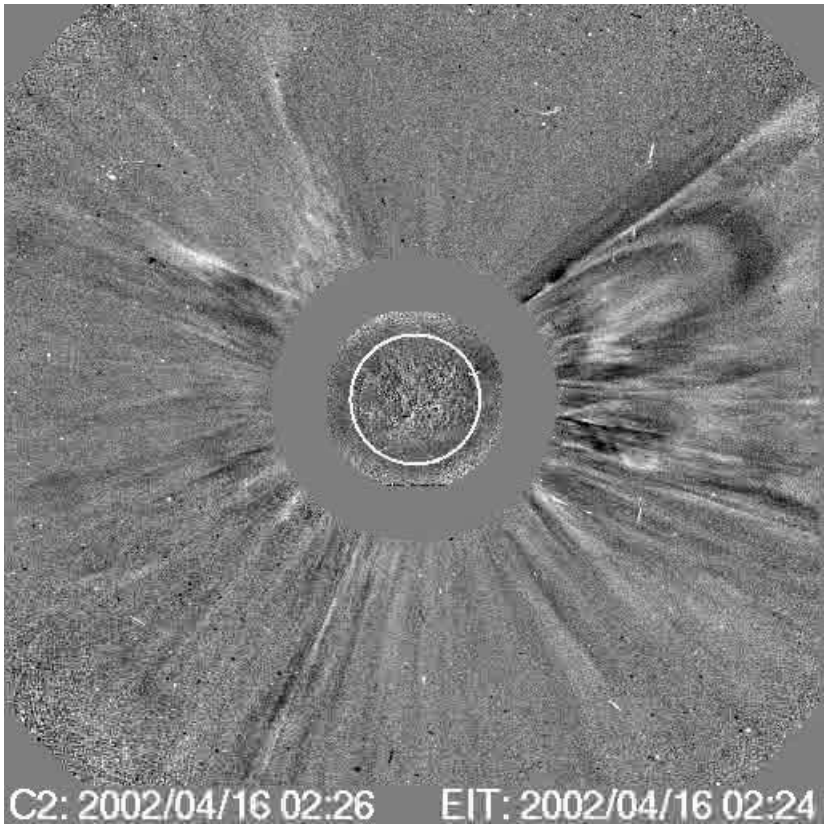
Sui & Holman, *The Astrophysical Journal Letters*, 2003

Centroid of Loop Top and Coronal Source in Three Energy Bands

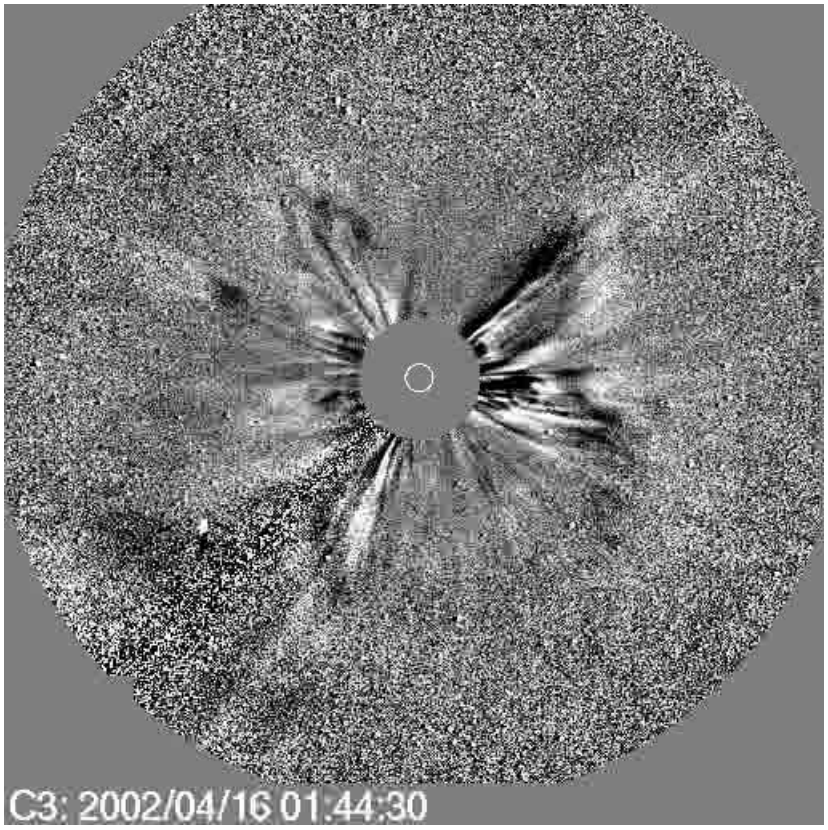


Coronal Mass Ejection

LASCO C2 2002/04/16

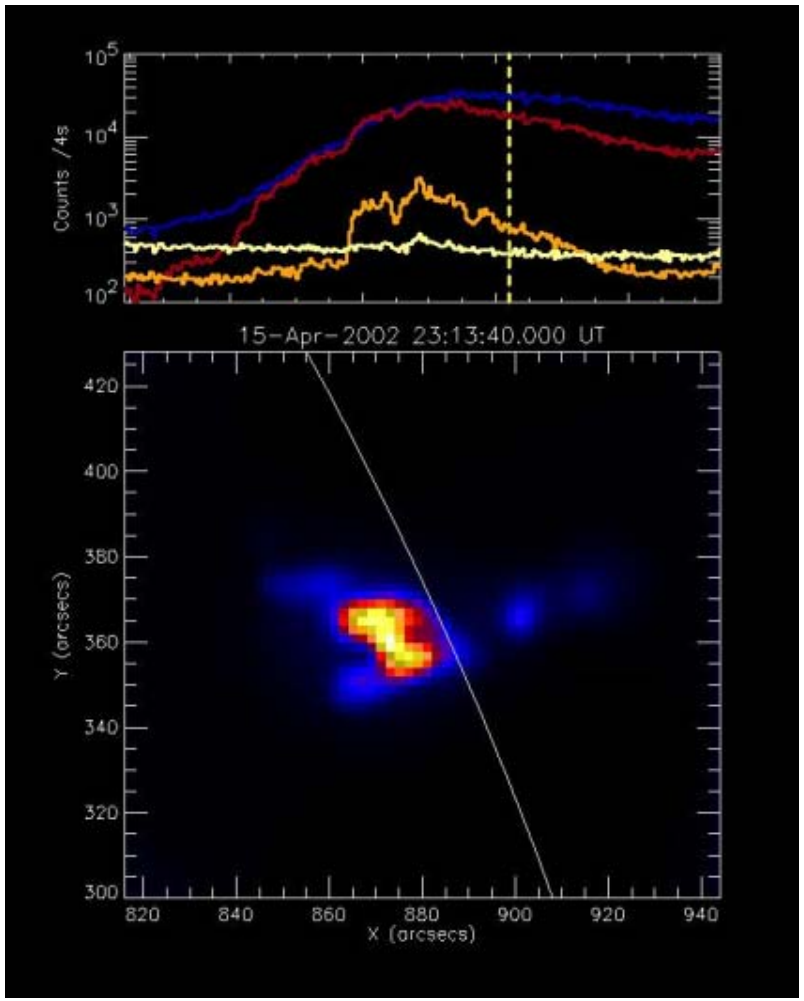


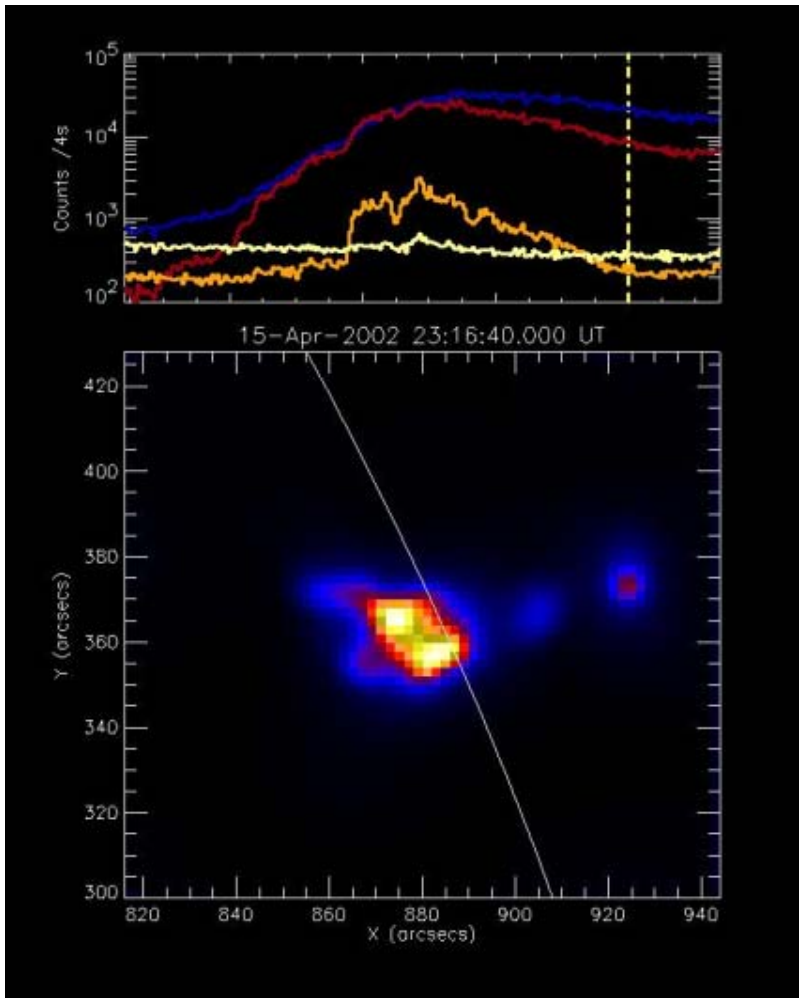
LASCO C3 2002/04/16



High Coronal X-ray Sources

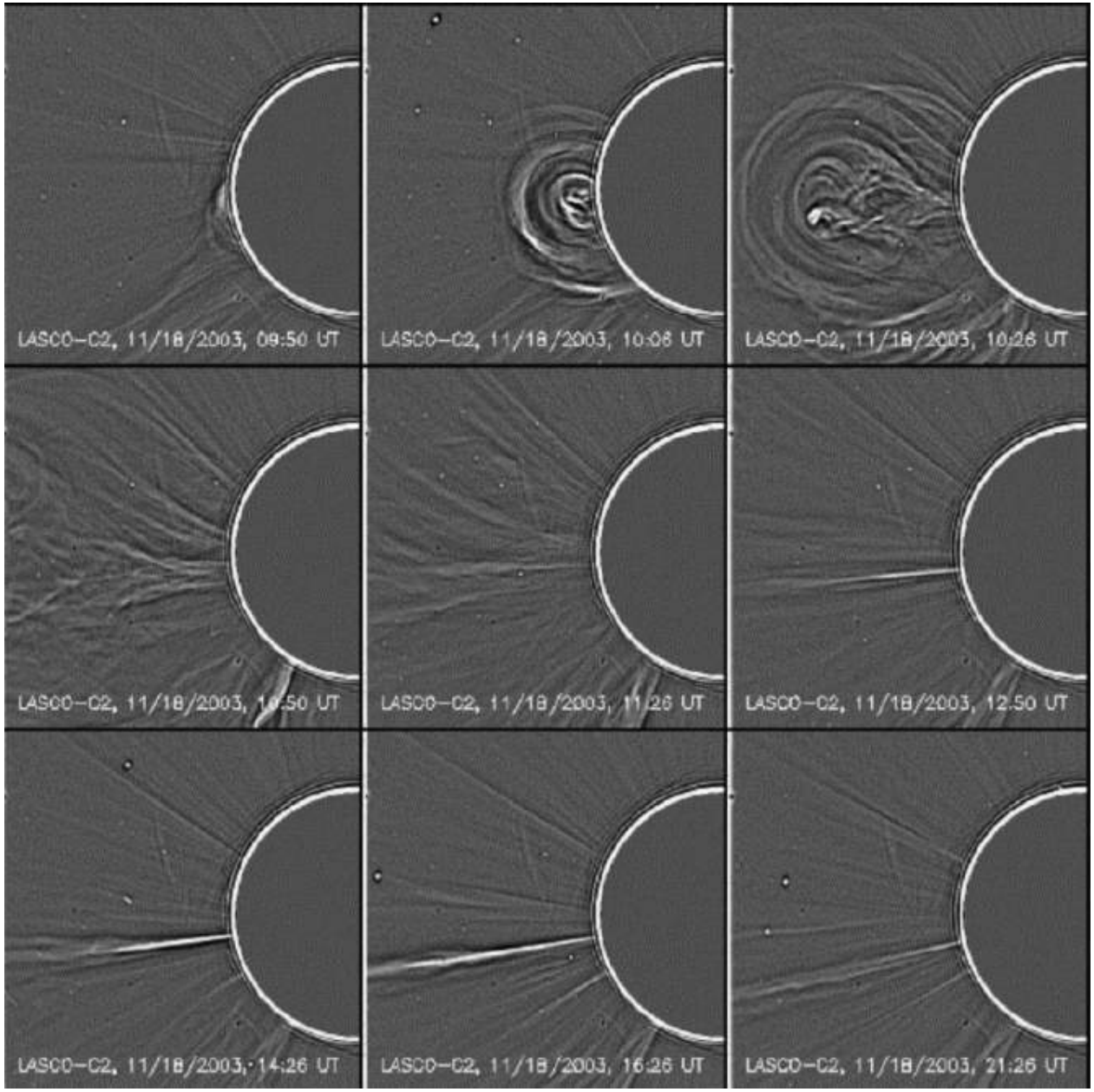
Tearing Mode Instability?





Sui et al., *The Astrophysical Journal*, 2005

2003 November 18 CME: Enhanced LASCO C2 Images



Lin, J., Ko, Y.-K., Sui, L., Raymond, J. C., Steinborg, G. A., Jiang, Y., Zhao, S. & Mancuso, S., 2005, Ap. J. 622, 1251

Flare-Associated Phenomena

- Solar Energetic Particles (SEPs)
  - Primarily accelerated in shock wave driven by coronal mass ejection (CME)
- Solar Radio Bursts
  - Type II: associated with shock wave
  - Type III: associated with streaming electrons
  - Type IV: associated with trapped electrons
- Space Weather

Bibliography

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