Energetic Phenomena II

N. Gopalswamy, NASA/GSFC

Topics:

What are flares?

H-alpha Flares

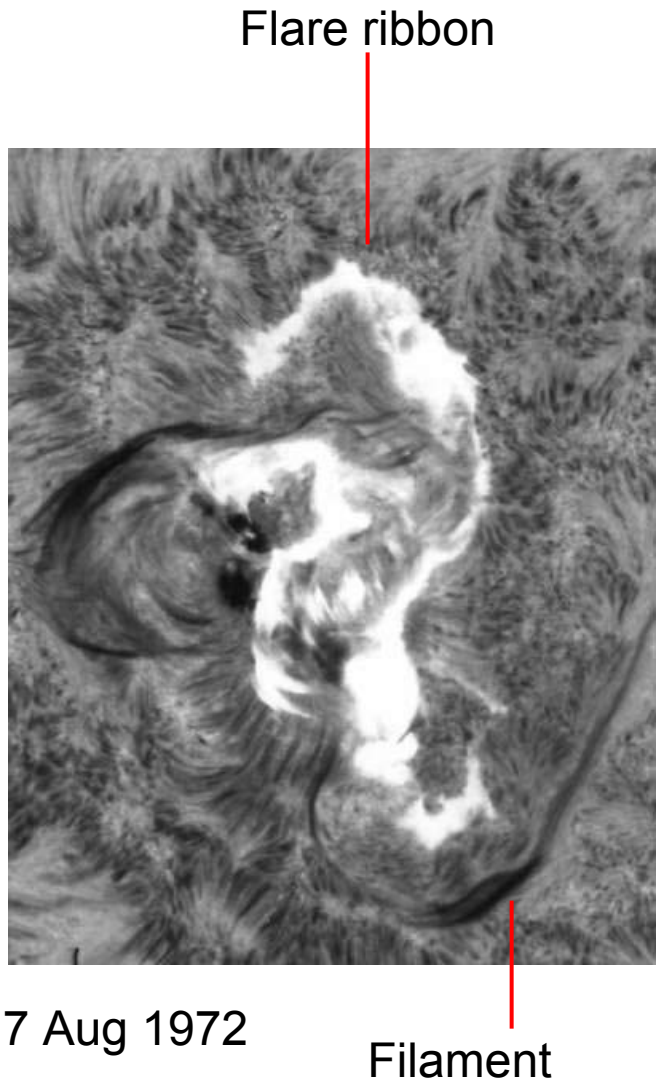
Soft X-ray flares

Flare models

Confined and eruptive flares

H-alpha flares

- Temporary emission within dark Fraunhofer line
- In spectroheliograms, flares appear as brightening of parts of the solar disk
- Area > 10^9 km^2 for large flares
- Area < 3×10^8 km^2 for subflares
- H-alpha flare area has been used as the basis for optical flare importance
- Area at flare peak measured as number of square degrees (1 heliographic degree = $2 \pi R/360$ = 12500 km with R = solar radius = 696000 km)
- Also measured as millionths of hemisphere (msh): $10^{-6}\ 2 \pi R^2$ or $\sim 3 \times 10^6$ km^2
- A scale of 0-4 is used with additional suffix for brightness (faint, normal, brilliant)
- 4b is the highest importance; SF is the lowest

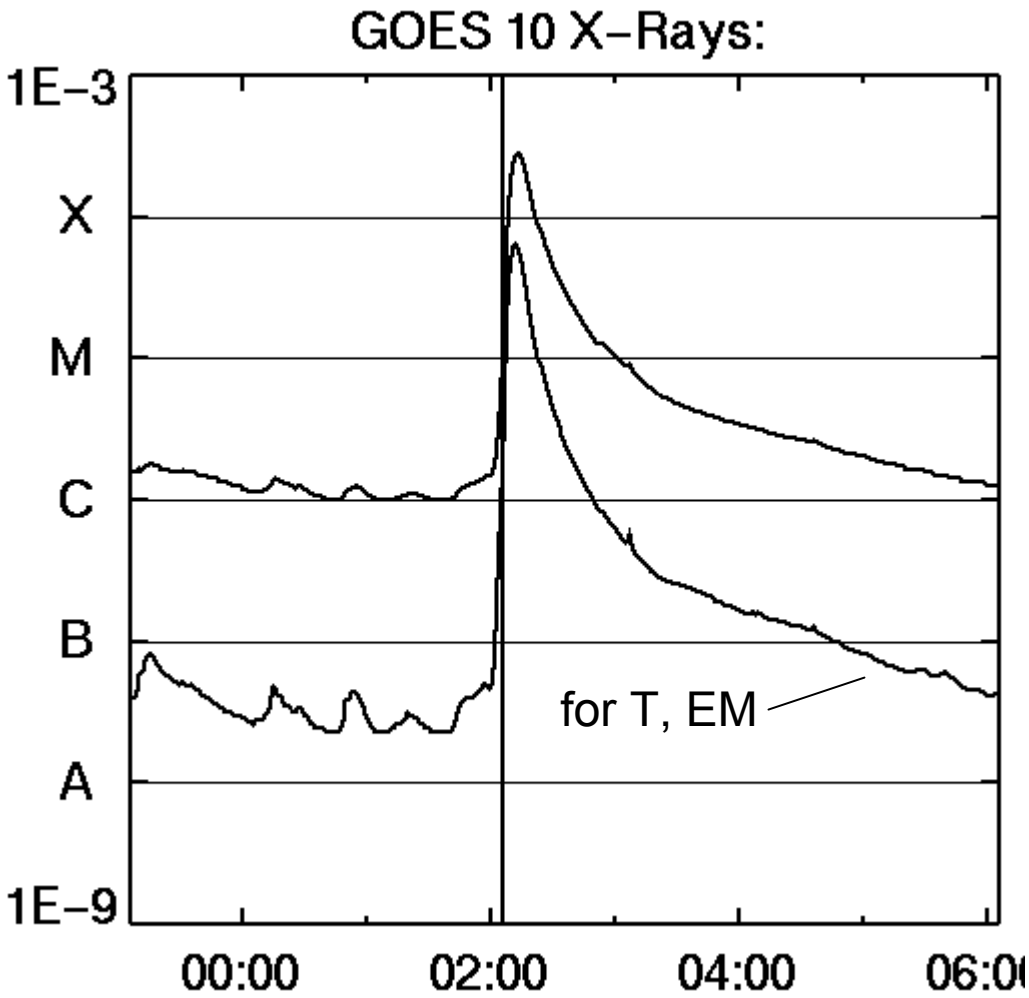


H-alpha Flares: Classification

Flare Area msh (Square degree)	faint	normal	brilliant
<100 (2.06)	Sf	Sn	Sb
100-250 (2.06-5.15)	1f	1n	1b
250-600 (5.15-12.4)	2f	2n	2b
600-1200 (12.4-24.7)	3f	3n	3b
>1200 (>24.7)	4f	4n	4b

msh = millionths of solar hemisphere

Soft X-ray Flares



Global photon output in the 1-8 A band
Originally C. M, X used to indicate the flare size (X2.5 = 2.5×10^{-3} wm^{-2})

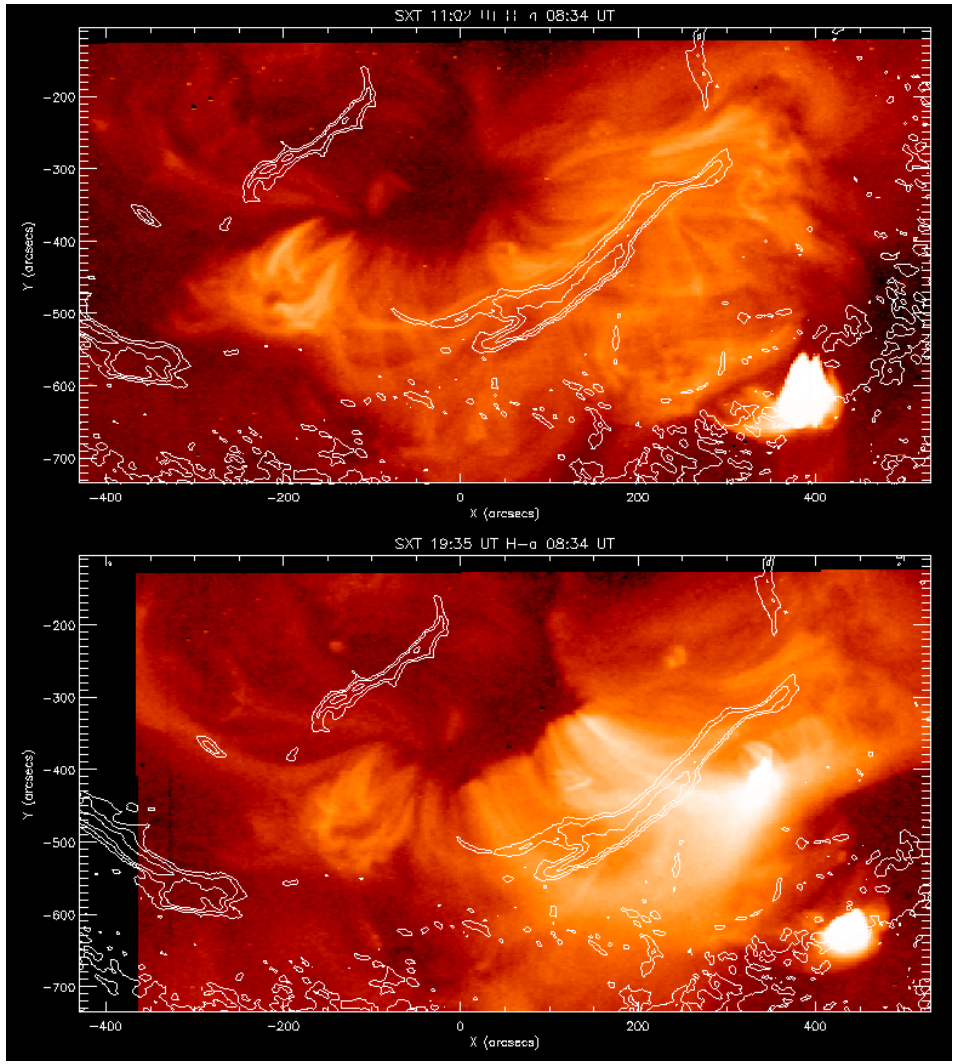
B, A added for weaker flares

Flares larger than X10 simply state the multiplier, e.g. X28

Importance class	Peak flux in 1-8 Å w/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

Soft X-ray flare image & H-alpha filament

Yohkoh/SXT

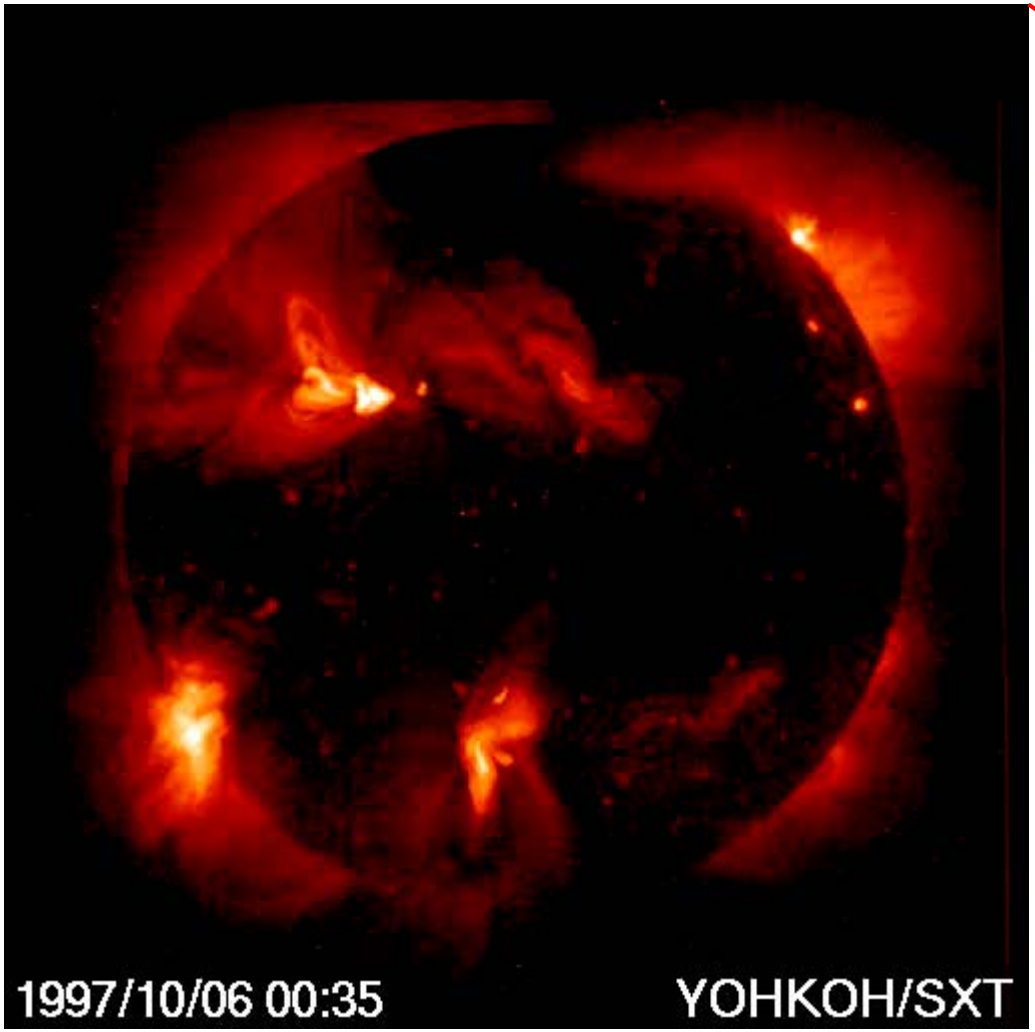


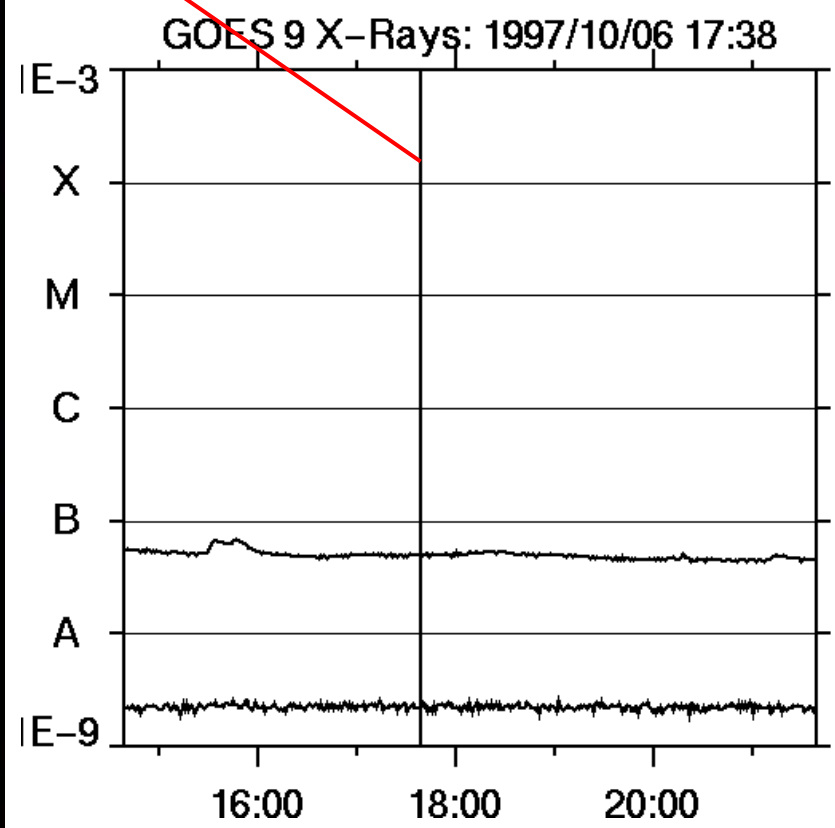
Pre-eruption
Sheared loops parallel
To the filament

Post-eruption
Arcade orthogonal
To filament position

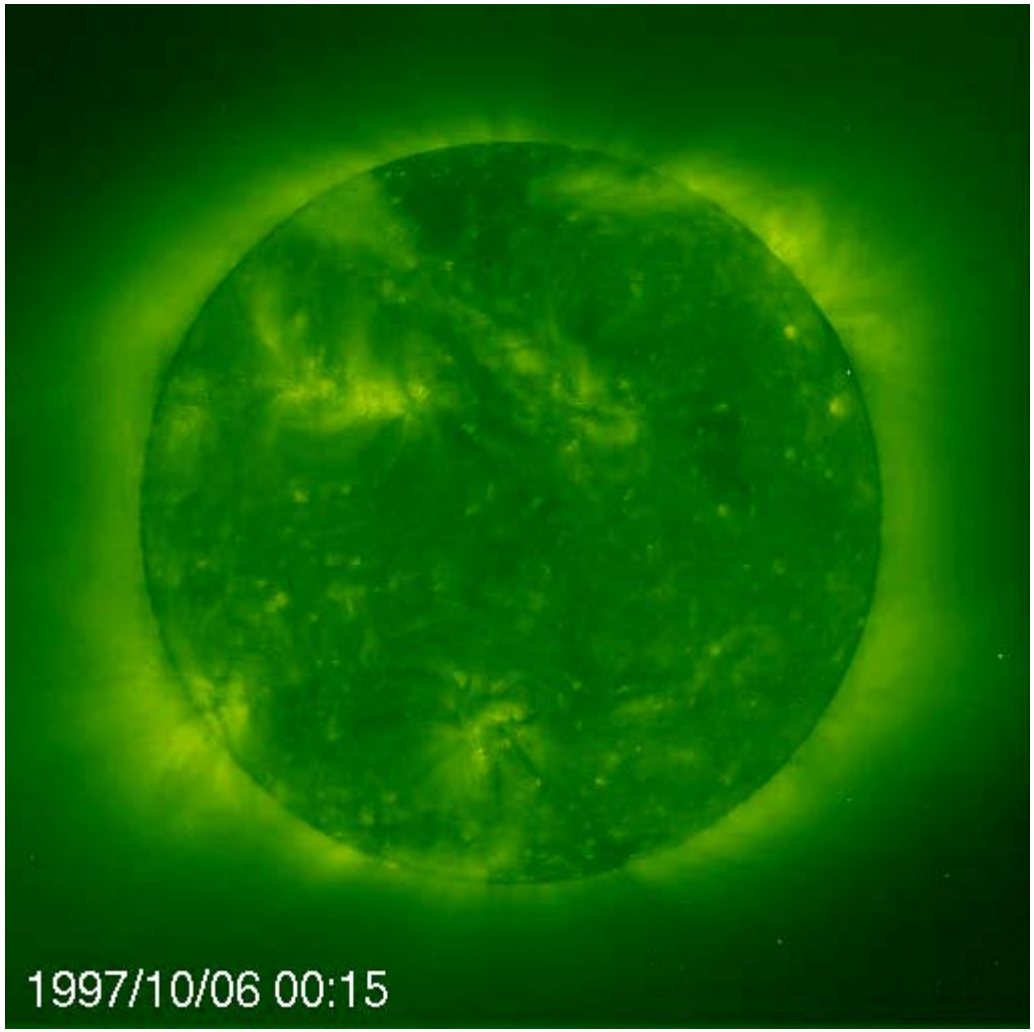
Very weak flare

movie

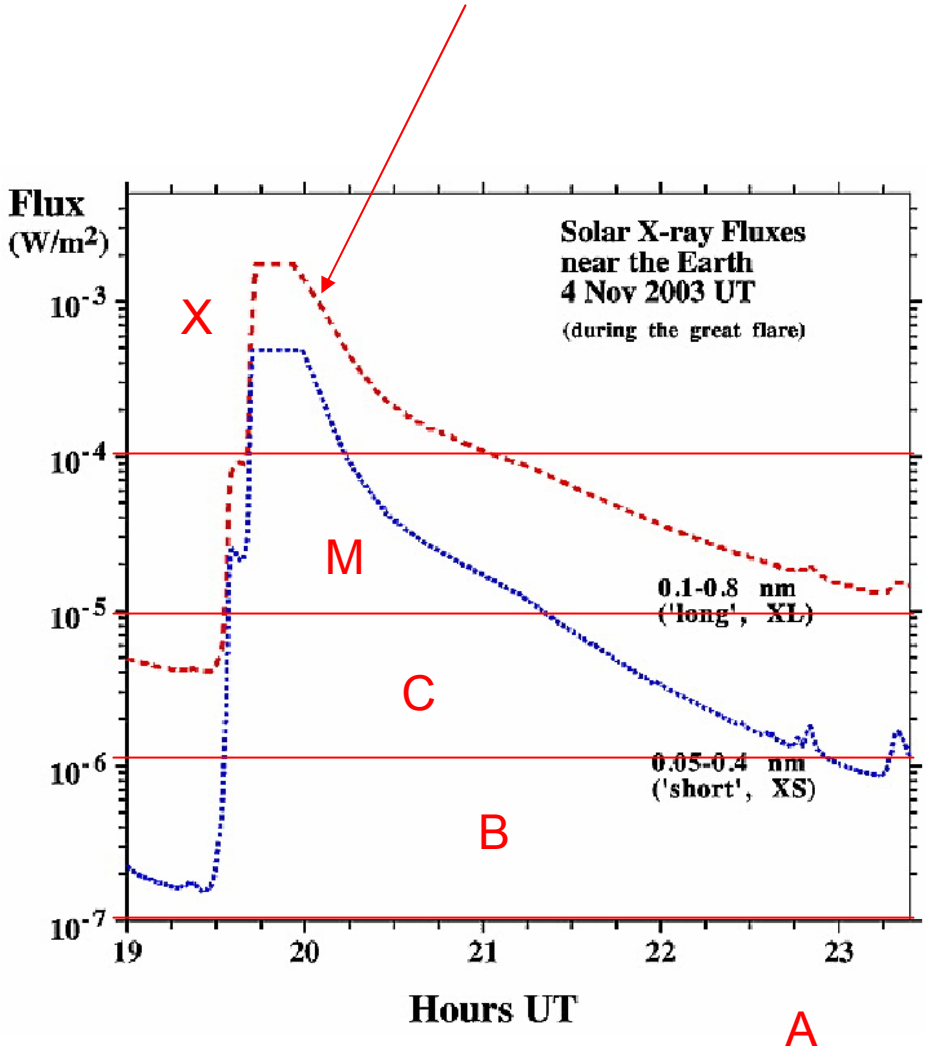




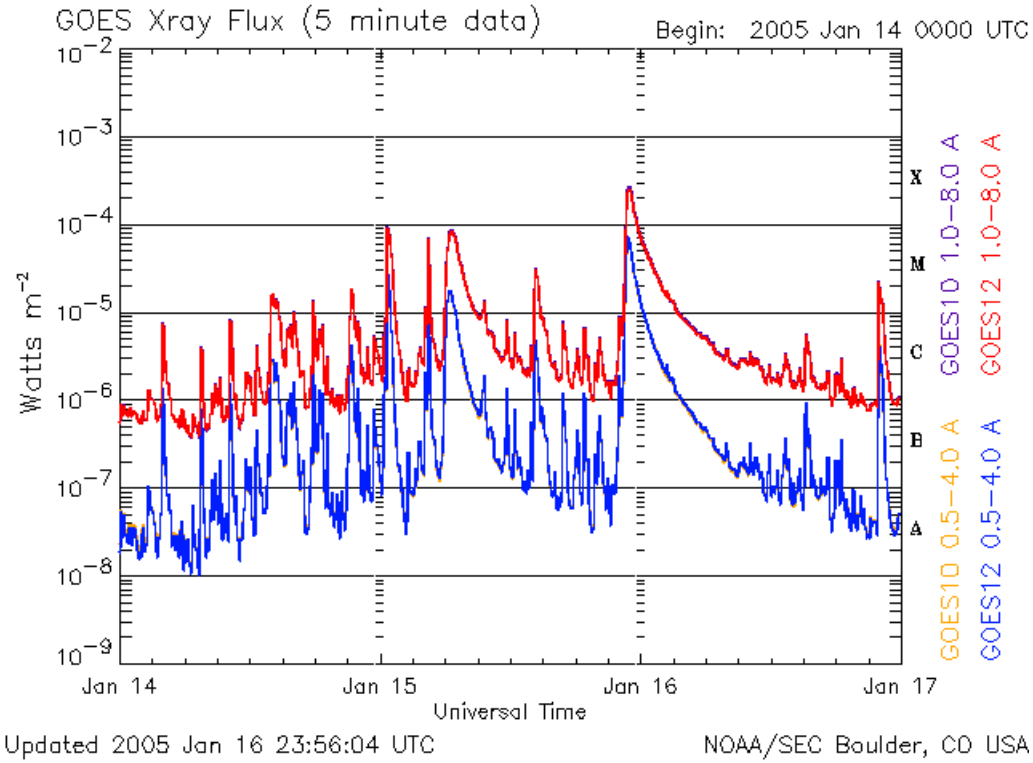
Filament eruption movie



Biggest Soft X-ray Flare of cycle 23 (saturated)



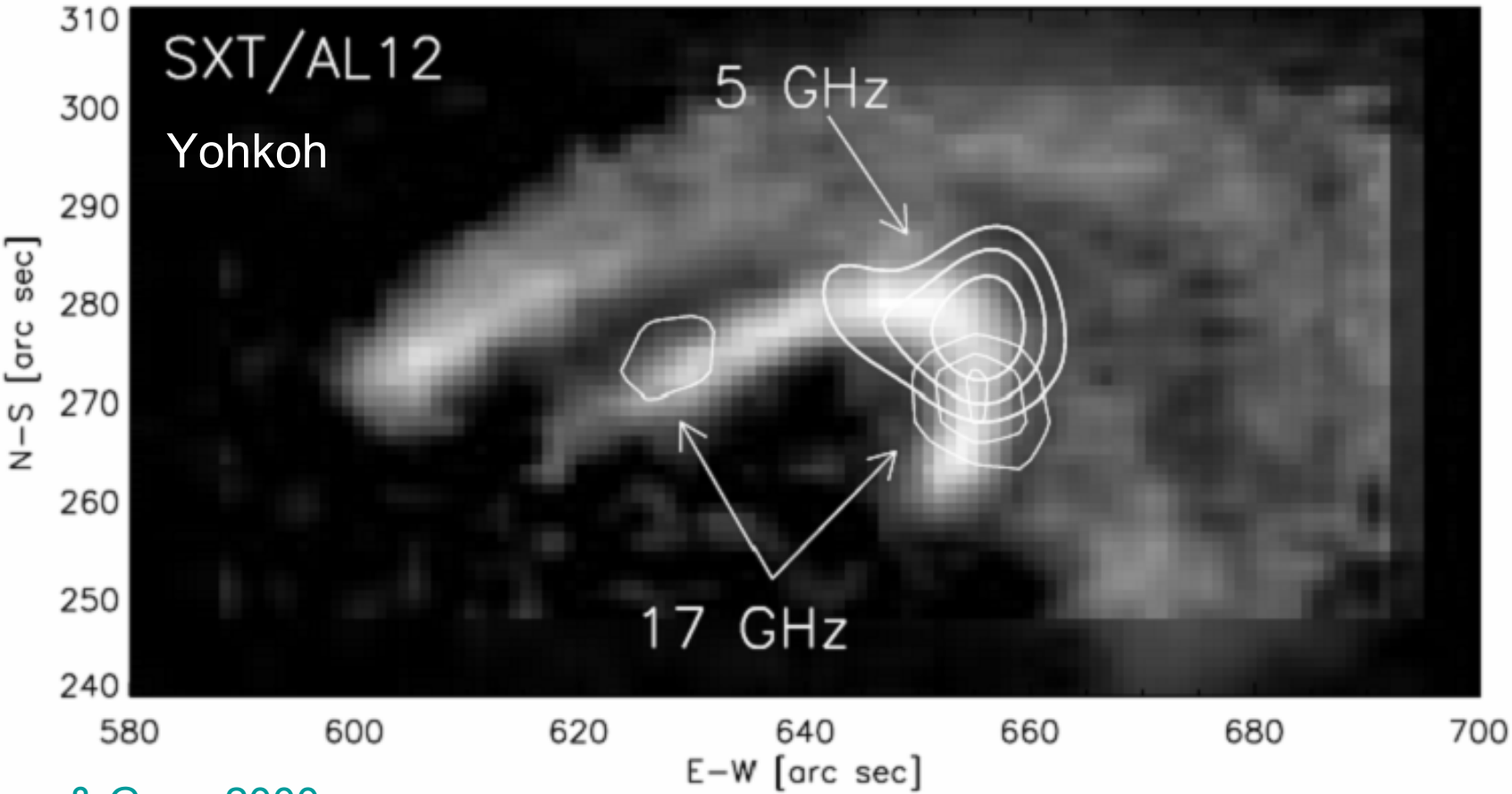
Period of high flare activity



Importance class	Peak flux in 1-8 Å w/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

X-class: 1, M-class: 9; C-class: many

A Flare in Soft X-rays & Microwaves



Lee & Gary, 2000

radio: gyrosynchrotron emission from 100s of keV electrons

ω = eB/mc gyro frequency; 10-100 harmonics

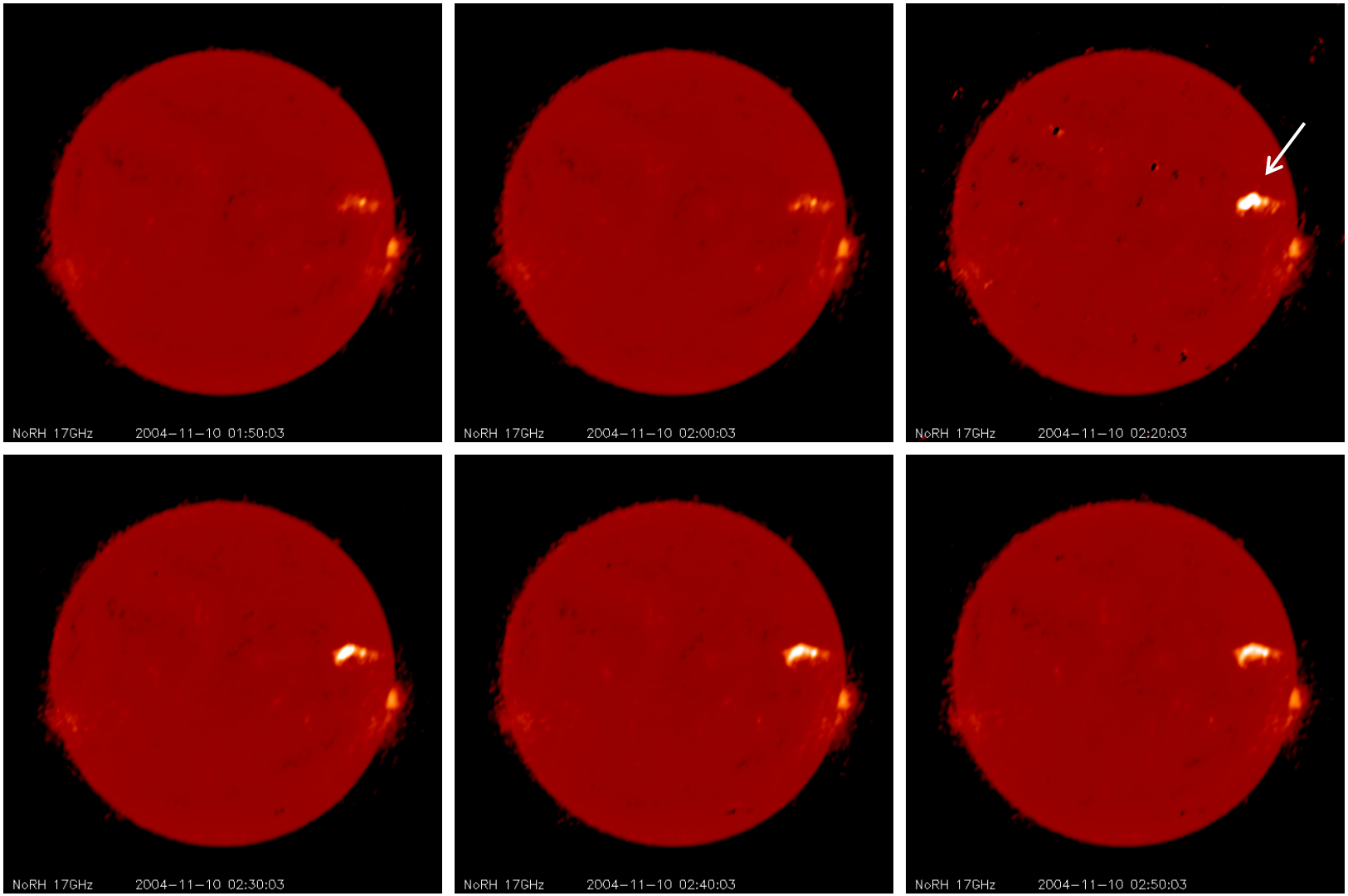
H-alpha and Radio Flares

Flare Area msh (Square degree)	faint	normal	brilliant	radio flux at 5 GHz (sfu)
<100 (2.06)	Sf	Sn	Sb	<5
100-250 (2.06-5.15)	1f	1n	1b	30-1300
250-600 (5.15-12.4)	2f	2n	2b	1300-23000
600-1200 (12.4-24.7)	3f	3n	3b	23000 - 30000
>1200 (>24.7)	4f	4n	4b	>30000

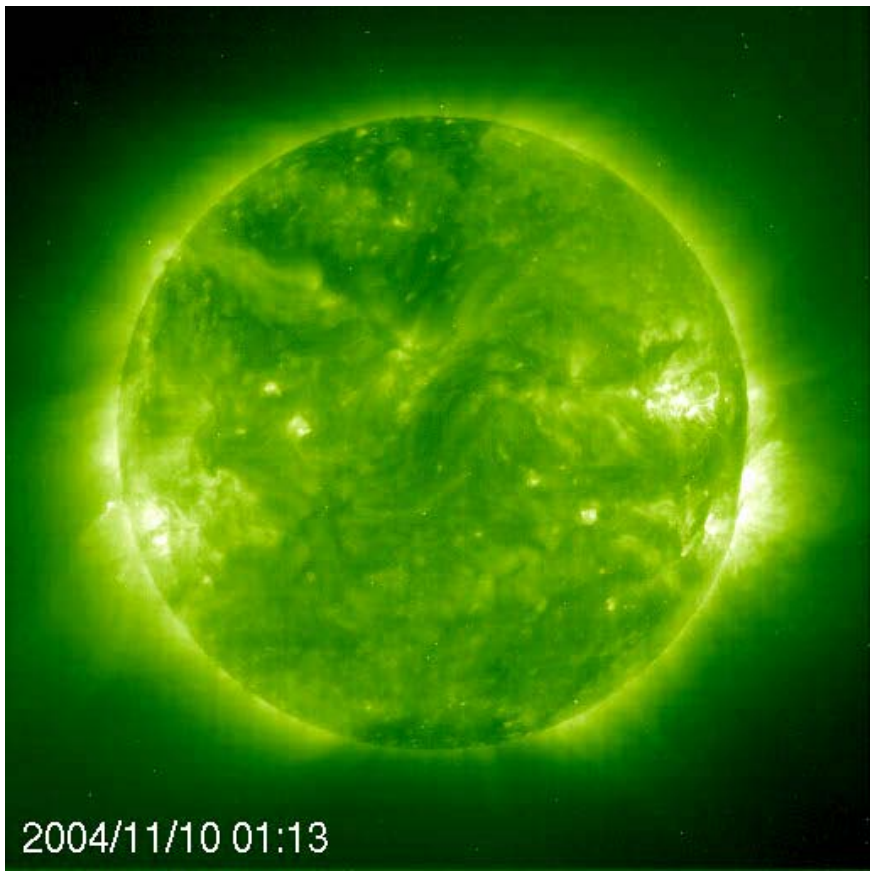
msh = millionths of solar hemisphere

Imp = log S – 0.5; S radio flux in sfu (10^{-22} Wm^{-2})

A microwave flare (17 GHz)



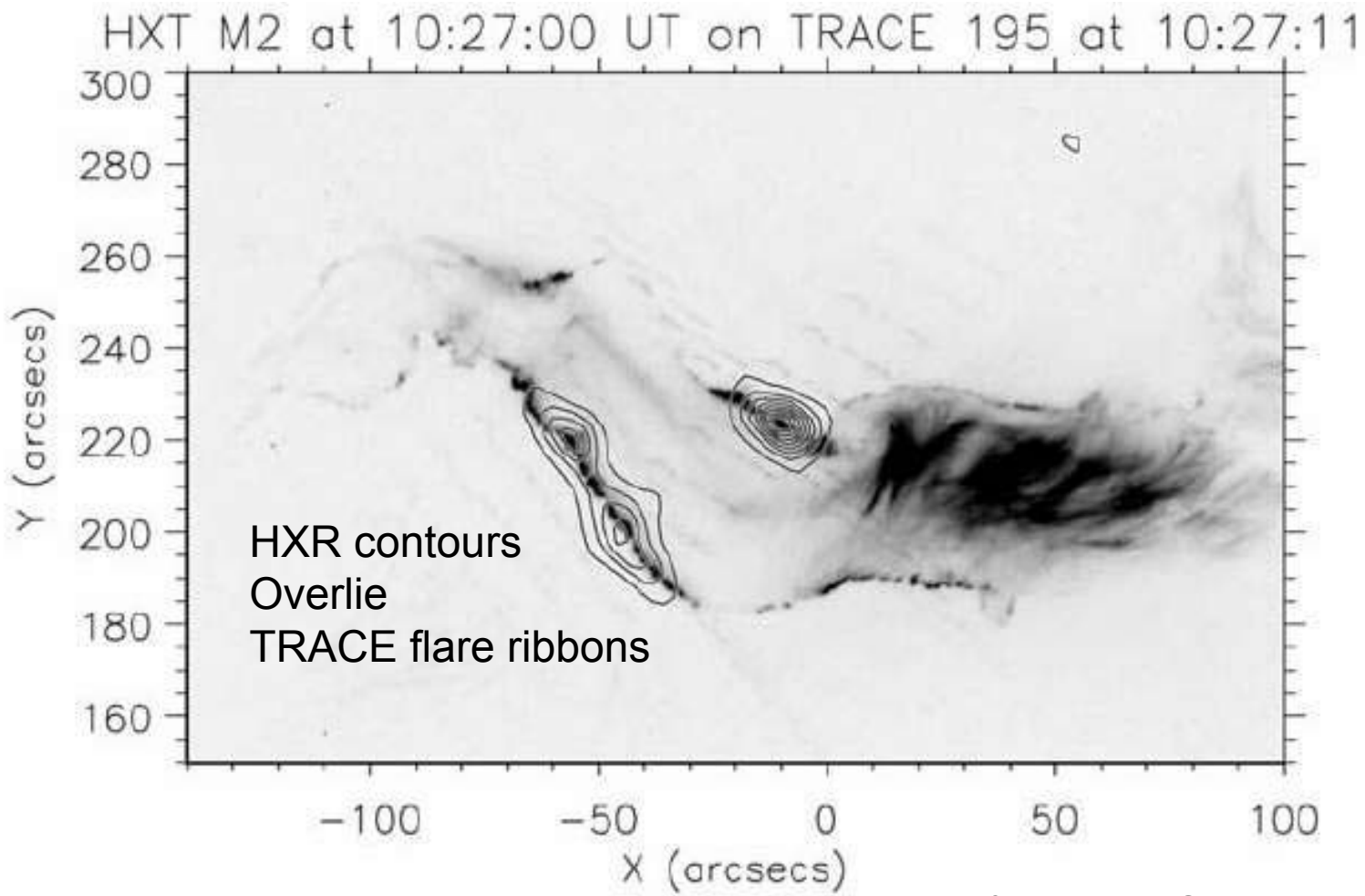
Flare in EUV (SOHO/EIT 195 A)



Somewhat similar to soft X-rays

Additional wave-like feature due to CME

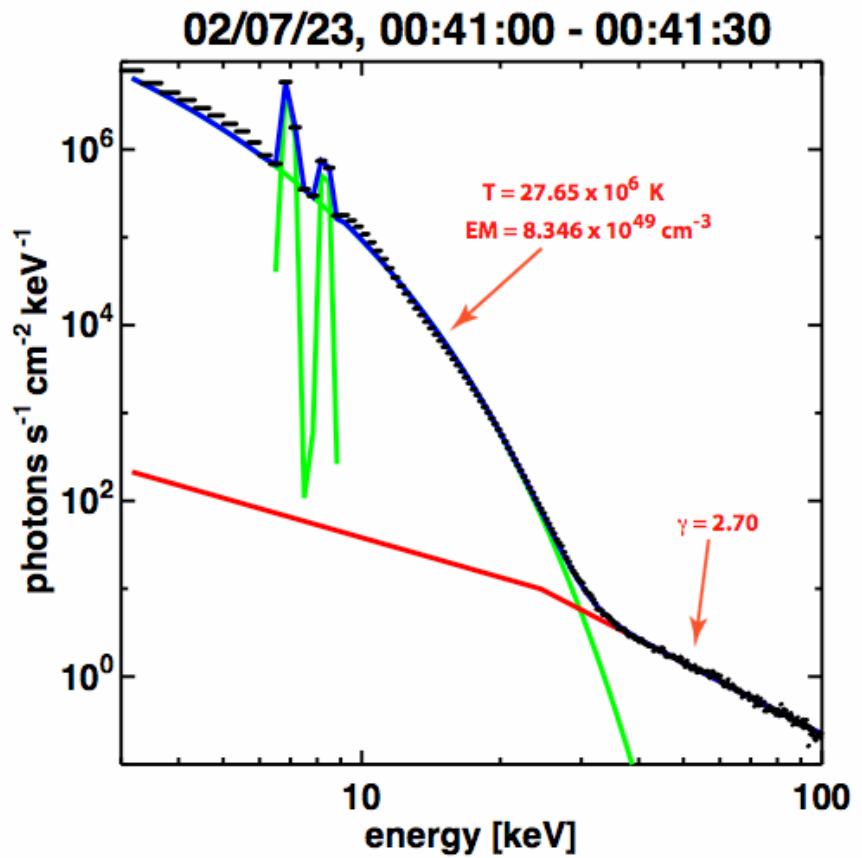
Flare Ribbons (TRACE) and Hard X-Rays (Yohkoh)

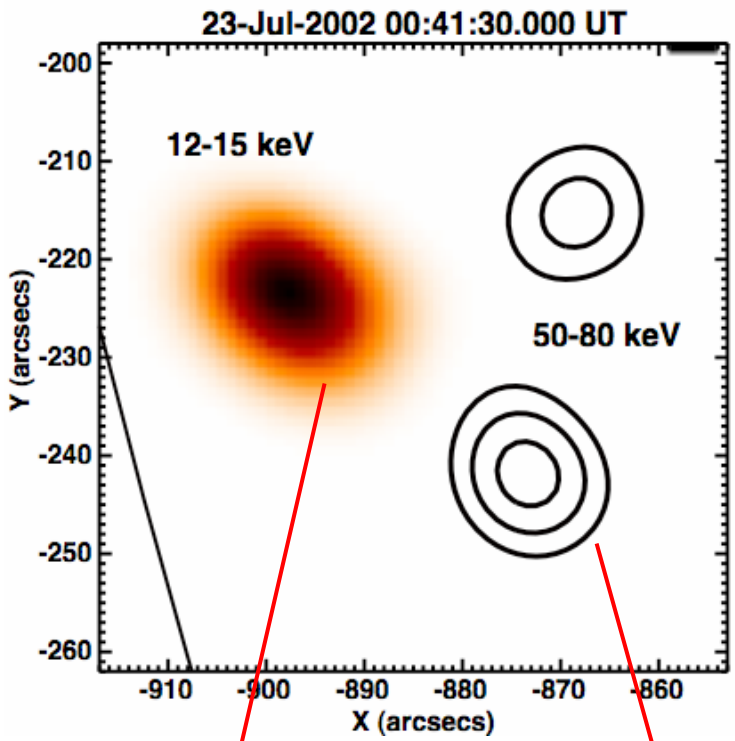


Fletcher & Hudson, Solar Physics, 2001

RHESSI Imaging Spectroscopy

Caspi & Lin, 2005

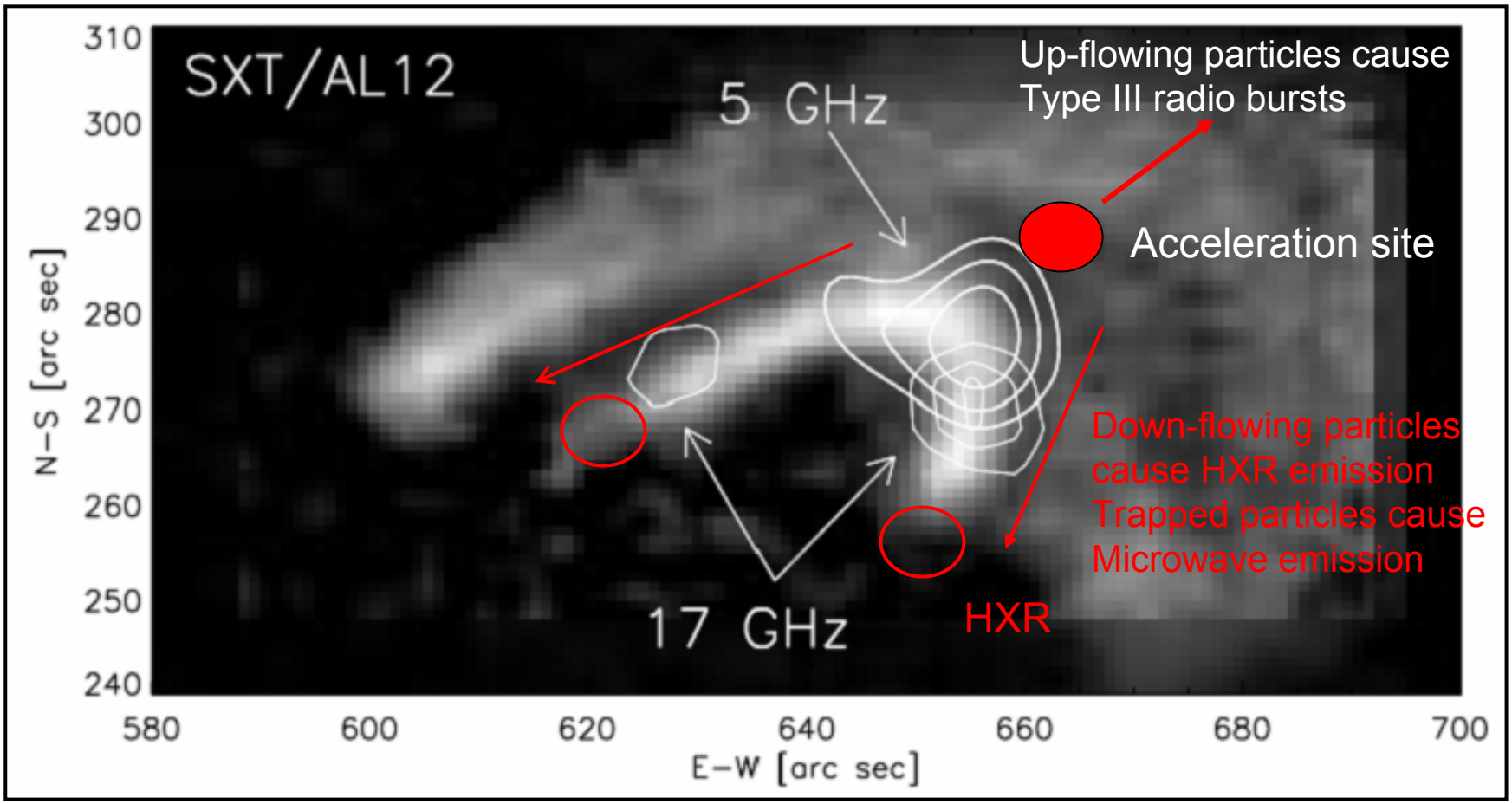


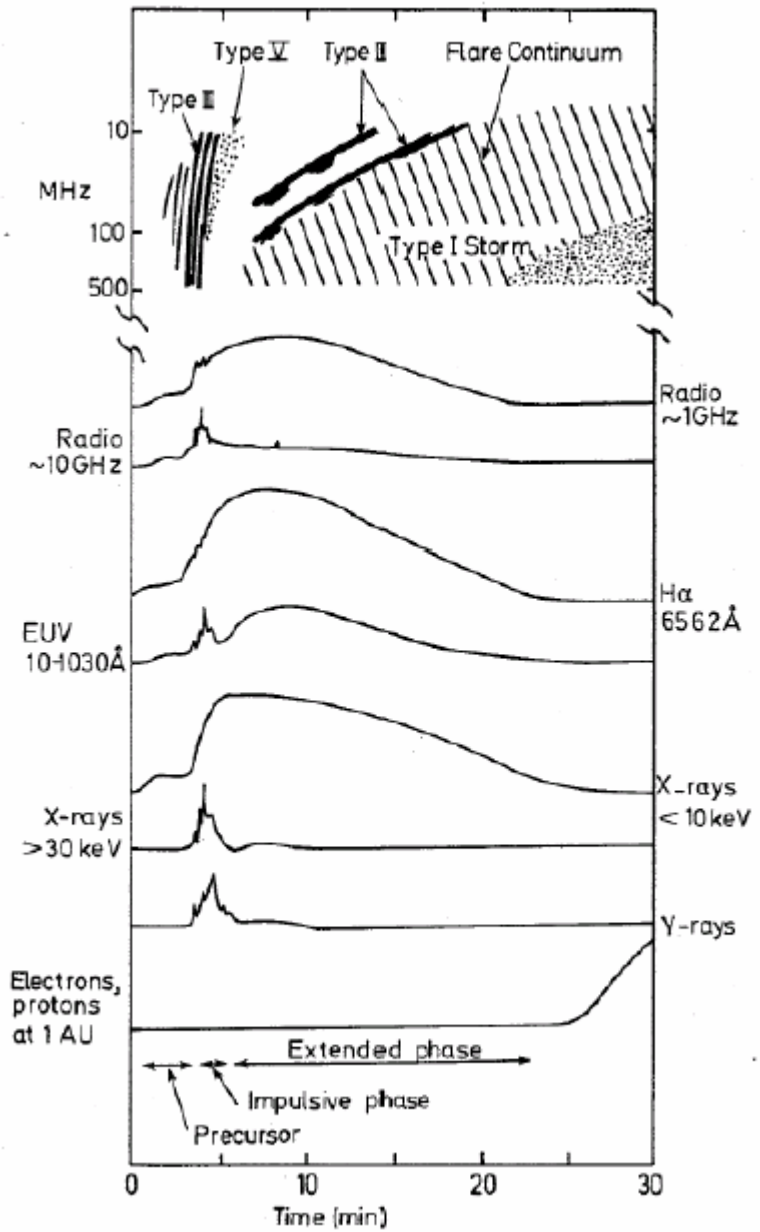


Loop-top source: thermal

Foot-point sources: nonthermal

Upward & Downward electrons





A generic Flare

Thermal (gradual profile)
and nonthermal (impulsive profile)
Components are observed in most flares

The top part is a radio dynamic spectrum
Showing
Type III, V bursts due to electron beams from the flare site
Type II busts: due to shocks from the associated CME
Type IV bursts (aka flare continuum) due to electrons trapped in post-flare loops

Type I storm sometimes develops after flare effects end

A Type II Radio Burst

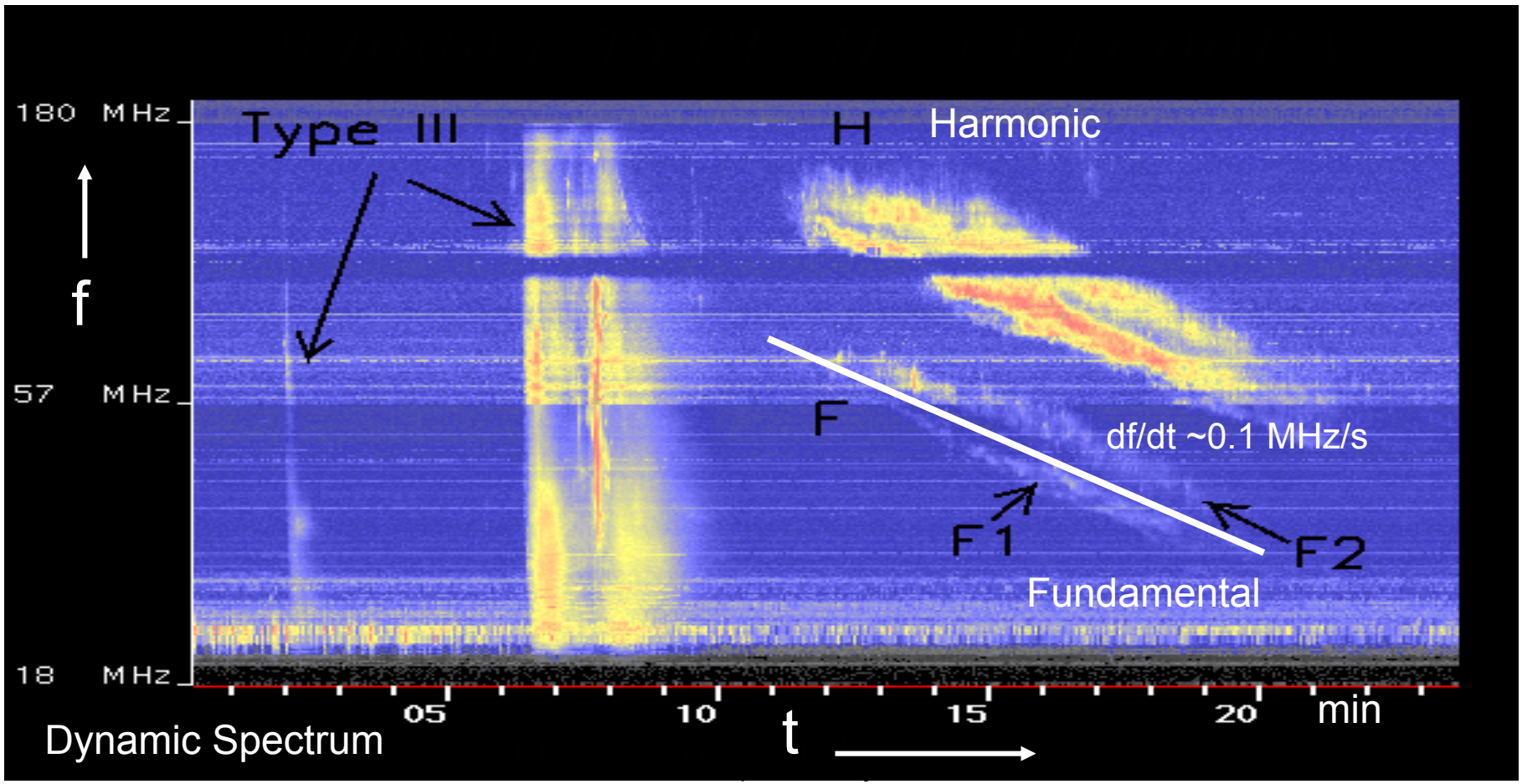
Type III (electron beams) v ~ 0.3 c

Type II (shocks) v ~ 500 km/s

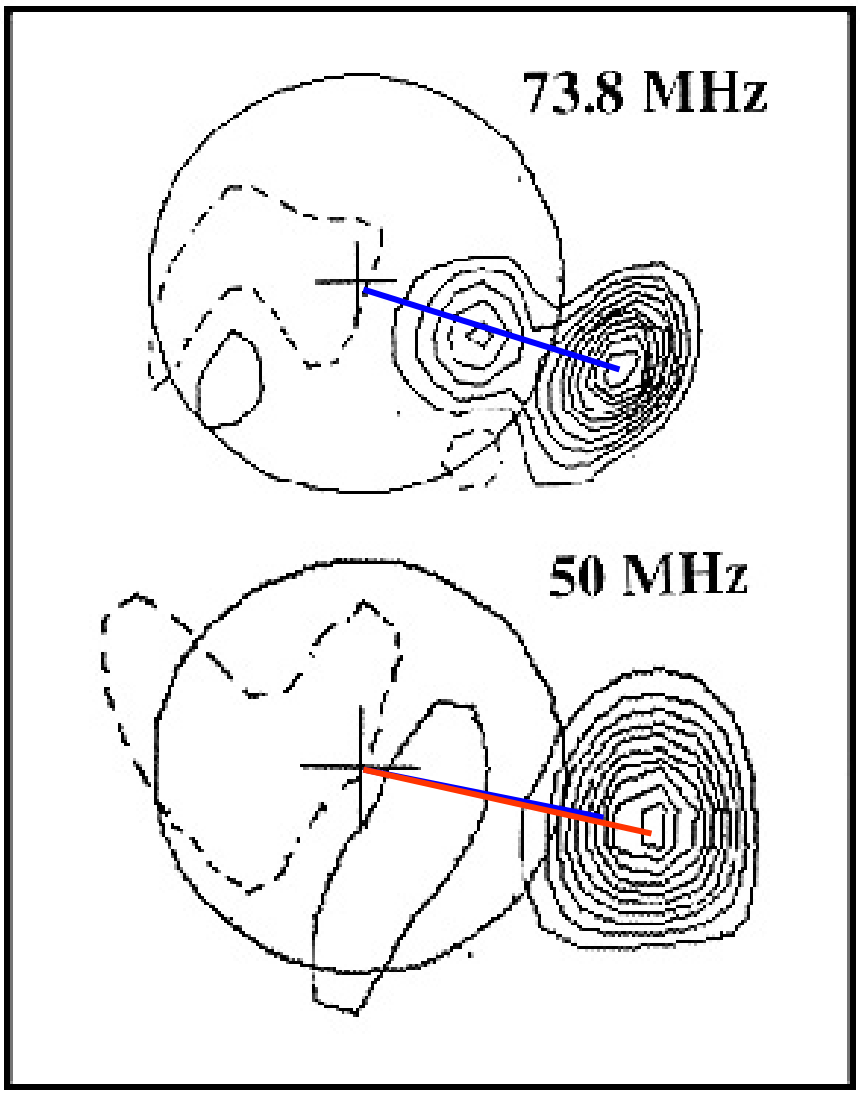
$df/dt = df/dr.dr/dt = (V/2)\, f\, n^{-1}(dn/dr)$

$V = 2L(d\ln f/dt)$

$f \sim n^{1/2}$ (plasma frequency)

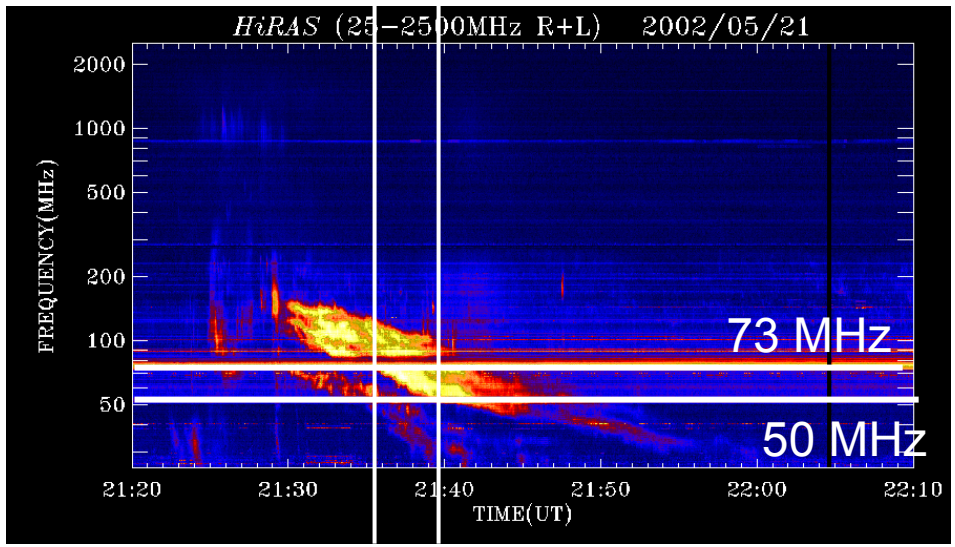


Images of a type II Burst

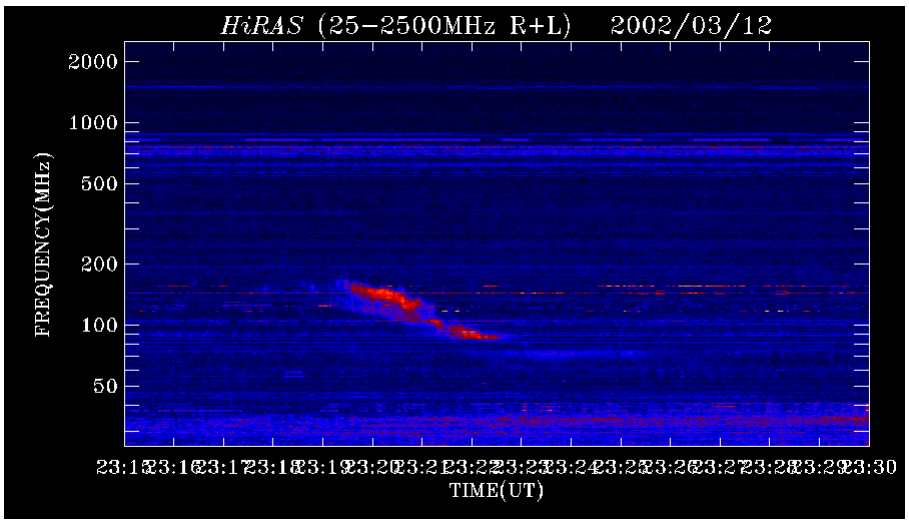


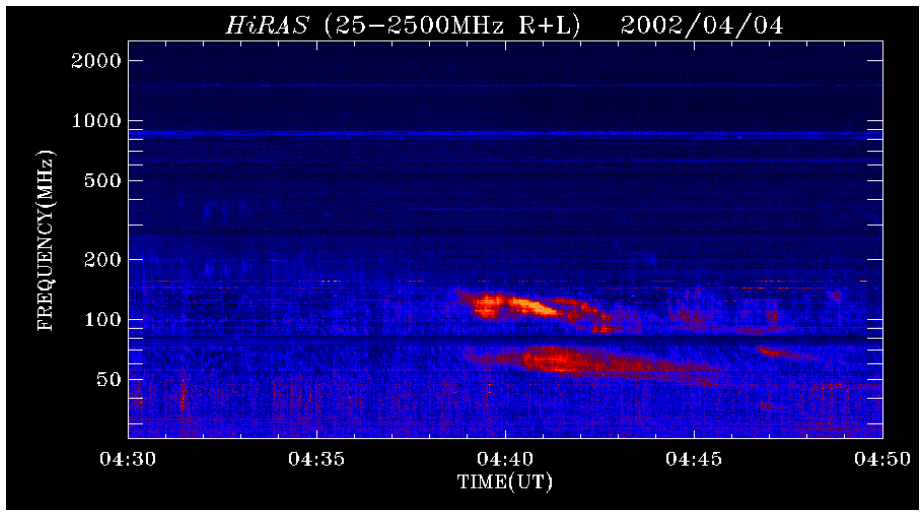
- Imaged by the Clark Lake Radioheliograph in the 1980s
- Brightness temperature contours

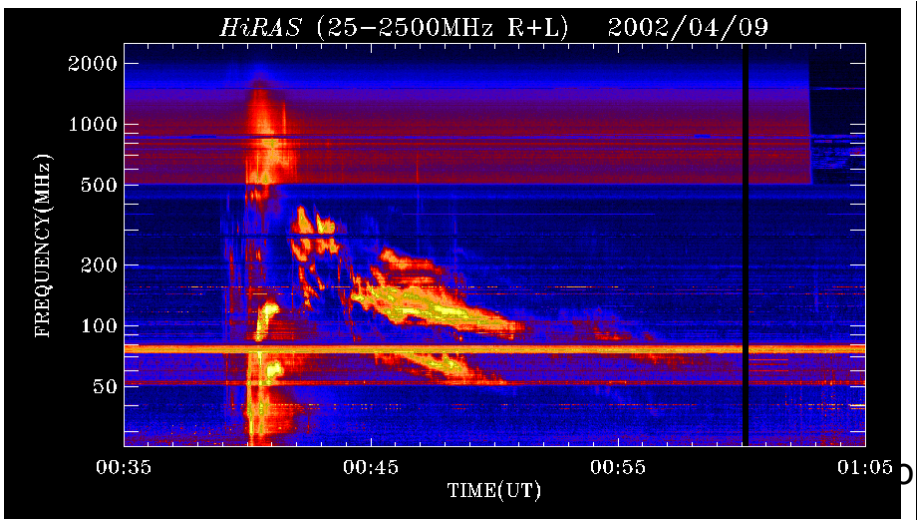
- Lower frequency burst occurs farther from the Sun (also later in time, hence the drift)

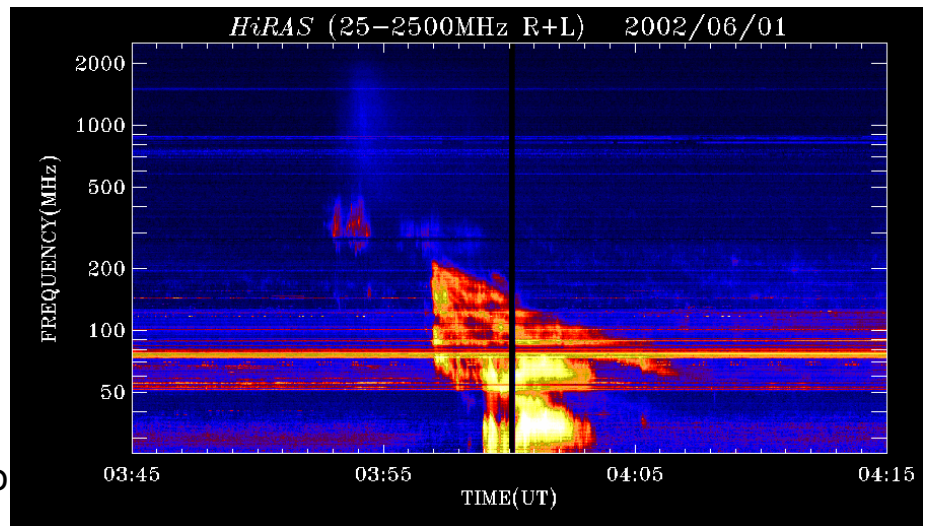


Type IIs with & w/o type IIIs





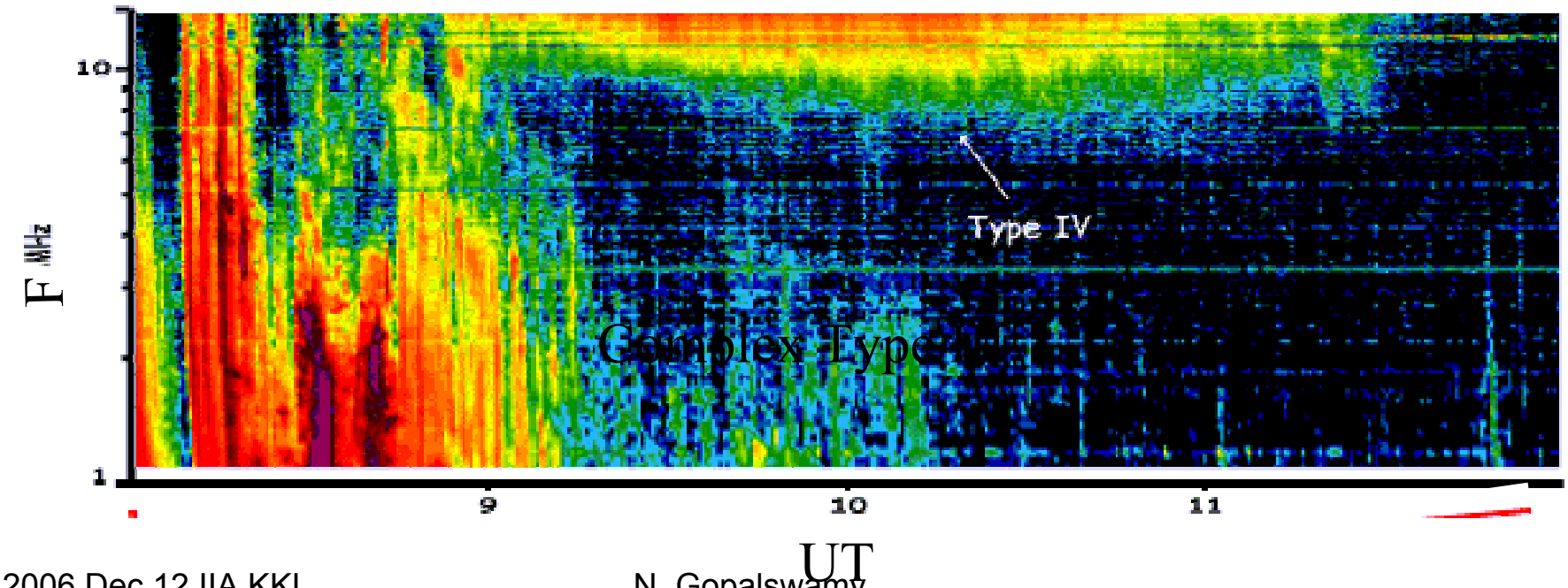




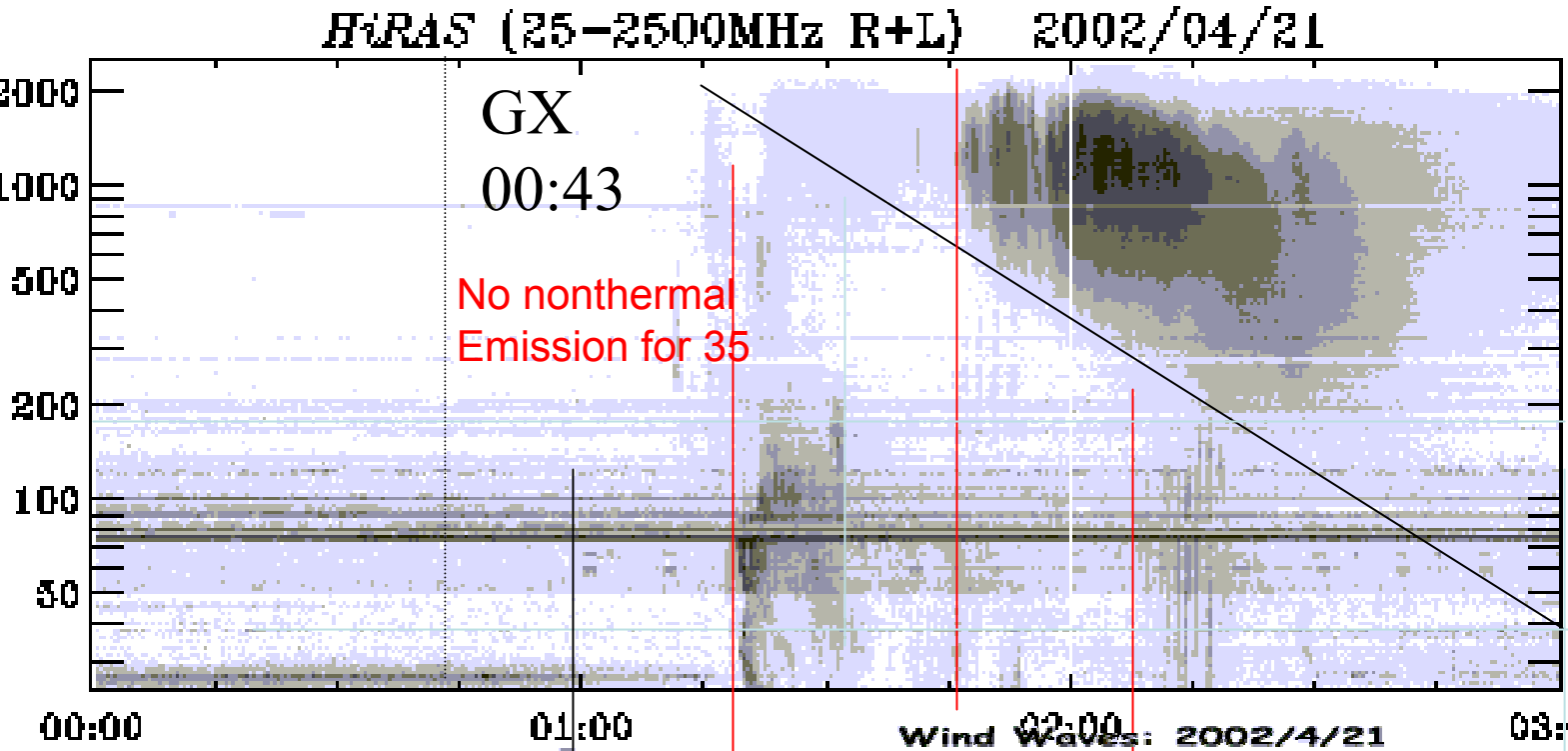
Low Frequency type IV

From tall Post eruption arcades

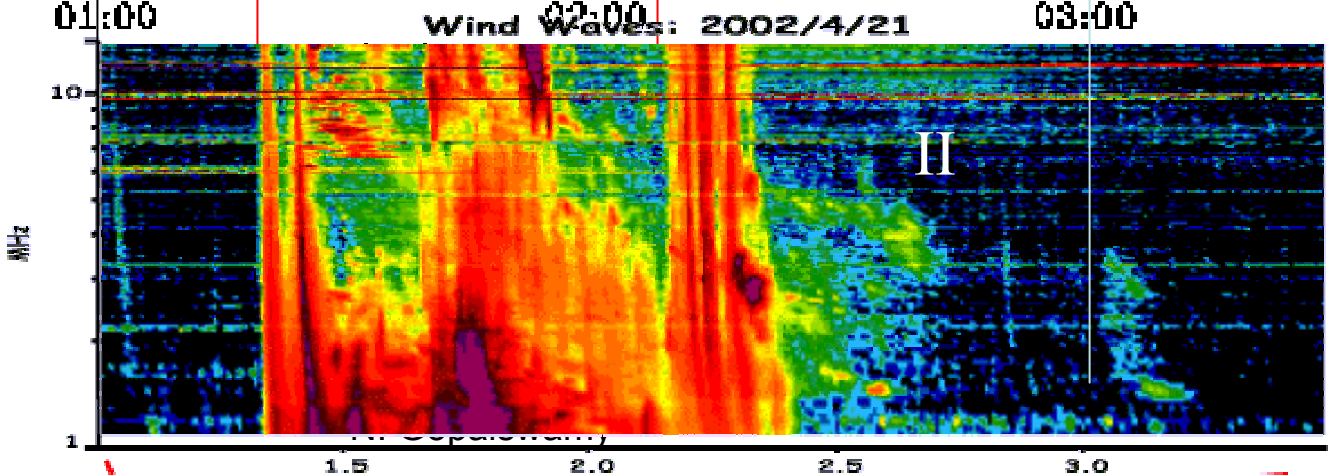
2002 04 17



1:47 to 2:45 slow drift continuum: 2000 to 200 MHz; df/dt = 0.5 MHz/s

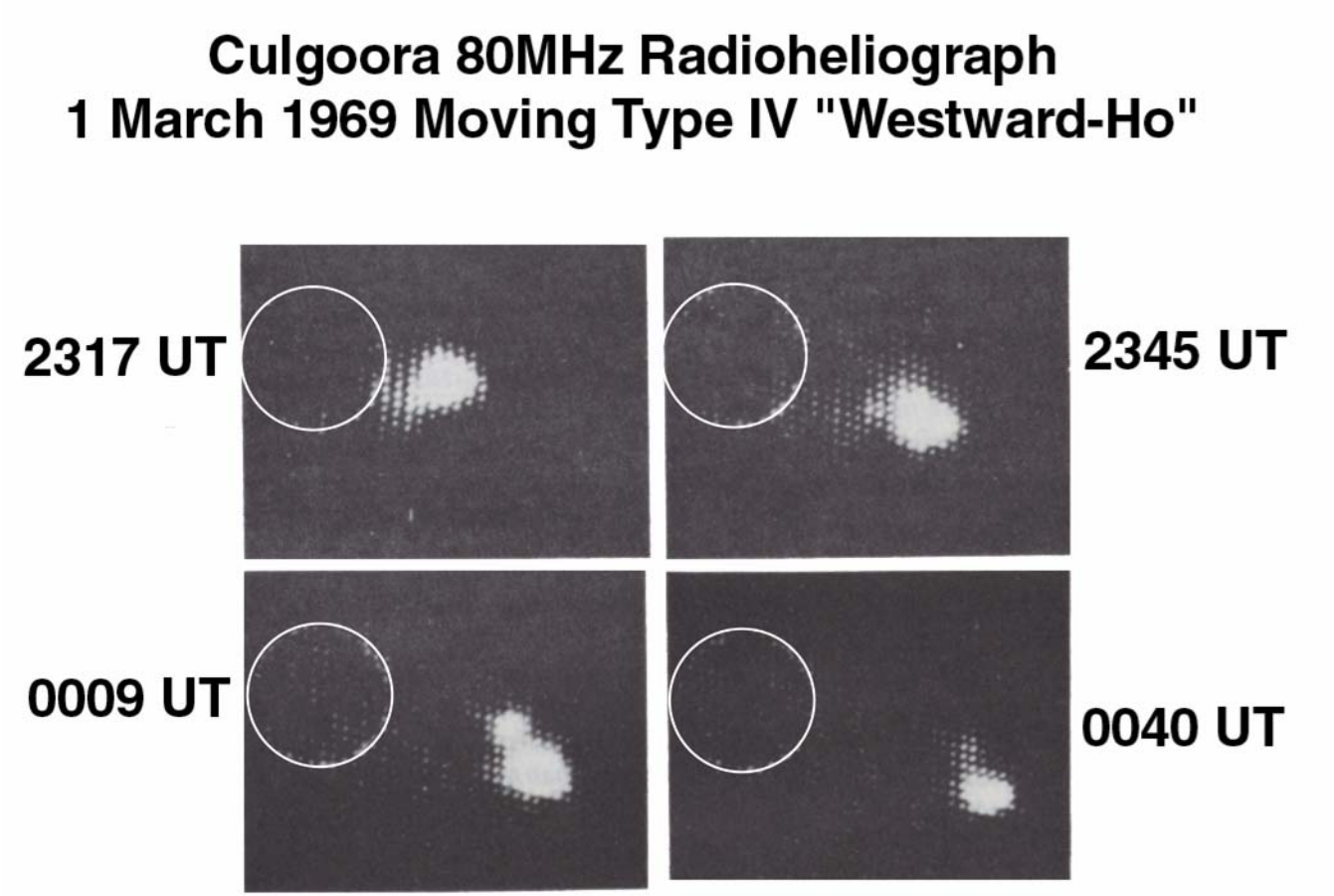


SEP release is consistent with onset of radio

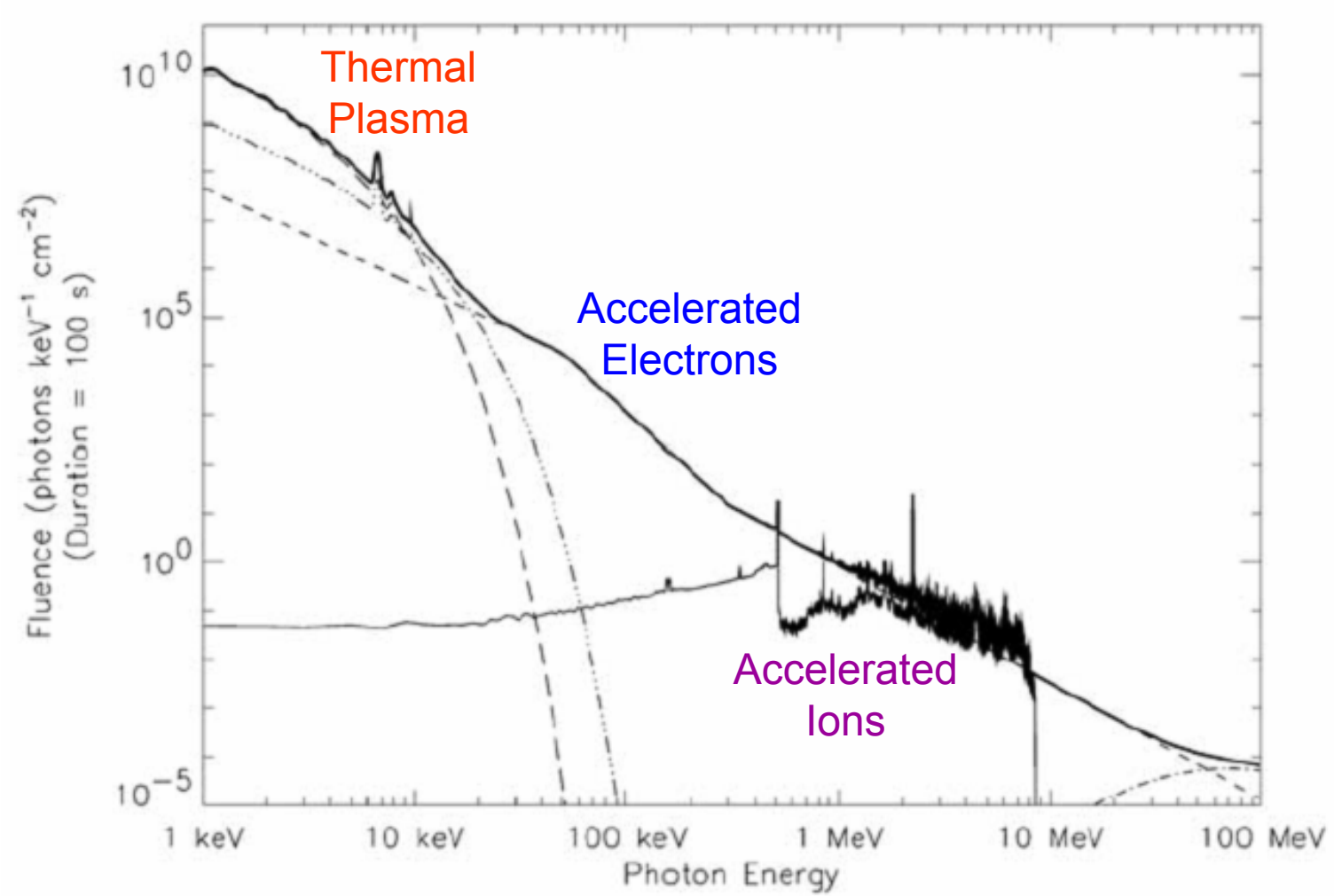


2006 Dec 12 IIA KKL

Moving type IV burst (Related to CMEs)



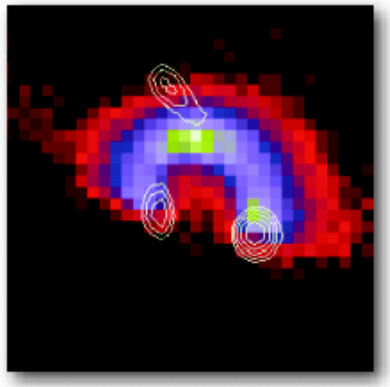
Composite Spectrum from a Large Flare: electrons and ions



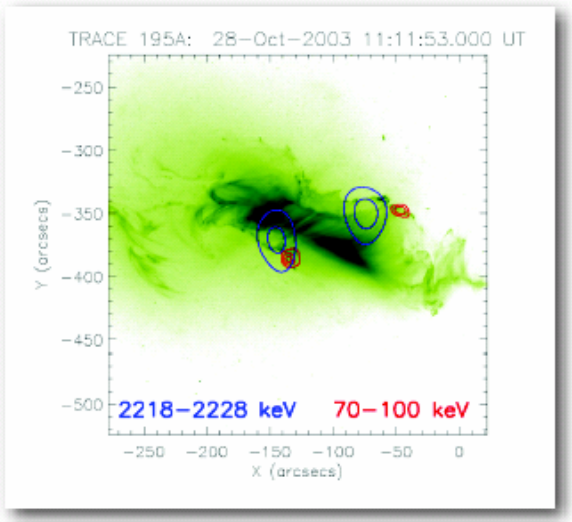
Holman

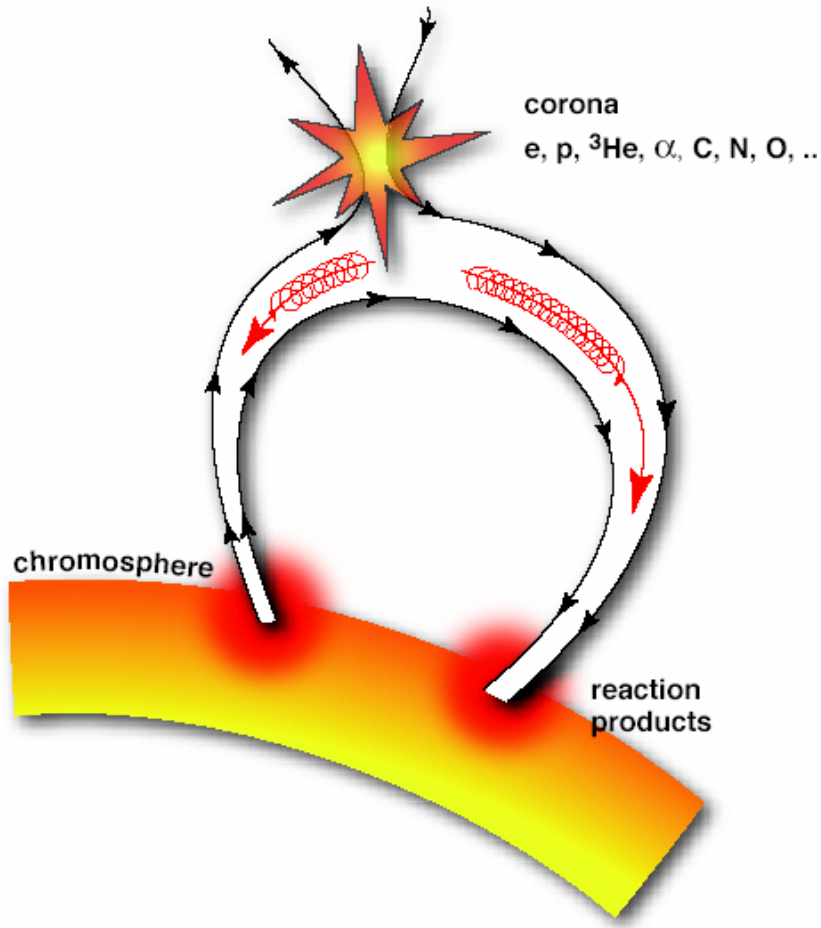
Particle Acceleration in flares

Yohkoh



RHESSI





Murphy

Flare-accelerated electrons and ions

- Electrons

- X-ray and gamma-ray continuum

- Ions

- excited nuclei → gamma-ray line radiation (1-8 MeV)

- Radioactive nuclei → positron + gamma

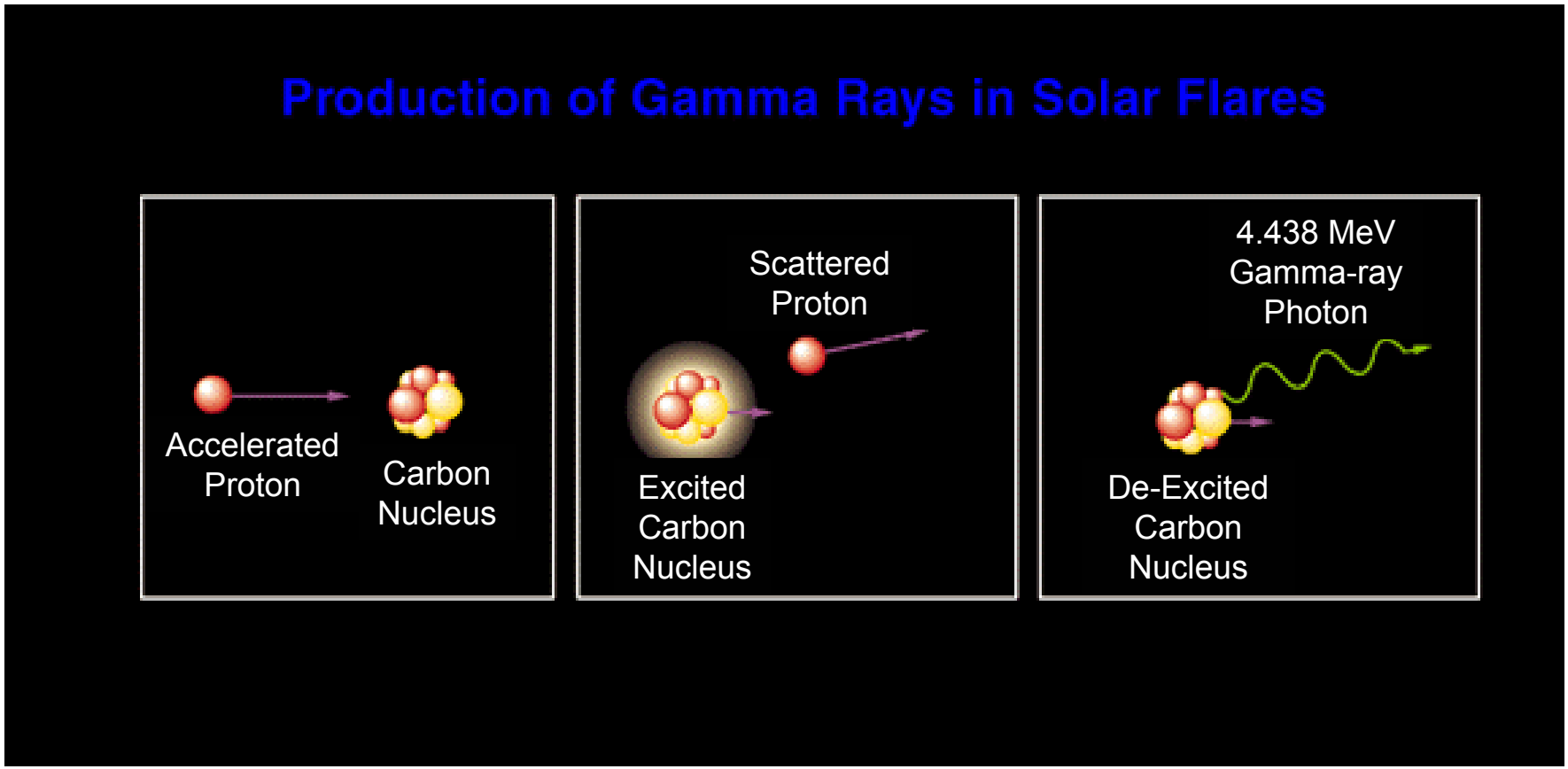
- Pions → electrons, positrons, neutrinos, gamma

- neutrons

- - Escape to space (direct detection by neutron telecopes)

- - Capture on H to produce 2.223 MeV line

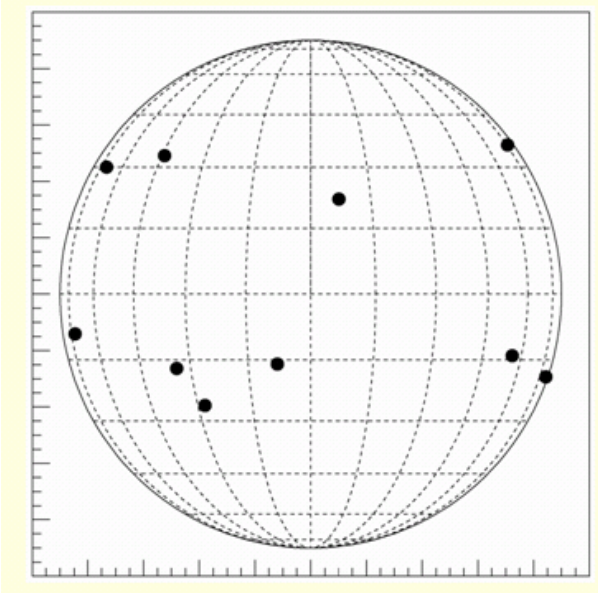
Example: Nuclear De-Excitation leading to 4.4 MeV gamma ray line



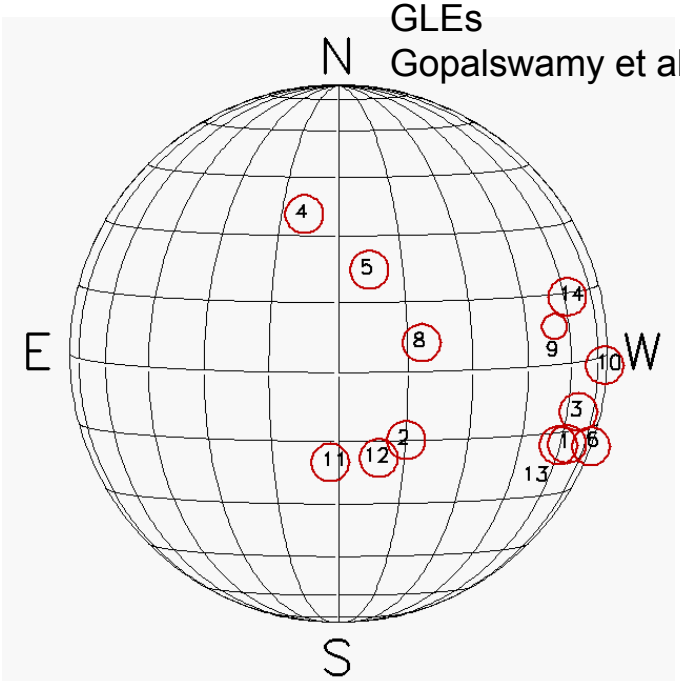
Holman

neutrons

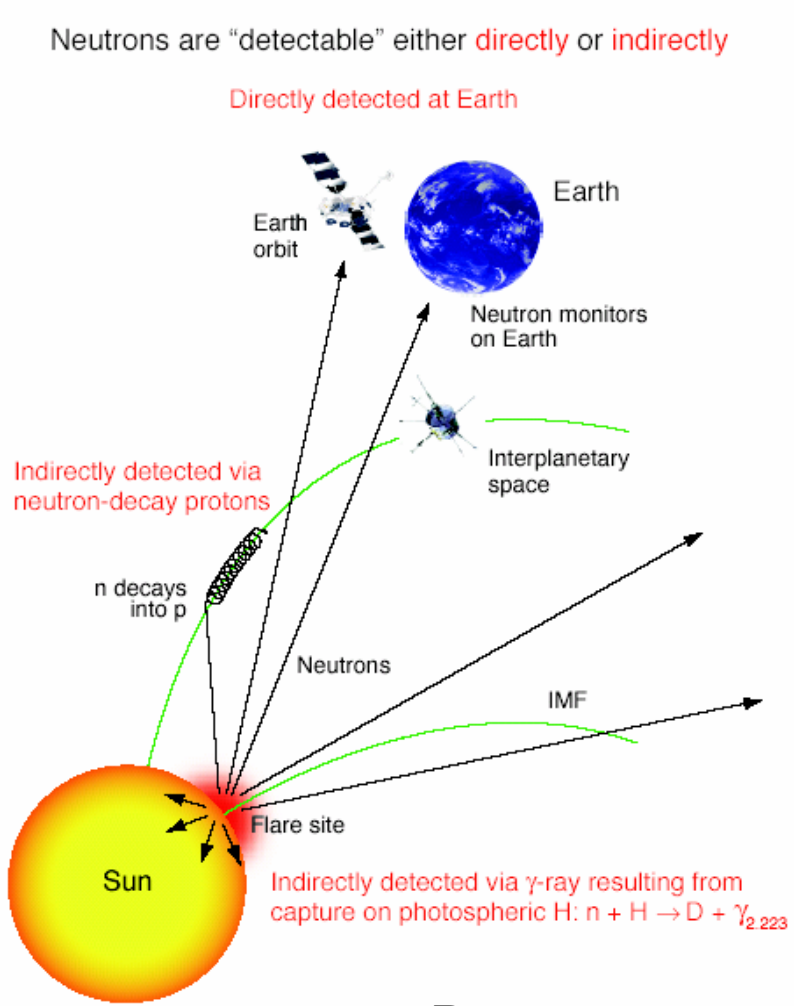
Direct neutrons:
Watanabe et al. 2005



GLEs
Gopalswamy et al. 2005



N. Gopalswamy



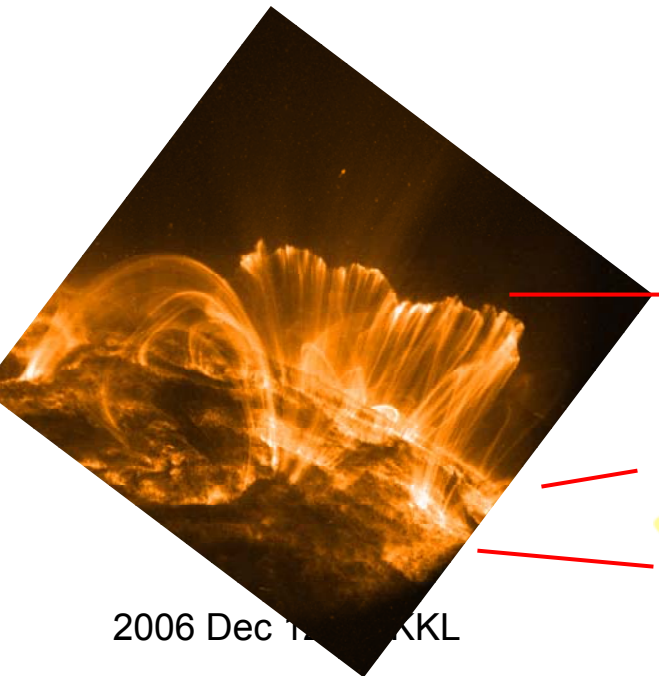
Ryan

Confined vs. Eruptive Flares

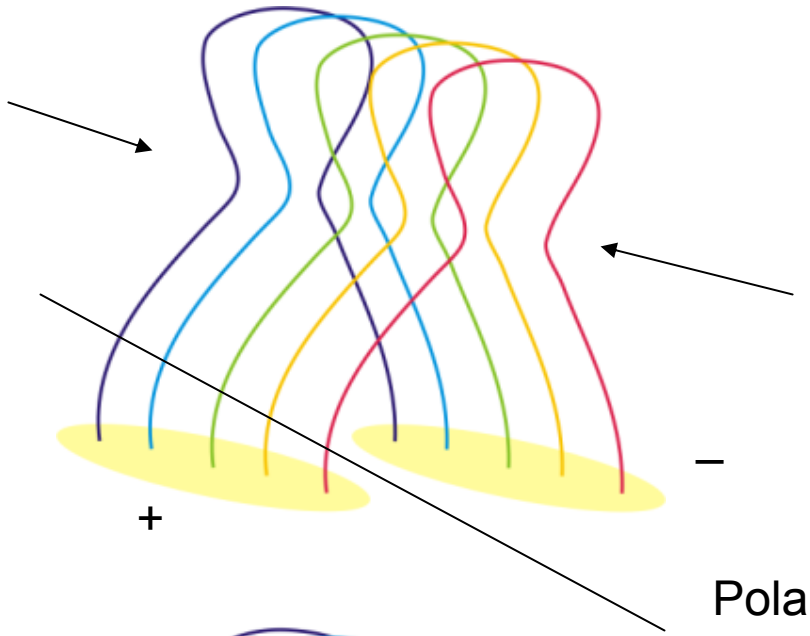
- Confined: generally a single loop
- Eruptive:
- associated with erupting prominence
- CME
- type II radio burst
- two - ribbon flares
- Post-eruption arcade

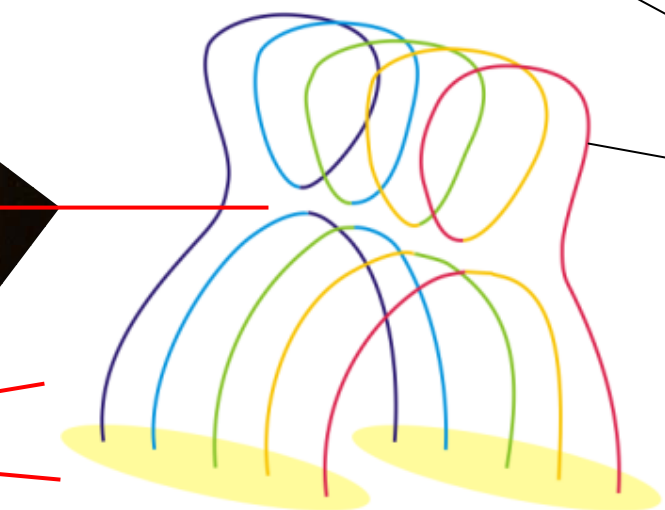
- Impulsive and gradual flares

3-D Reconnection for Eruptive Flares



2006 Dec 1[illegible]KKL

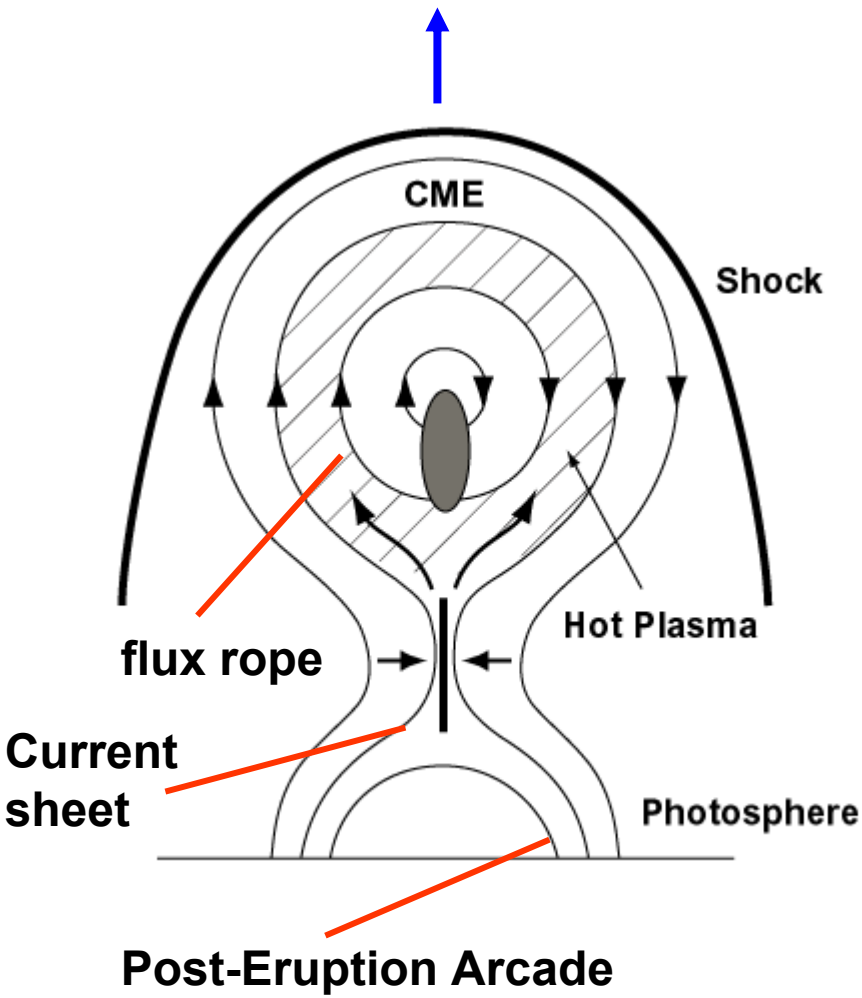




N. Gopalswamy

Holman

Eruptive flares and radio bursts



Particles injected both upwards and downwards.

Upward particles trapped in the CME produce moving type IV bursts.

Those trapped in the flare loops produce “stationary” type IV bursts

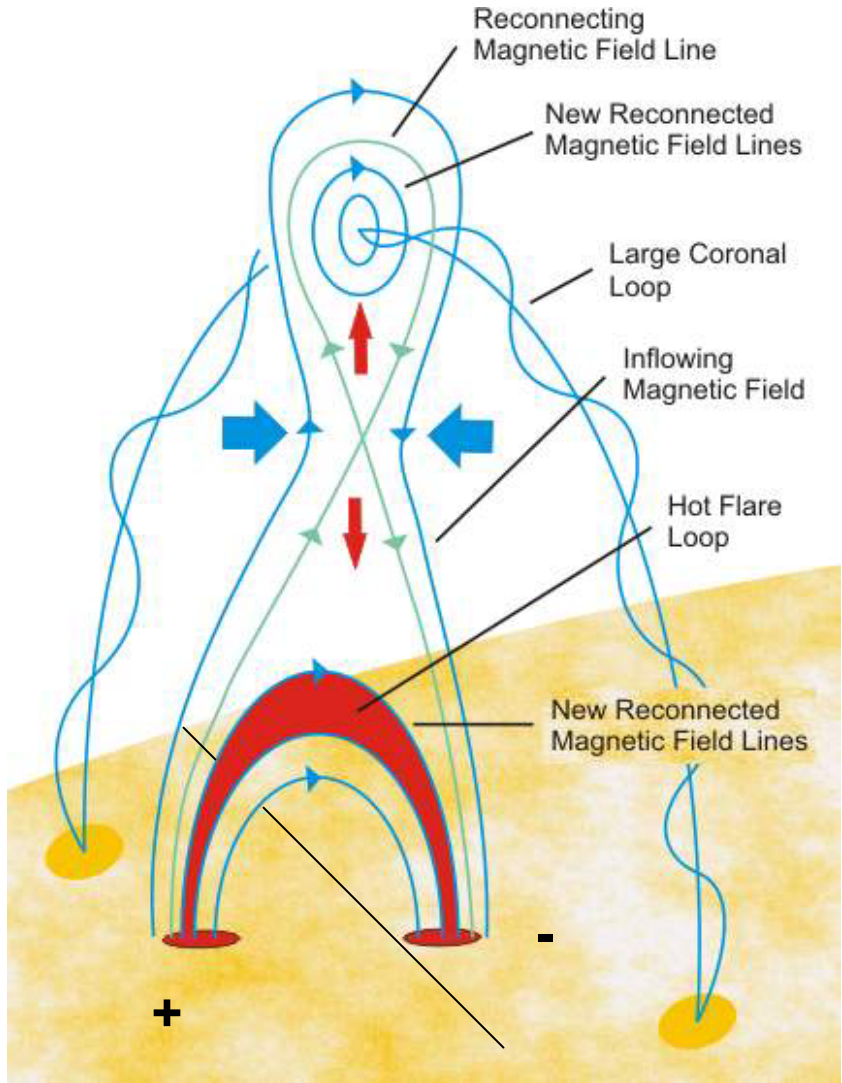
The reconnection takes place at the current sheet heating the plasma. The hot plasma is trapped in the CME structure.

Higher temperature results in higher charge states, which get frozen near the Sun because the ions do not interact in the IP medium.

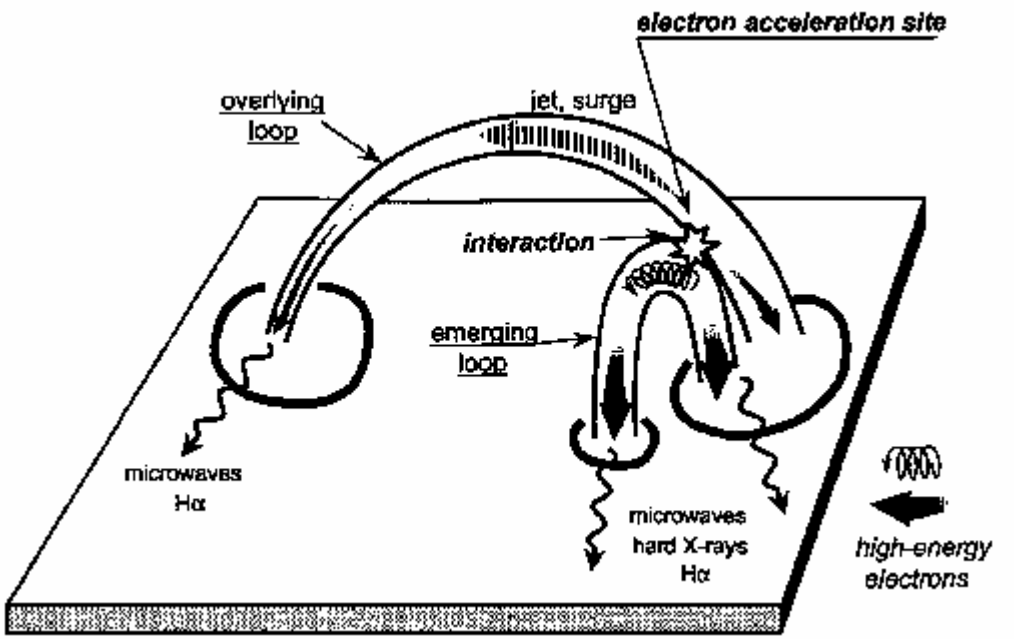
The prominence material is rarely seen at 1 AU because it typically has a smaller volume.

Martens and Kuin

The “Standard” Model for Eruptive Flares



Interacting Loops



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

Solar Energetic Particles (SEPs)

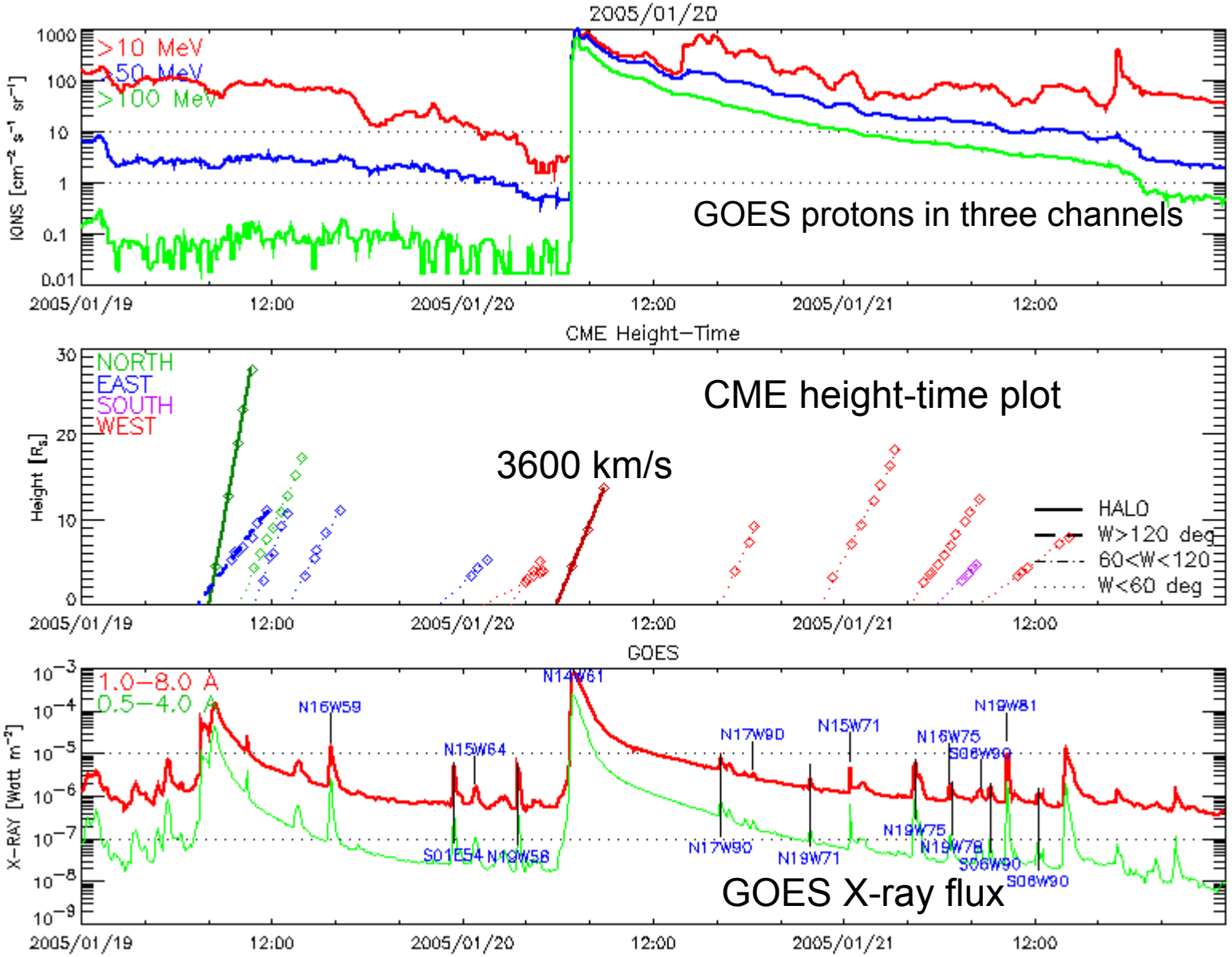
- From flares or CMEs
- Ions inferred from X-ray and gamma-ray observations indicate flare origin
- Interplanetary data indicate CMEs
- Some mixed events, especially in western events
- CME shock accelerates particles from previous flares and/or concomitant flare?

Solar Energetic Particles

- **Solar Energetic Particles (SEPs) are ions and electrons that are accelerated to energies from 1 MeV to over 1GeV**
- **They can be accelerated in a Flare or by a CME Shock (Reames, 1997) and can be divided into two classes:**

		Impulsive	Gradual
	Source	**Flares**	**CMEs**
Particles		Electron Rich	Proton Rich
	3He/4He	~1	~0.0005
	Fe/O	~1	~0.1
	H/He	~1	~100
Duration		Hours	Days
Longitude Cone		<30 Deg	~180
X-Rays		Impulsive	Gradual
Events/Year		~1000	~10

SEPs in the IP Medium



3-day plots useful for connecting CMEs, flares, and SEPs.

The flare Locations are also given.

This major SEP event was associated with an ultrafast CME and a major flare

Some Outstanding Issues

- How are the energetic particles “seen” in microwaves related to those “seen” in hard X-rays?
- How can electron and ion produced sources be in different locations?
- What is the exciter of white light flares?
- Relationship of impulsive SEPs and particles producing flare X-ray and gamma-ray emission.
- What is the relative amount of energy injected directly into plasma heating vs. particle acceleration?
- What is the relative amount of energy injected into electrons vs. ions?
- What is the relative amount of energy injected directly into cooler plasma vs. “hot” plasma?
- What is the total magnetic energy released in each flare?