X-ray and γ-ray observations of solar flares

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Overview

- The impulsive phase
- Non-thermal flare emission; hard X-rays, UV/WL, μwaves
- The collisional thick target model
- Challenges for the collisional thick target model
- Summary

*With major help from
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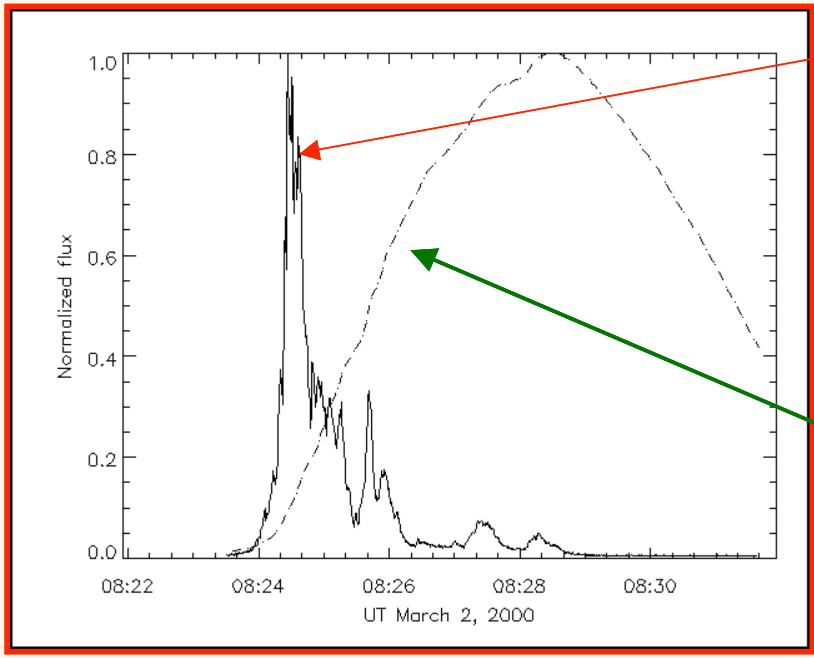
U. of Glasgow, UK

A flare/CME seen in EUV and X-rays

Red RHESSI 6-12 keV, blue 50-100 keV, gold images TRACE 195A

Impulsive phase and gradual phase

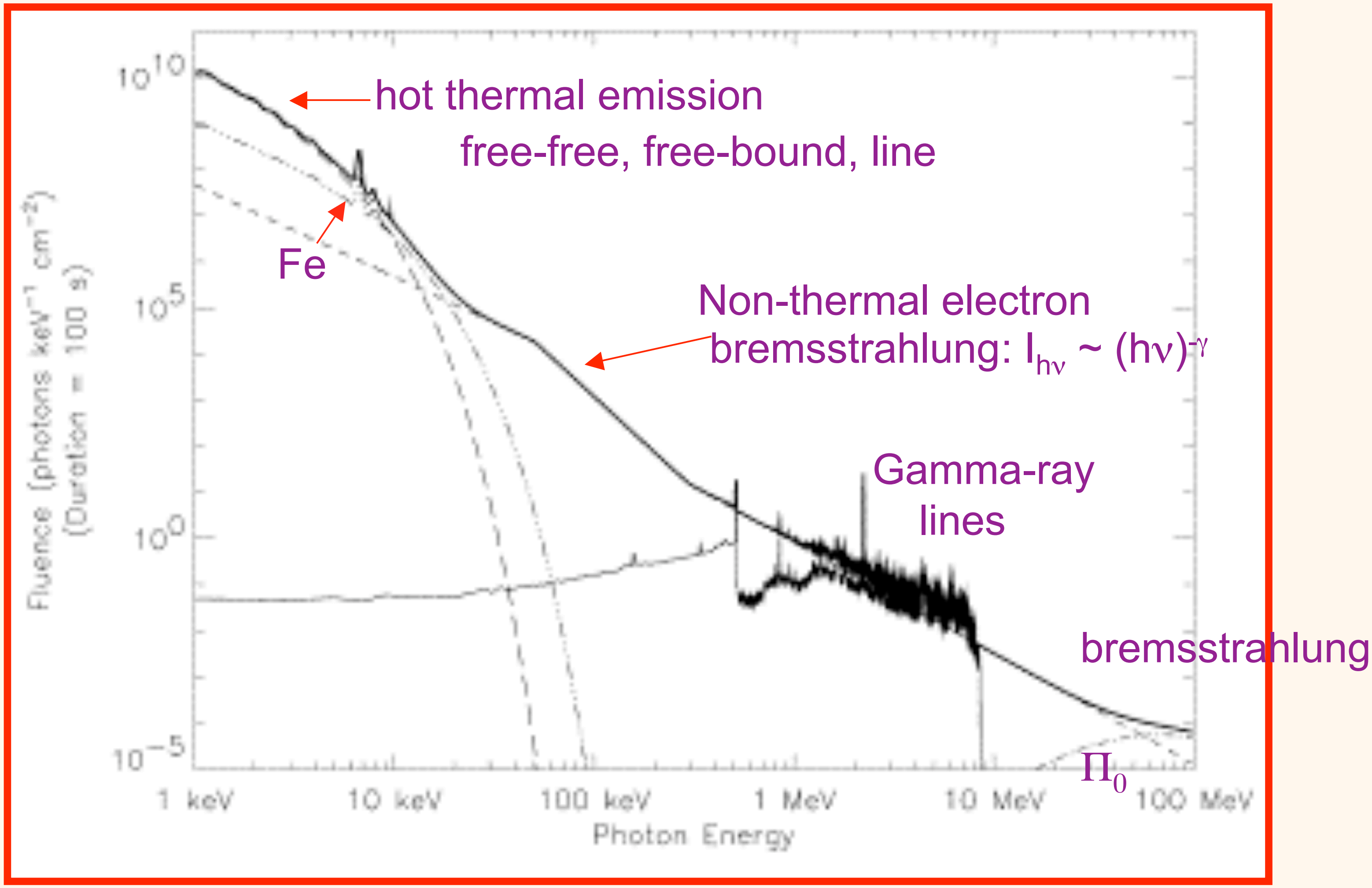


Impulsive phase – primary energy release
- hard X-rays (10s of keV)
- white light, UV, μwaves - broad spectrum
- duration < few minutes
- intermittent and bursty time profile, 100ms

Gradual phase - response to input
- thermal emission (kT ~0.1-1 keV)
- rise time ~ minutes

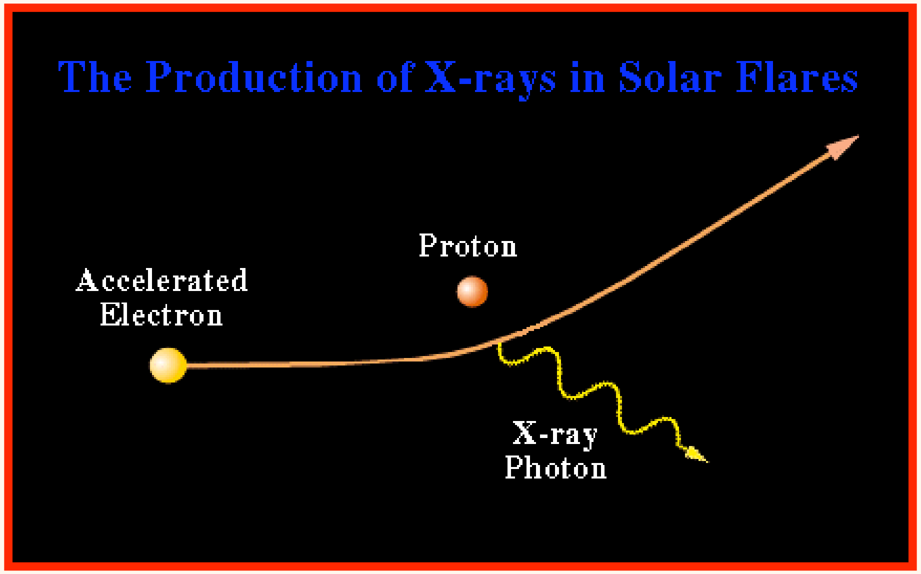
Impulsive phase:
- > few tenths of the total flare energy released (up to 10^{32} ergs)
- Significant role for non-thermal electrons
- CME acceleration

Impulsive Phase Spectrum



X-Rays

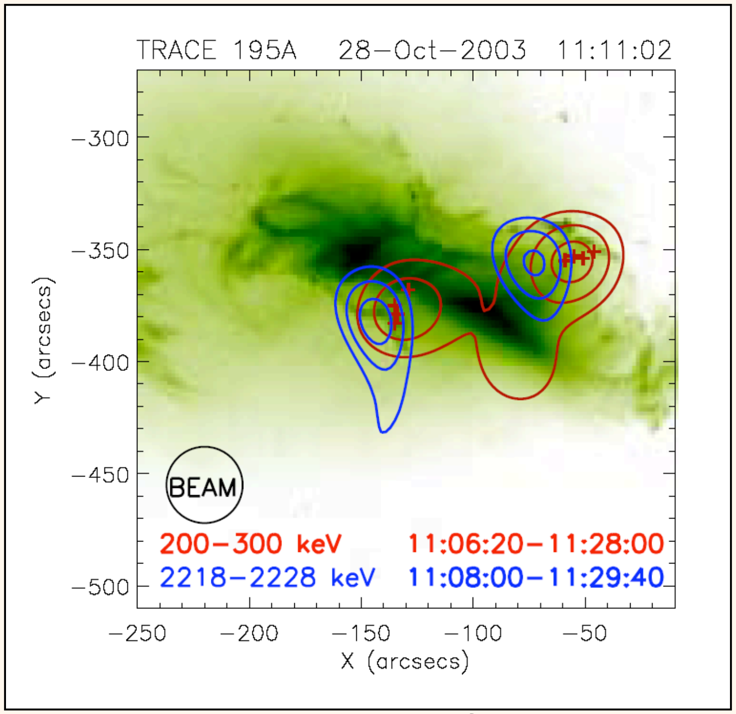
X-rays observed by e.g. RHESSI are primarily electron-proton bremsstrahlung from energetic electrons (>15 keV)



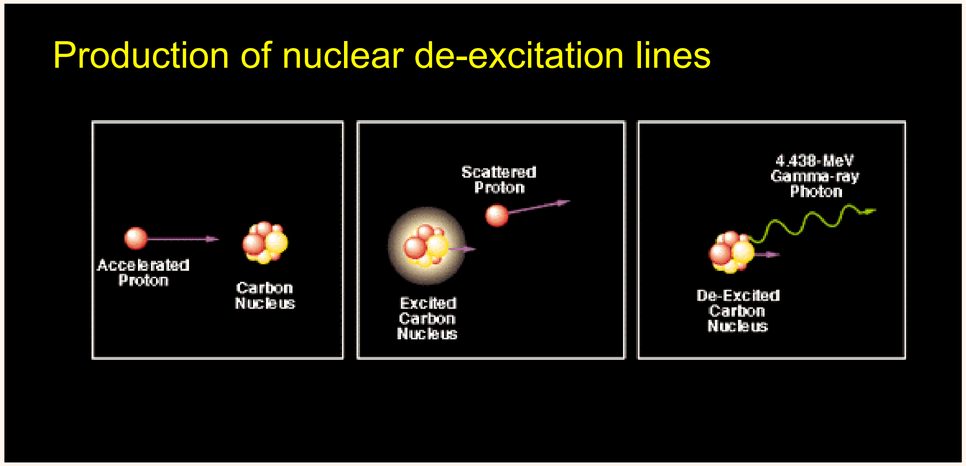
- Non-thermal bremsstrahlung: E_e >> kT and photon spectrum $I_{h\nu} \sim (h\nu)^{-\gamma}$
  - not a significant energy loss: ~ 10^{-5} of the energy radiated as X-rays
- Thermal bremsstrahlung: E_e ~ kT and photon spectrum $I_{h\nu} \sim e^{-h\nu/kT}$
  - significant energy loss from electrons in a hot gas
- Free-free, free-bound, and bound-bound (line) transitions

Gamma-rays

Nuclear de-excitation lines caused by bombardment of nuclei by 10-30 MeV protons; also neutron emission



Hurford et al 2003



Neutron capture line at 2.23 MeV - n(p,γ)D

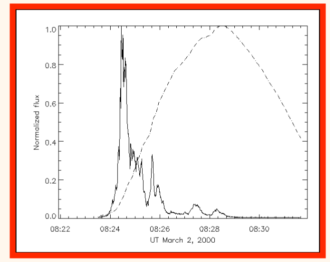
- shows location of 10s of MeV protons

Π_0 -> 2γ decay continuum shows ~100 MeV;

e^+ annihilation line (511 kev) complicated

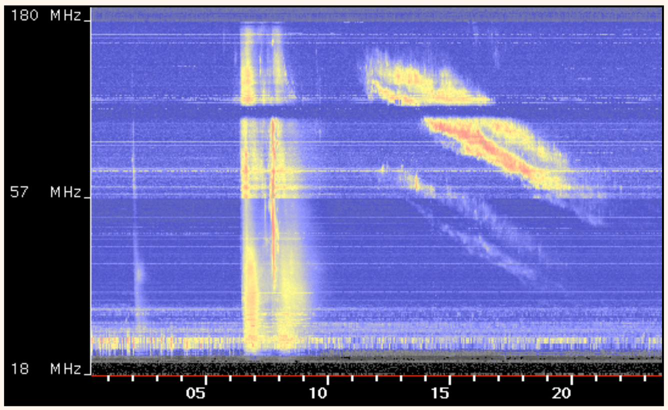
Radio waves

Basic opacity (hence emissivity) of the plasma is the ***free-free process***, which depends on n_e n_i, and T_e. Prominent in the flare gradual phase.



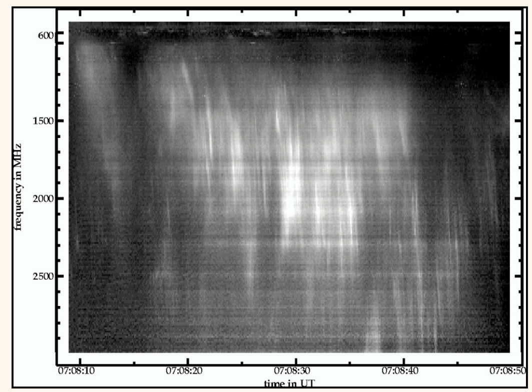
Fast electrons of the impulsive phase emit ***synchrotron emission***. Depends non-linearly on several parameters including **B**.

frequency



time

frequency



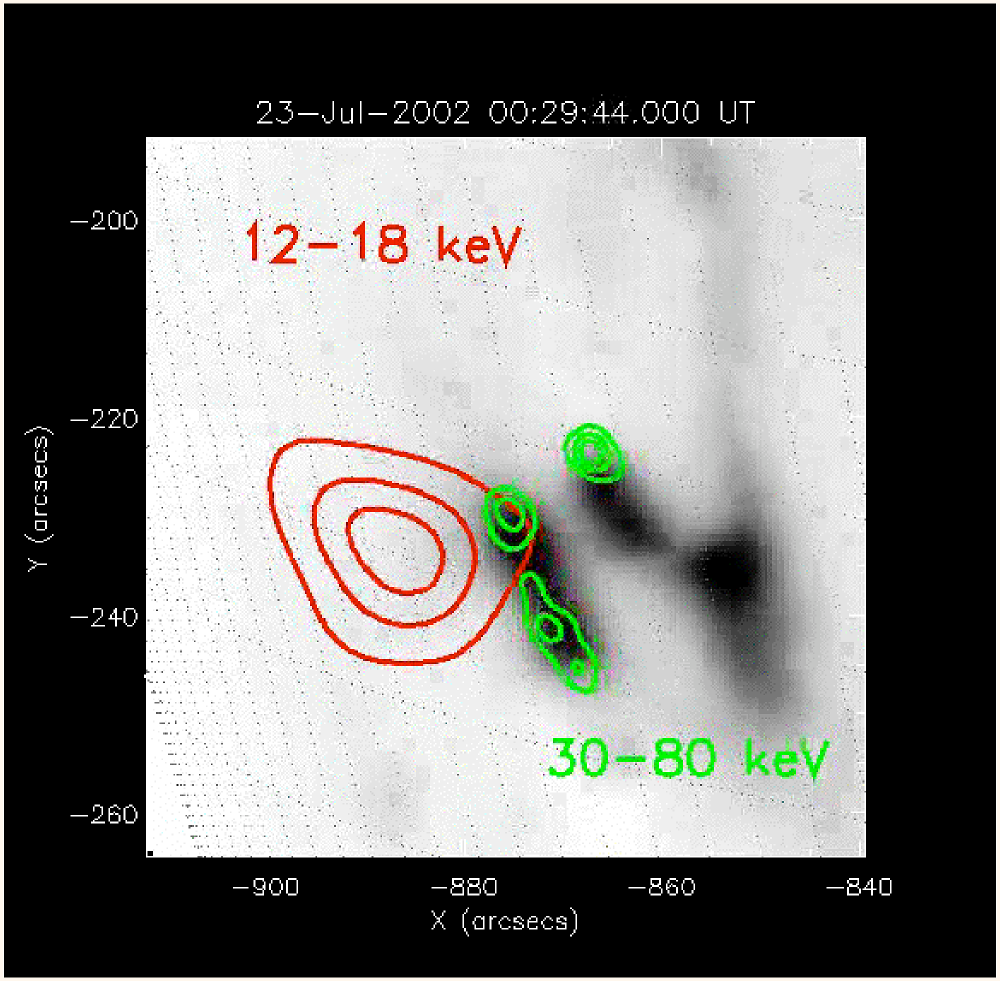
time

Isliker & Benz 1994

Metric and decimetric Type III bursts are often ***plasma radiation*** produced by electron beams (from Langmuir waves at $f_p \sim n_e^{0.5}$).

Upward and downward-going *beams* sometimes observed, occurring at peak time of HXR emission. *Spectrograms* reveal the dynamics.

Footpoints and Looptops



Usual behavior:

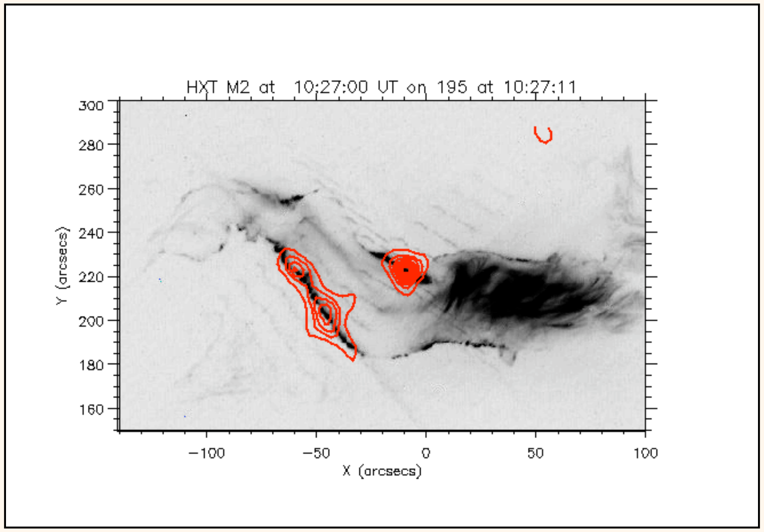
low energy X-rays with a thermal spectrum are emitted high in the corona (at the tops of flaring coronal loops)

Higher energy X-rays with a power-law spectrum are emitted at the footpoints of flare loops.

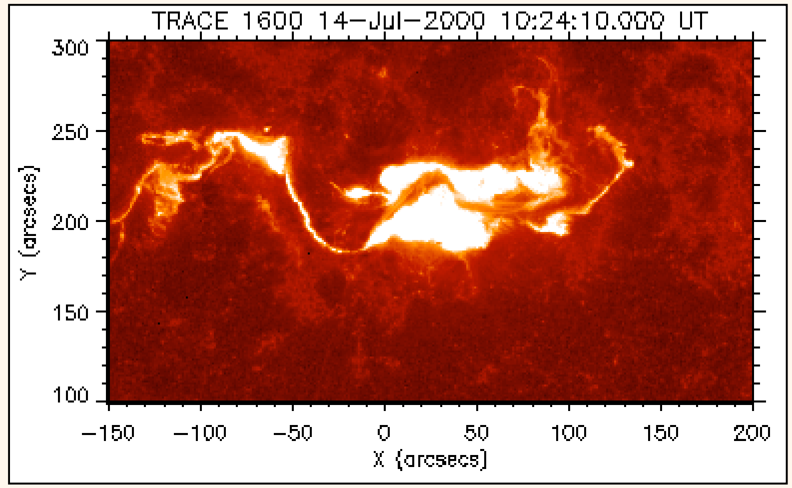
Krucker 2002

Other Impulsive Phase Emission

UV/EUV, H_α and (sometimes) optical emission demonstrate excitation of lower atmosphere



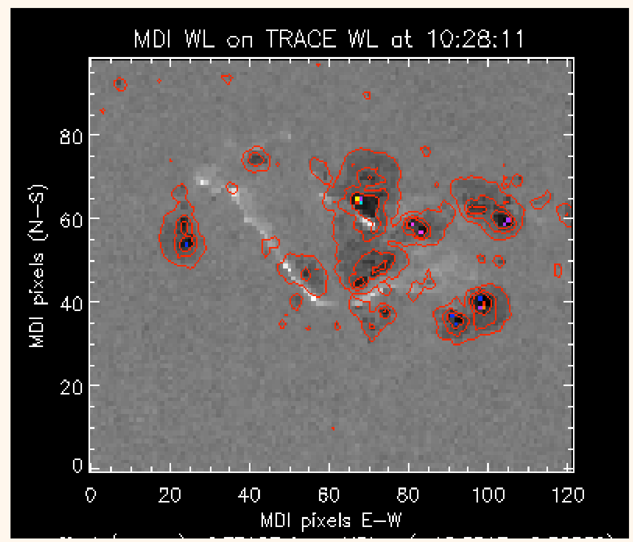
Yohkoh HXR contours on 195A emission



1600A broadband emission

Optical/UV/EUV emission from heat deposition / ionization / collisional / radiative excitation

White-light luminosity can be directly measured.



White-light footpoints

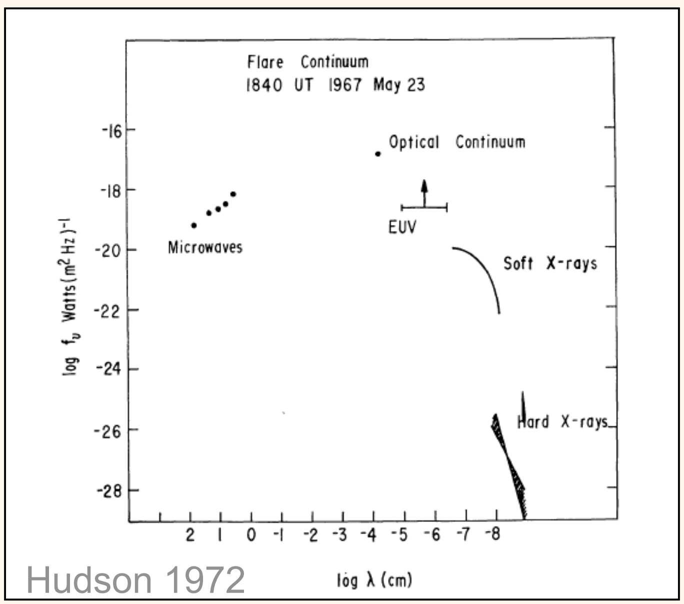
Fletcher & Hudson 2001

Role of 'white light' in total flare luminosity

Substantial fraction of total flare energy radiated in broadband UV-IR

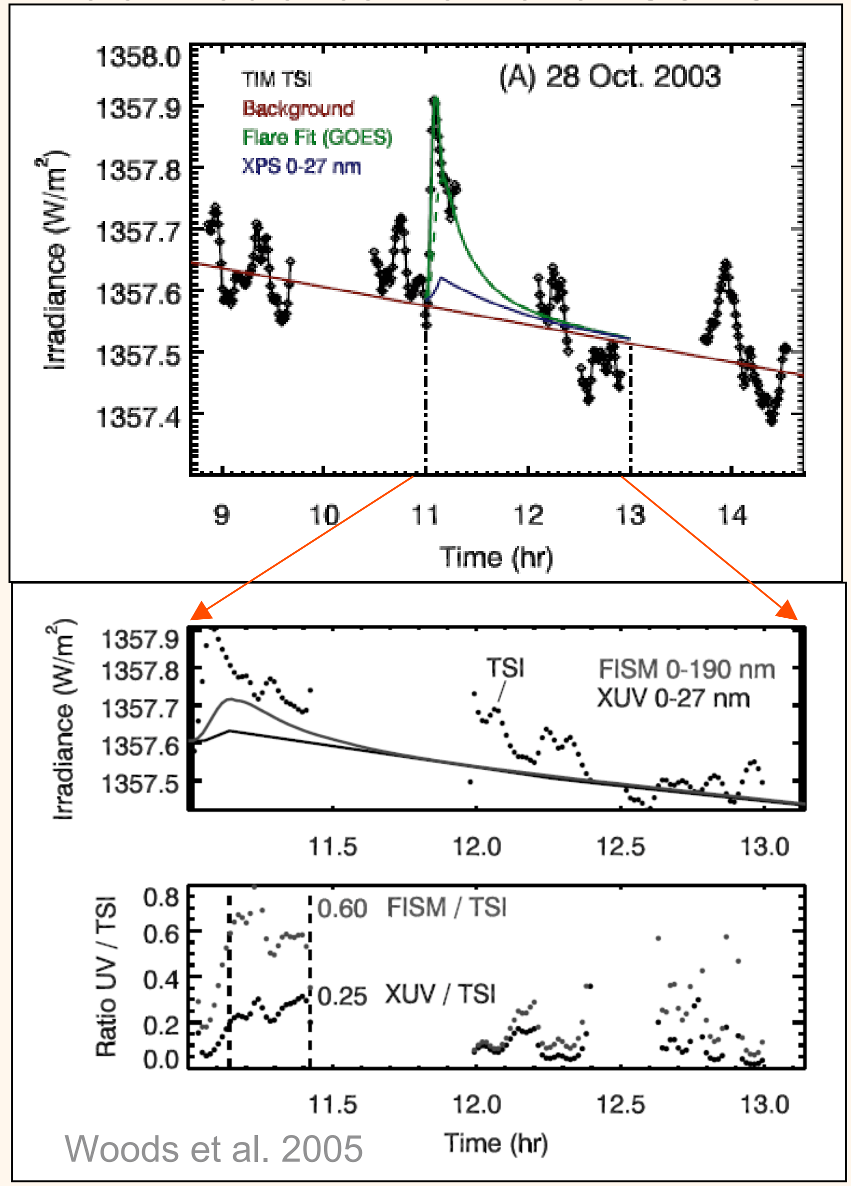
In Oct-Nov 2003 flares, integrated irradiance ~ 3 - 6 $\times 10^{32}$ erg

Spectral modelling $\Rightarrow$ 40-50% of this at $\lambda \geq 1900$Å, ~ 100 times soft X-ray irradiance



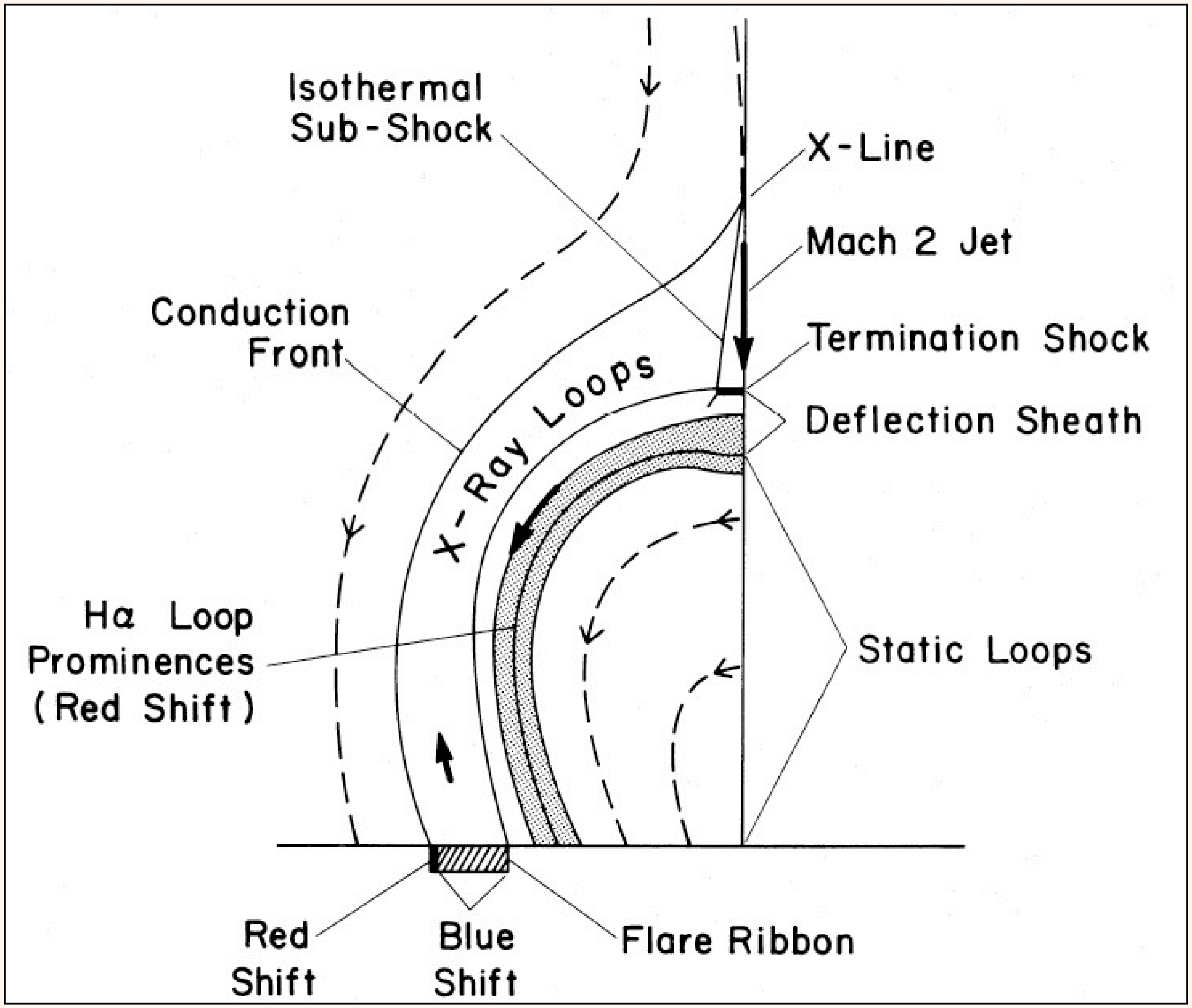
Hudson 1972

Total Irradiance Monitor on SORCE



Woods et al. 2005

The 'standard' 2D cartoon (for orientation)



Schmieder, Forbes et al. 1987

(http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons)

The bigger view

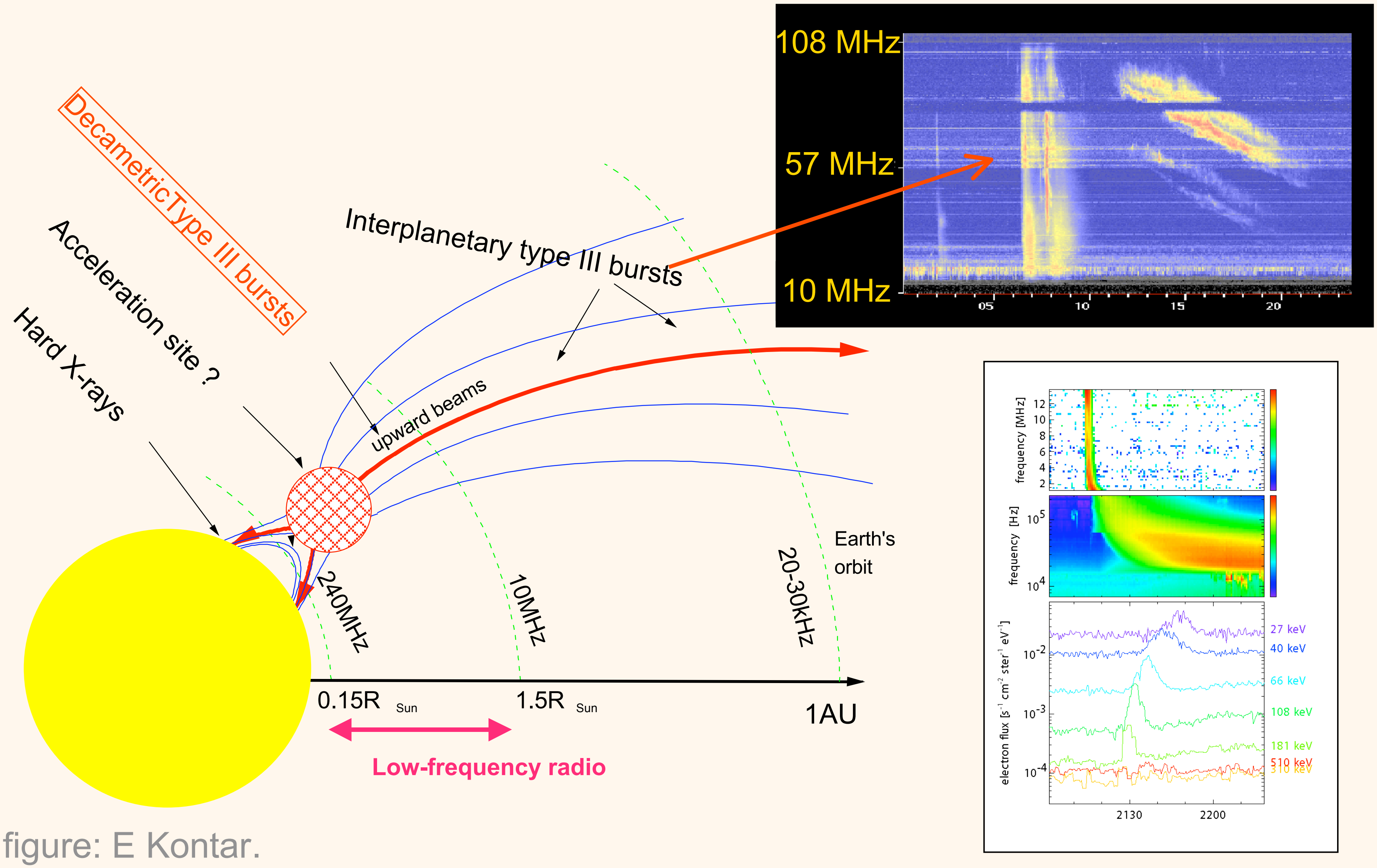


figure: E Kontar.

Collisional thick-target model

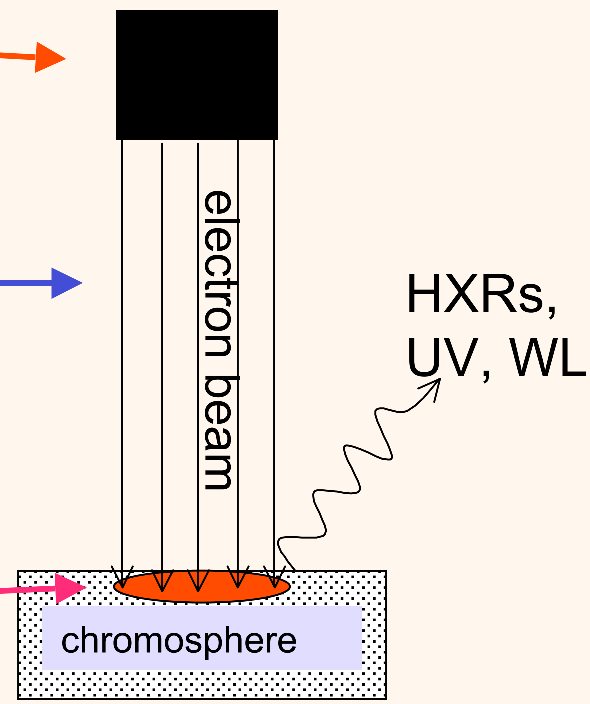
Collisional thick target model has dominated interpretations of flare non-thermal emission for > 3 decades.

Assumes hard X-ray emission is primarily electron-proton bremsstrahlung from electron beam, accelerated in the corona and stopped in chromosphere

Coronal accelerator

Coronal electron transport (generally, 1D and no treatment of plasma collective effects). Much unfinished work…

Bremsstrahlung HXRs and heating/excitation in 'thick target' (single pass) in chromosphere



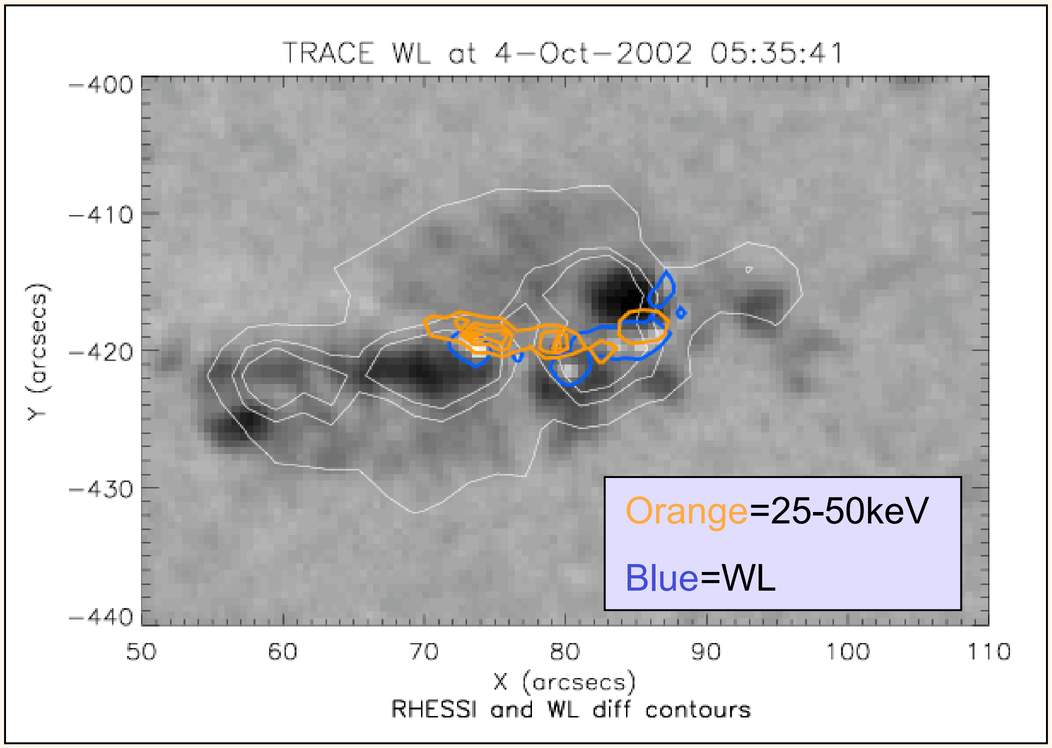
(e.g. Kane & Anderson '69, Brown '71, Hudson'72)

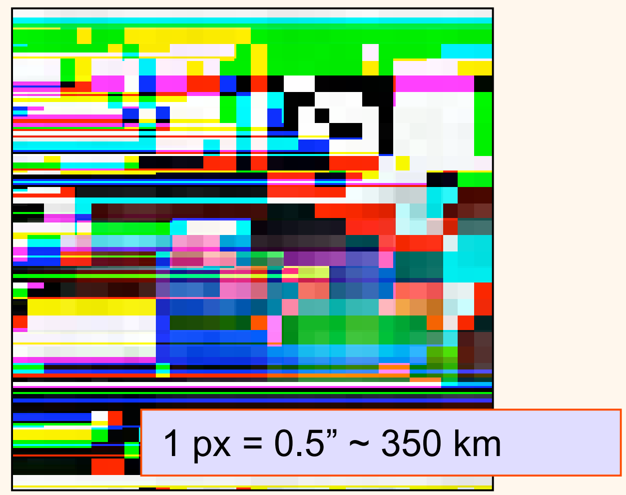
Thick target energetics / beam fluxes

In thick-target theory, can use HXR photon spectrum to calculate parent electron spectrum in chromosphere (Brown 1971).

The inferred requirement on electron number is - 10^{34}-10^{36} electrons s^{-1} (ie coronal volume of $10^{27} cm^3$, n = 10^9 e^- cm^{-3} should be emptied in ~10s)

Beam density can be inferred using white-light footpoint areas as a proxy for beam ‘area’.





White light footpoint area ~ $10^{17} cm^2$

Beam power & number fluxes from HXR & WL

date	class	WL area (cm^2)	P > 20keV (erg s^{-1})	N > 20keV ($e^- s^{-1}$)	P/cm^2 (ergs $cm^{-2} s^{-1}$)	N/cm^2 ($e^- cm^{-2} s^{-1}$)
07/26/02	M1.0	4.0×10^{16}	2.0×10^{27}	4.7×10^{34}	5.0×10^{10}	1.2×10^{18}
10/04/02	M4.0	1.0×10^{17}	3.4×10^{28}	6.6×10^{35}	3.4×10^{11}	6.6×10^{18}
10/05/02	M1.2	7.0×10^{16}	2.0×10^{27}	4.7×10^{34}	3.5×10^{10}	6.7×10^{17}
10/23/03	M2.4	1.0×10^{17}	6.4×10^{28}	1.6×10^{36}	6.4×10^{11}	1.6×10^{19}
07/24/04	C4.8	1.3×10^{17}	1.6×10^{28}	2.9×10^{35}	1.2×10^{11}	2.3×10^{18}

Fletcher et al (2007)

At speed v ~ 0.5c, beam density is comparable to coronal density!

Theoretically, this beam cannot propagate stably through corona (e.g. Brown & Melrose 1977, Petkaki et al. 03)

Acceleration in the corona requires a *high fraction* of a *large volume* of electrons to be accelerated to *high energies*

'Volumetric' acceleration:

Wave-particle turbulence (e.g. Larosa et al, Miller et al)

Stochastic current sheets (e.g. Turkmani et al)

Betatron acceleration (Brown-Hoyng, Karlicky-Kosugi)

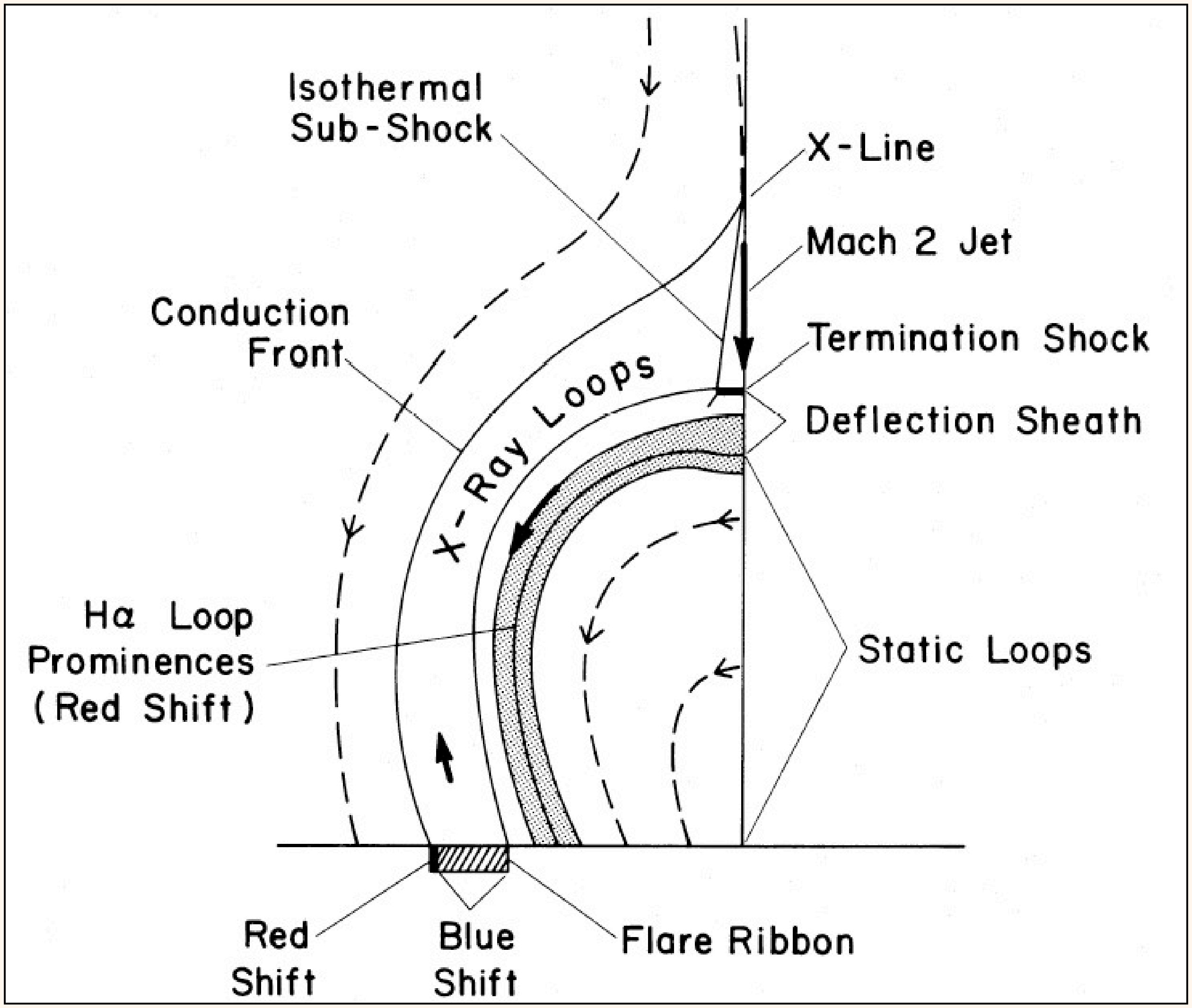
Diffusive shock or shock drift acceleration (e.g. Tsuneta & Naito, Mann et al)

Reconnecting X-line or current-sheet acceleration

Multiple X-lines/islands (e.g. Kliem, Drake)

Single macroscopic current sheet (e.g. Litvinenko & Somov, Somov & Kosugi)

The ‘standard’ 2D cartoon (for orientation)



Schmieder, Forbes et al. 1987

(http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons)

Acceleration in the corona requires a *high fraction* of a *large volume* of electrons to be accelerated to *high energies*

'Volumetric' acceleration:

Wave-particle turbu... ...rosa et al, Miller et al)

St... ...urrent sheets (e.g. Turkmani et al)

Betatron acceleration (e.g. Brown ... ...icky et al)

Diffusive shoc... ...t acceleration (e.g. Tsuneta & ... Mann et al)

High energy, low fraction, high volume

Moderate energy, high fraction, moderate volume

Reconnecting X-line or current-sheet acceleration

Multiple X-lines/islands (e.g. Kliem, D...

Single macrosc... ...heet (e.g. Litvinenko & Som... & Kosugi)

High energy, high fraction, low volume

Summary

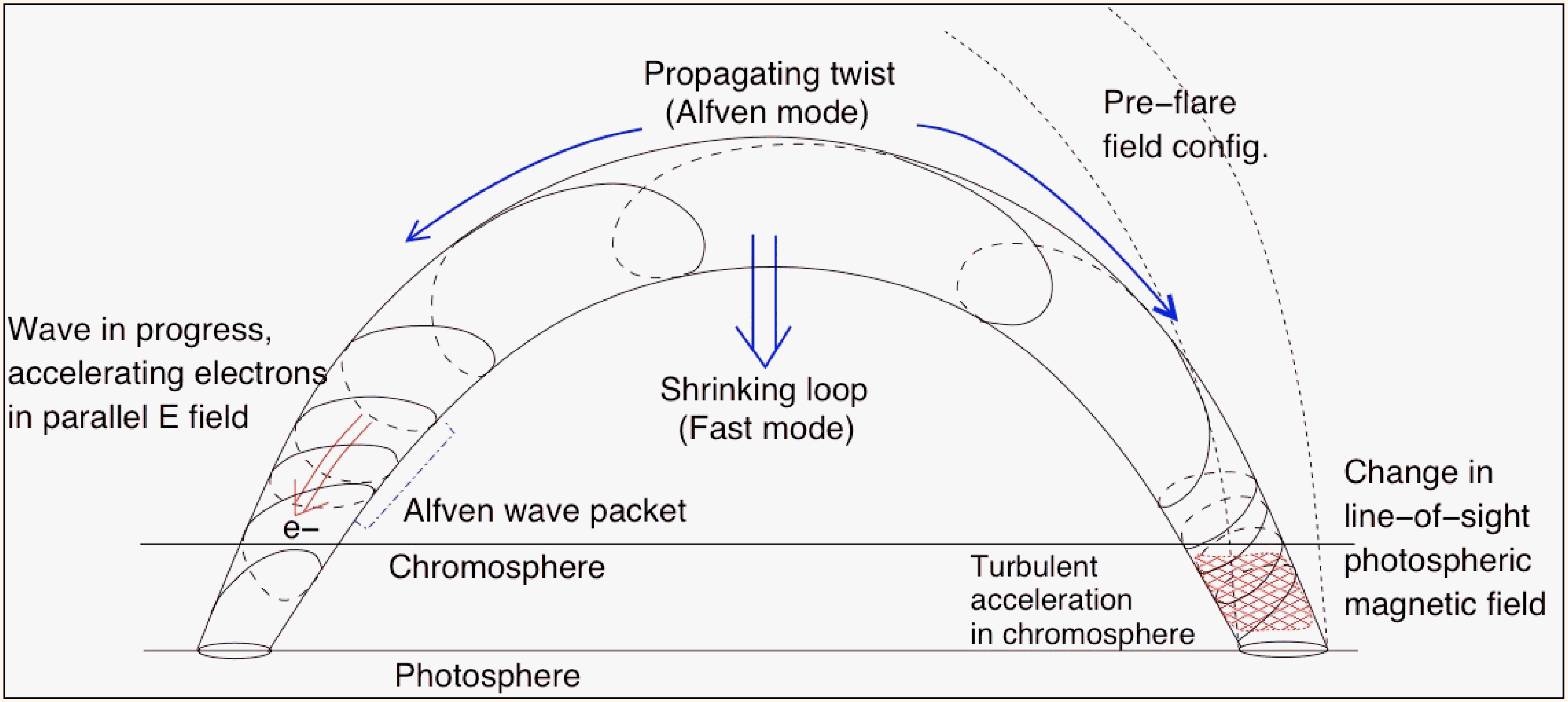
- Impulsive phase emission requires 10-50% of flare magnetic energy.
- Emissions usually interpreted as bremsstrahlung, heating & excitation by non-thermal electrons in the chromosphere.
- *Thick-target* hard X-rays imply more electrons accelerated than can be easily supplied by corona.
- At inferred fluxes, a beam/return current system cannot propagate stably
- The acceleration process remains unknown.

Alternative scenarios?

♣ Much smaller number of electrons accelerated in corona and then 'reaccelerated' locally in chromosphere (MacKinnon 06, Brown et al.)

- Flare energy transported by high-speed Alfvén waves to chromosphere and dissipated there (Emslie & Sturrock 82, Fletcher & Hudson 08)
- …..etc?

Understanding the impulsive phase requires physics beyond ideal MHD



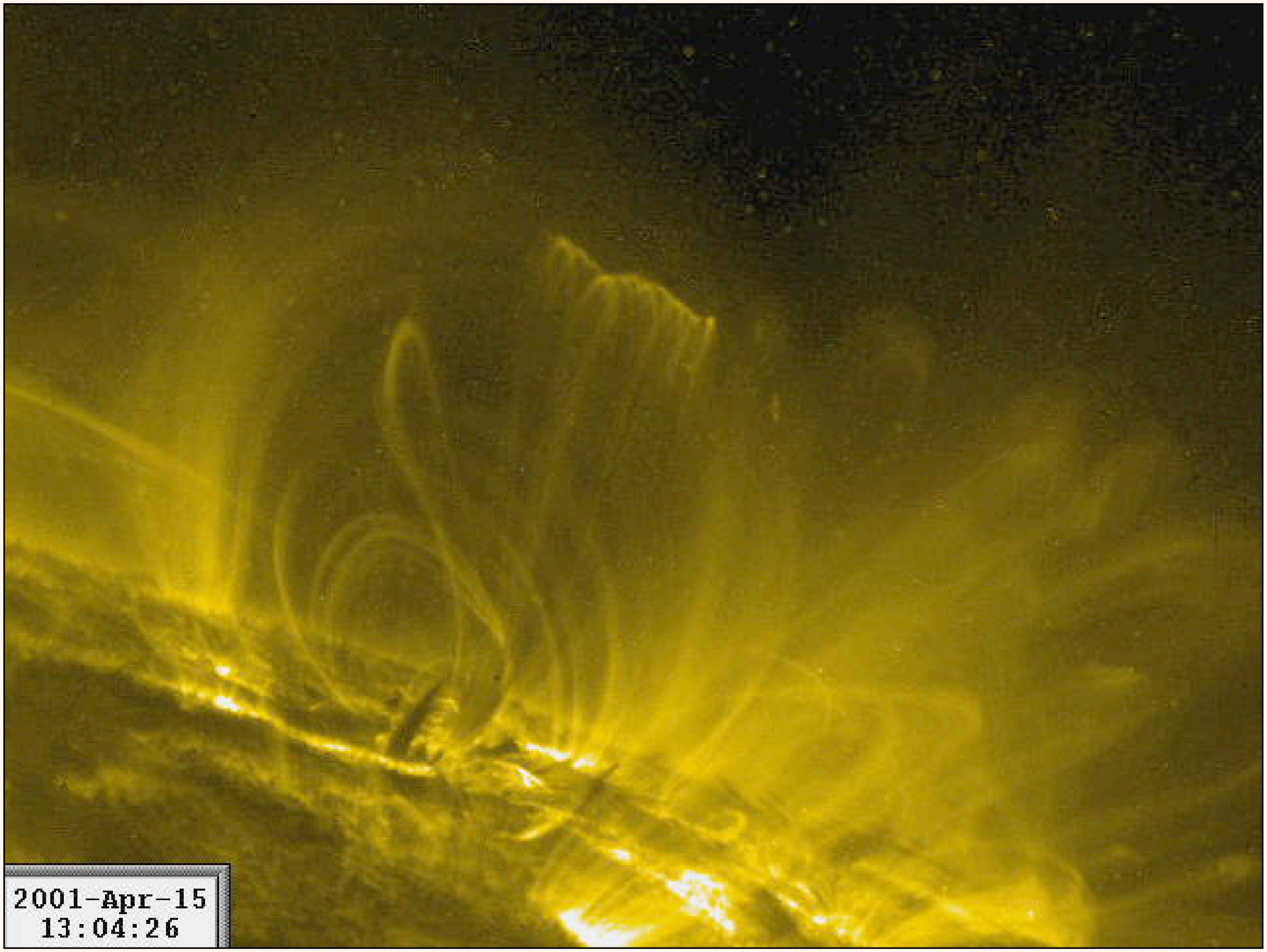
Fletcher & Hudson 2008

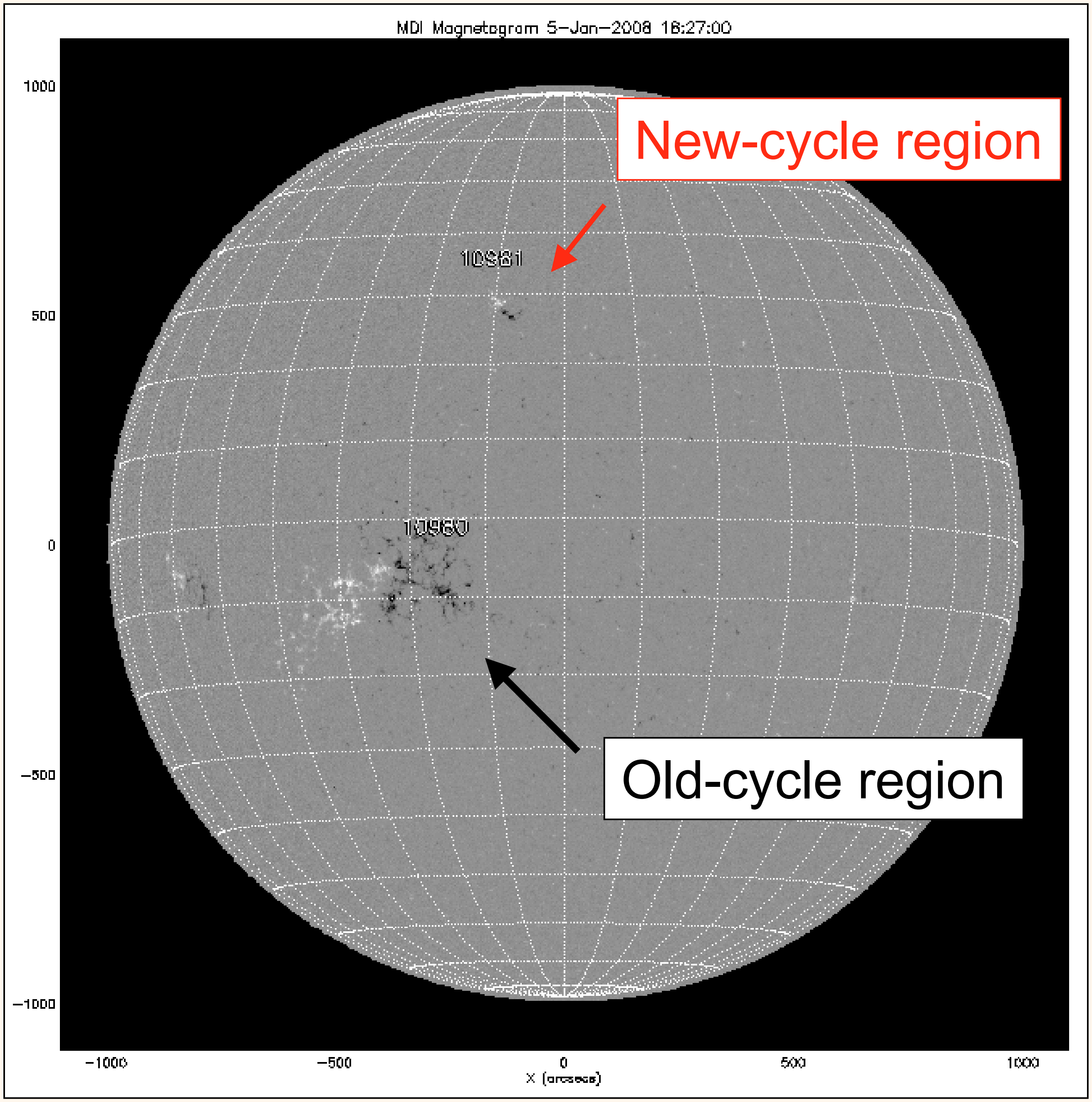
http://solarmuri.ssl.berkeley.edu/~hhudson/cartoons/

Conclusions

- The impulsive phase of a flare (acceleration phase of associated CME) is the most important energetically
- The physics is challenging because it intimately involves both large scales and particles
- Flare physics (astrophysics) has much to learn from space plasma physics

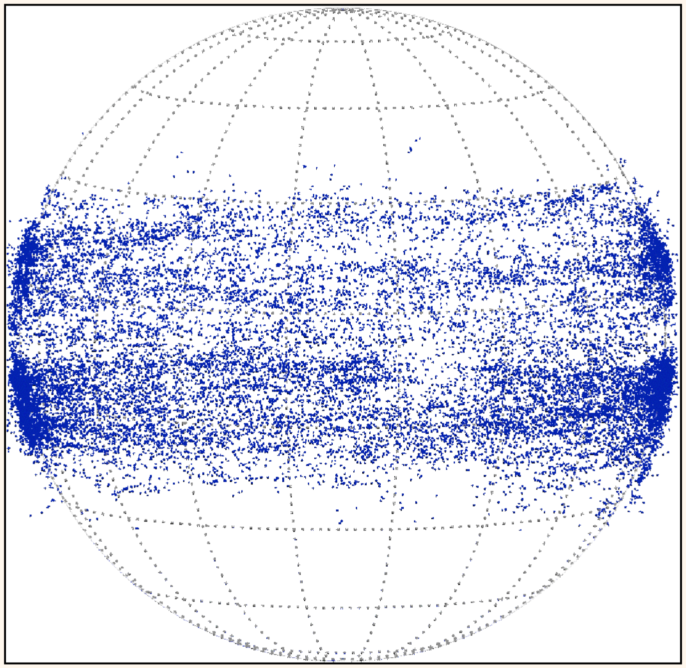
A TRACE movie that shows everything





MDI Magnetogram 5-Jan-2008 16:27:00
New-cycle region
10981
10980
Old-cycle region
1000
500
0
-500
-1000
-1000
-500
0
500
1000
X (arcsecs)

Microflares now, major flares soon



RHESSI microflare locations, 2002-2007