Observations of solar and stellar eruptions, flares, and jets

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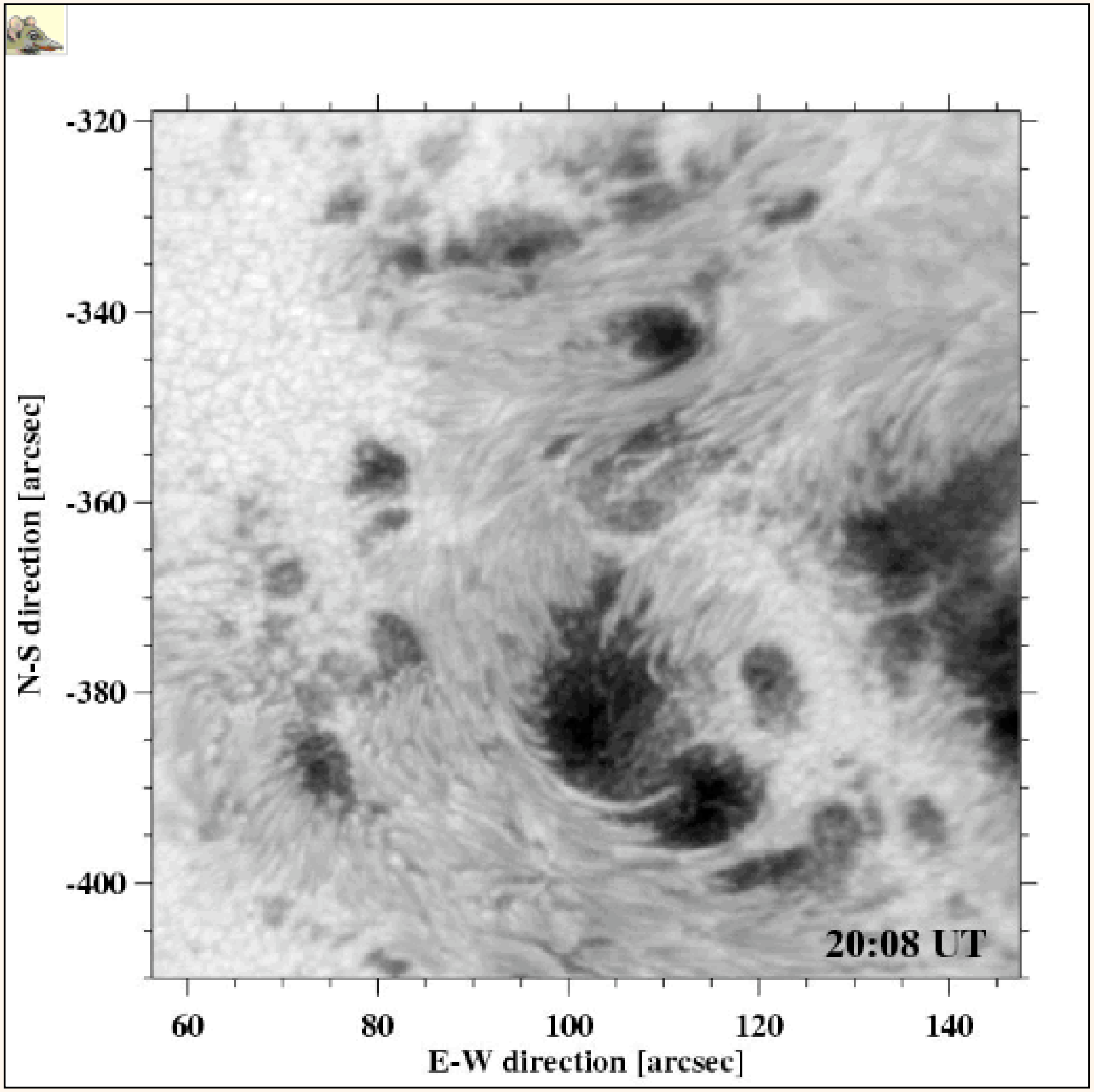
- Flare Phases
- Flare Phenomena
- Flare and CME Energetics
- Analogs: stellar, solar, terrestrial
- How to observe magnetic reconnection
- Conclusions

A flare/CME seen in EUV and X-rays

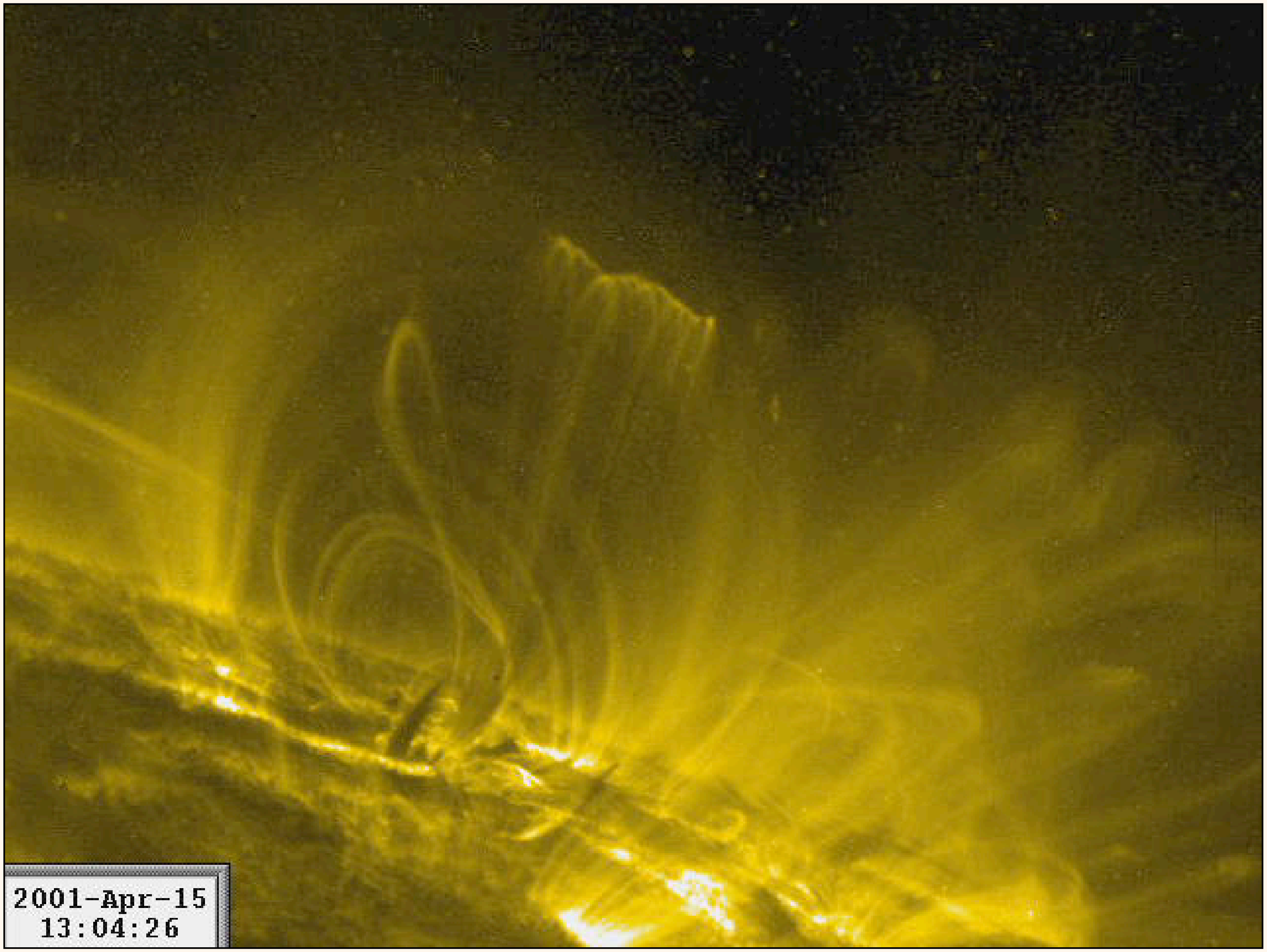
Red RHESSI 6-12 keV, blue 50-100 keV, gold images TRACE 195A

An IR movie from the "opacity minimum"

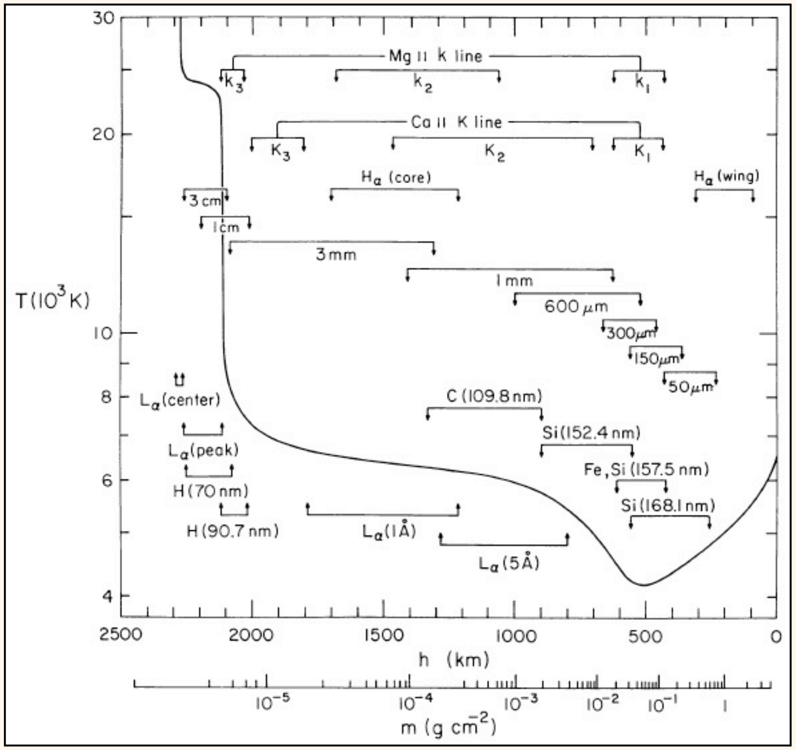


Xu et al. 2005

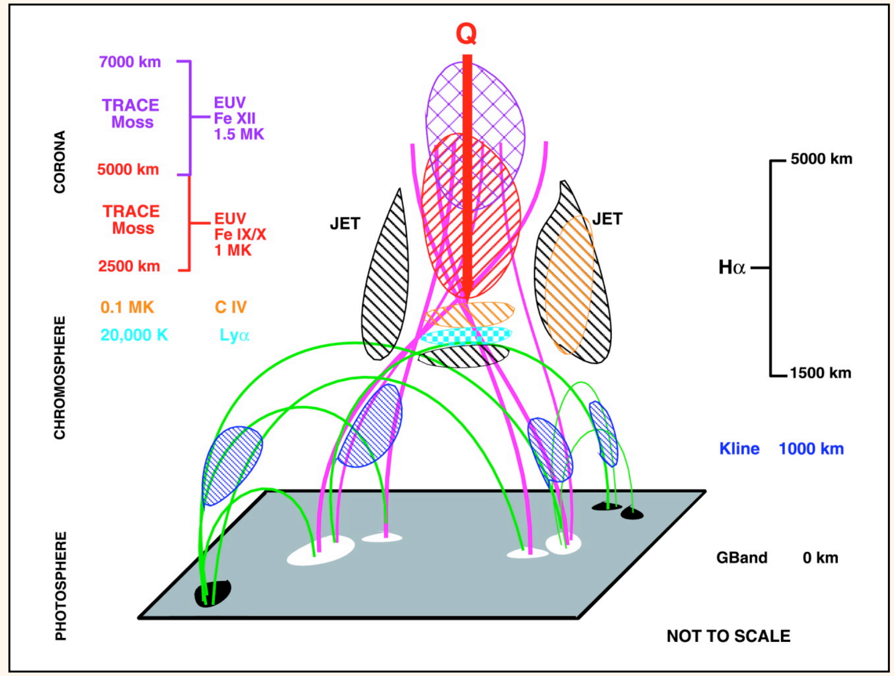
A TRACE movie that shows everything



Where does this all fit in?



Vernazza et al. 1981 (“VAL-C”)



De Pontieu et al 2003

- Two views of the chromosphere/transition region
- But how about the corona?

Outline

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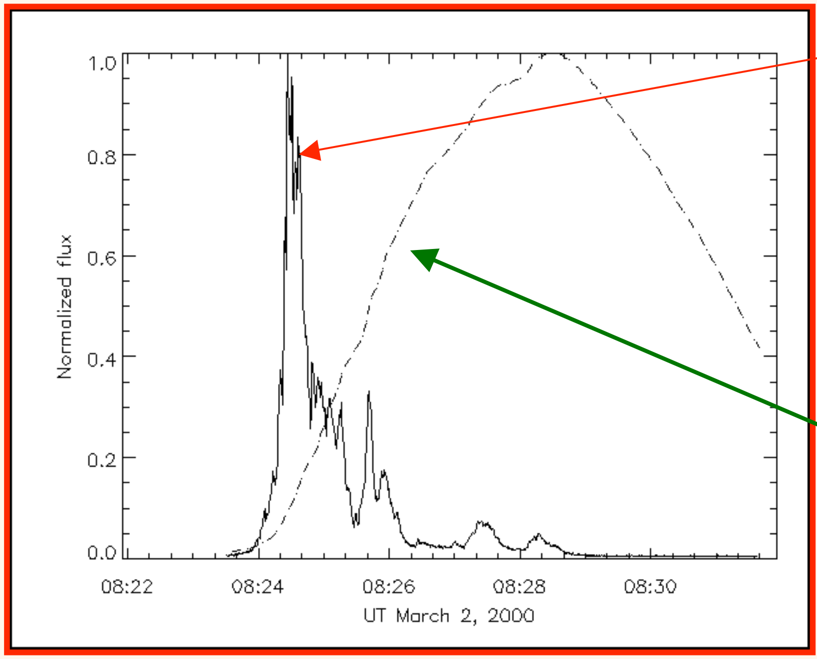
Impulsive phase and gradual phase: The Neupert Effect



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
- energy injection

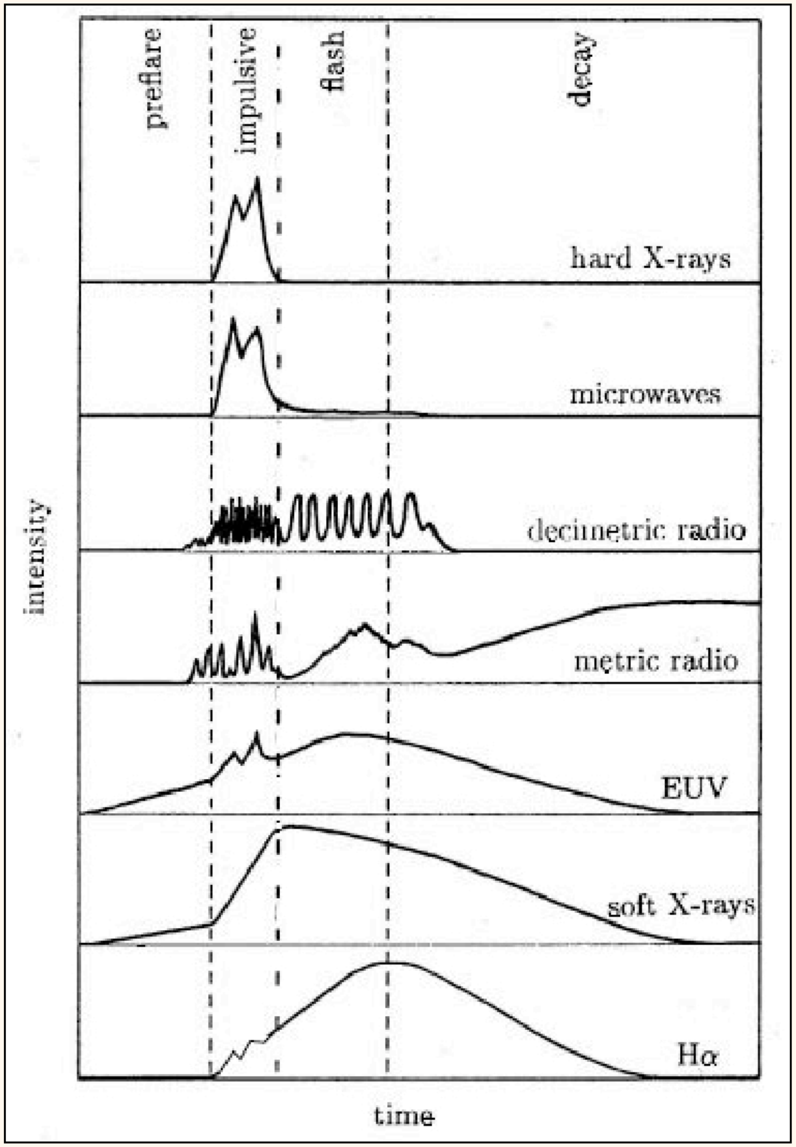
Gradual phase - response to input

- thermal emission (kT ~0.1-1 keV)
- rise time ~ minutes
- coronal reservoir

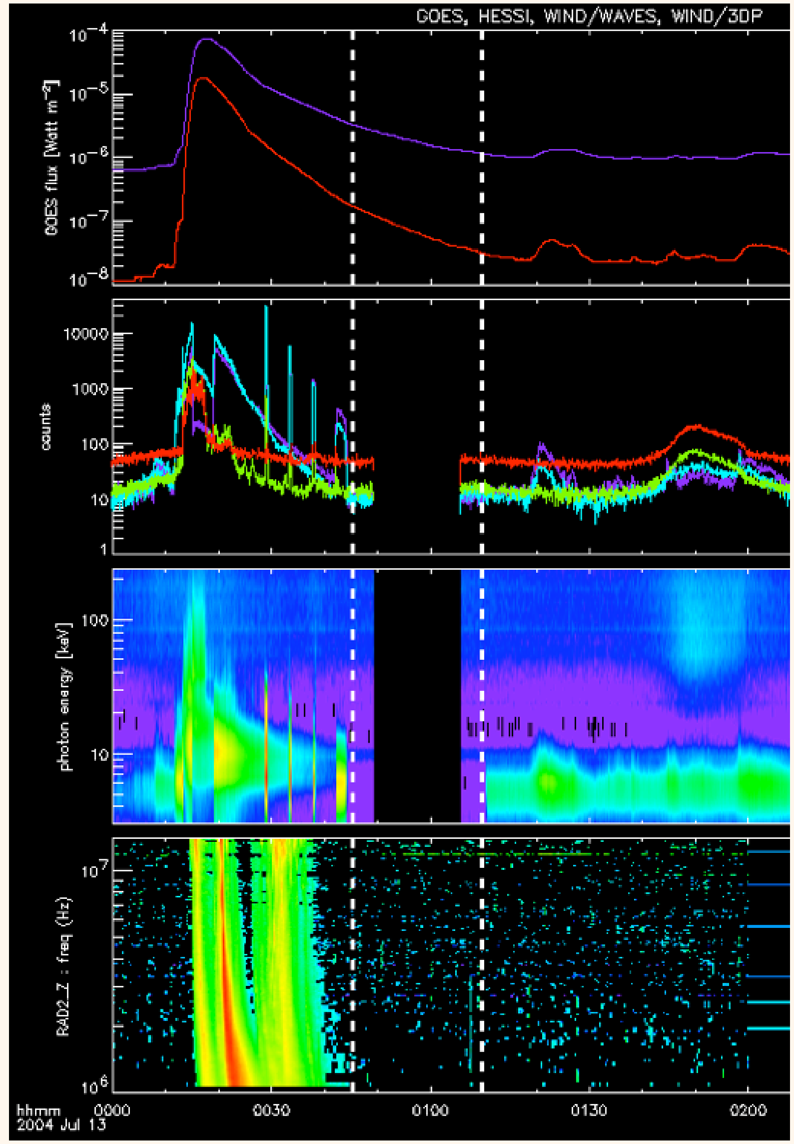
Impulsive phase:

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

Flare Phases



Benz, 2002



http://sprg.ssl.berkeley.edu/~tohban/browser

Impulsive Phase: the thick-target model

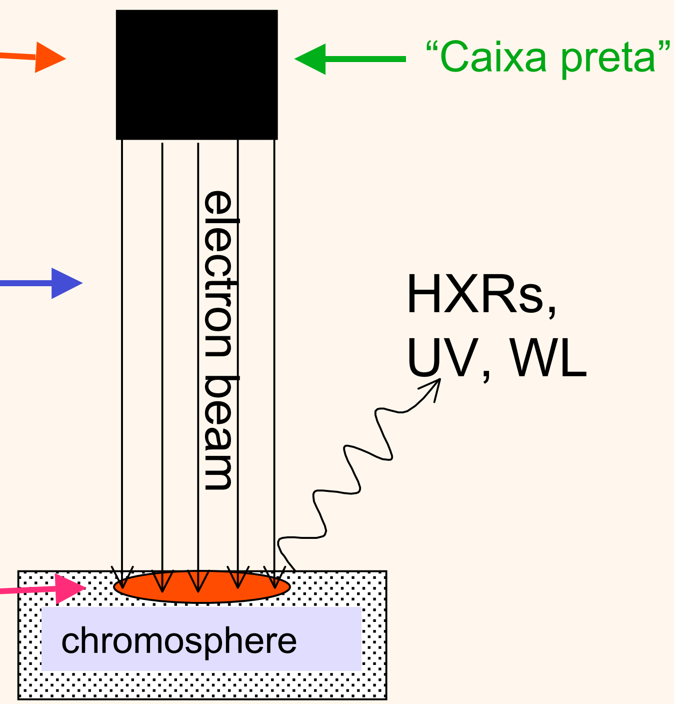
Collisional thick target model has dominated interpretations of flare non-thermal emission for > 3 decades.

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

Coronal accelerator

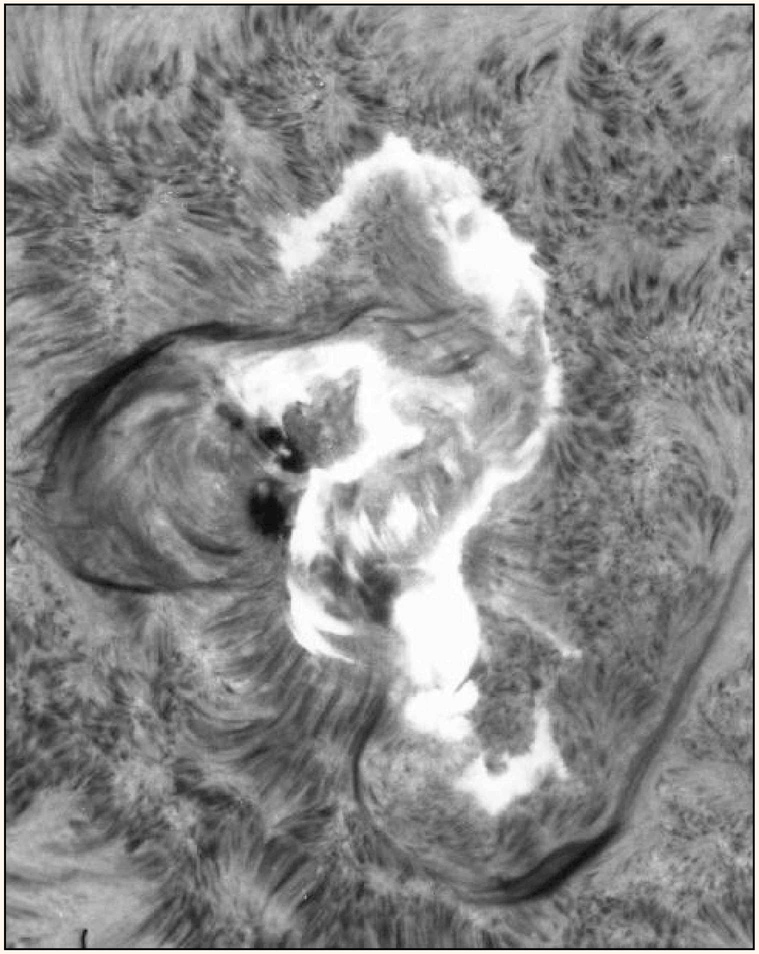
Coronal electron transport (generally, 1D and no treatment of plasma collective effects). Much unfinished work…

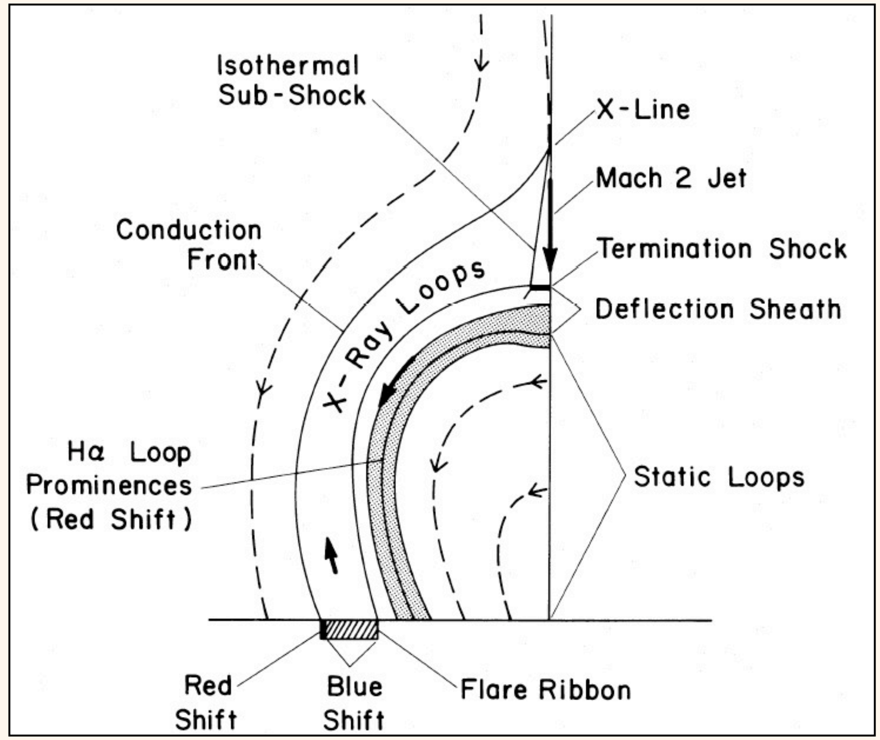
Bremsstrahlung HXRs and heating/excitation in ‘thick target’ (single pass) in chromosphere



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

Gradual phase: reconnection model





- Ribbon separation
- Loop temperature sequence
- Outer edge spectral signature
- Coronal cusp development
- Other signatures

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- **Flare phenomena**
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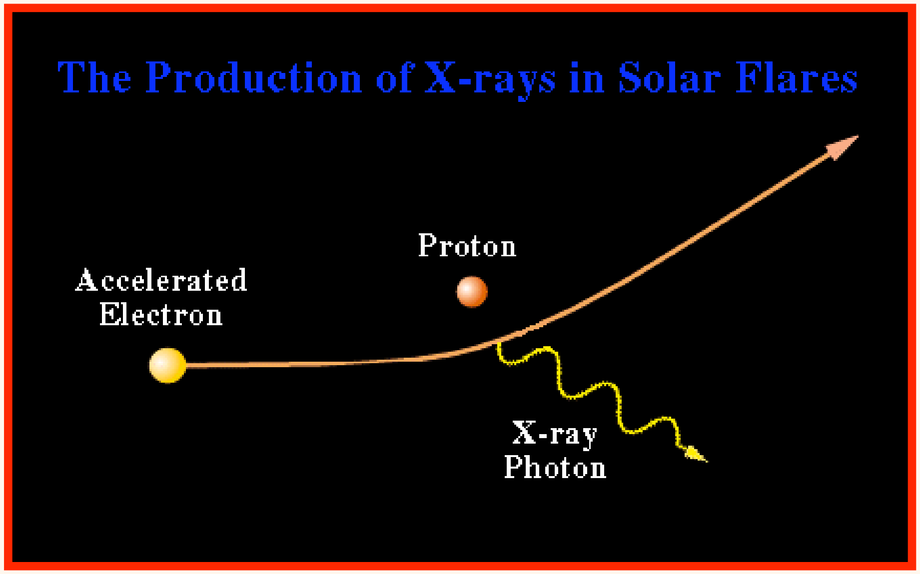
X-Rays

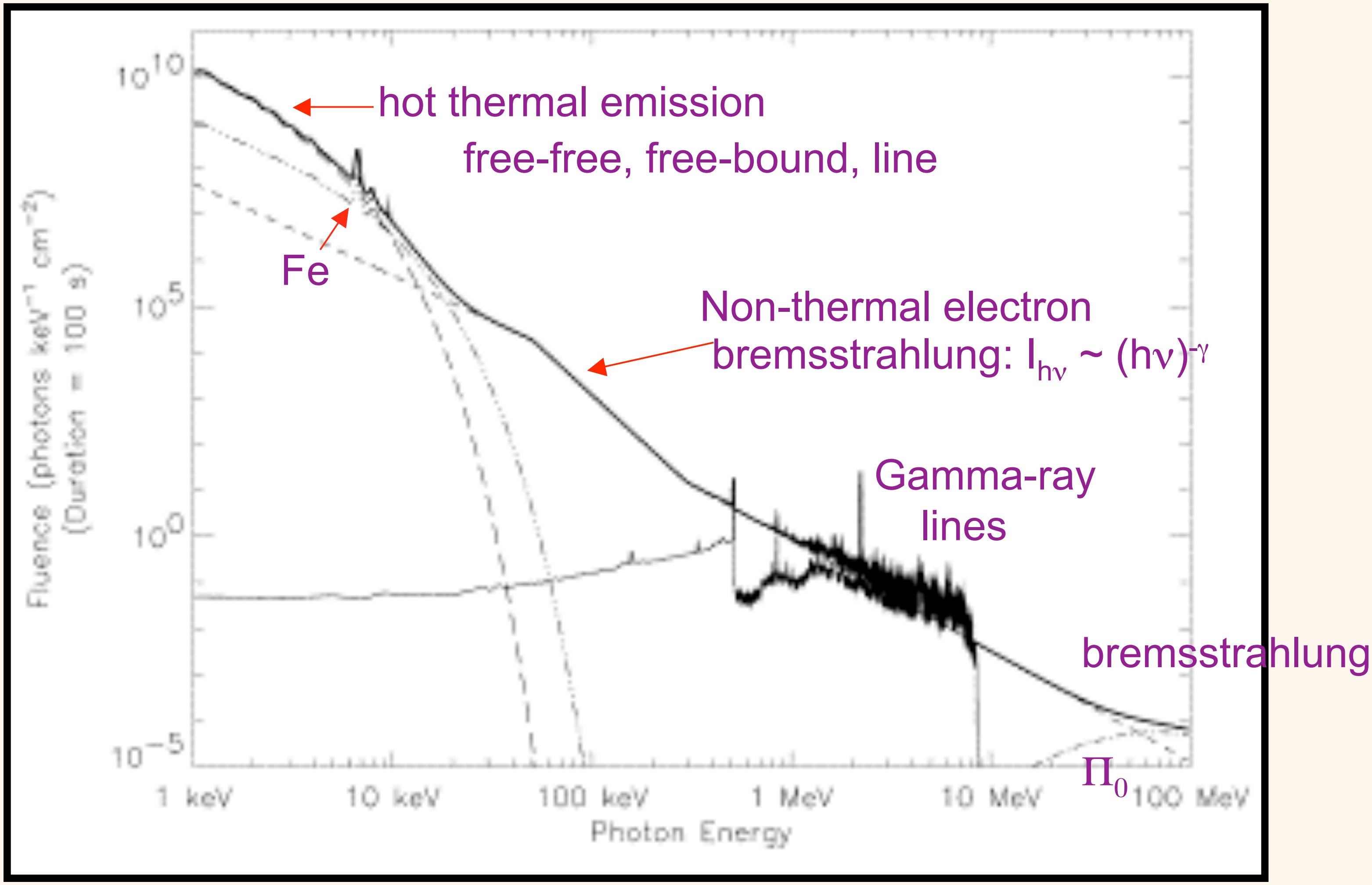
X-rays observed by (e.g.) RHESSI are primarily electron-proton *bremsstrahlung* from energetic electrons (>15 keV)



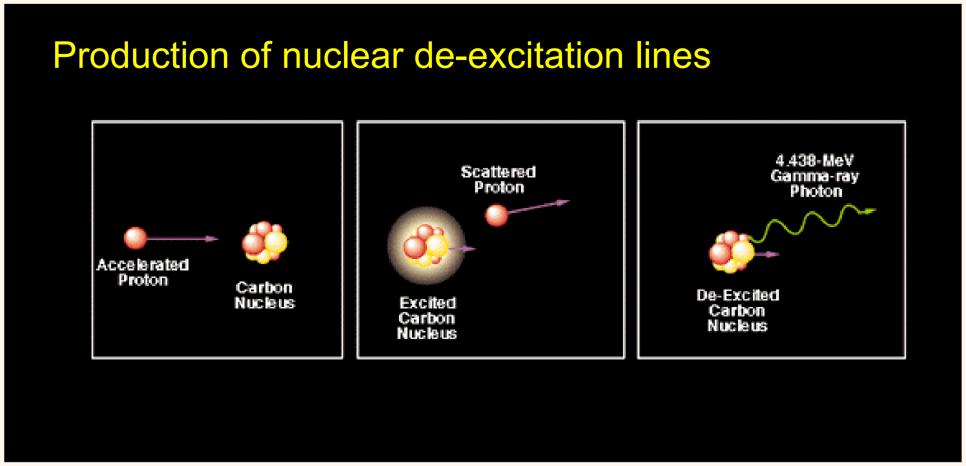
This is not a Feynman diagram!

- 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: $E_e \sim kT$ and photon spectrum $I_{h\nu} \sim e^{-h\nu/kT}$
  - significant energy loss from electrons in a hot gas (1-10% of flare energy)
- Free-free, free-bound, and bound-bound (line) transitions

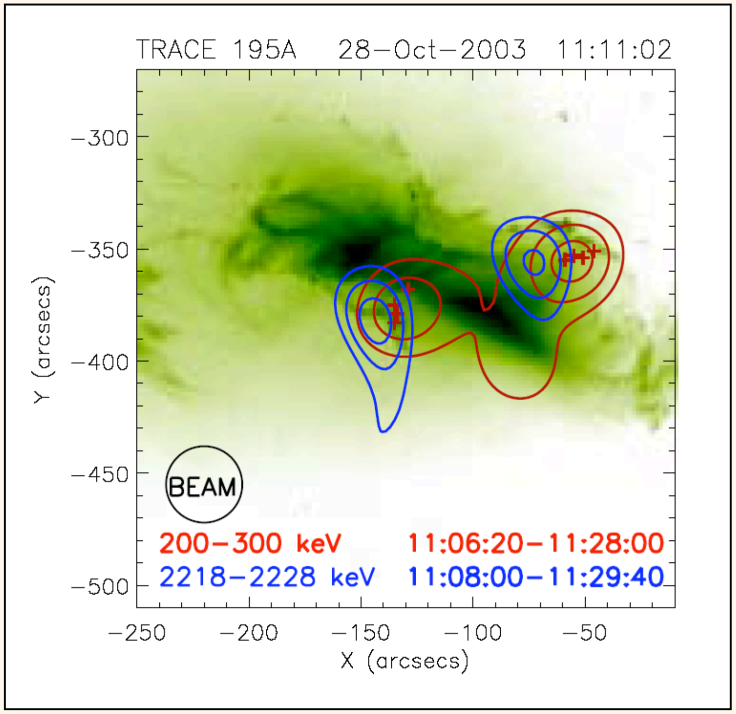
X-rays and gamma-rays



Gamma-rays



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

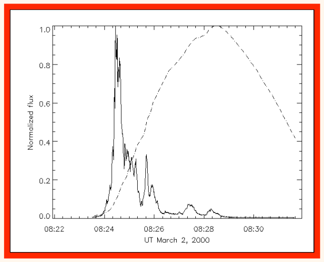


Hurford et al 2003

Neutron capture line at 2.23 MeV - n(p,γ)D
- shows location of 10s of MeV protons
- direct detection of neutrons also possible

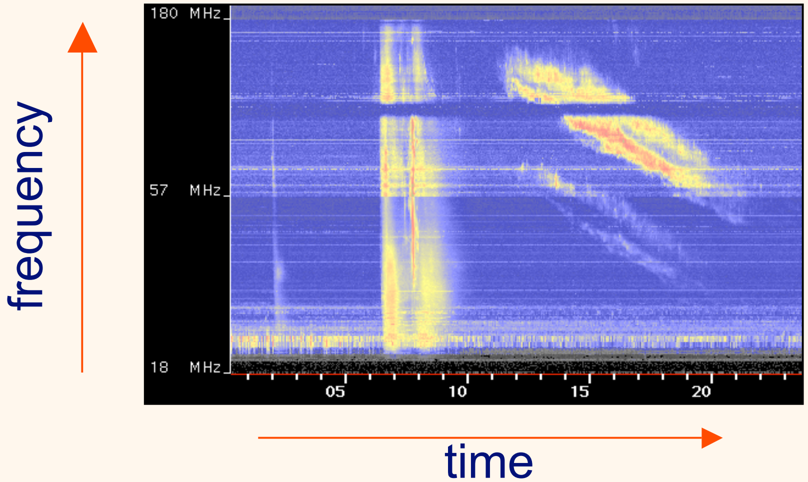
Π_0 -> 2γ decay continuum shows ~100 MeV;
e^+ annihilation line (511 kev) - complicated!

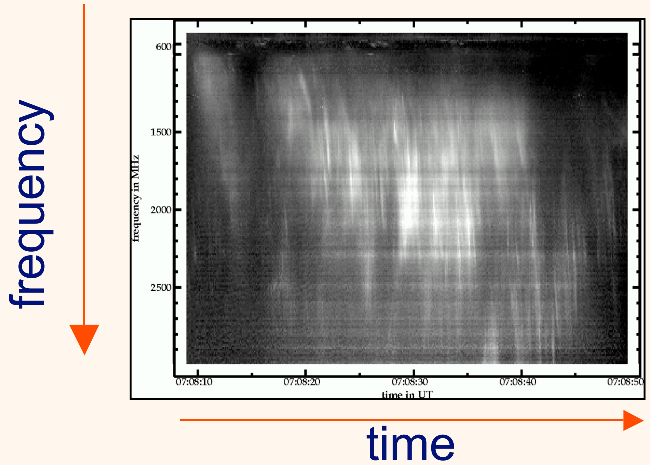
Radio waves



Basic opacity (hence emissivity) of the plasma is the ***free-free process (bremsstrahlung)***, which depends on n_e n_i, and T_e.

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





Isliker & Benz 1994

Metric and decimetric Type III bursts are often ***plasma radiation*** produced by electron beams (from Langmuir waves at $f_p \sim 9000\ n_e^{0.5}$ cgs).

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

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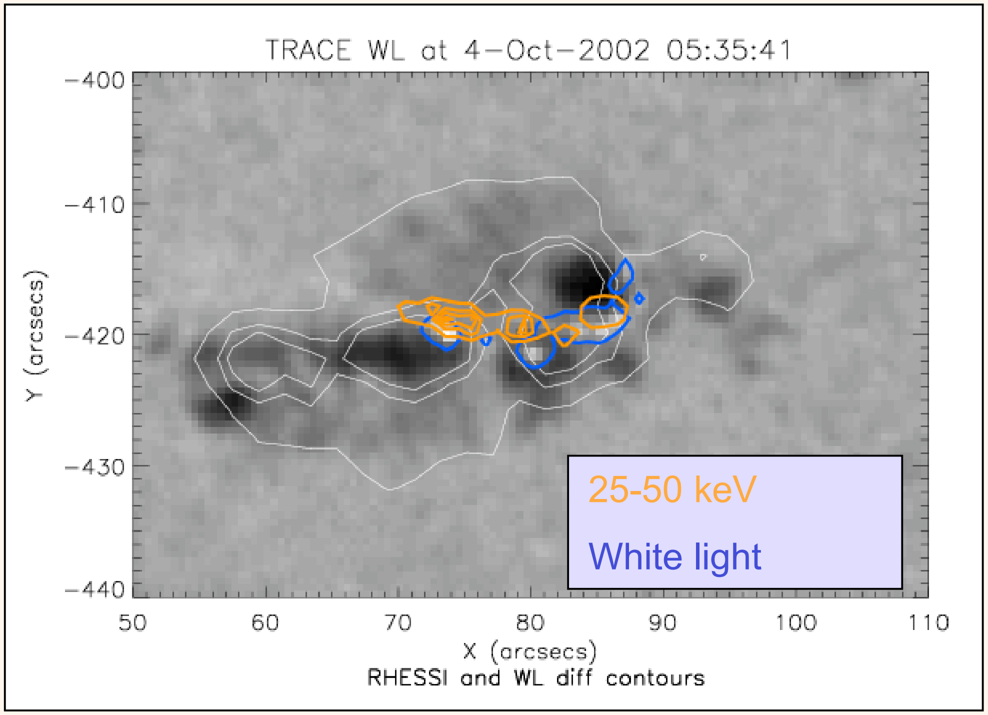
Thick target energetics / beam fluxes

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)

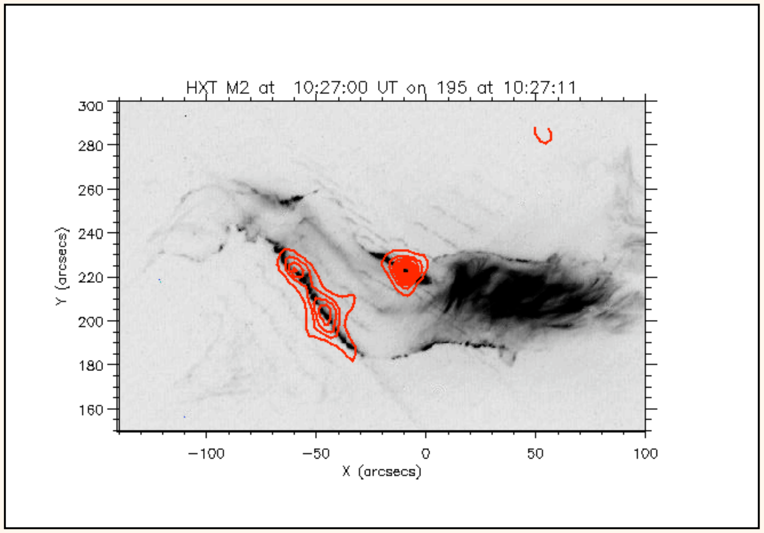
Beam density can be inferred using white-light footpoint areas as a proxy for beam 'area'.



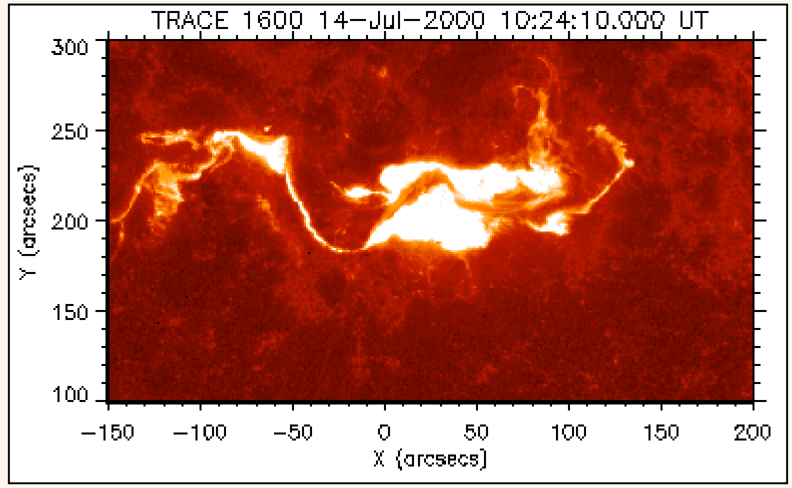
White light footpoint area ~ 10^{17} cm^2

Ribbons in the impulsive phase

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



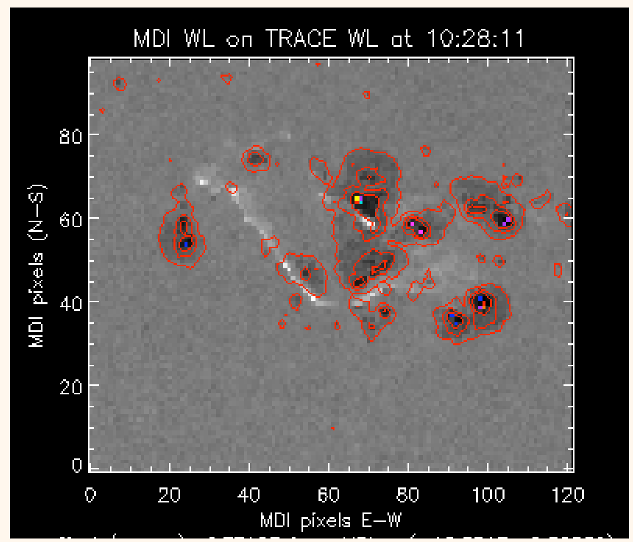
Yohkoh HXR contours on 195A emission



1600A broadband emission

Optical/UV/EUV emission from conduction, “precipitation”, or waves

White-light luminosity can be directly measured.

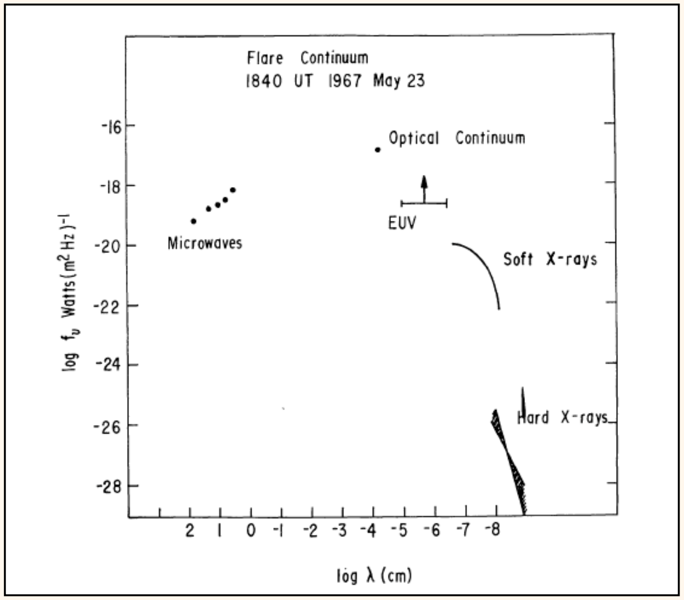


White-light footpoints

Fletcher & Hudson 2001

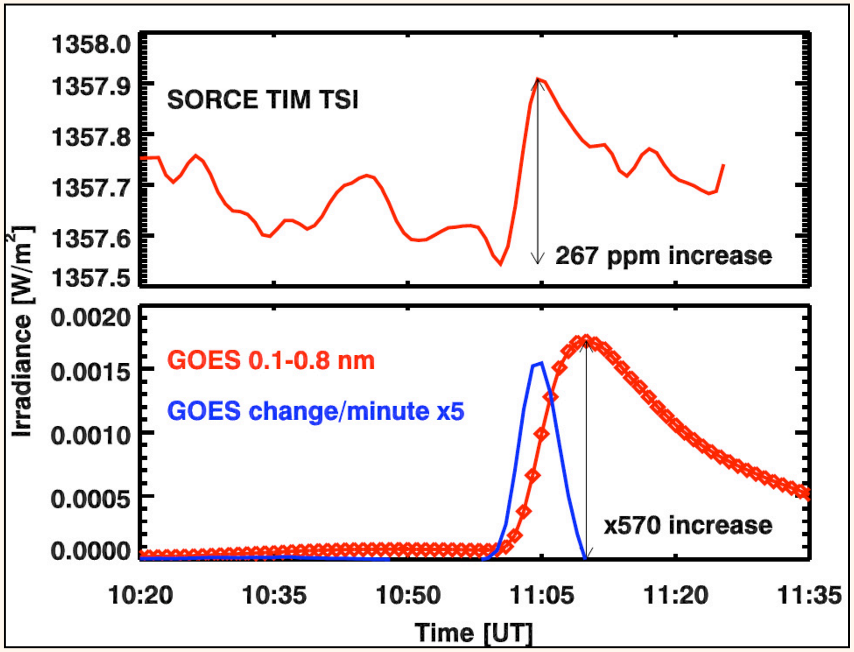
Role of 'white light' in total flare luminosity

- 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

- TIM shows an impulsive component

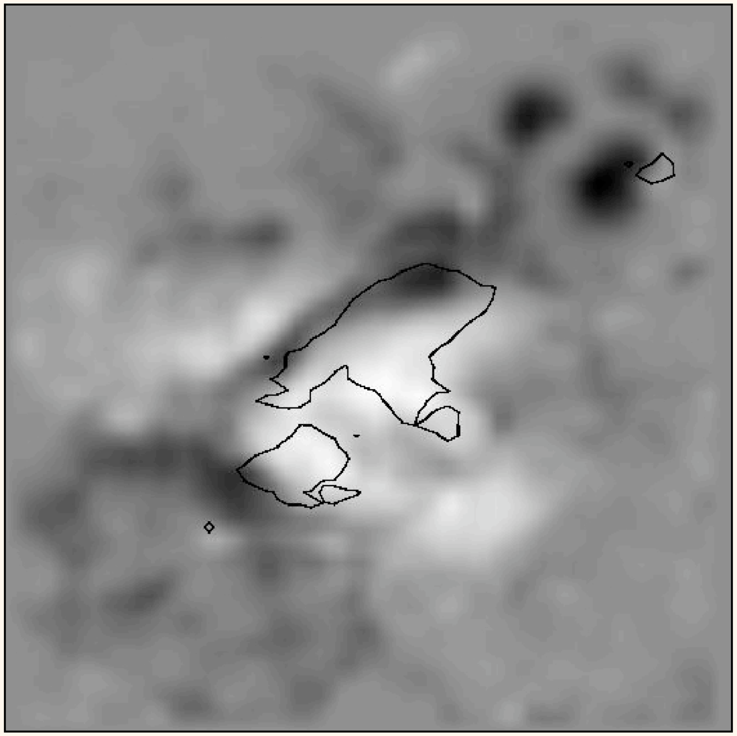
Particle acceleration in the impulsive phase

- The 10-100 keV electrons that emit hard X-rays contain a large fraction of the total flare energy. This is radiated in the UV and detected now in the total irradiance
- Although γ-ray observations are much less sensitive, it appears that 10-100 MeV proton acceleration is equally important
- The CME is accelerated at the impulsive phase, and its energy also may dissipate via “solar cosmic ray” acceleration in the accompanying shock wave
- **Particle acceleration is the most important theoretical problem in solar flare research**

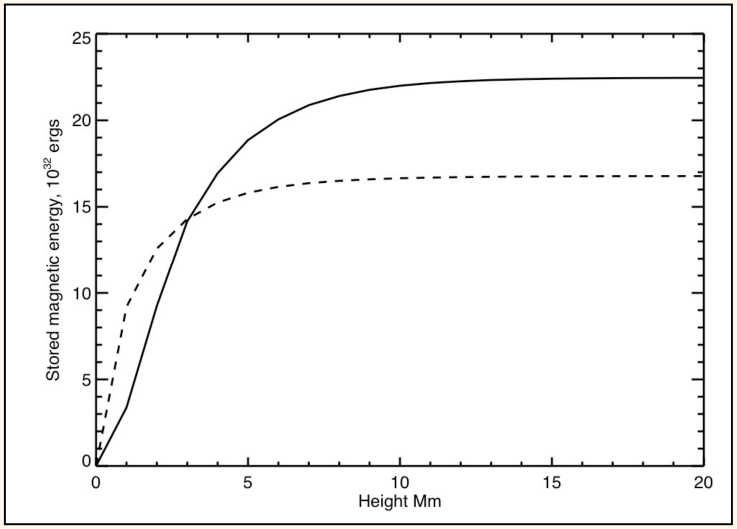
Magnetic energy storage

- Need to find locus of $\mathbf{B}^2/8\pi$
- Have force-free condition

  $\textbf{Curl(B)} = \alpha(x,y)\mathbf{B}$
- Extrapolation of photospheric field observations
  - Potential (α = 1)
  - Linear force-free (α constant)
  - Non-linear force-free NLFFF (α general)

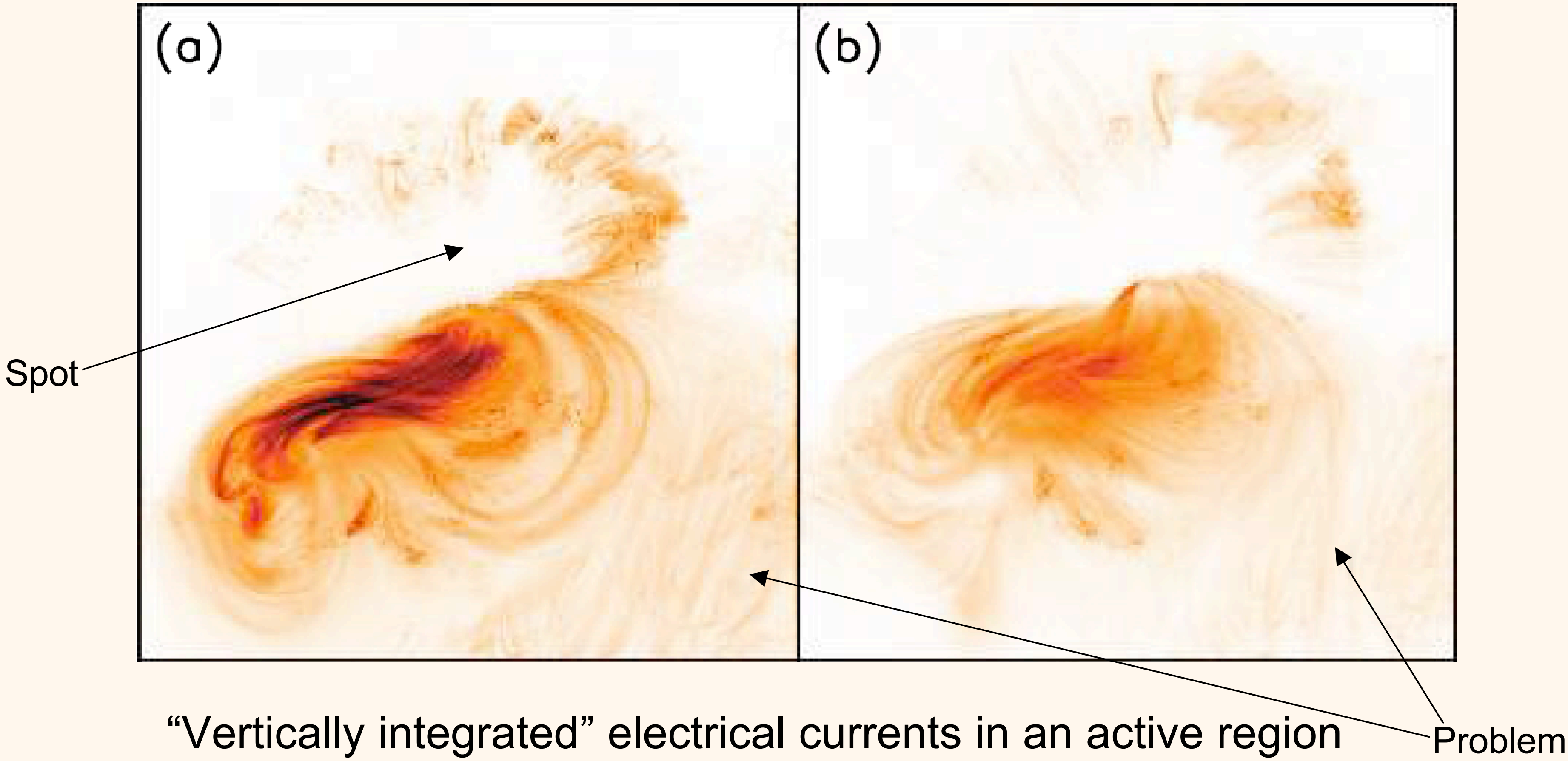


B_{los} in a solar active region and the 50% contour of $\mathbf{B}^2$



Integral distribution of stored energy (NLFFF vs potential) in height

Magnetic energy storage



“Vertically integrated” electrical currents in an active region before (a) and after (b) an X-class flare (Schrijver et al., 2008). Note the apparent organization into a flux rope.

- **The magnetic energy in an active region is stored at low altitudes and may reside in a filament channel.**

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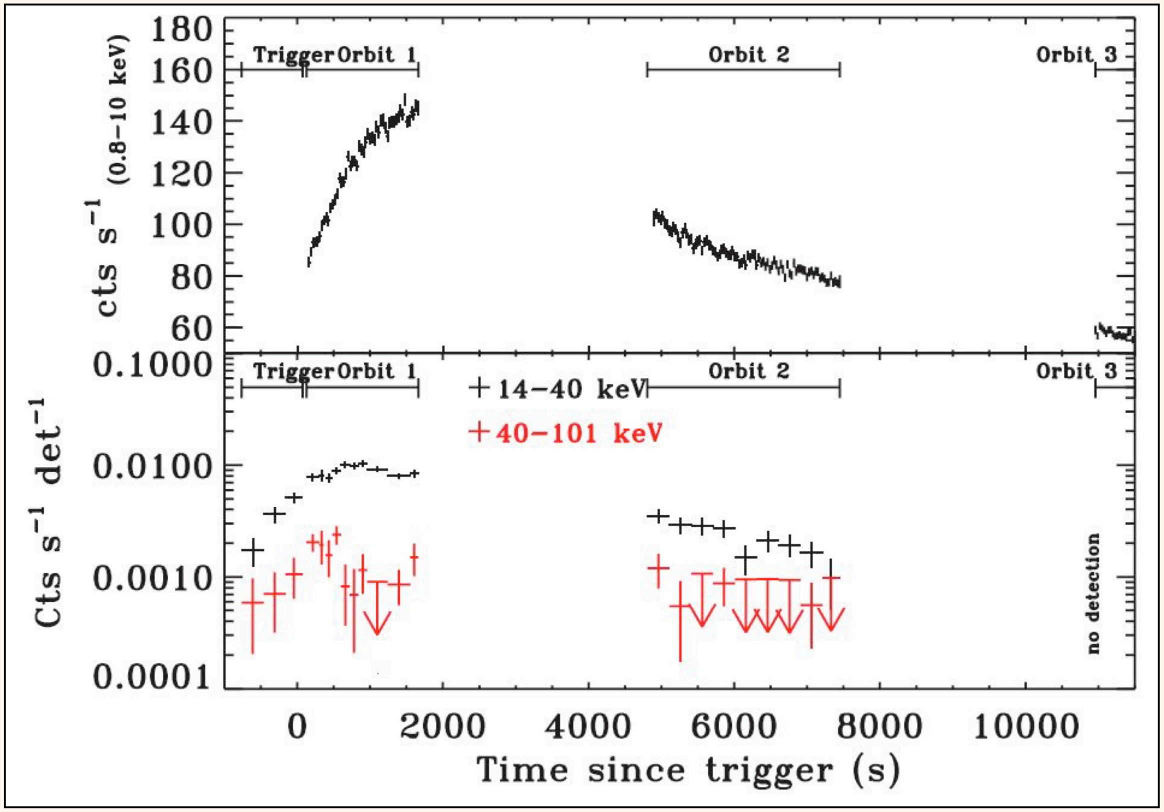
A powerful solar-paradigm stellar flare



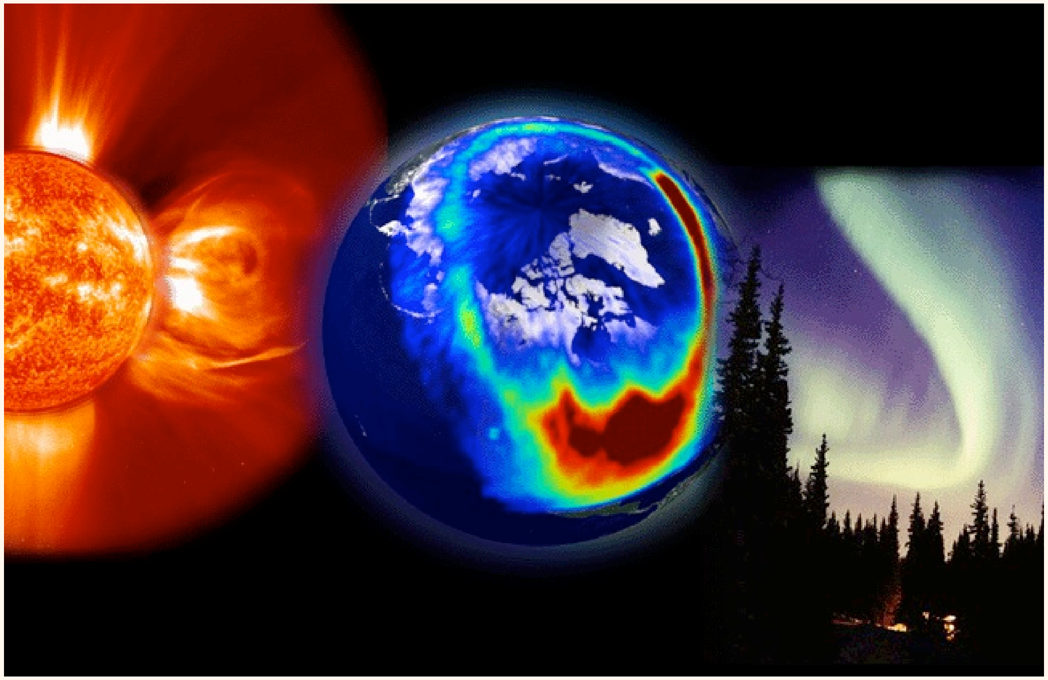
Osten et al. 2006

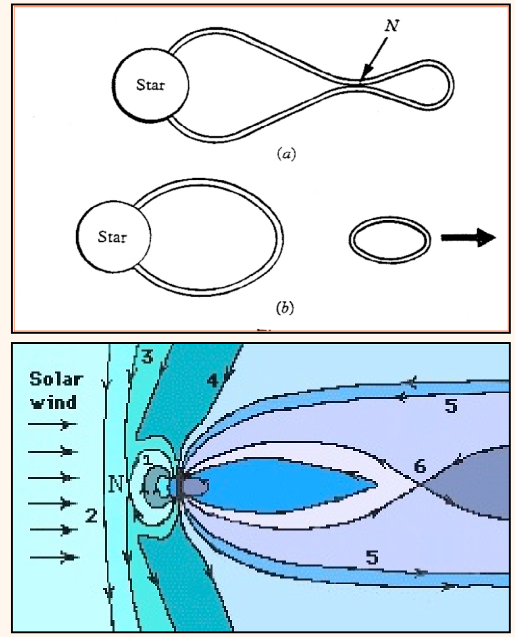
An exceptional event!

- II Pegasi active binary
- Swift observations
- Impulsive/gradual phases
- Neupert effect
- Thermal T ~ 80 MK
- Thermal n^2V ~ 6 x 10^{54} cgs
- NT energy 10^{37} erg/s

But squarely on the paradigm?

Flares and aurorae



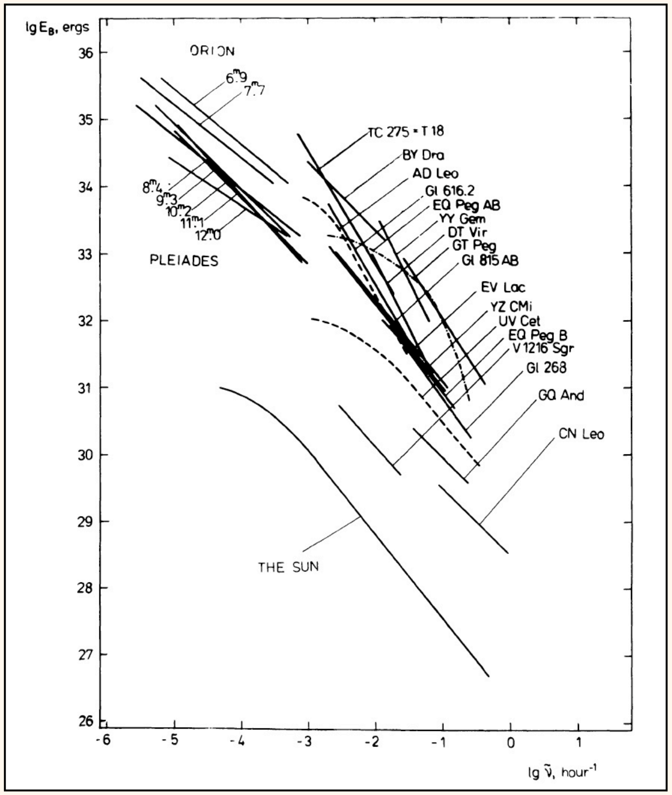


Cartoons by Dungey

Analogy pro
- Flare ribbons <=> conjugate polar caps
- Magnetic reconnection/plasmoid formation
- Non-thermal particles

Analogy con
- No large convective electric field in the corona
- No neutral atmosphere below the corona
- Equatorwards edges vs. ribbon outer edges

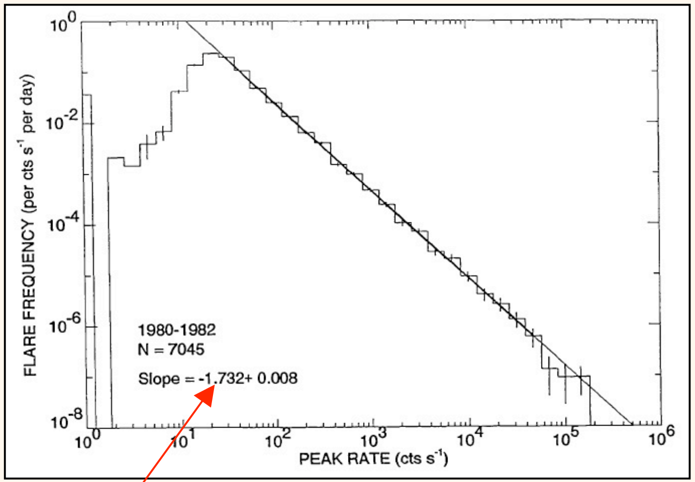
Likely stellar analogs: dMe stars



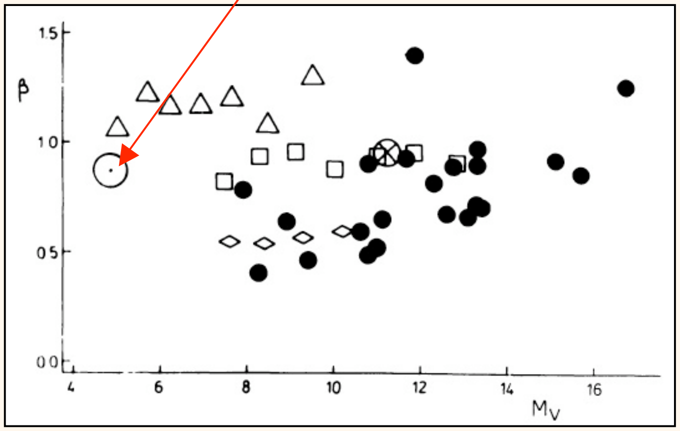
Shakovskaya 1989

Flare occurrence statistics:

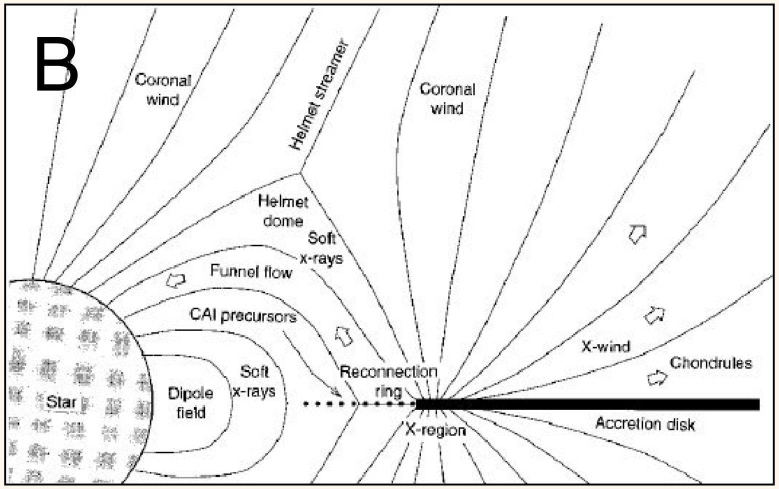
$dN/dE \sim E^{-\beta}$

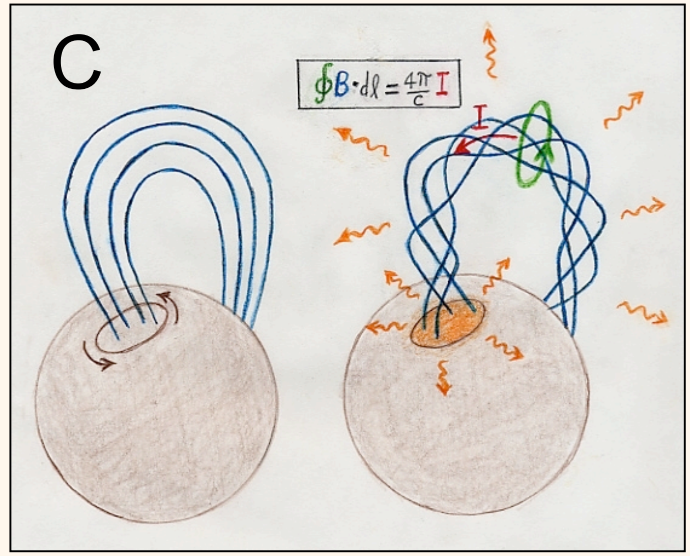


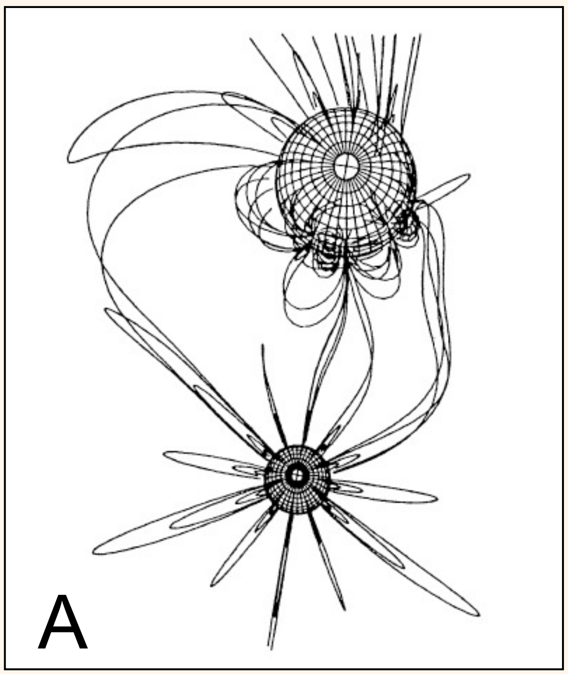
Crosby et al. 1993



Extreme stellar analogs







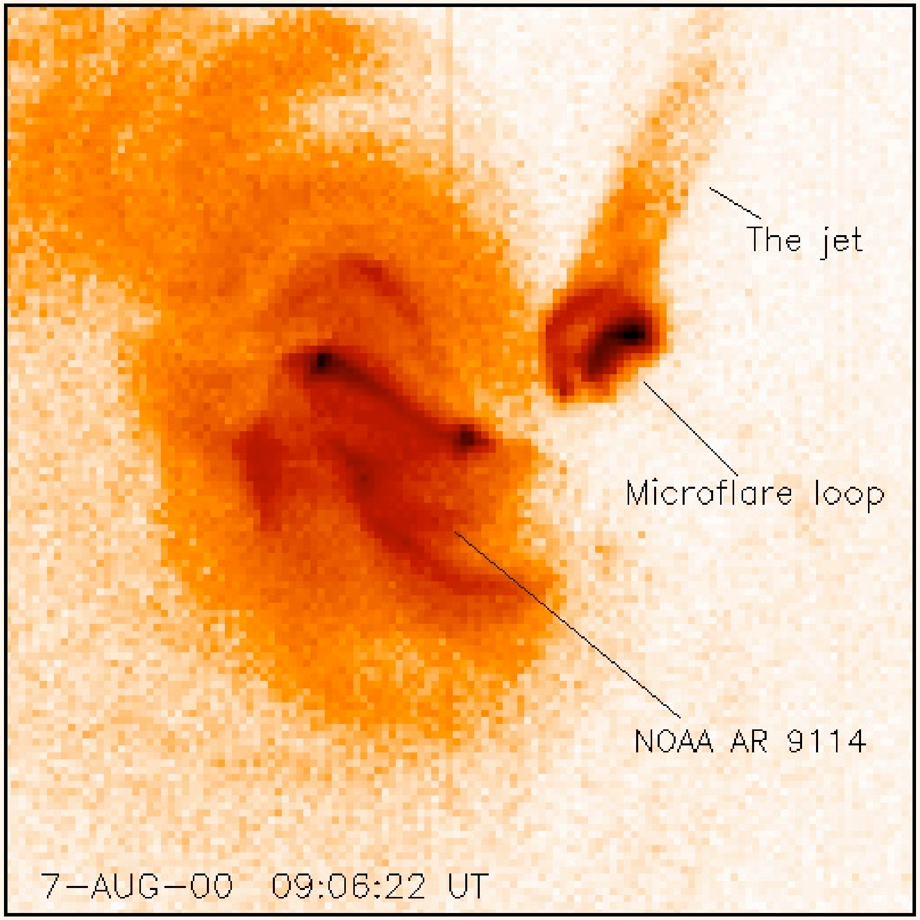
A. “Magnetic duplicity” (Uchida & Sakurai)
B. The X-wind model for T Tauri (Shu)
C. Magnetars (Duncan)

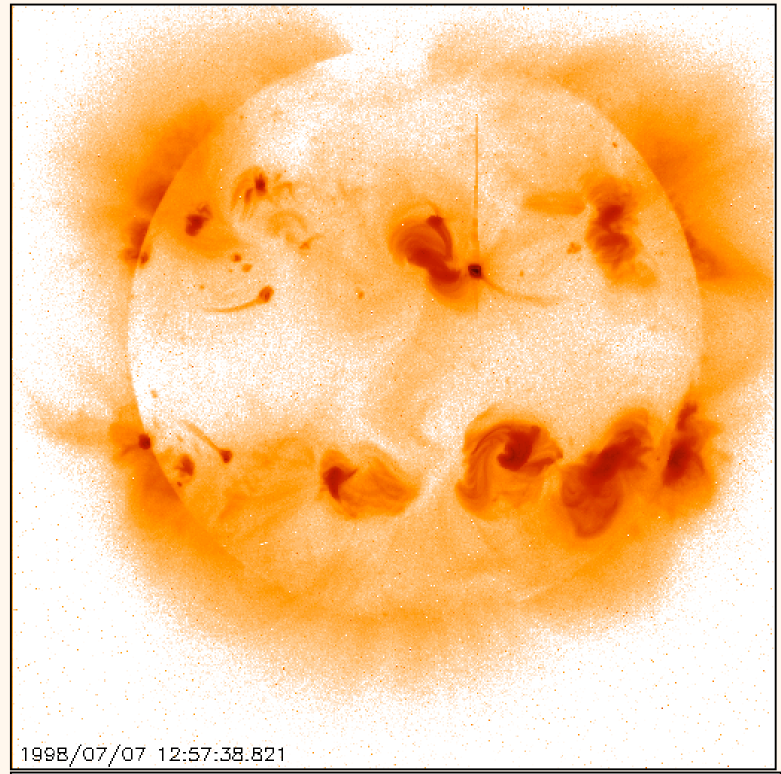
These models all seek different ways to drive currents through the stellar environment and thereby to stress the magnetic field to form an energy reservoir

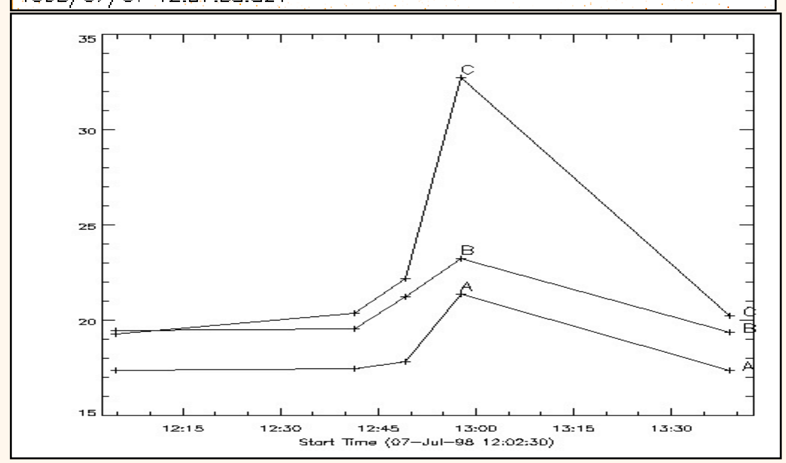
Are there other solar paradigms?

- X-ray jets
- Microflares/nanoflares
- "Extended flare" phenomena
- Masuda flare
- Non-thermal ejecta
- Shock waves
- Double layers
- Coronal thick-target events
- Impulse-response events

X-ray Jets (Hα surges, sprays)



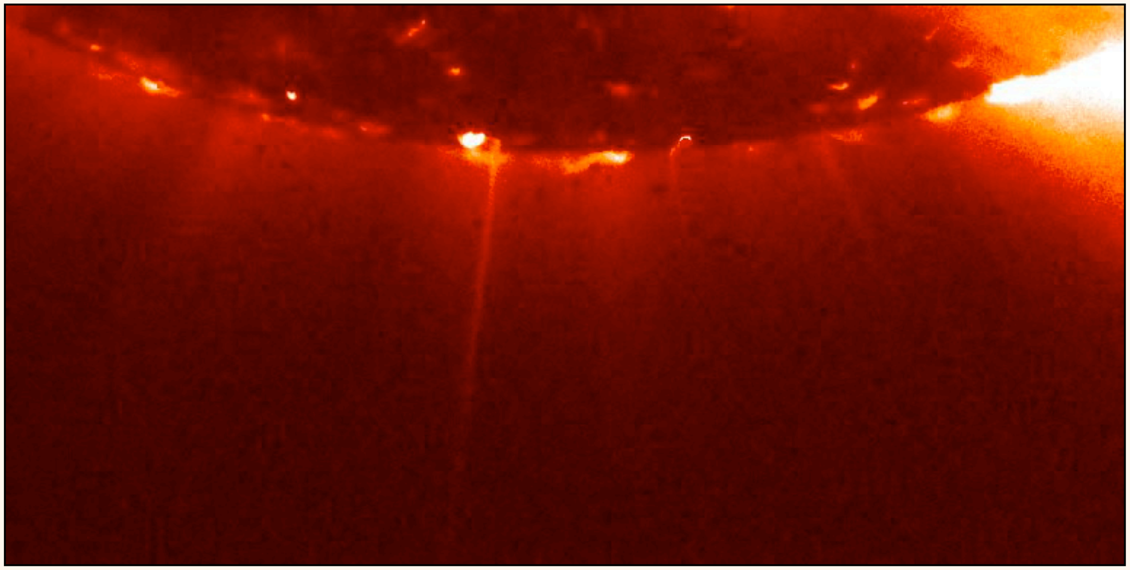




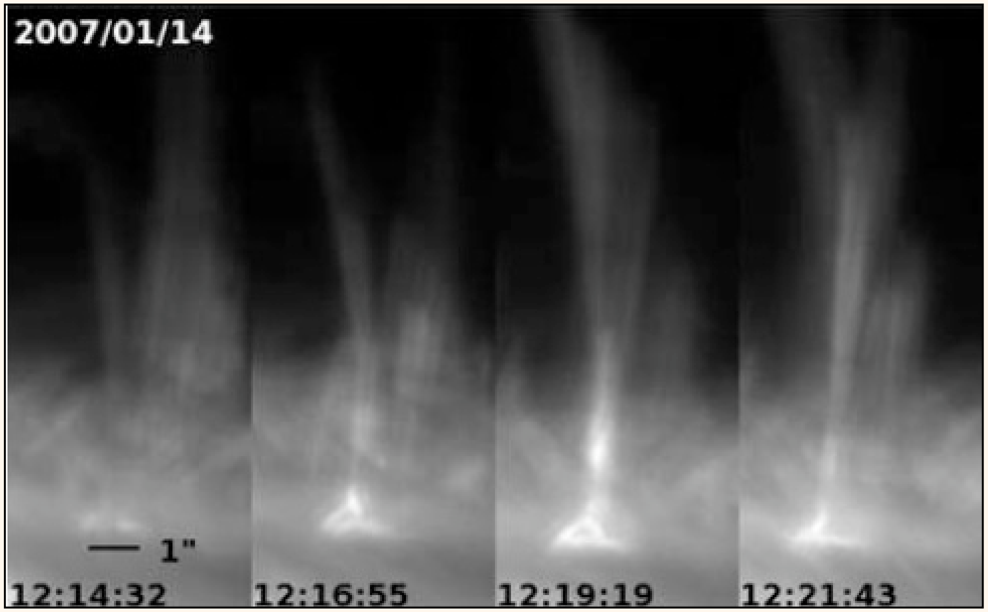
From a Yohkoh Science Nugget

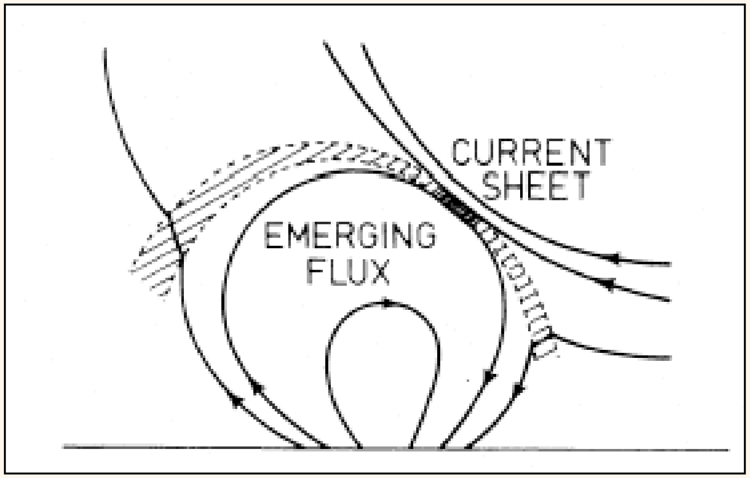
http://solar.physics.montana.edu/nuggets/

Other Jets



Cirtain et al. ???? *Hinode*

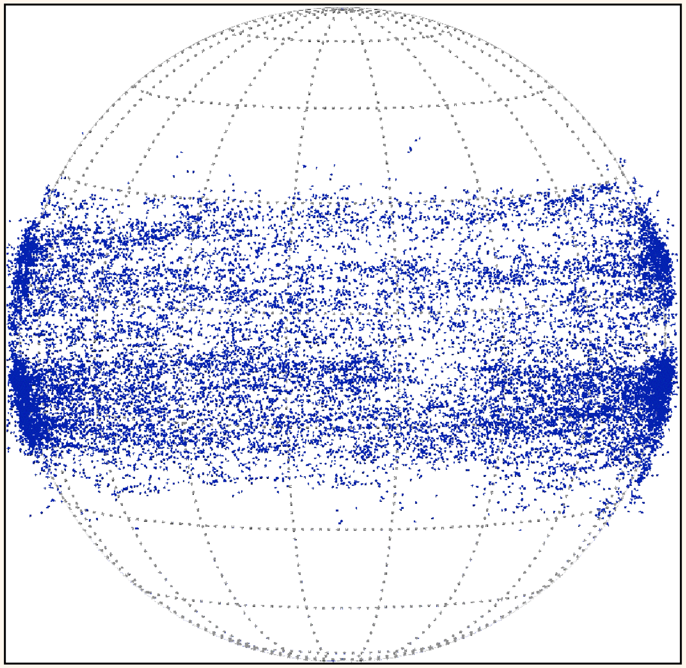




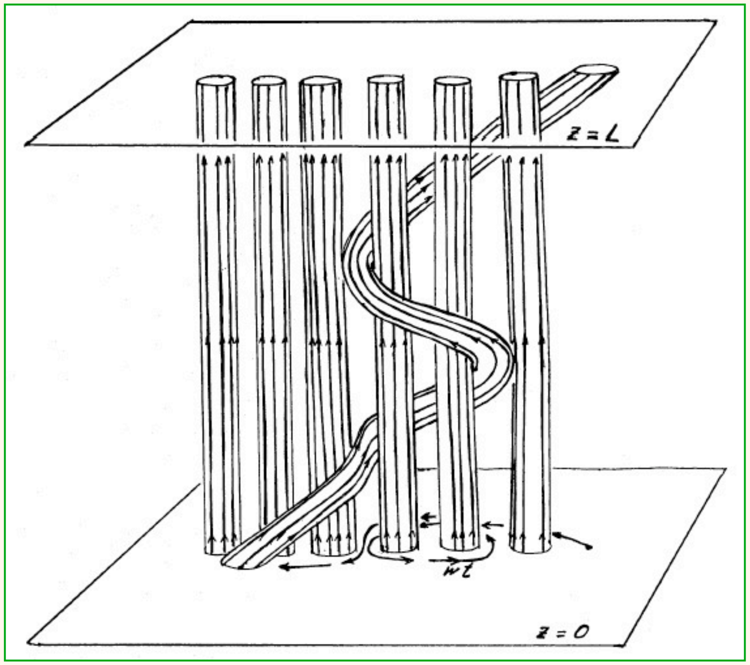
Heyvaerts et al. 1977

Shibata et al. 2007

Microflares and nanoflares



RHESSI microflares, 2002-2007



Parker's nanoflare cartoon

- Major flares have ~10^{32} ergs total energy
- Microflares (>10^{26} ergs) occur in active regions
- Nanoflares are conjectural and weaker still

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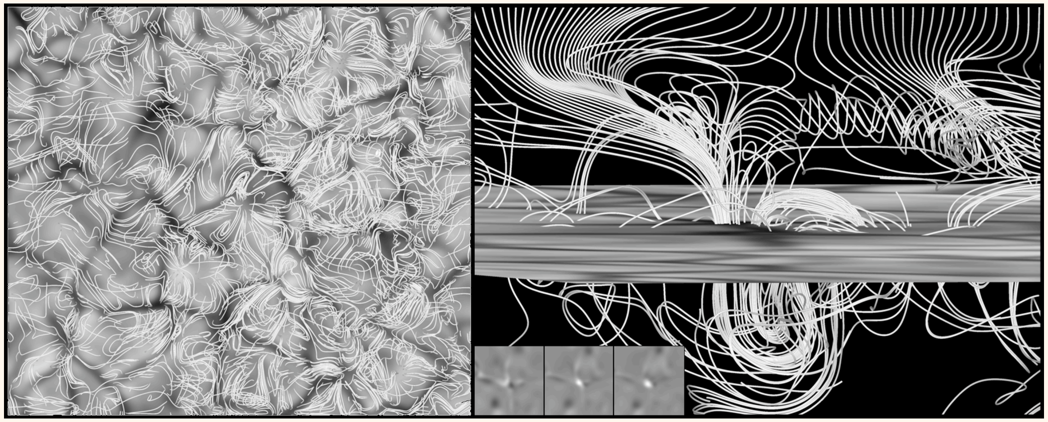
What do we mean by "magnetic reconnection"?

- The solar corona has low plasma beta:
  beta = $2nkT/(B^2/8\pi)$
- It appears to have a cellular structure, with magnetic domains separated by current sheets
- A flare may be associated with a restructuring of such domains
- The microphysics can be studied in the laboratory and in space plasmas



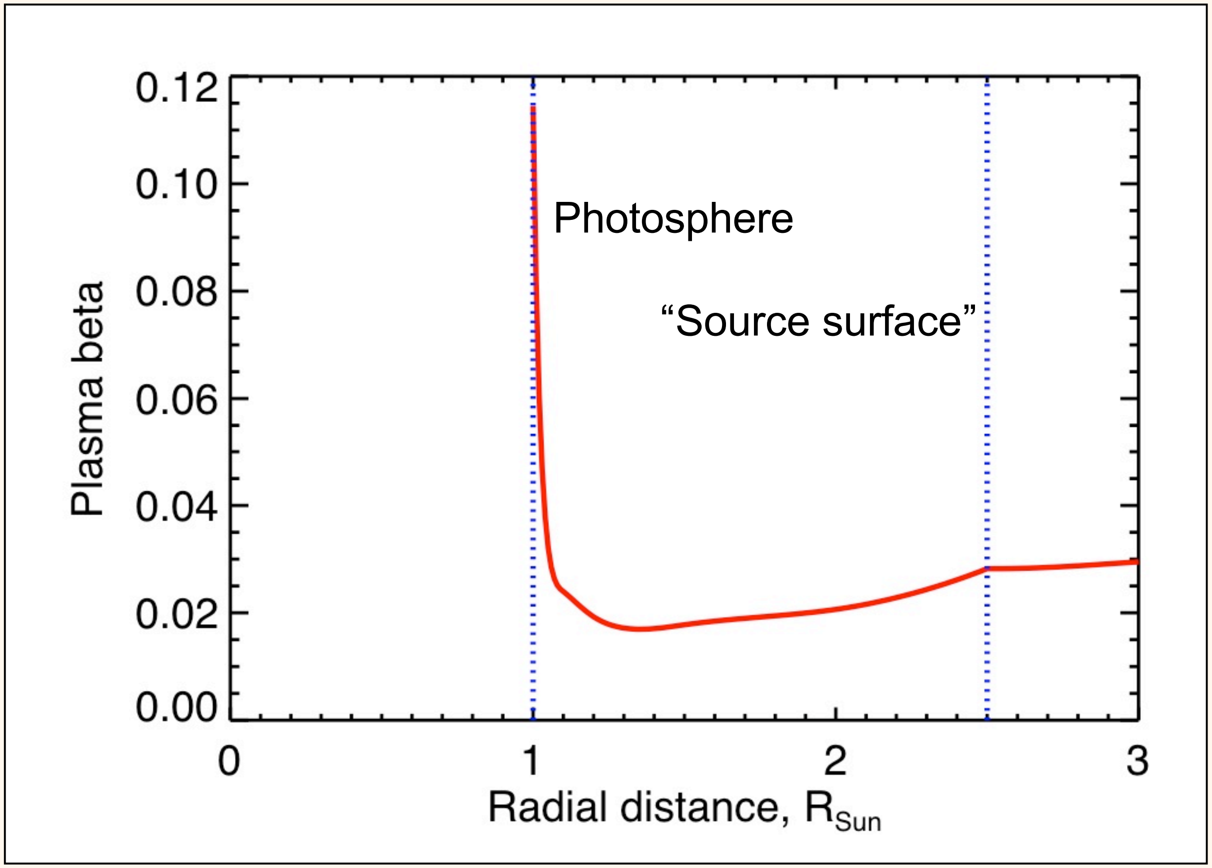
Above

MHD Simulation

Below

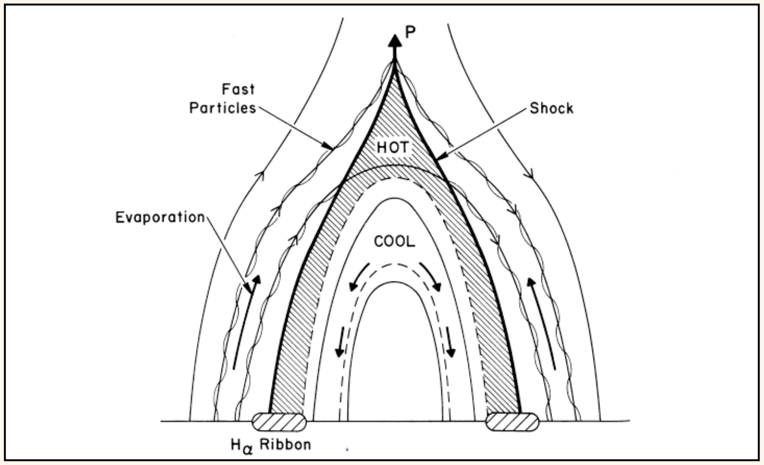
Abbett, 2008

Beta in the solar corona

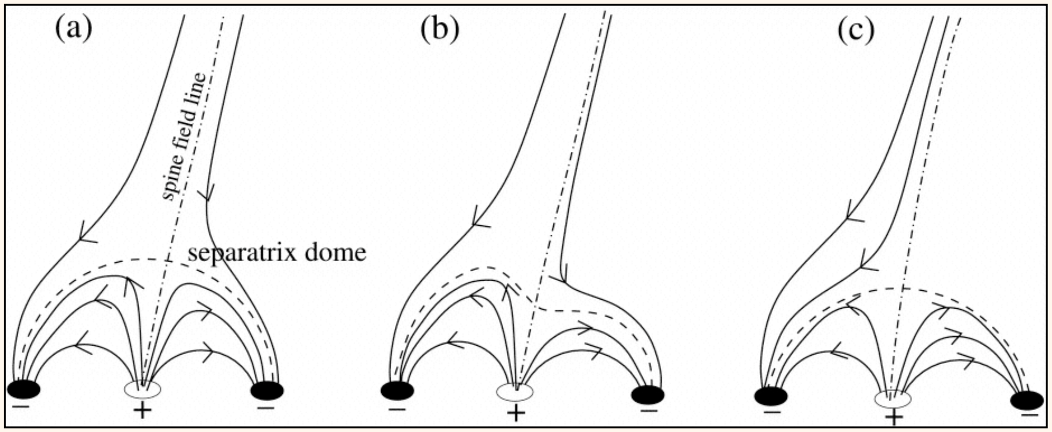


Plasma beta from a G. Withbroe solar-wind model
n.b. beta can be much lower in active regions

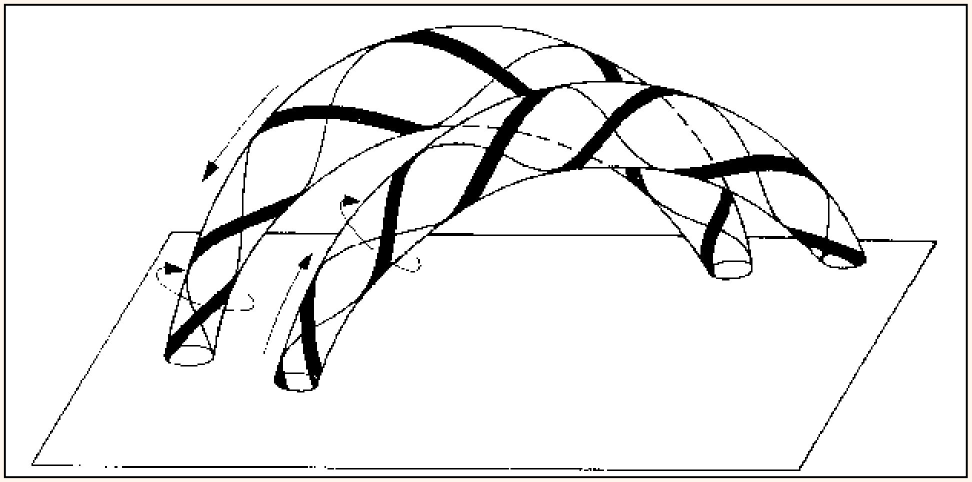
Reconnection cartoons



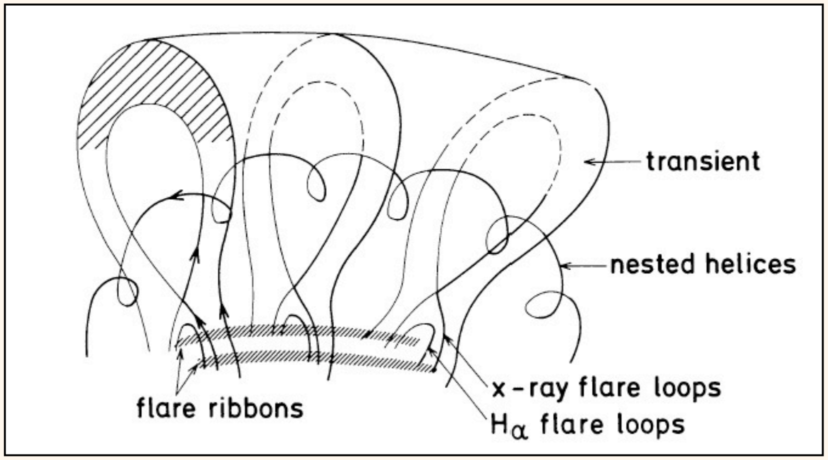
Cargill & Priest 1983



Fletcher et al. 2001

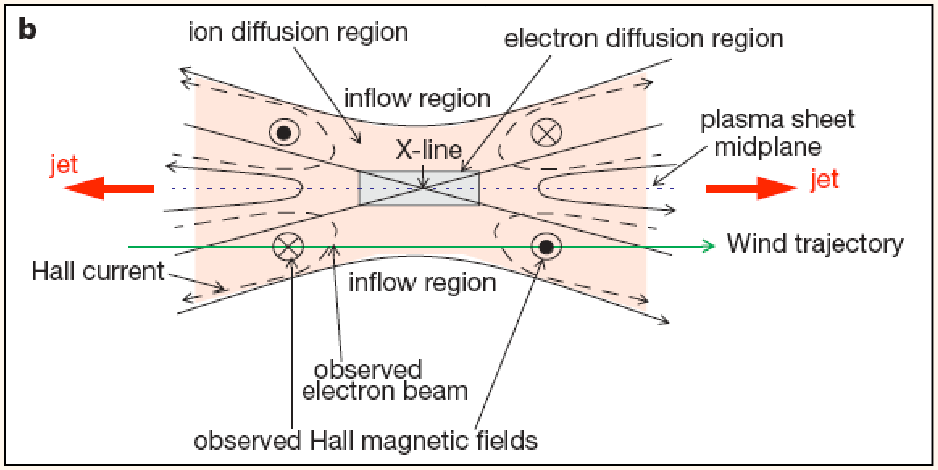


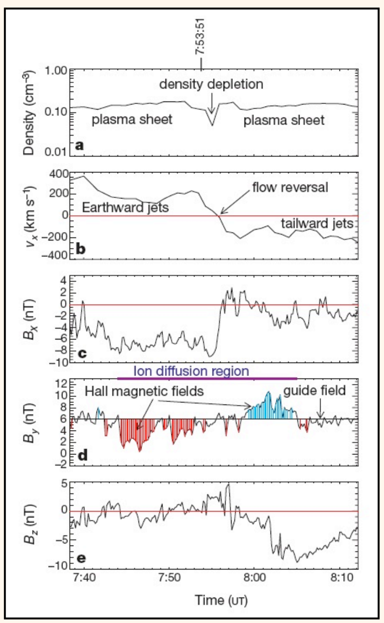
Gold & Hoyle 1961



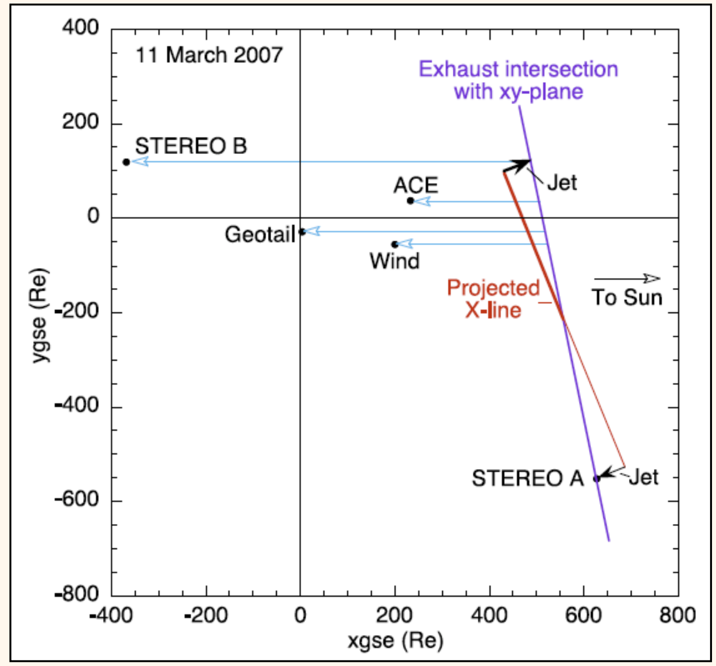
Anzer-Pneuman 1982

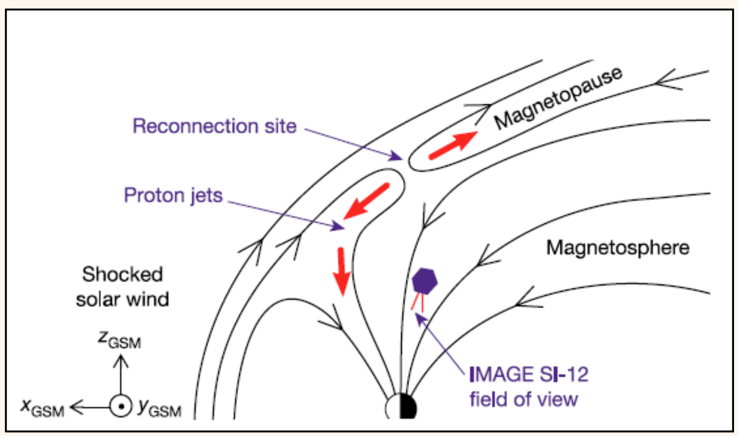
Reconnection microphysics





Geotail: Oieroset et al. 2001





Solar wind: Gosling et al. 2007

Magnetopause: Frey et al. 2003

Coronal acceration?

'Volumetric' acceleration:

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

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

Collapsing traps (e.g. Somov & Bogachev)

Betatron acceleration (e.g. Brown-Hoyng, Karlicky-Kosugi)

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

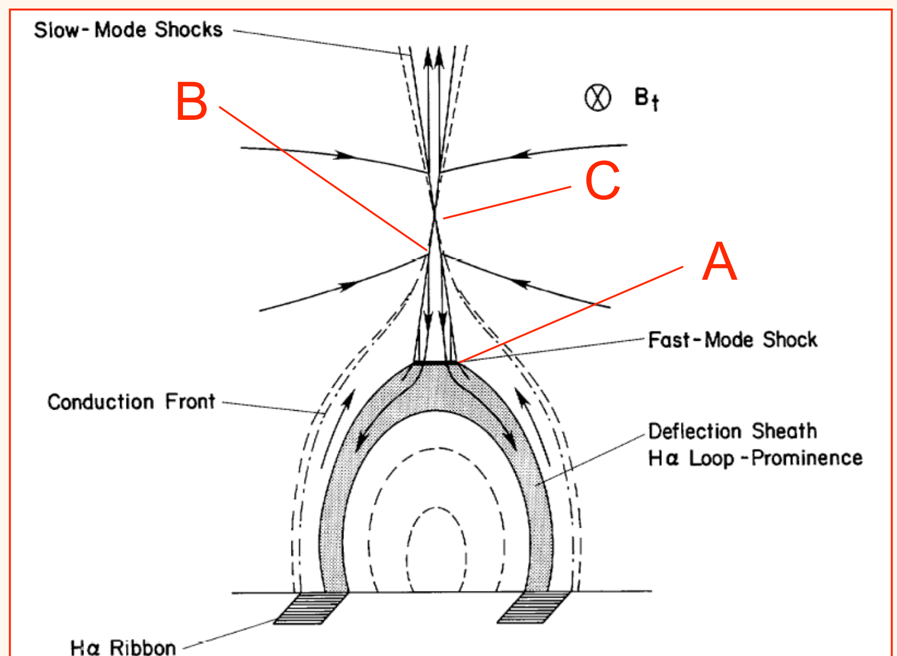
Reconnecting X-line or current-sheet acceleration

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

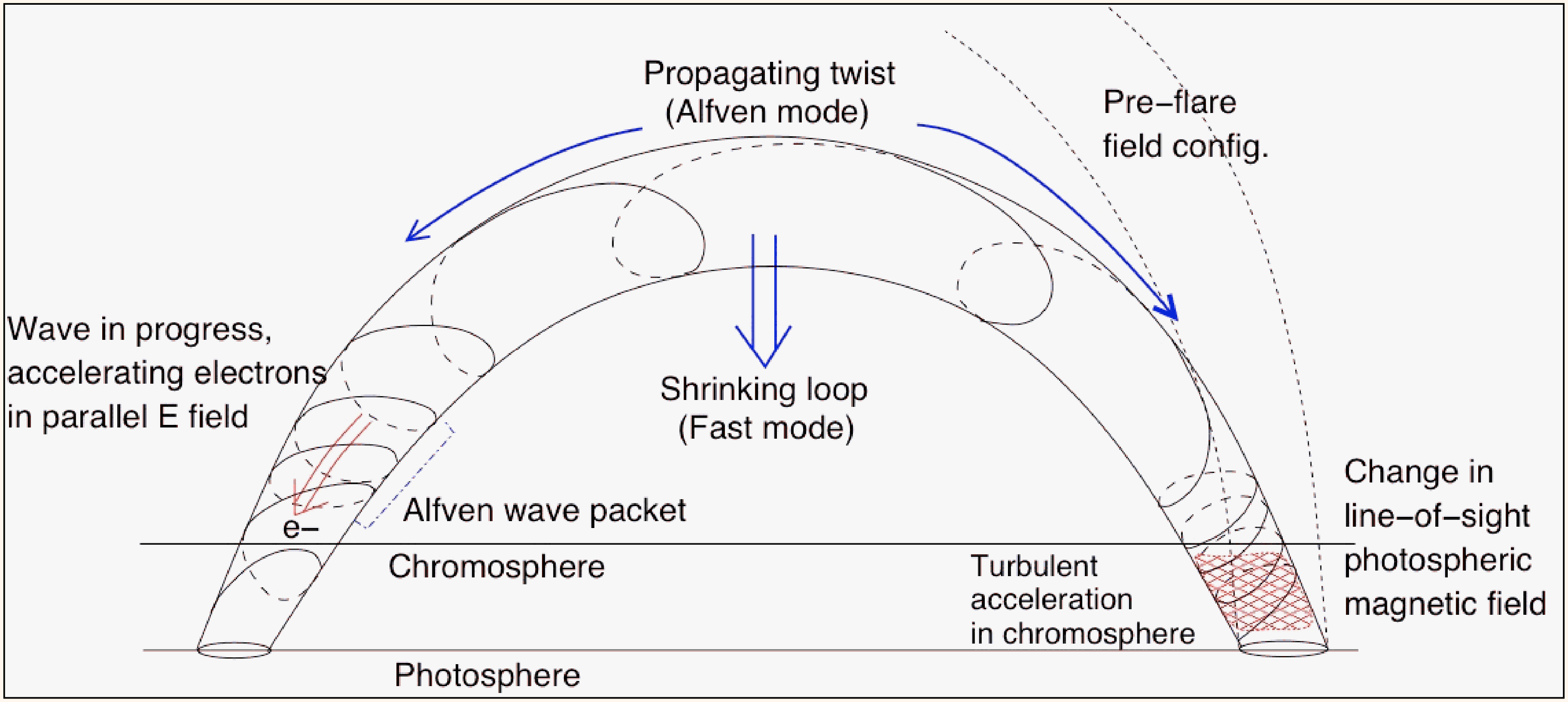
Single macroscopic current sheet (e.g. Litvinenko & Somov, Somov & Kosugi)

Problems for coronal acceleration

- Location (fast shock A, slow shock B, current sheet C - are any of these real?)
- The “number problem” - where to get the particles?
- How to get “flare particles” into the heliosphere?
- Beam dynamics - return currents and inductive effects



New non-MHD ideas



Fletcher & Hudson 2008

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

Outline

- Flare Phases
- Flare Phenomena
- Flare and CME Energetics
- Analogs: stellar, solar, terrestrial
- How to observe magnetic reconnection
- **Conclusions**

Most crucial future observations

- Flare-associated field variations
- The deepest layers: γ-rays, IR, seismic waves
- Particle acceleration

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- In-situ corona