

Observations of solar and stellar eruptions, flares, and jets

H.S. Hudson

Space Sciences Lab, UC Berkeley

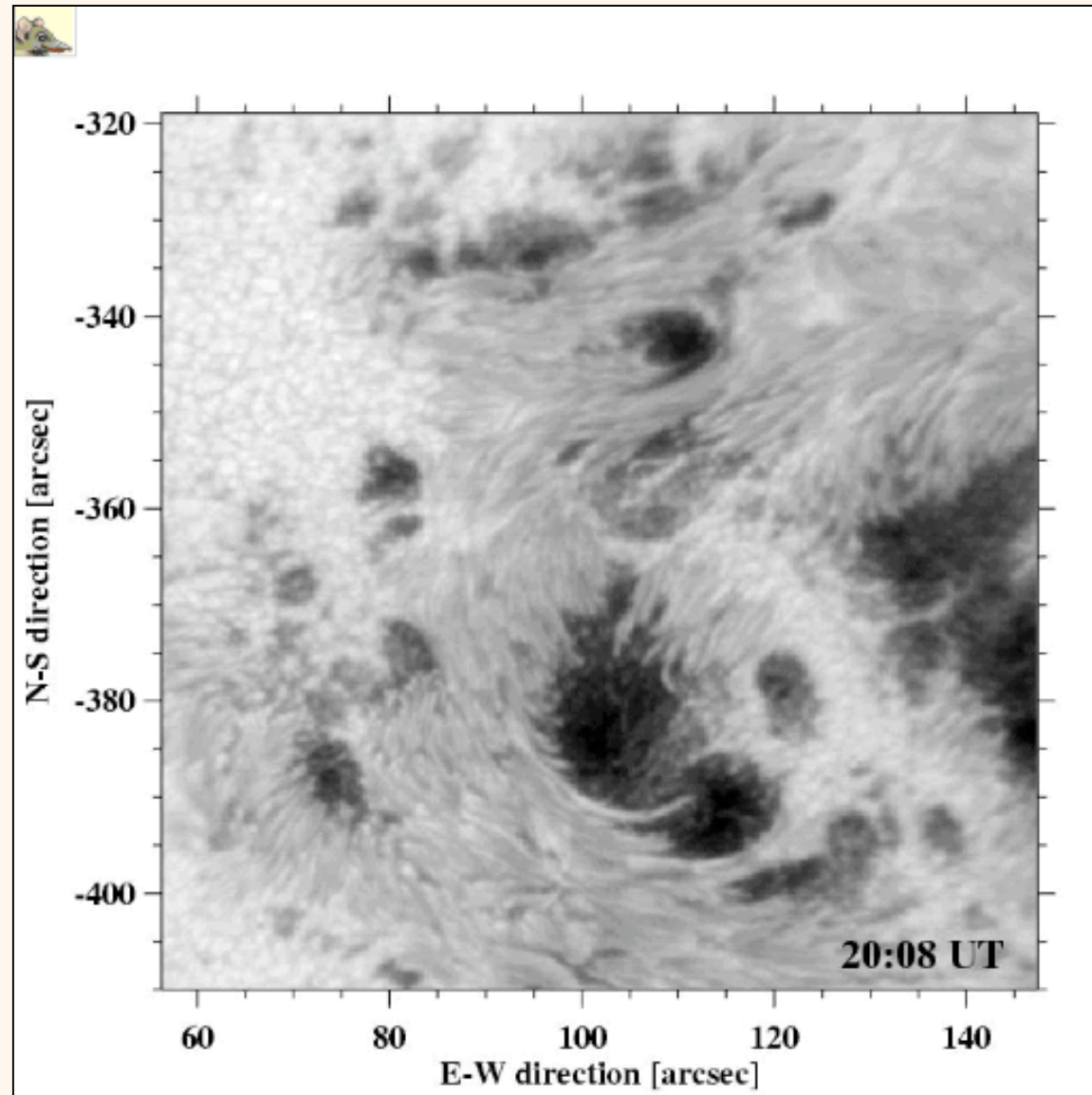
- Flare Phases
- Flare Phenomena
- Flare and CME Energetics
- Analogs: stellar, solar, terrestrial
- How to observe magnetic reconnection
- Conclusions

A flare/CME seen in EUV and X-rays



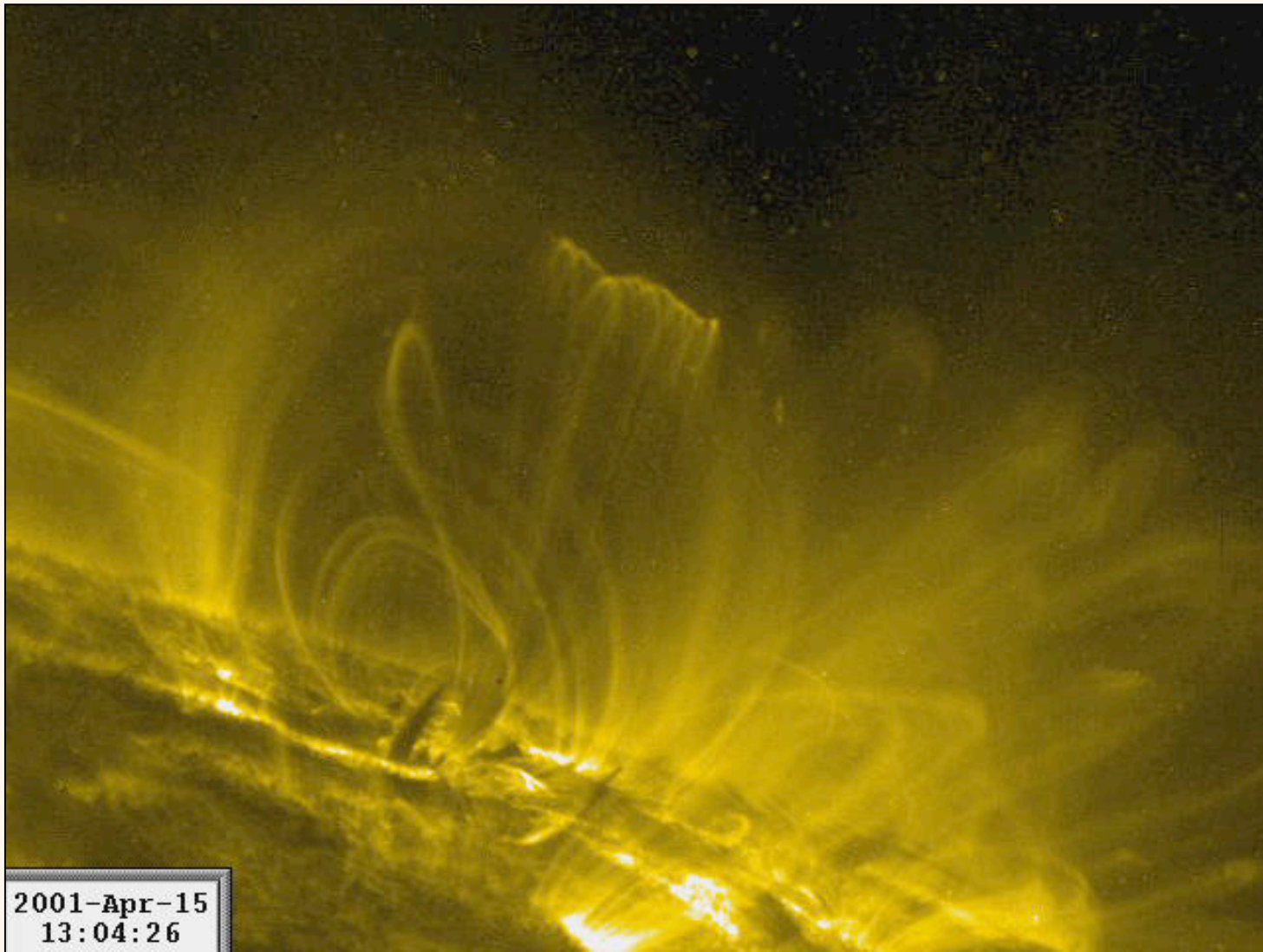
Red RHESSI 6-12 keV, blue 50-100 keV, gold images TRACE 195A

An IR movie from the “opacity minimum”

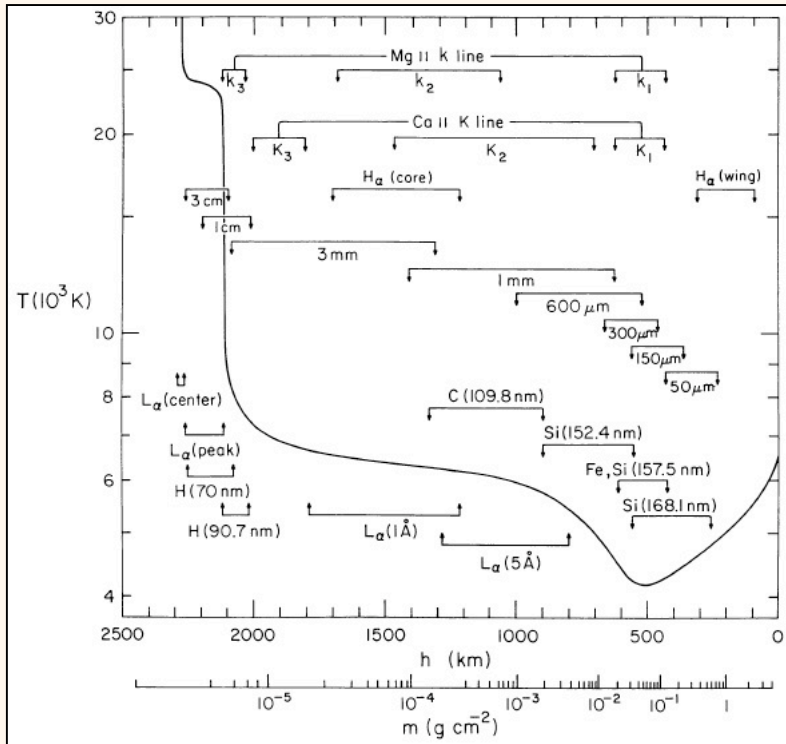


Xu et al. 2005

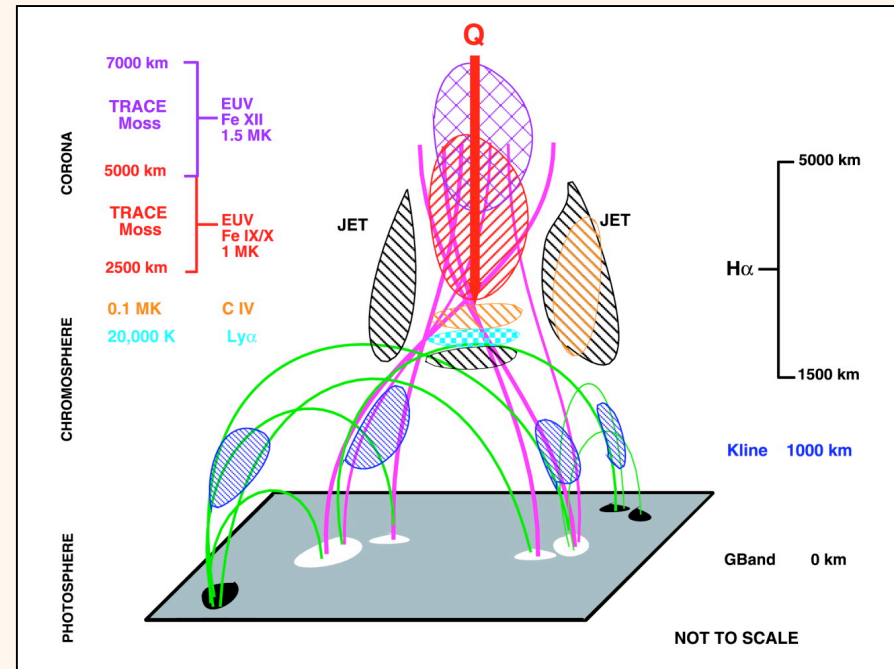
A TRACE movie that shows everything



Where does this all fit in?



Vernazza et al. 1981 ("VAL-C")



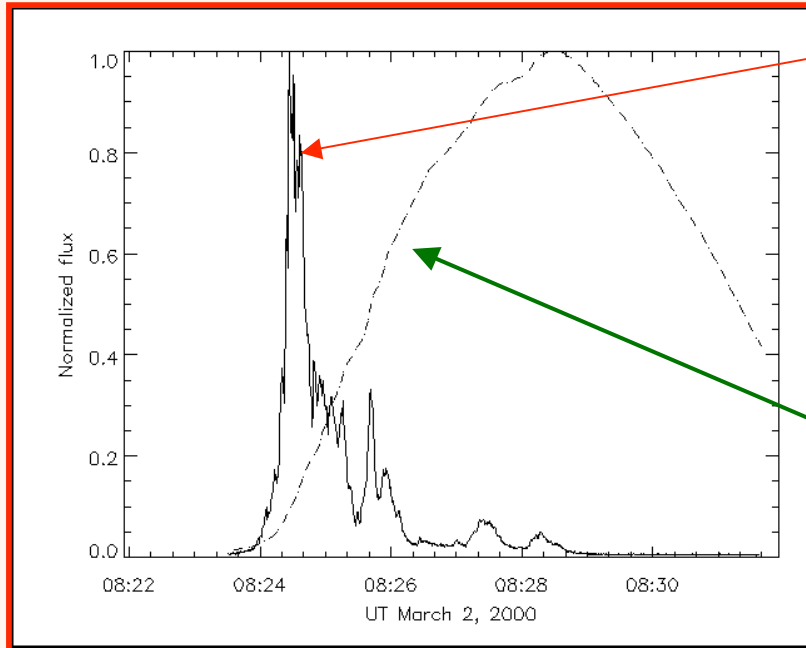
De Pontieu et al 2003

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

Outline

- **Flare Phases**
- Flare Phenomena
- Flare and CME Energetics
- Analogs: stellar, solar, terrestrial
- How to observe magnetic reconnection
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Impulsive phase and gradual phase: The Neupert Effect



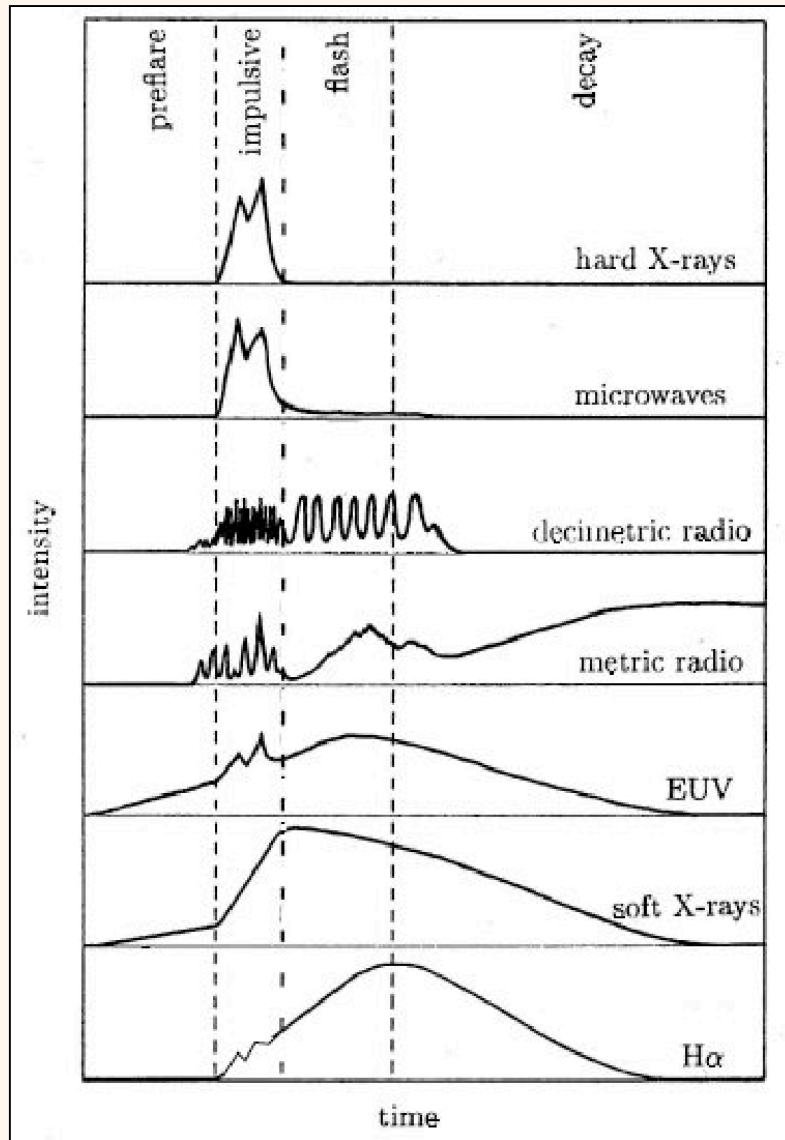
- Impulsive phase* – primary energy release
- hard X-rays (10s of keV)
 - white light, UV, μ waves - broad spectrum
 - duration < few minutes
 - intermittent and bursty time profile, 100ms
 - **energy injection**

- Gradual phase* - response to input
- thermal emission (kT \sim 0.1-1 keV)
 - rise time \sim minutes
 - **coronal reservoir**

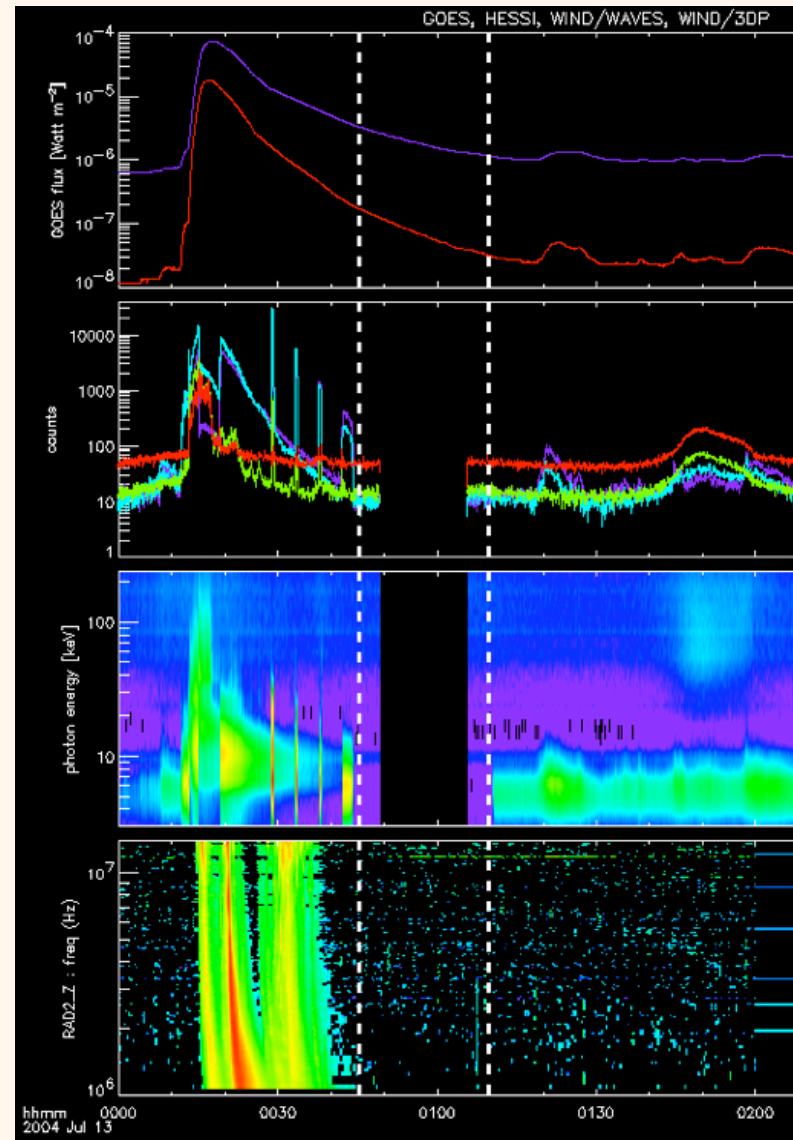
Impulsive phase:

- > 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

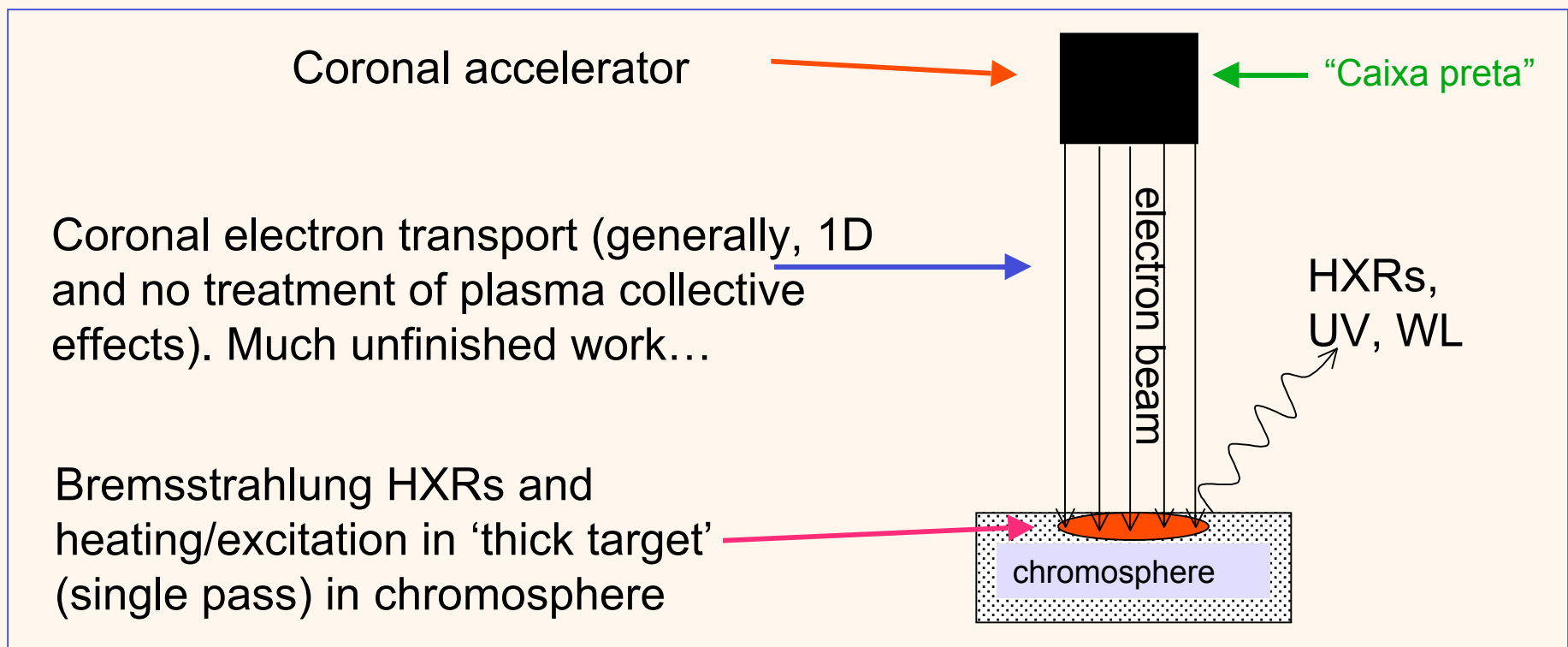


<http://sprg.ssl.berkeley.edu/~tohban/browser>

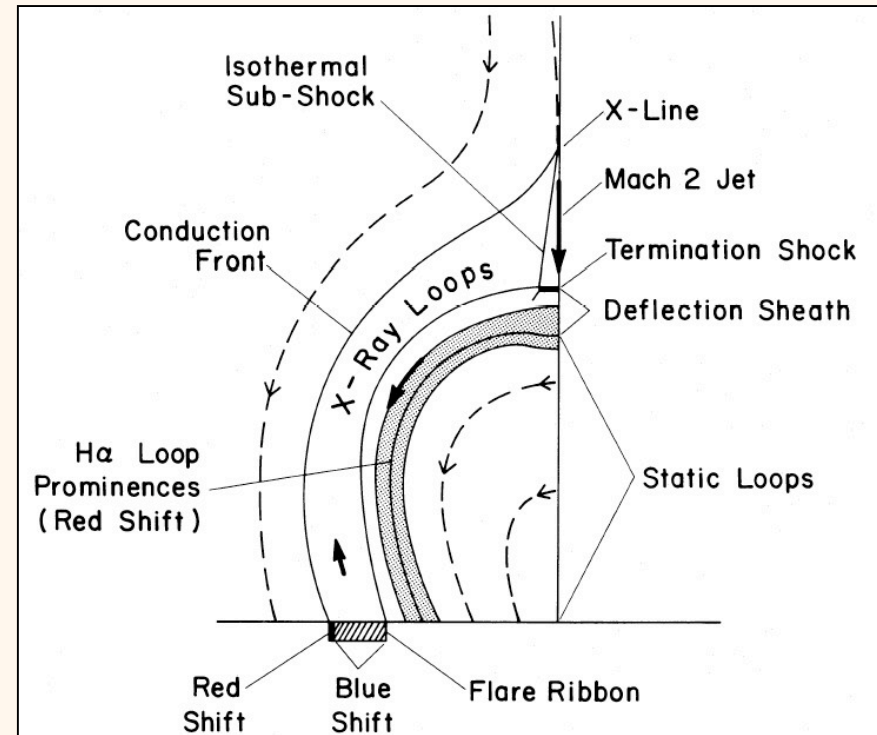
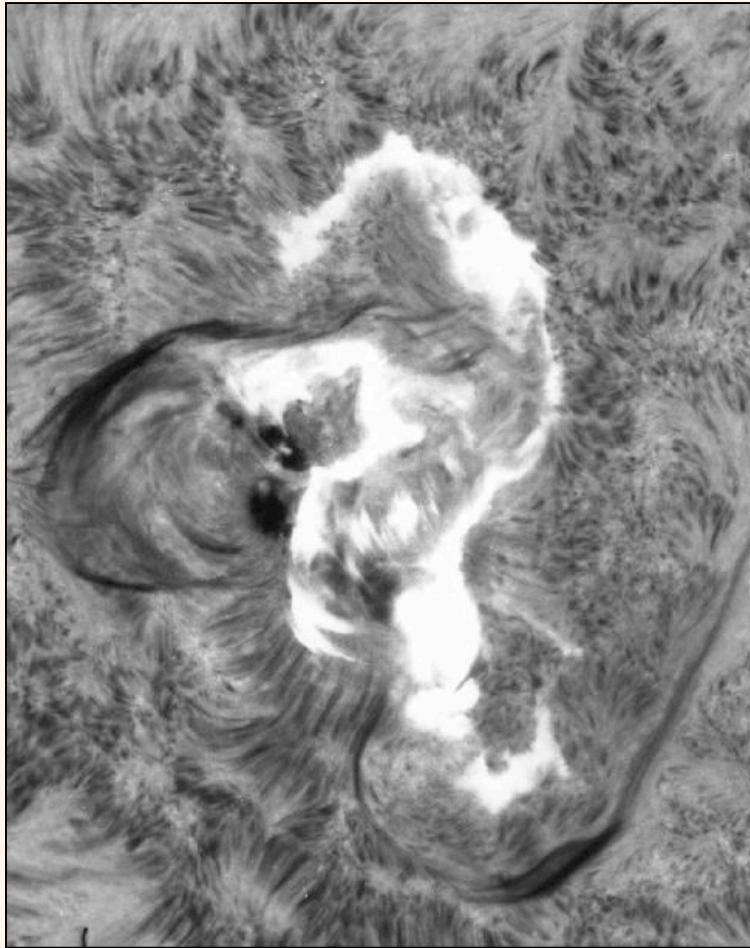
Impulsive Phase: the thick-target model

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



Gradual phase: reconnection model



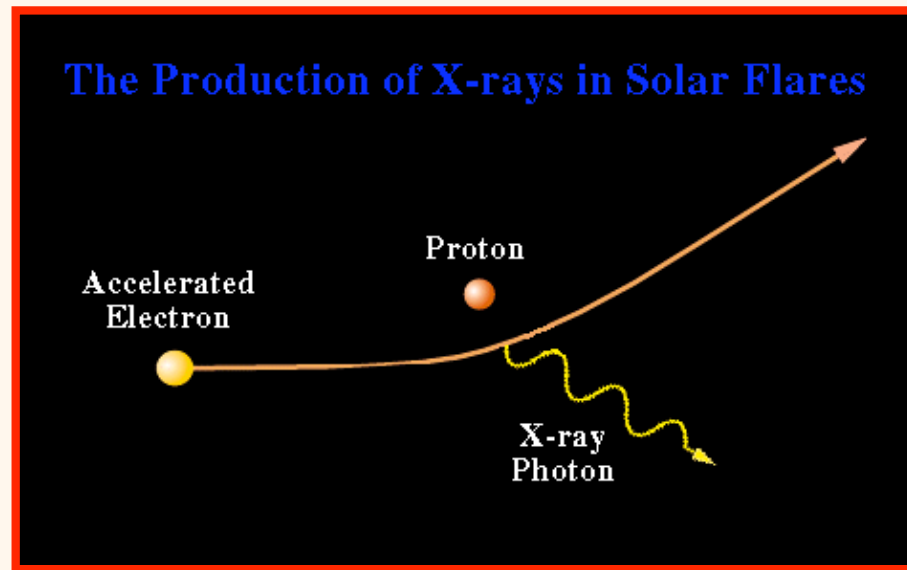
- Ribbon separation
- Loop temperature sequence
- Outer edge spectral signature
- Coronal cusp development
- Other signatures

Outline

- Flare Phases
- **Flare phenomena**
- Flare and CME energetics
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X-Rays

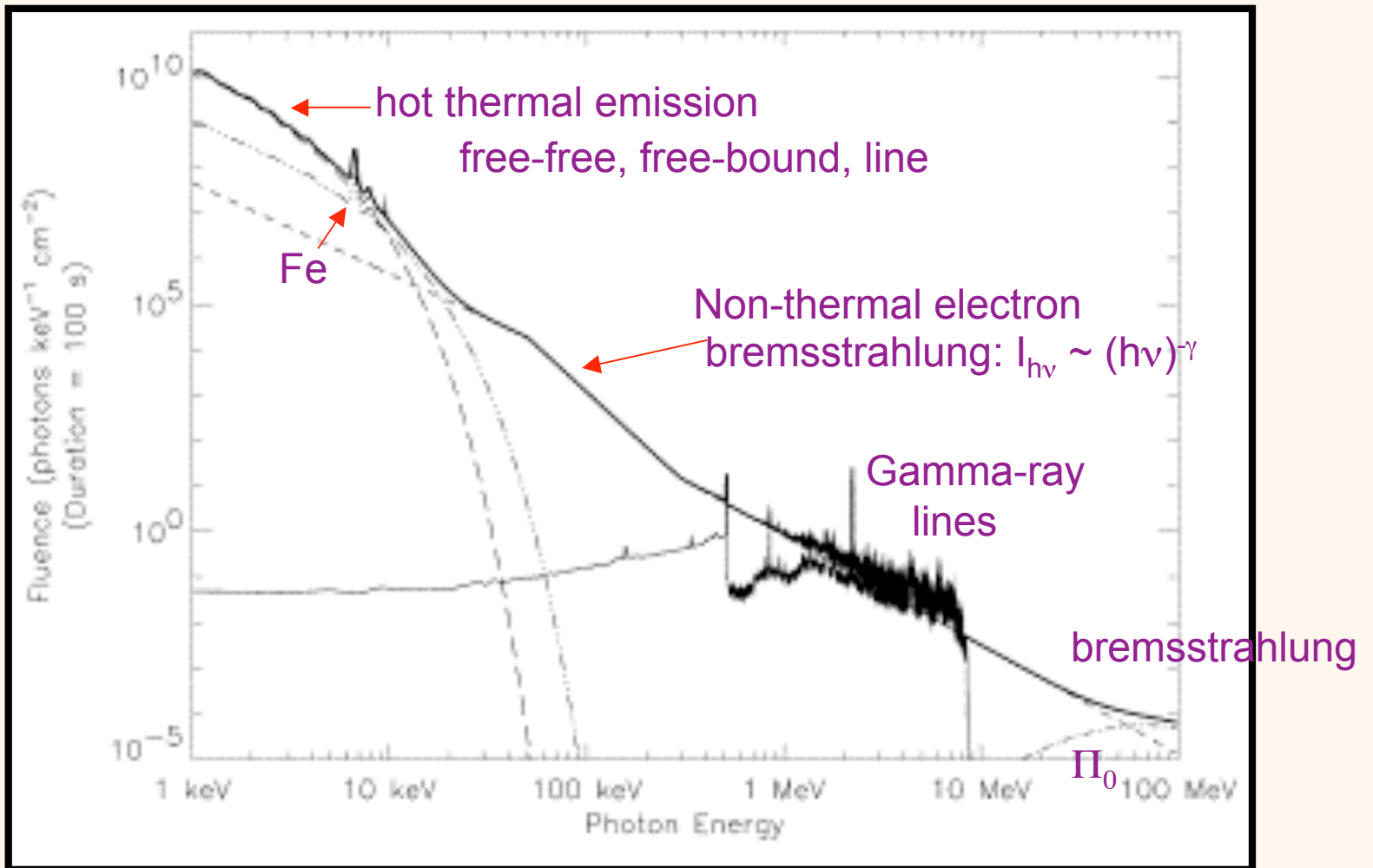
X-rays observed by (e.g.) RHESSI are primarily electron-proton *bremsstrahlung* from energetic electrons (>15 keV)



*This is not a
Feynman diagram!*

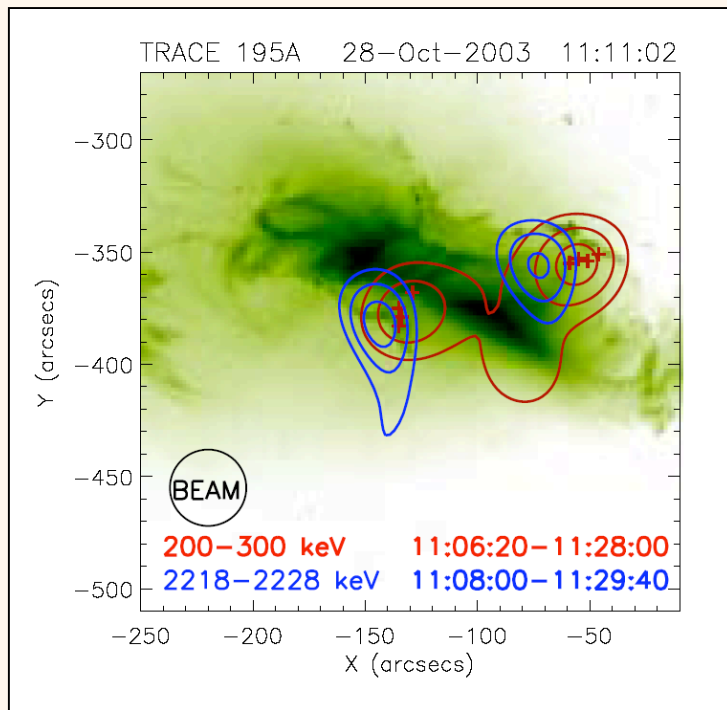
- Non-thermal bremsstrahlung: $E_e \gg kT$ and photon spectrum $I_{h\nu} \sim (h\nu)^{-\gamma}$
 - not a significant energy loss: $\sim 10^{-5}$ of the energy radiated as X-rays
- Thermal bremsstrahlung: $E_e \sim kT$ and photon spectrum $I_{h\nu} \sim e^{-h\nu/kT}$
 - significant energy loss from electrons 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

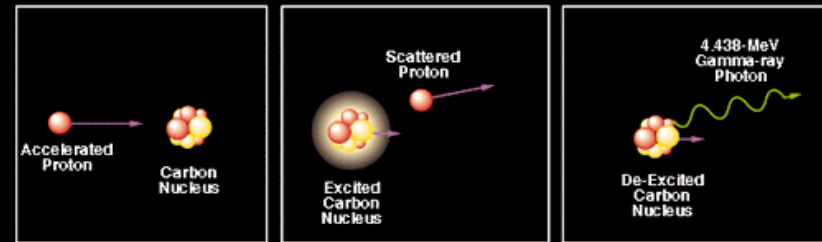
Nuclear de-excitation lines
caused by bombardment of
nuclei by 10-30 MeV protons;
de-excitation also via neutrons



Hurford et al 2003

Boulder 23 July 2008

Production of nuclear de-excitation lines

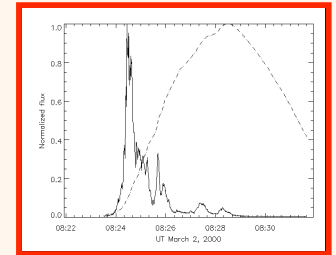


Neutron capture line at 2.23 MeV - $n(p,\gamma)D$
- shows location of 10s of MeV protons
- direct detection of neutrons also possible

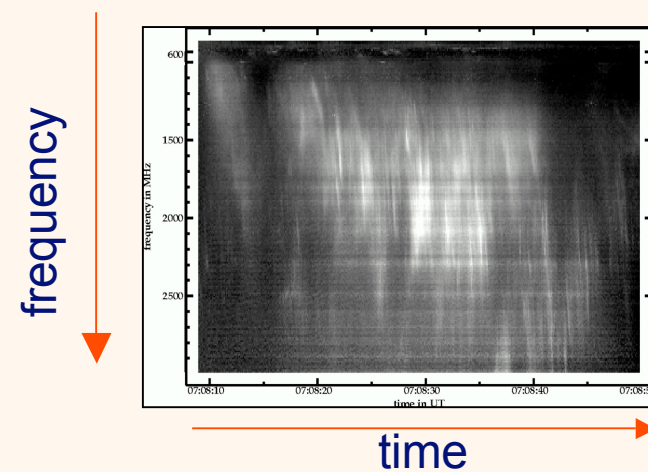
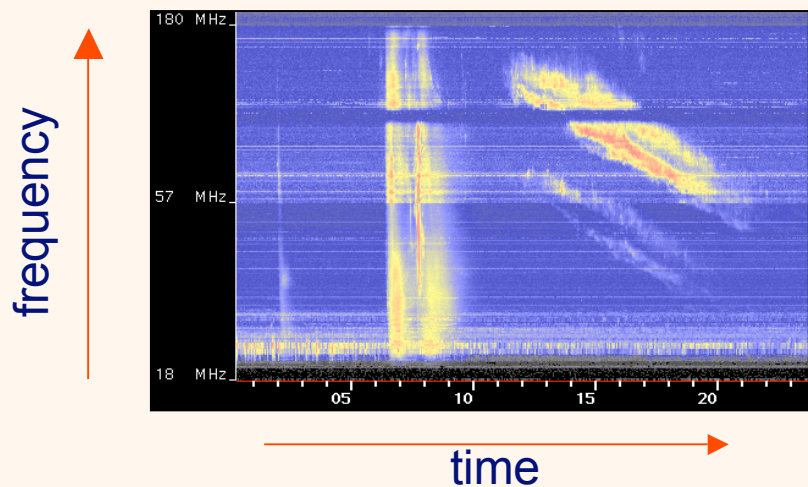
$\Pi_0 \rightarrow 2\gamma$ decay continuum shows ~ 100 MeV;
 e^+ annihilation line (511 keV) - complicated!

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.

Outline

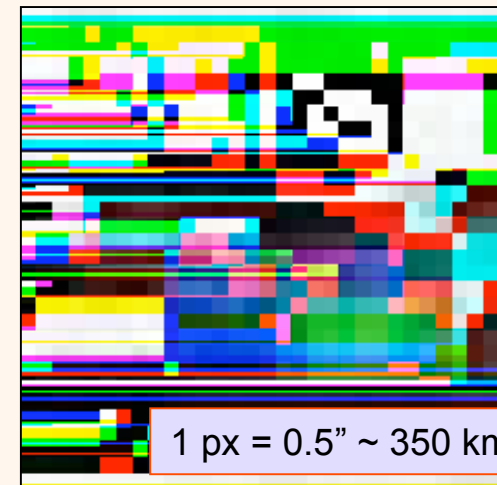
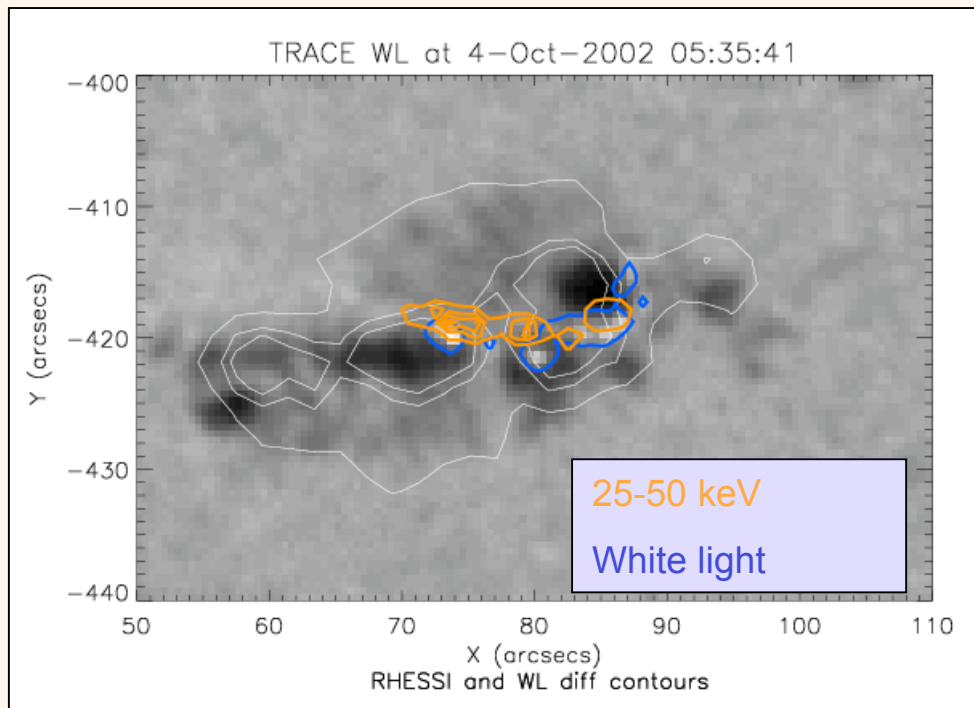
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Thick target energetics / beam fluxes

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 ~ 10 s)

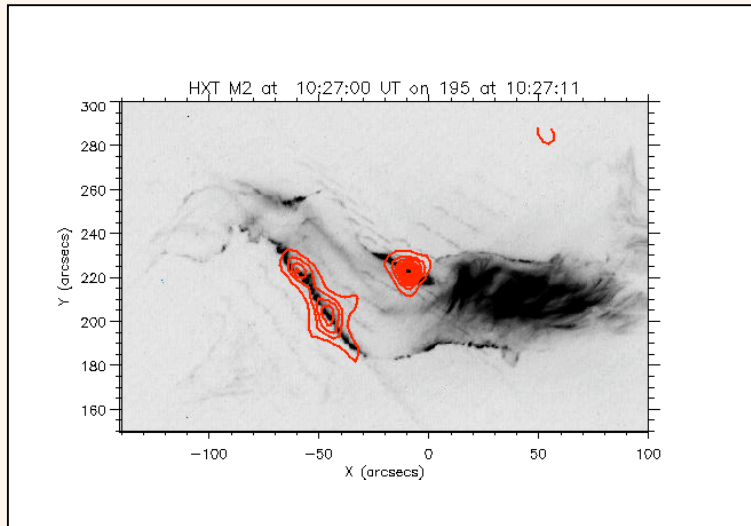
Beam density can be inferred using white-light footpoint areas as a proxy for beam 'area'.



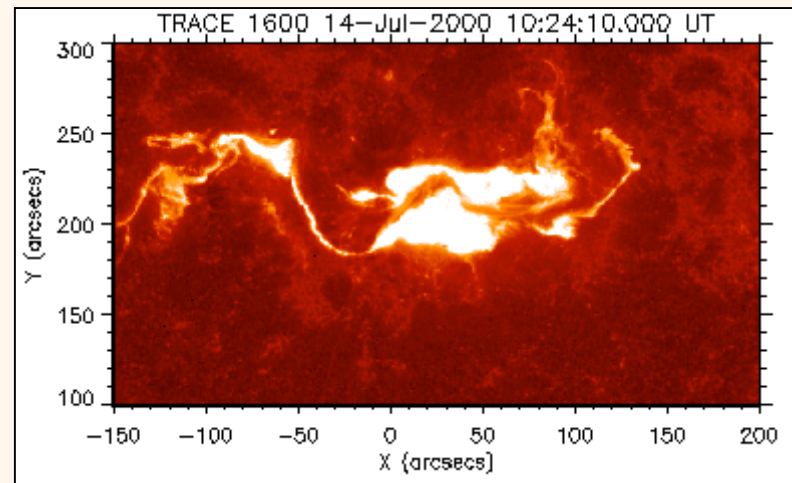
White light footpoint area $\sim 10^{17}$ cm^2

Ribbons in the impulsive phase

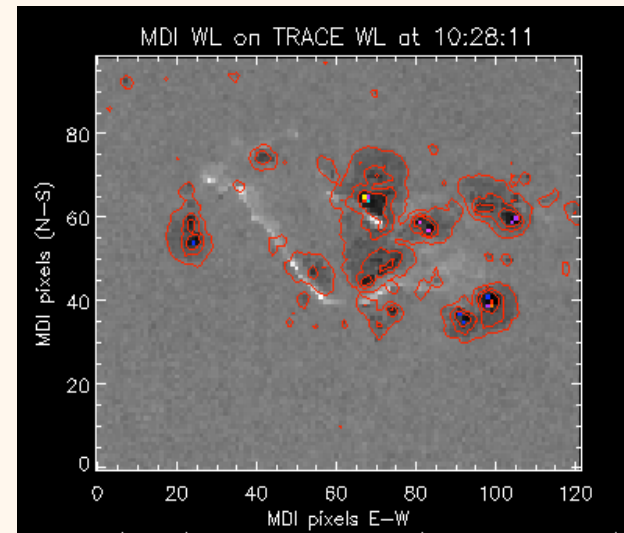
UV/EUV, H_{α} and (sometimes) optical emission demonstrate excitation of lower atmosphere



Yohkoh HXR contours on 195A emission



1600A broadband emission



White-light footpoints

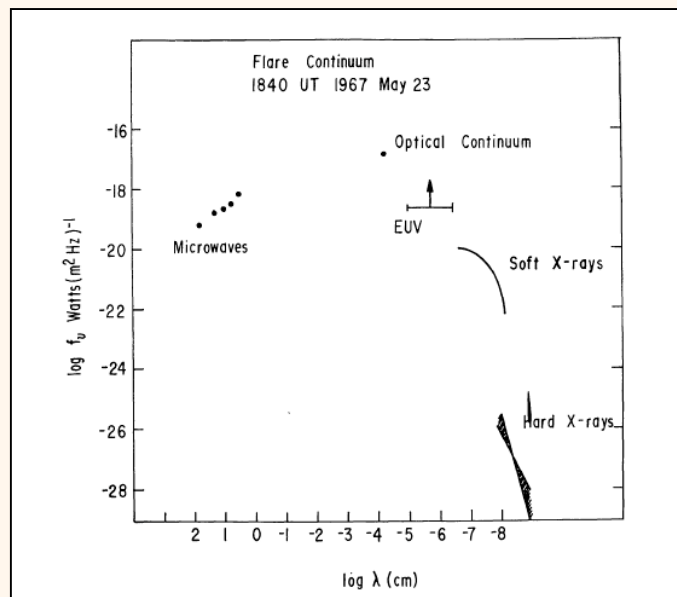
Optical/UV/EUV emission from conduction, “precipitation”, or waves

White-light luminosity can be directly measured.

Fletcher & Hudson 2001

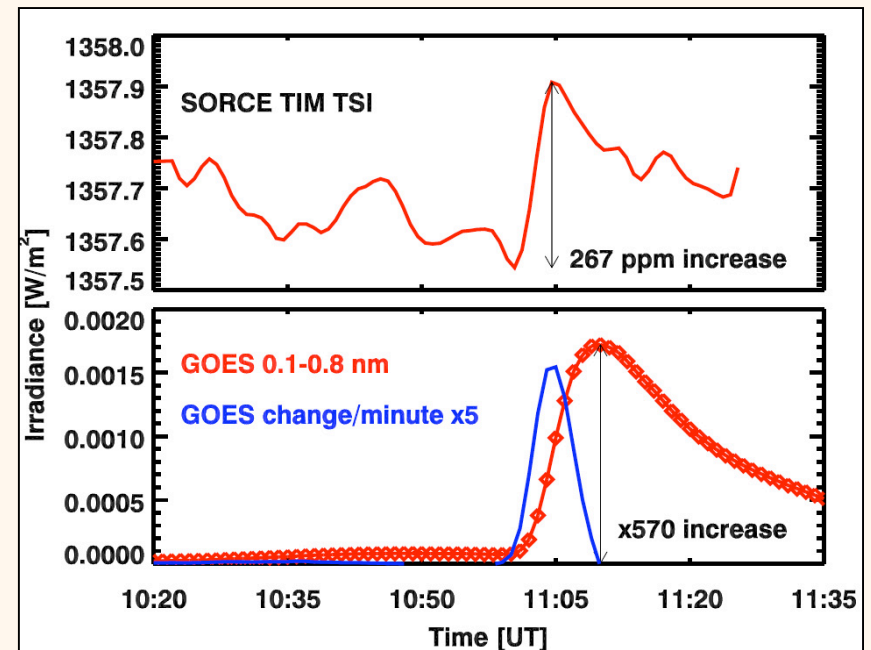
Role of 'white light' in total flare luminosity

- Substantial fraction of total flare energy radiated in broadband UV-IR
- In Oct-Nov 2003 flares, integrated irradiance $\sim 3 - 6 \times 10^{32}$ erg
- Spectral modelling \Rightarrow 40-50% of this at $\lambda \geq 1900\text{\AA}$, ~ 100 times soft X-ray irradiance



Hudson 1972

Total Irradiance Monitor on SORCE



Woods et al. 2005

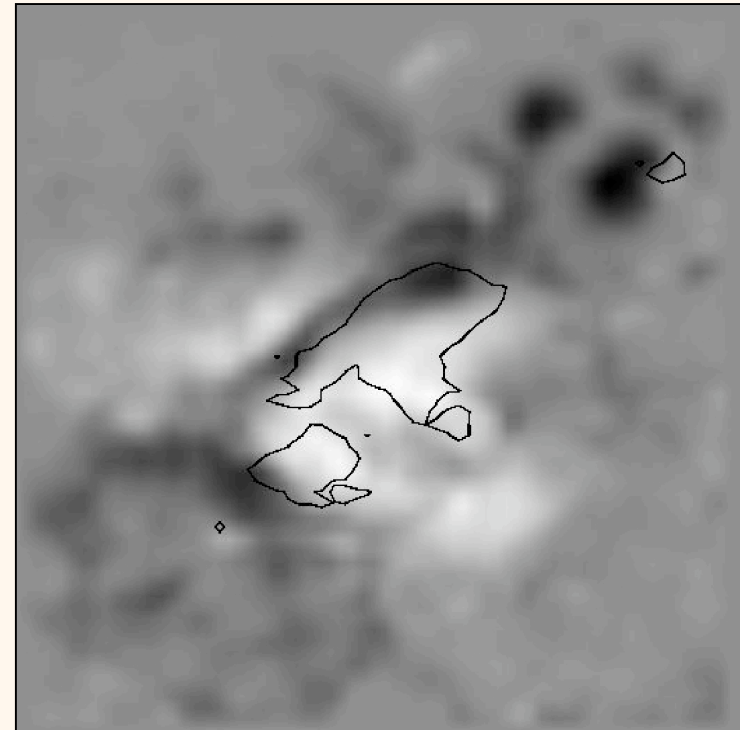
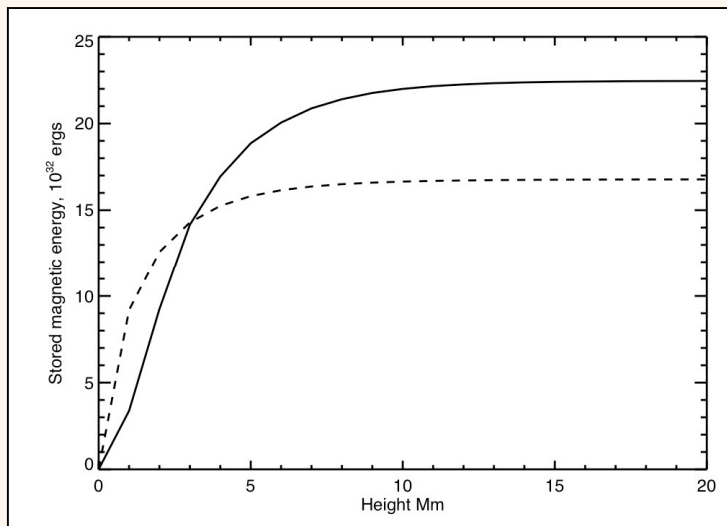
- TIM shows an impulsive component

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

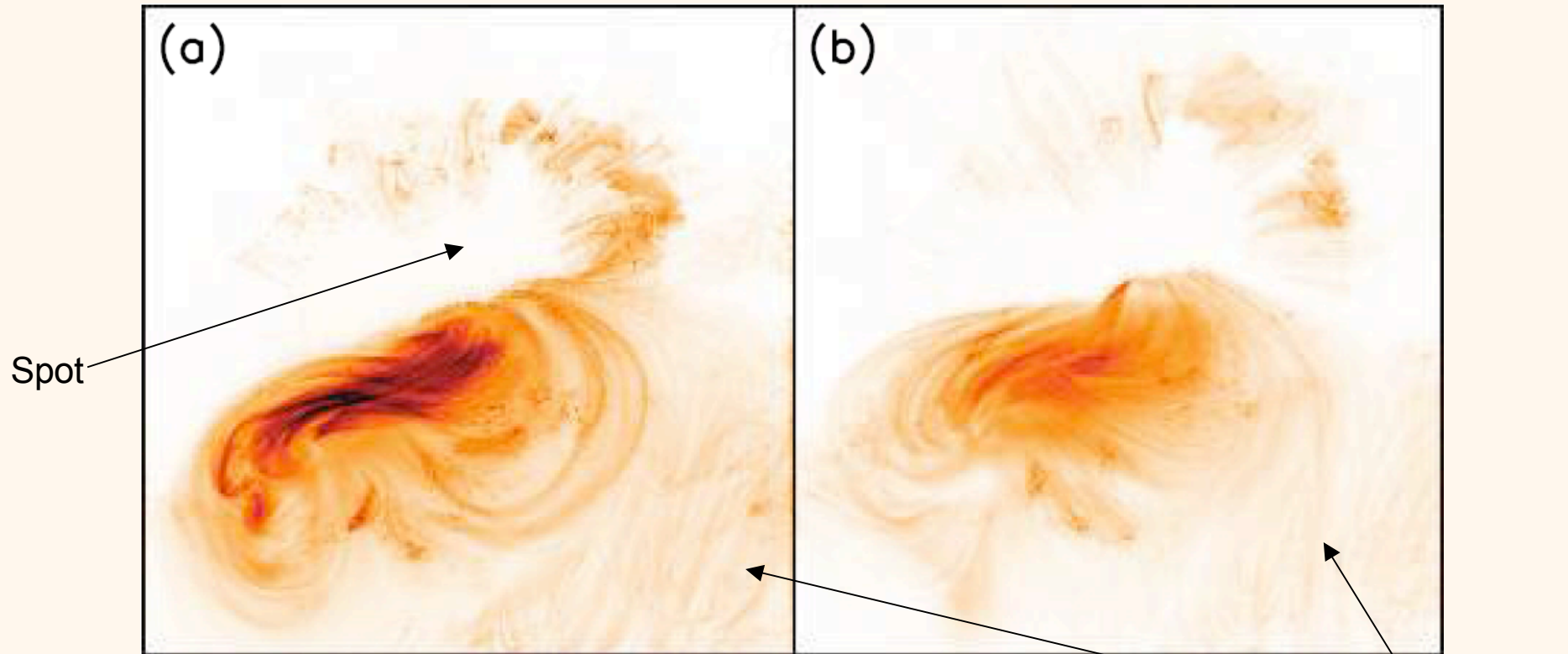
- Need to find locus of $\mathbf{B}^2/8\pi$
- Have force-free condition
 $\mathbf{Curl}(\mathbf{B}) = \alpha(x,y)\mathbf{B}$
- Extrapolation of photospheric field observations
 - Potential ($\alpha = 1$)
 - Linear force-free (α constant)
 - Non-linear force-free NLFFF (α general)



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



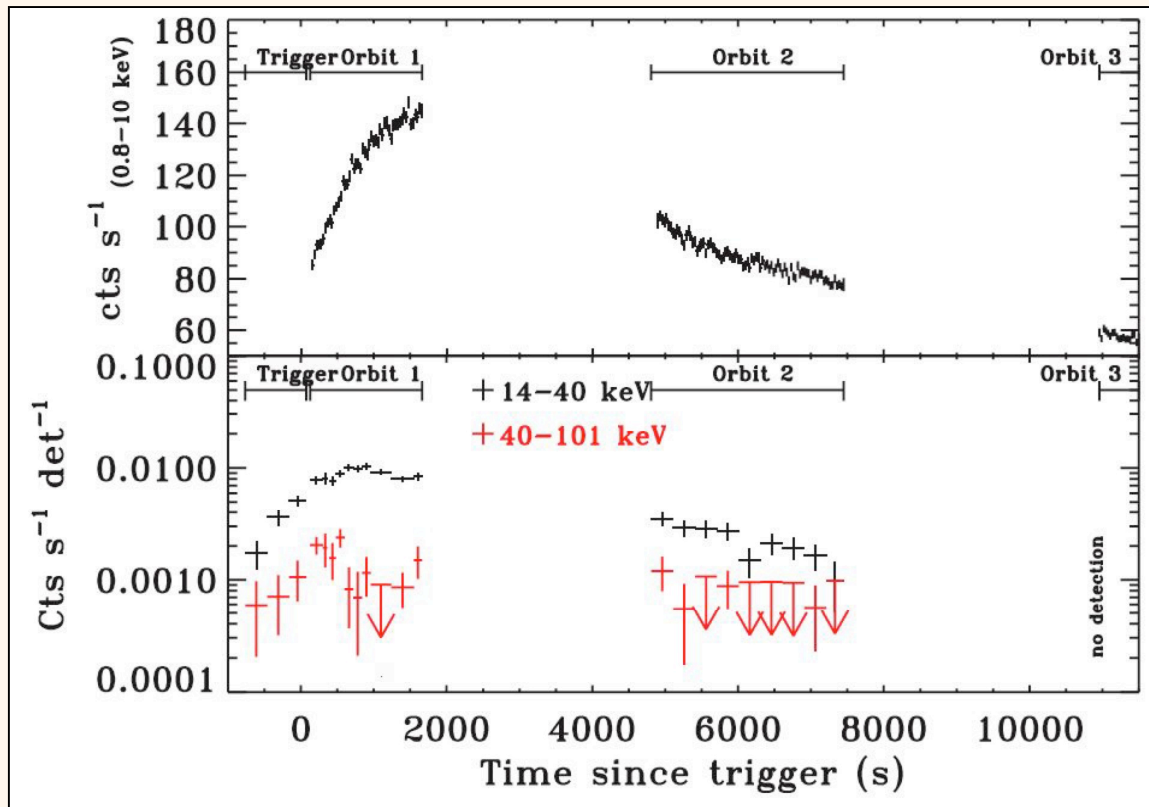
“Vertically integrated” electrical currents in an active region before (a) and after (b) an X-class flare (Schrijver et al., 2008). Note the apparent organization into a flux rope.

- **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



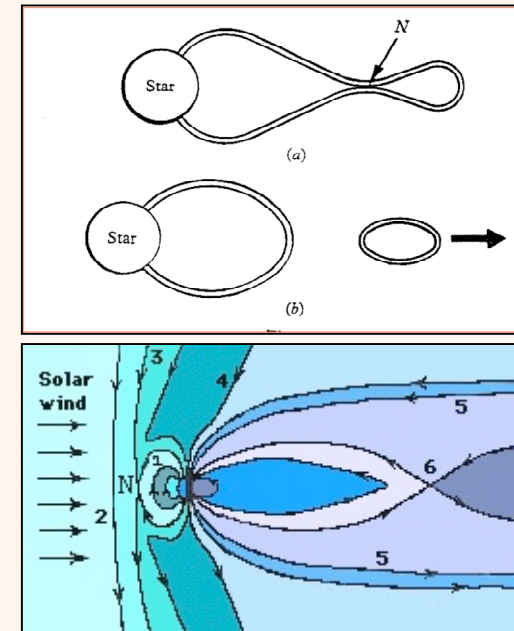
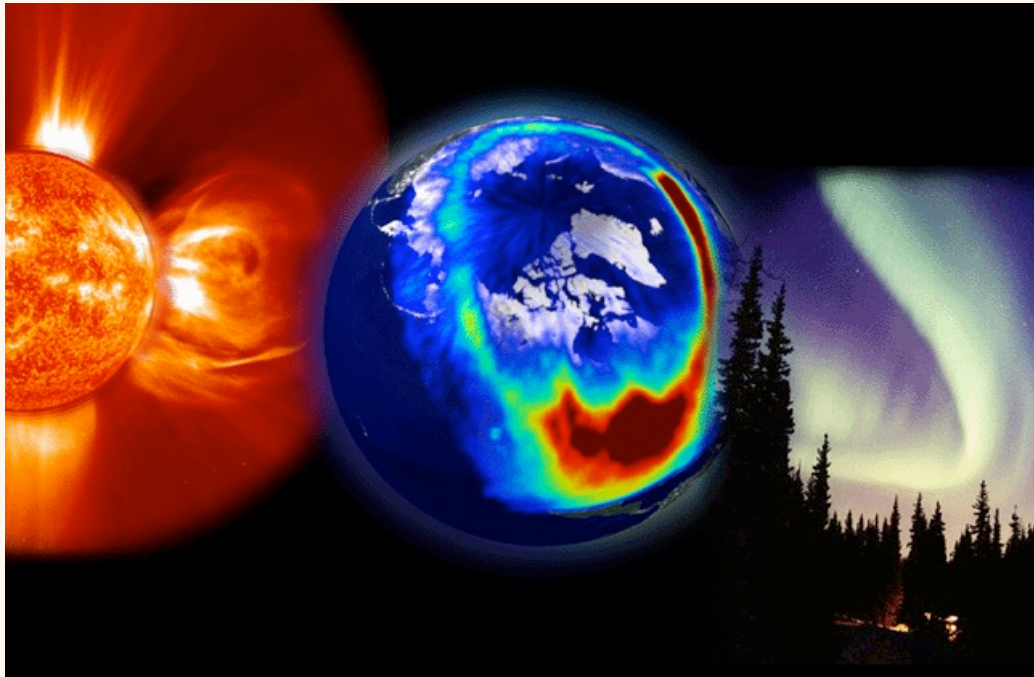
Osten et al. 2006

An exceptional event!

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

But squarely on the paradigm?

Flares and aurorae



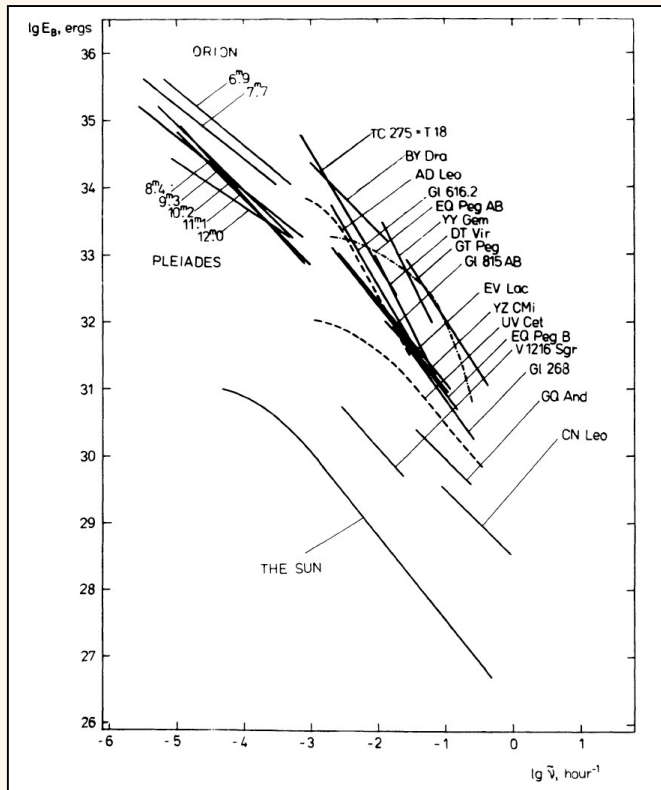
Cartoons by Dungey

Analogy pro

Analogy con

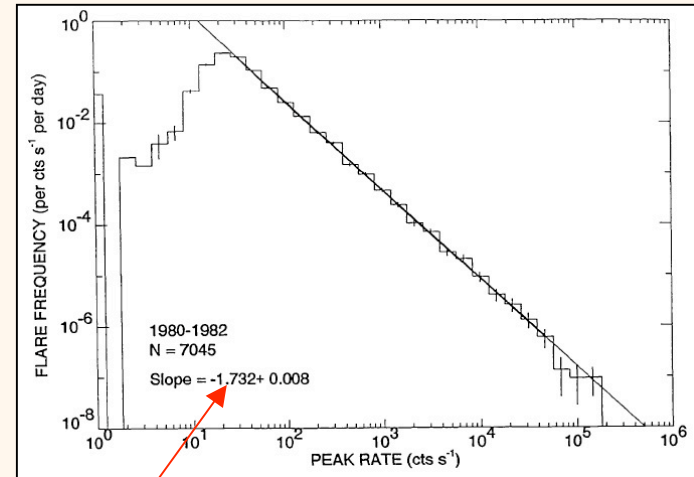
- Flare ribbons \Leftrightarrow conjugate polar caps
- Magnetic reconnection/plasmoid formation
- Non-thermal particles
- No large convective electric field in the corona
- No neutral atmosphere below the corona
- Equatorwards edges vs. ribbon outer edges

Likely stellar analogs: dMe stars

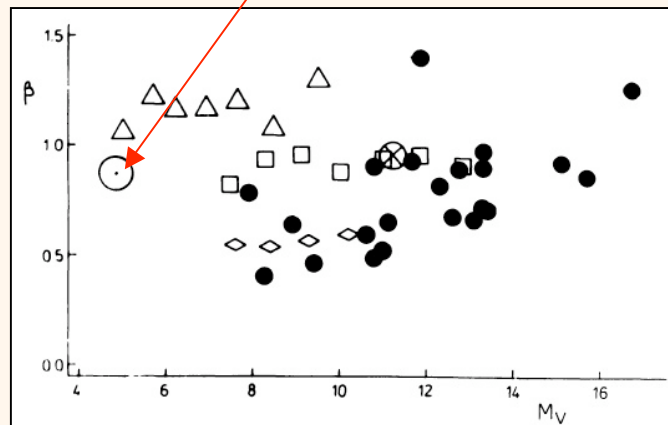


Shakovskaya 1989

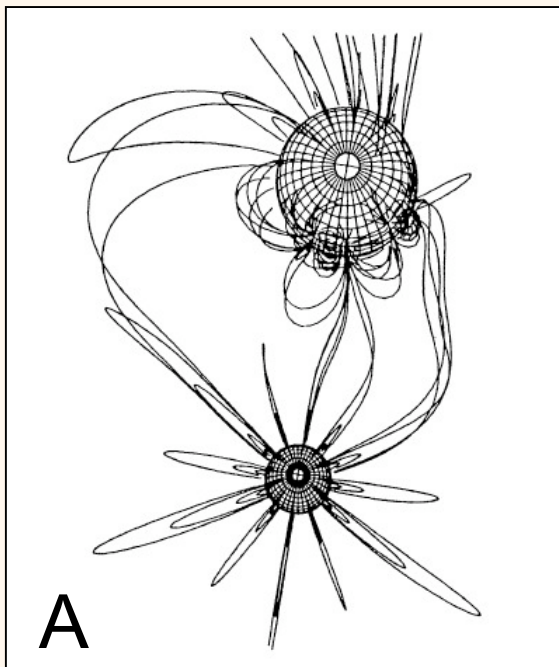
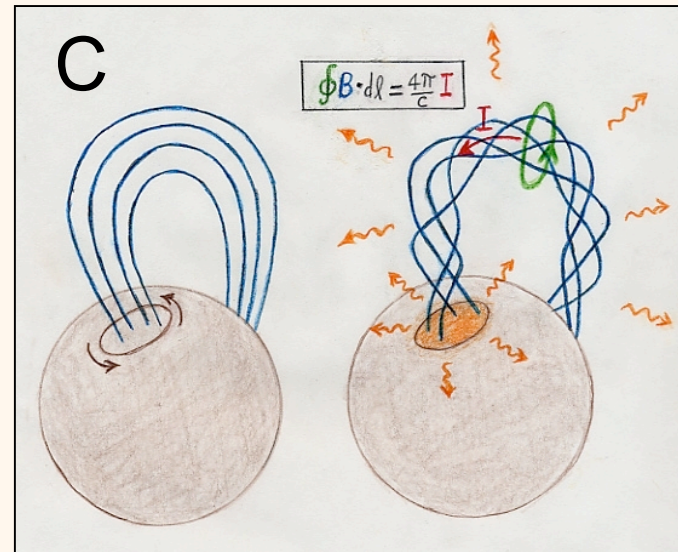
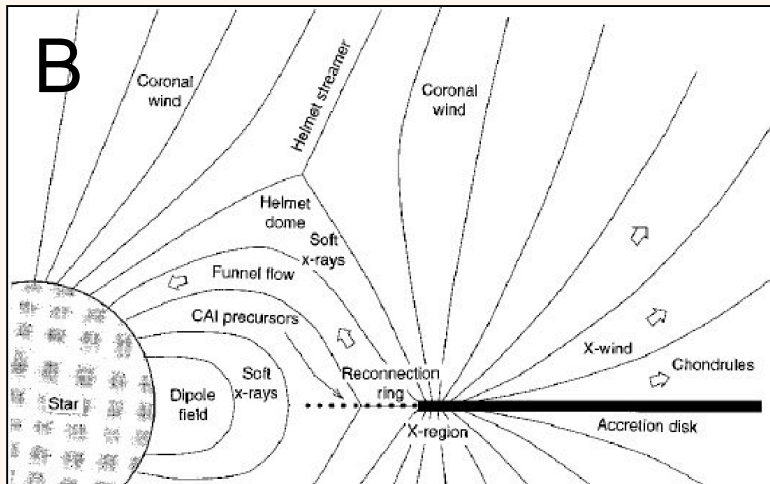
Flare occurrence statistics:
 $dN/dE \sim E^{-\beta}$



Crosby et al. 1993



Extreme stellar analogs



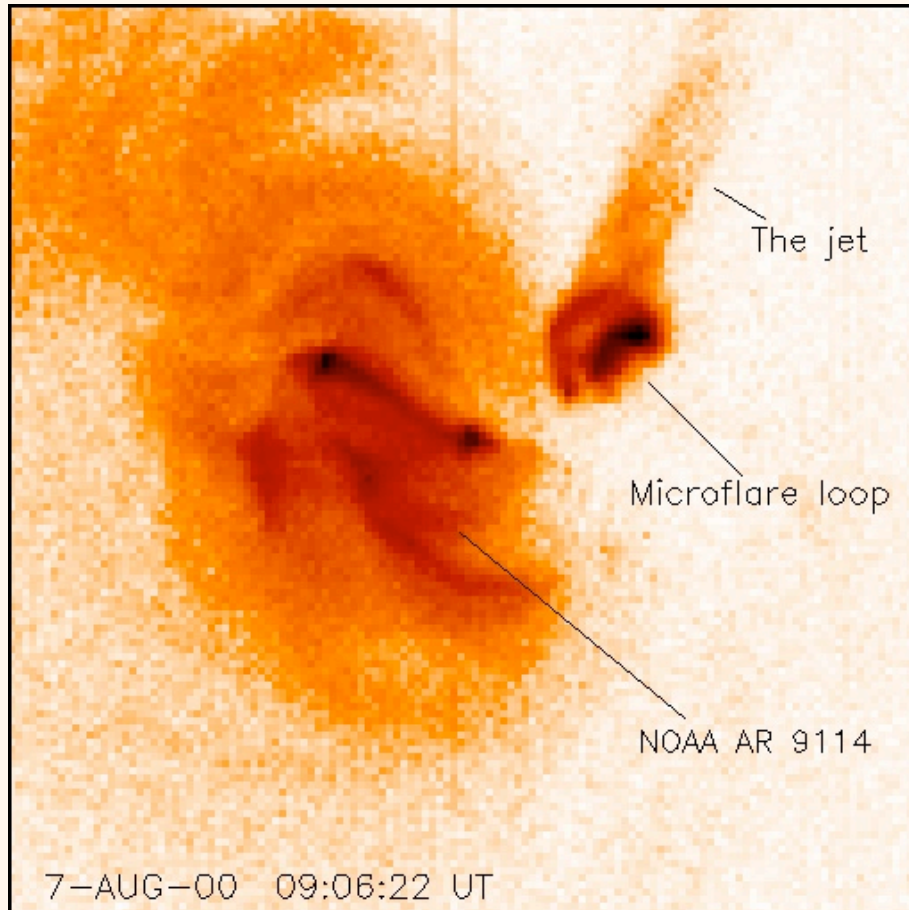
- A. "Magnetic duplicity" (Uchida & Sakurai)
- B. The X-wind model for T Tauri (Shu)
- C. Magnetars (Duncan)

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?

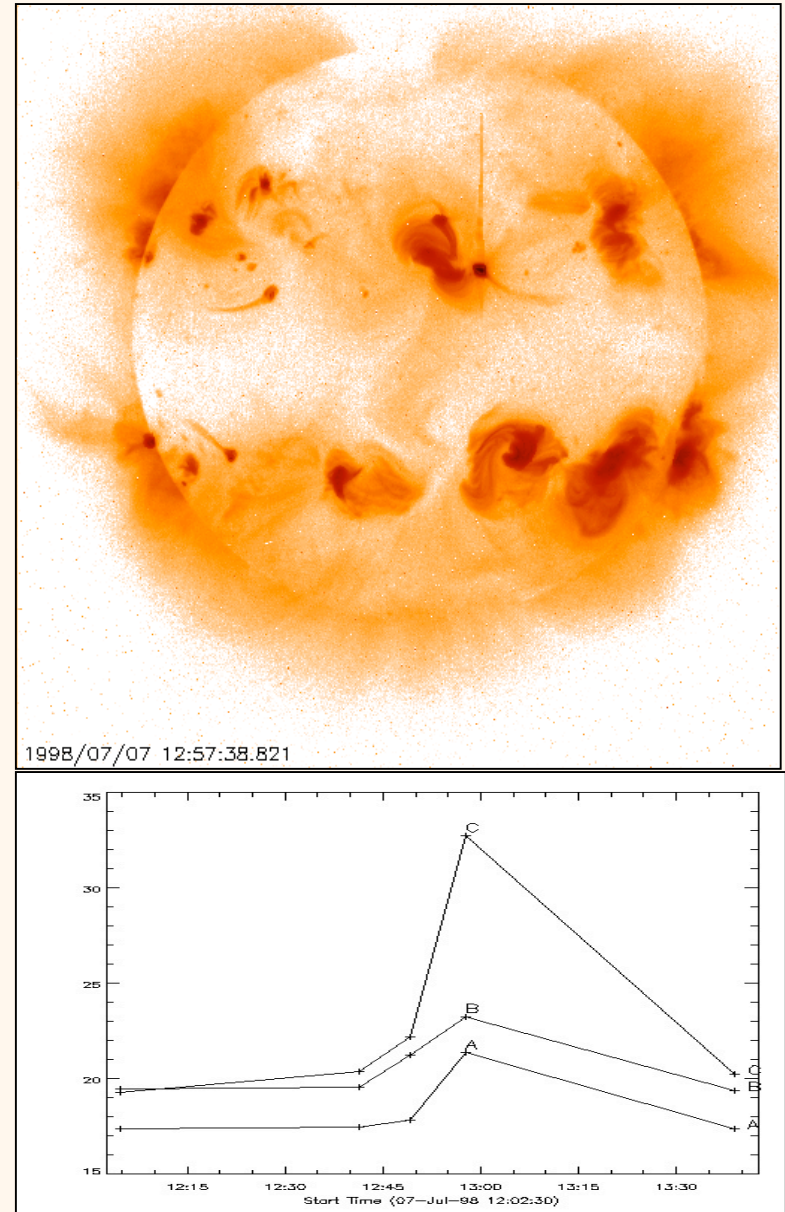
- X-ray jets
- Microflares/nanoflares
- “Extended flare” phenomena
- Masuda flare
- Non-thermal ejecta
- Shock waves
- Double layers
- Coronal thick-target events
- Impulse-response events

X-ray Jets ($H\alpha$ surges, sprays)

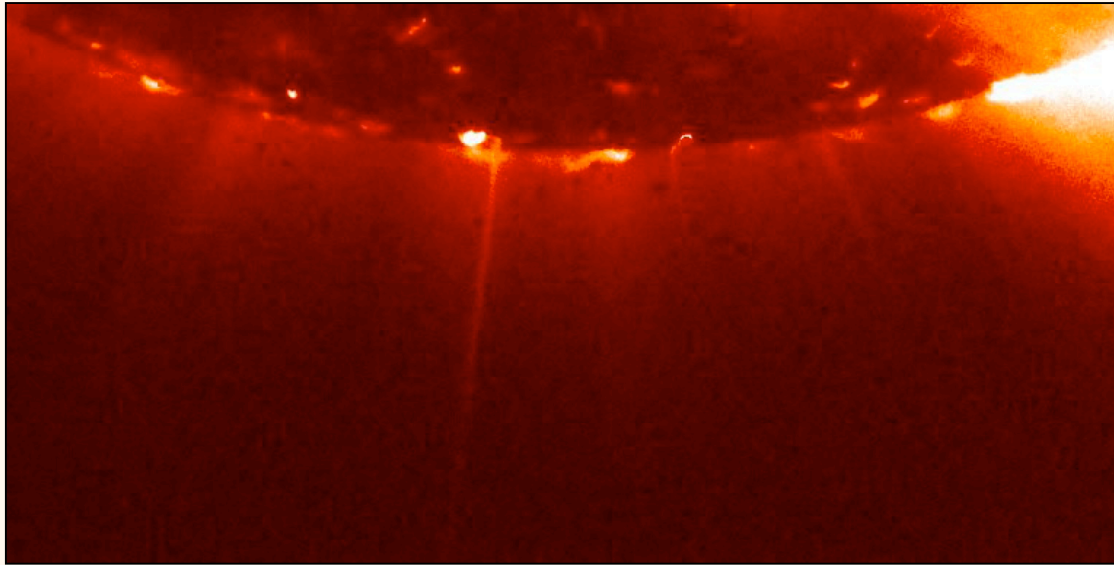


From a Yohkoh Science Nugget
<http://solar.physics.montana.edu/nuggets/>

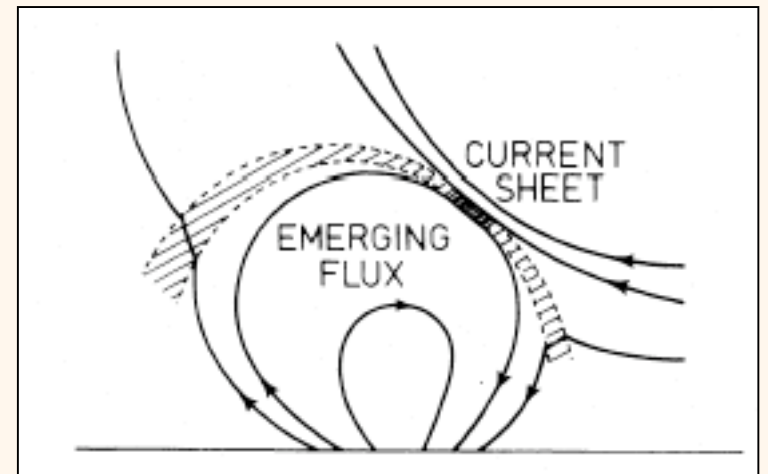
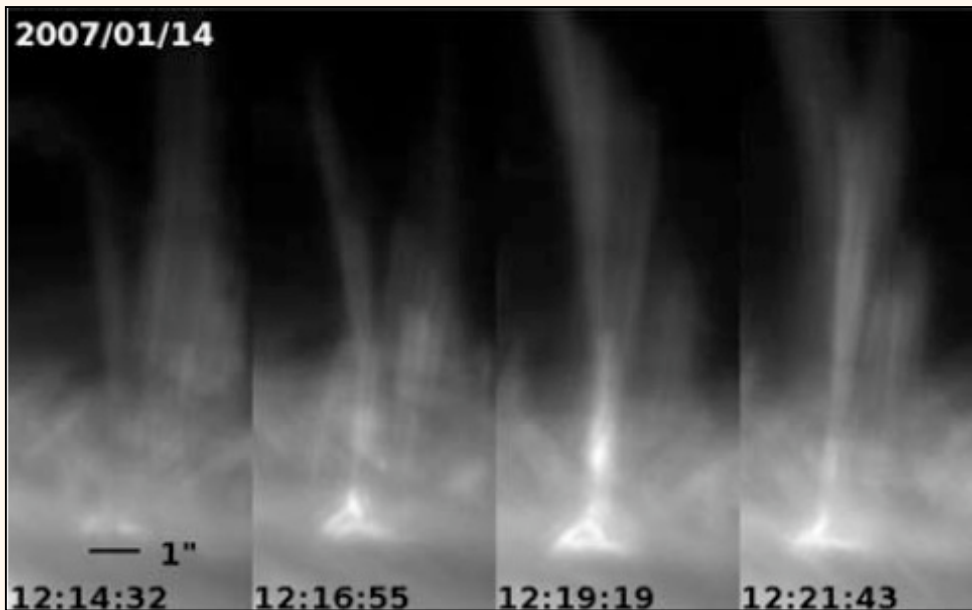
Boulder 23 July 2008



Other Jets



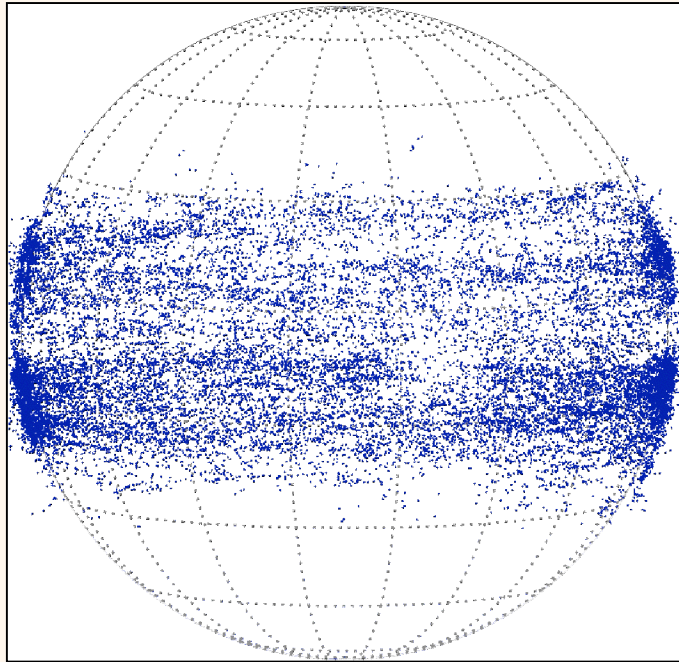
Cirtain et al. ??? *Hinode*



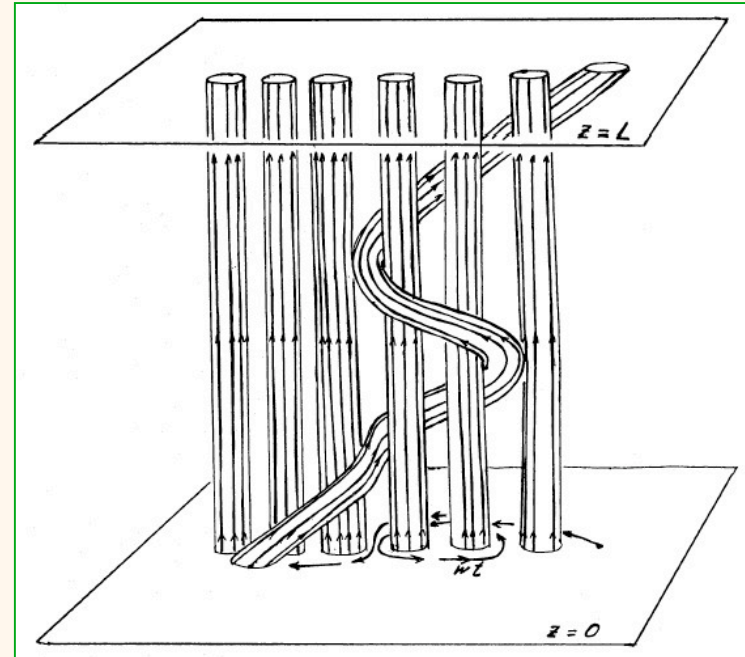
Heyvaerts et al. 1977

Shibata et al. 2007

Microflares and nanoflares



RHESSI microflares, 2002-2007



Parker's nanoflare cartoon

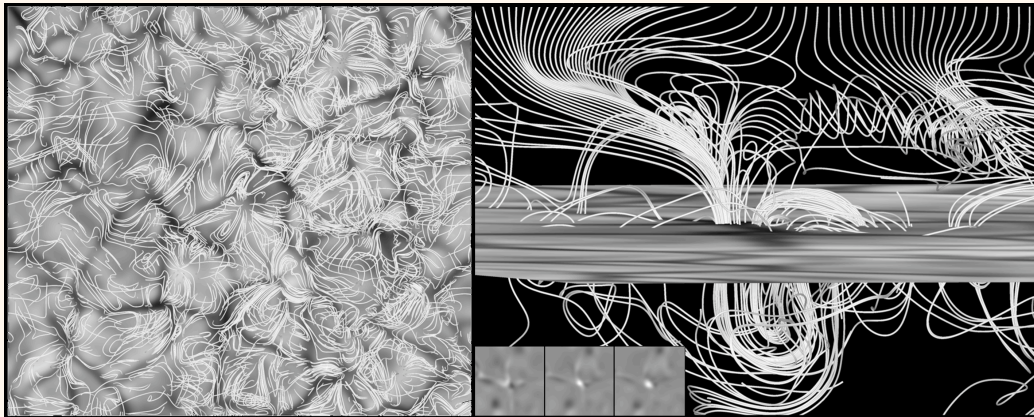
- Major flares have $\sim 10^{32}$ ergs total energy
- Microflares ($> 10^{26}$ ergs) occur in active regions
- Nanoflares are conjectural and weaker still

Outline

- Phases
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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



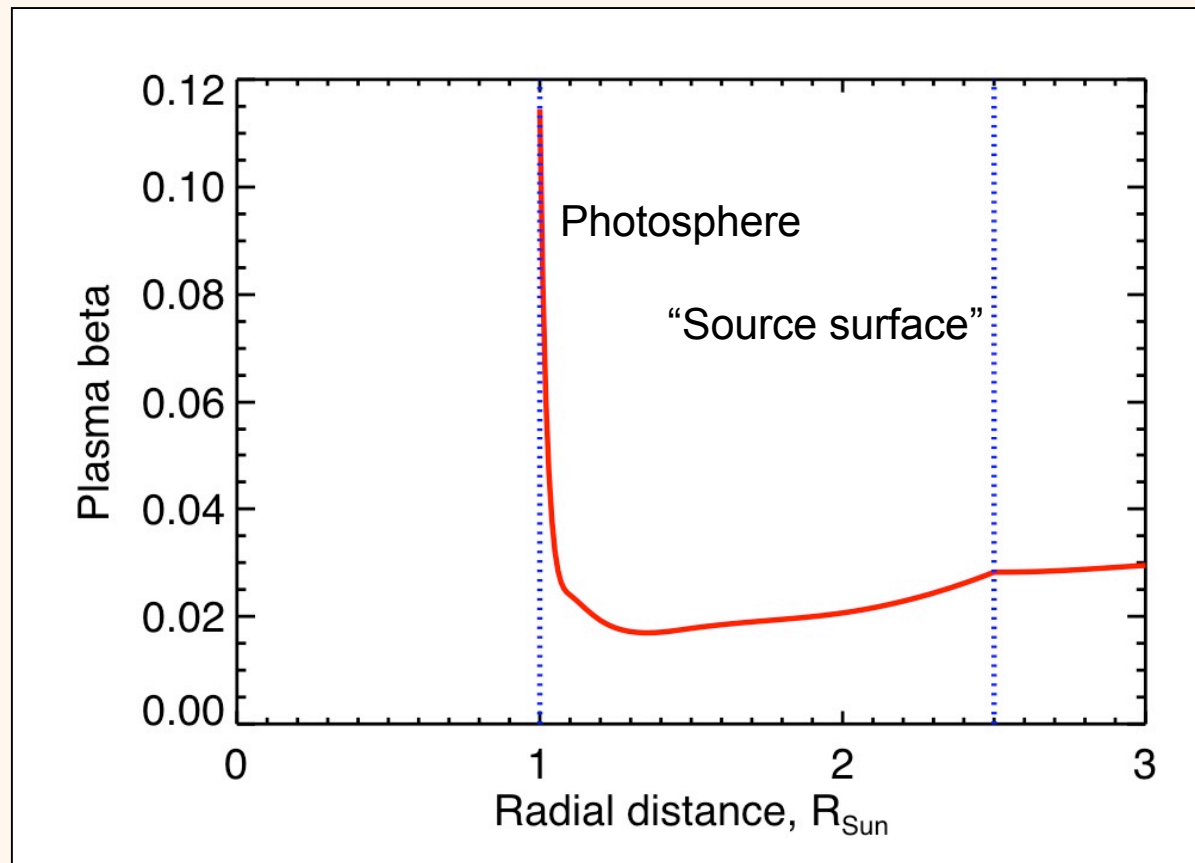
Above

MHD Simulation

Below

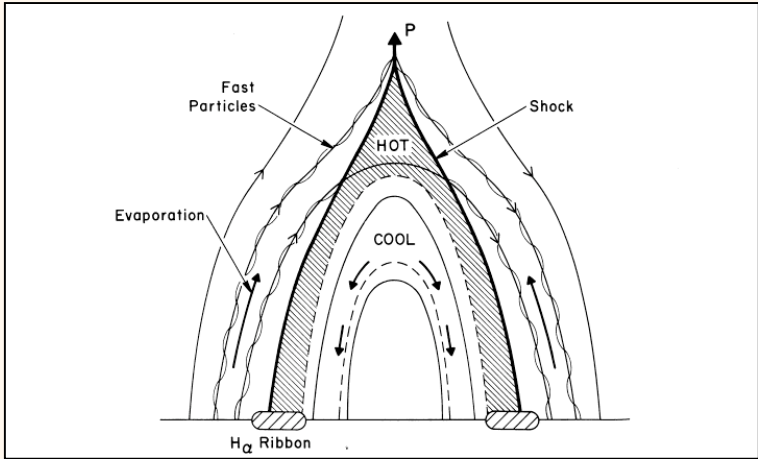
Abbett, 2008

Beta in the solar corona

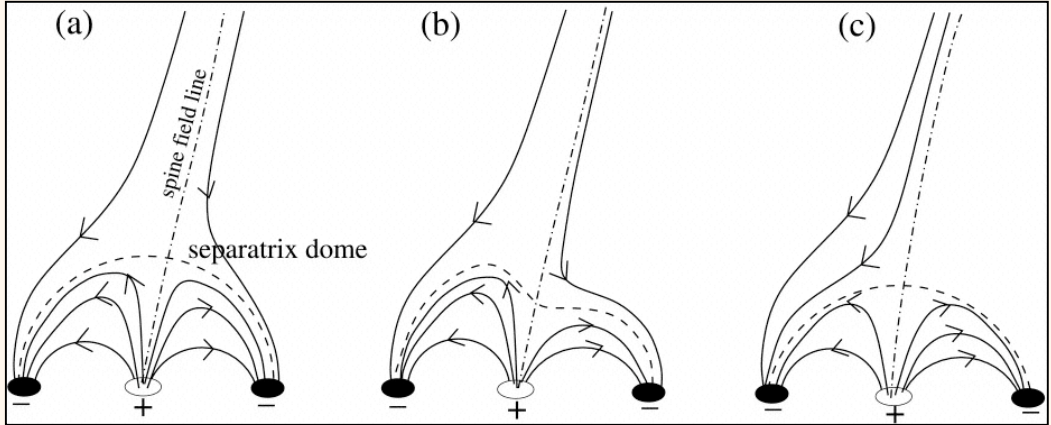


Plasma beta from a G. Withbroe solar-wind model
n.b. beta can be much lower in active regions

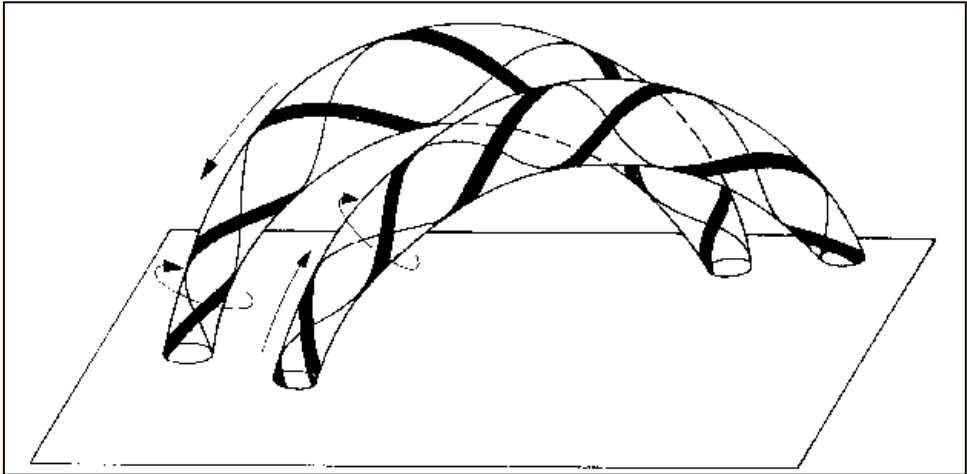
Reconnection cartoons



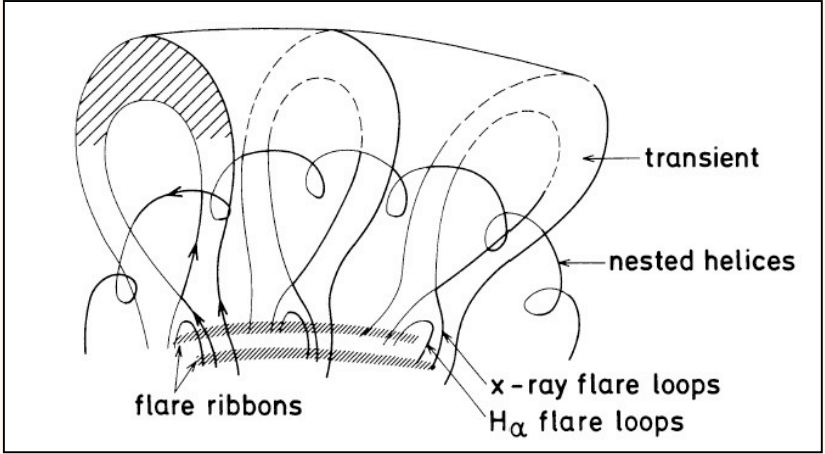
Cargill & Priest 1983



Fletcher et al. 2001

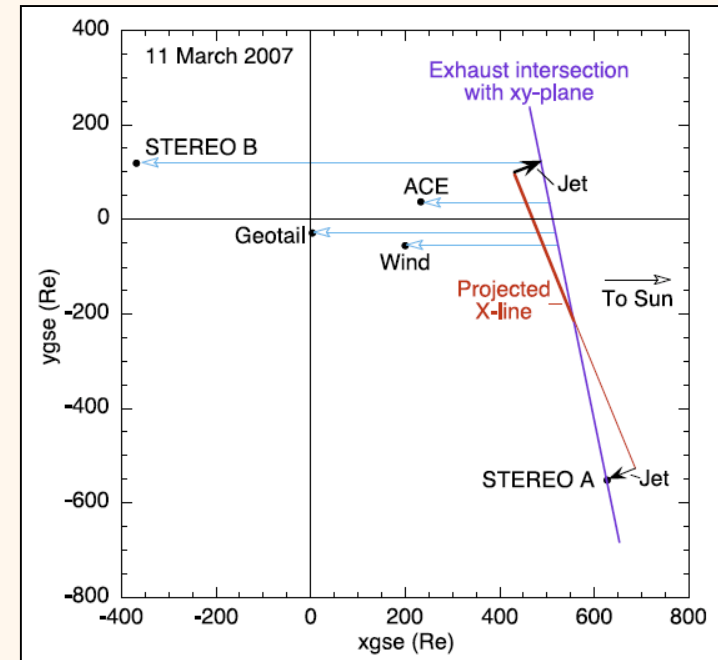
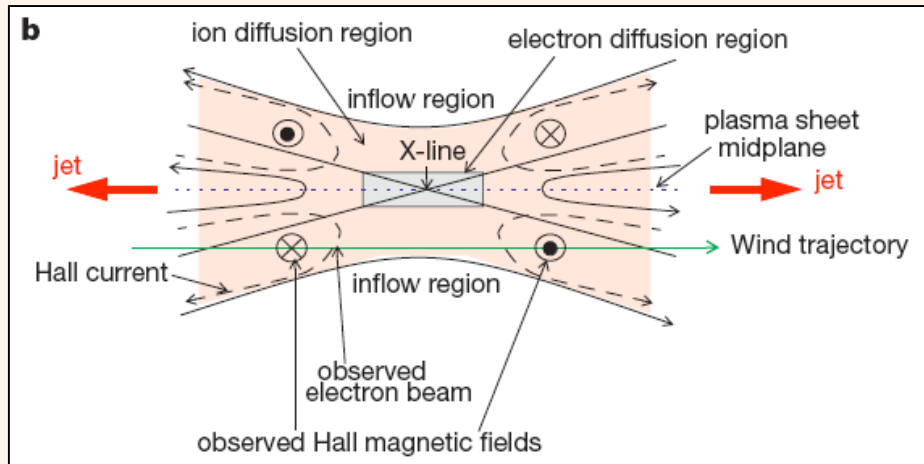


Gold & Hoyle 1961

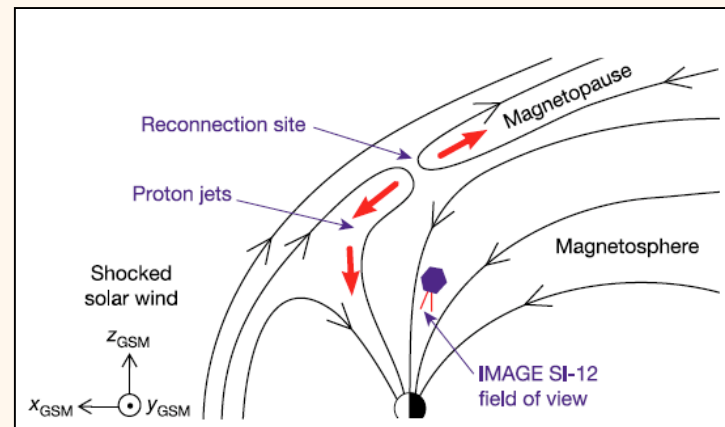
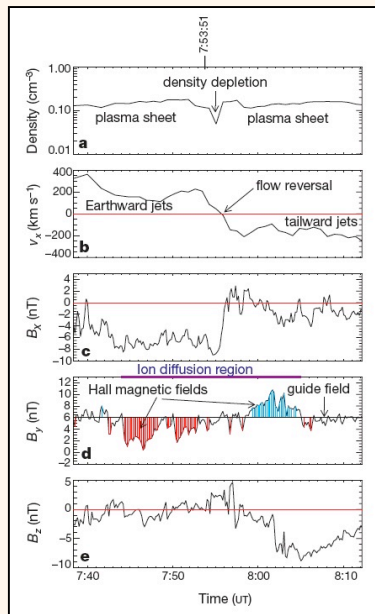


Anzer-Pneuman 1982

Reconnection microphysics



Geotail: Oieroset et al. 2001



Solar wind: Gosling et al. 2007

Magnetopause: Frey et al. 2003

Coronal acceleration?

'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)

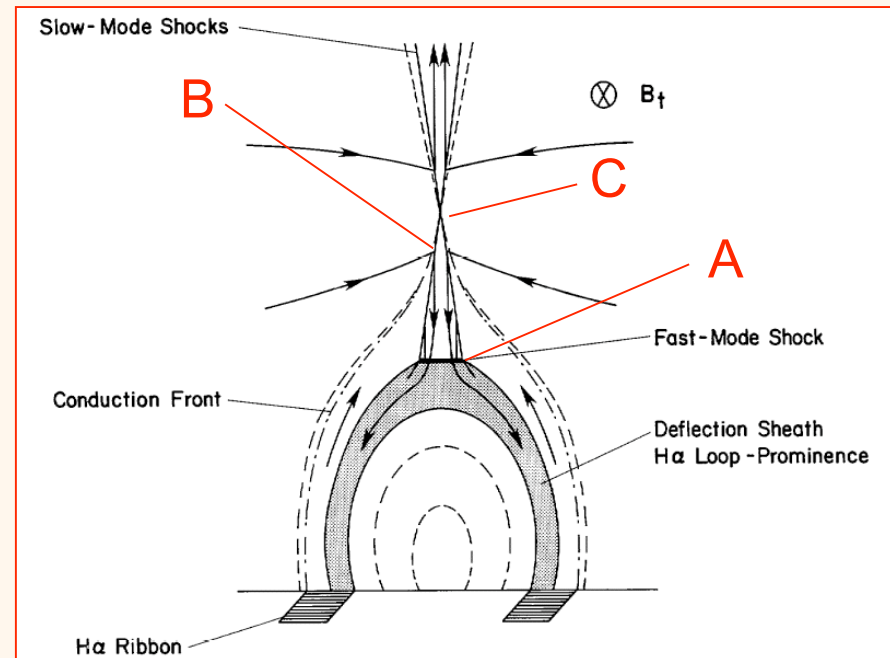
Reconnecting X-line or current-sheet acceleration

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

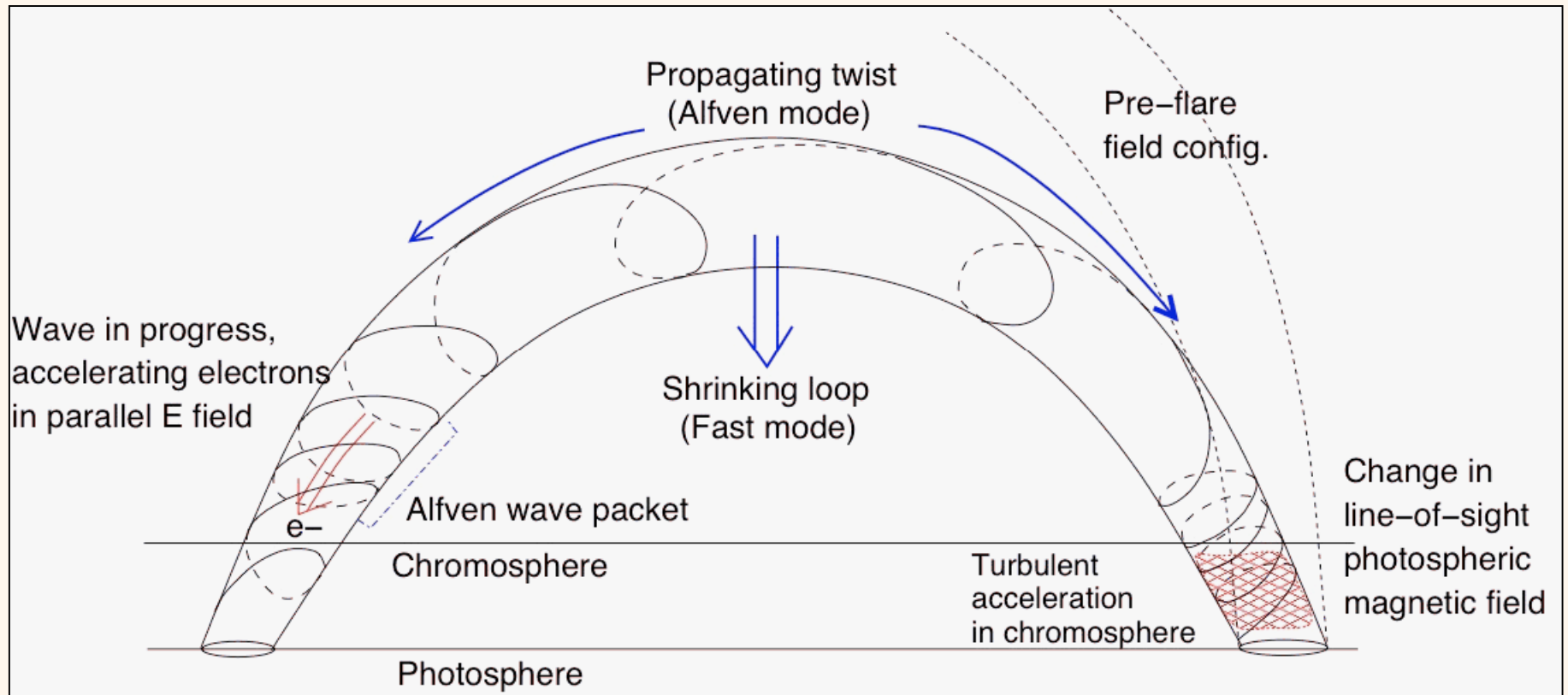
Single macroscopic current sheet (e.g. Litvinenko & Somov, Somov & Kosugi)

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/>

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Most crucial future observations

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

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- The deepest layers: γ -rays, IR, seismic waves
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- In-situ corona