Solar Flares

and

Coronal Mass Ejections

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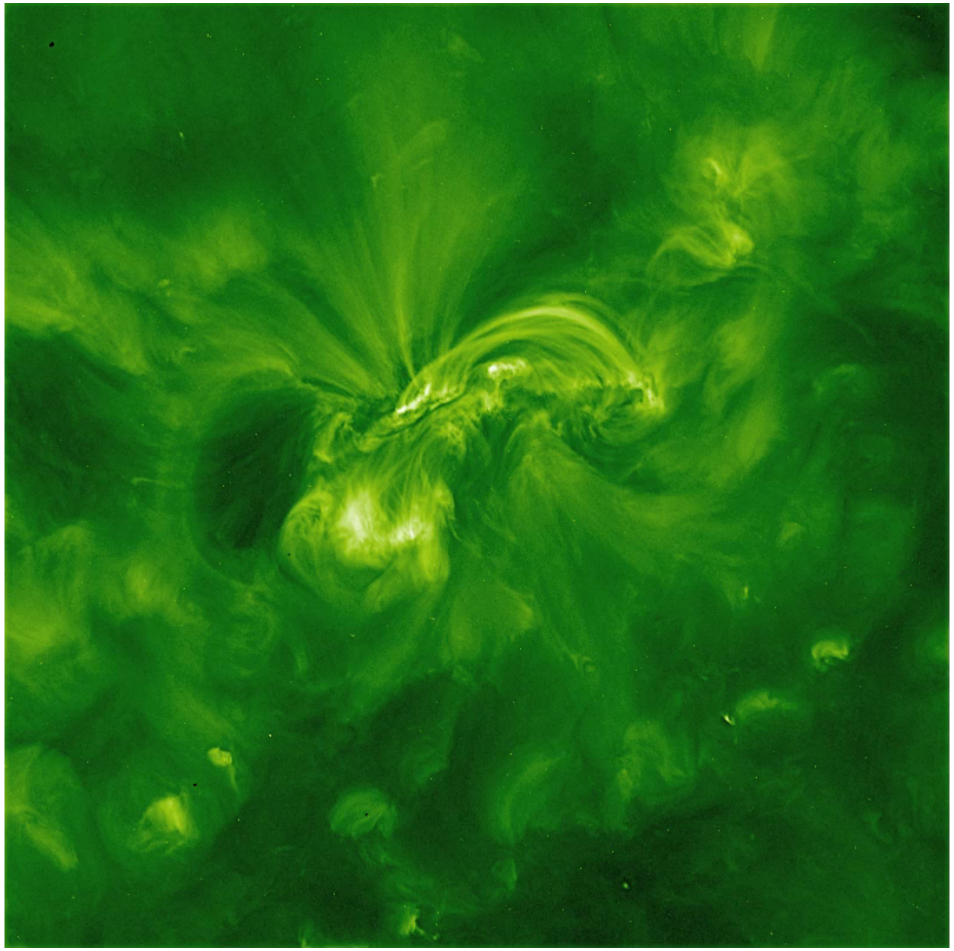
SOLARNET School, Wroclaw 2014


Apr 17 2002 23:59:32

What is a solar flare?



Movie: million degree plasma from NASA's Solar Dynamics Observatory/LMSAL

A localised, sudden & transient. brightening in the solar atmosphere, visible across all wavelengths.

- Associated with rapid reconfiguration of the magnetised solar corona.

NB, the flare is the increase in radiation. The associated mass motion is the coronal mass ejection

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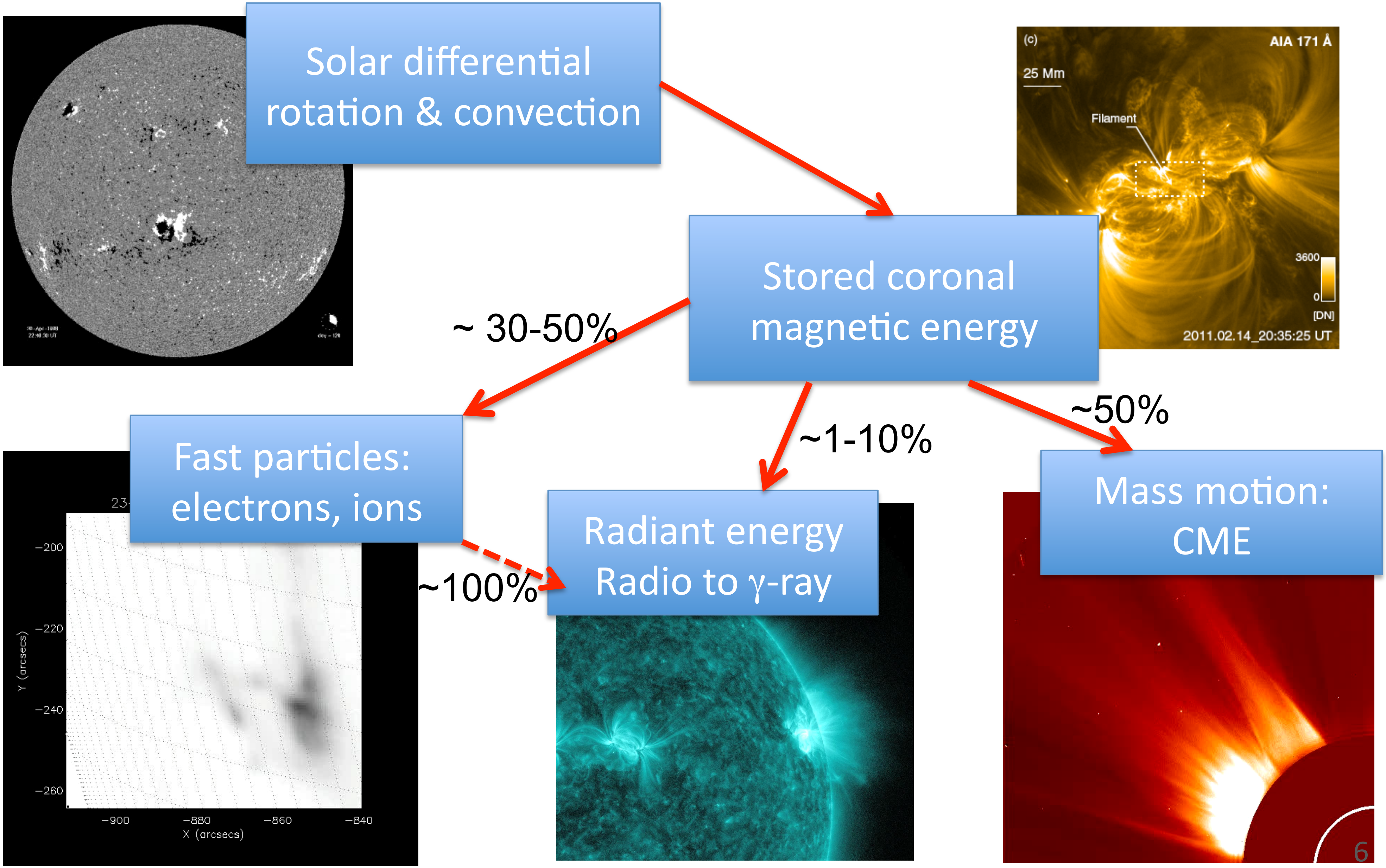
Why study flares?

- Basic physics: energy conversion - magnetic to thermal/nonthermal particle energies.
- ‘Practical’: effects on planets.
  - link to CMEs and enhanced shortwave radiation flux
- Stellar physics: magnetism, partition of star’s rotational/convective energy.

Energy flow

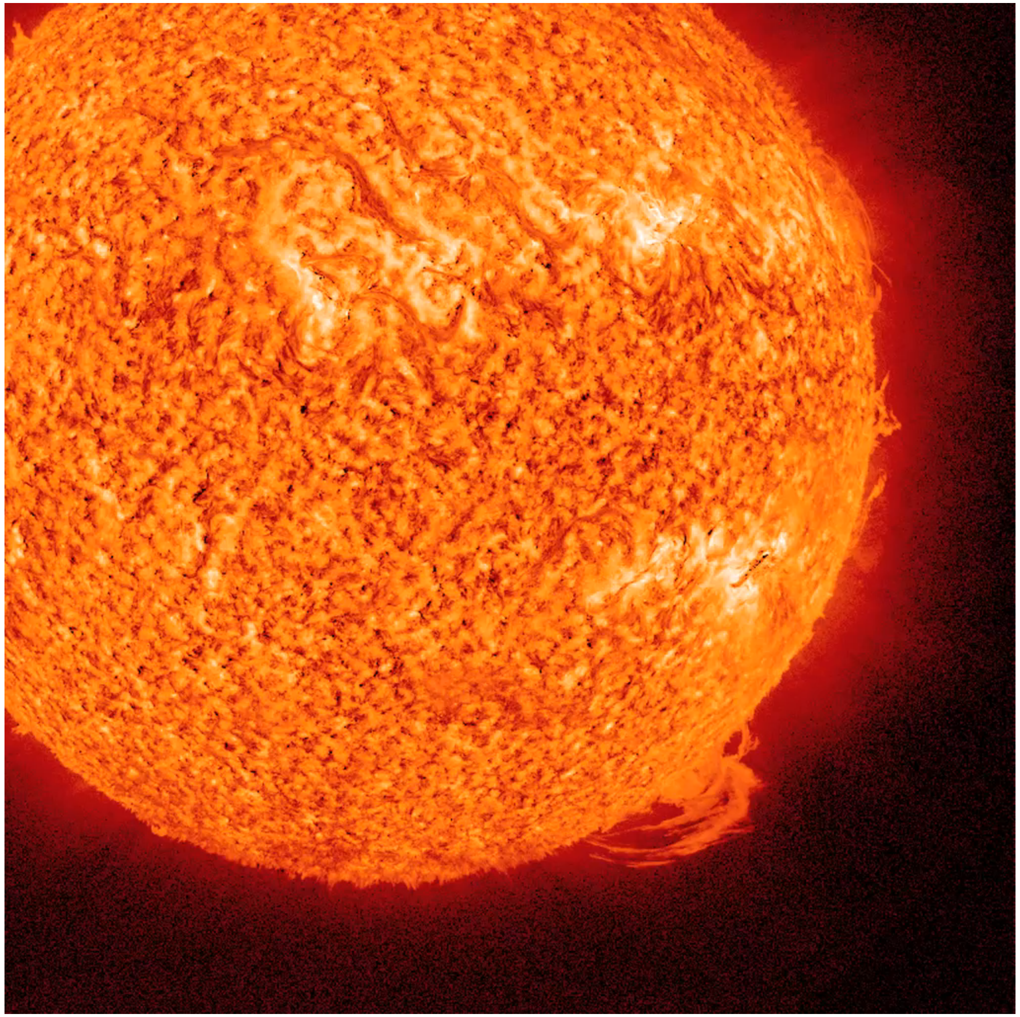

Solar differential rotation & convection
Stored coronal magnetic energy
(c)
AIA 171 Å
25 Mm
Filament
3600
0
[DN]
2011.02.14_20:35:25 UT
~ 30-50%
~1-10%
~50%
Fast particles: electrons, ions
Radiant energy Radio to γ-ray
Mass motion: CME
~100%
−200
−220
−240
−260
Y (arcsecs)
−900
−880
−860
−840
X (arcsecs)

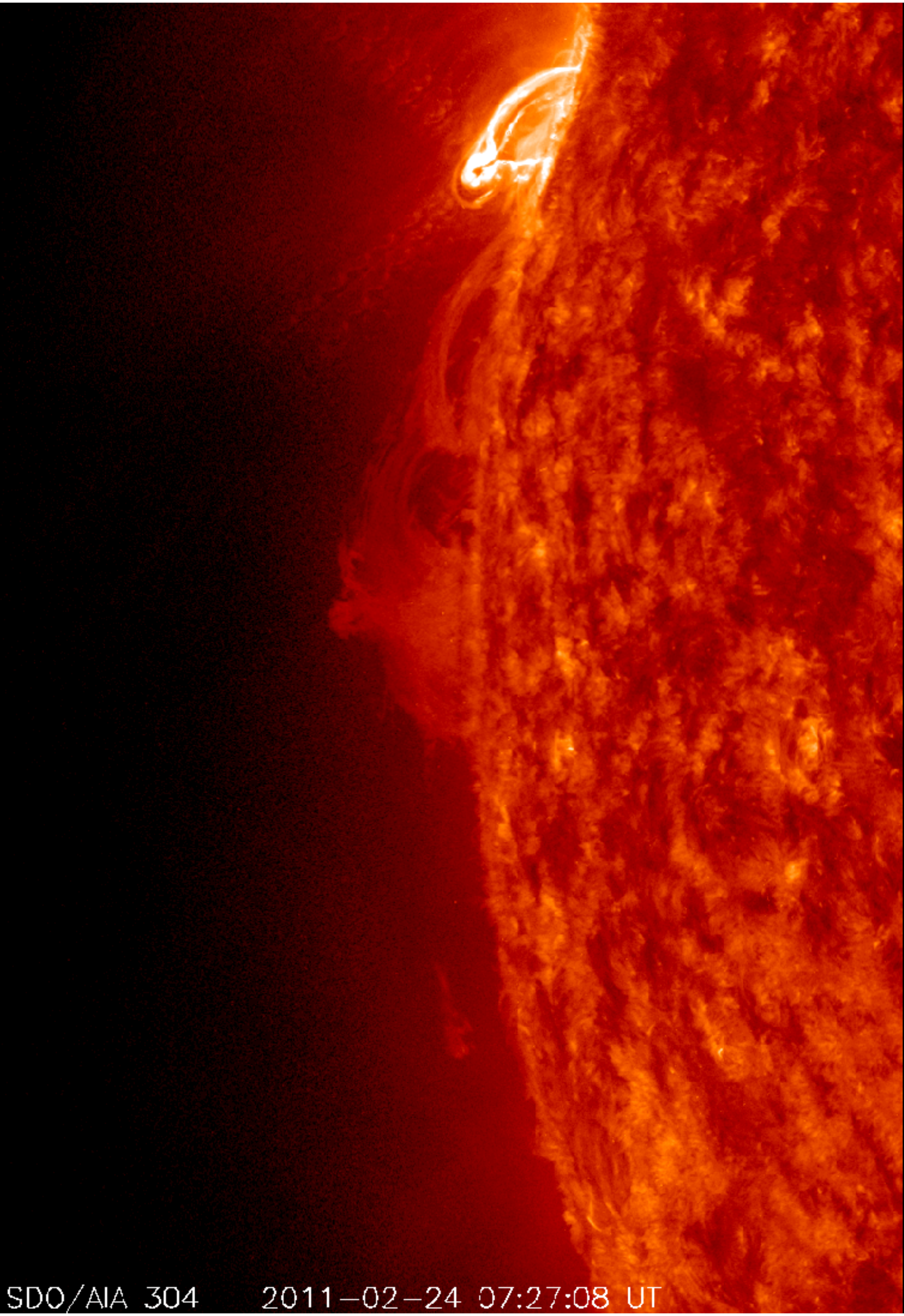
Solar flares

Statement of the problem:

A region of the Sun suddenly brightens, heats and produces very large numbers of accelerated particles.

Where does the energy to heat the corona come from, what form does it take, and how is it dissipated?




SDO/AIA 304 2011-02-24 07:27:08 UT

The first known flare

e.g. The Carrington flare of 1859 - first recorded flare observation, and probably the largest. Had this occurred in the modern era its effects could have been catastrophic.

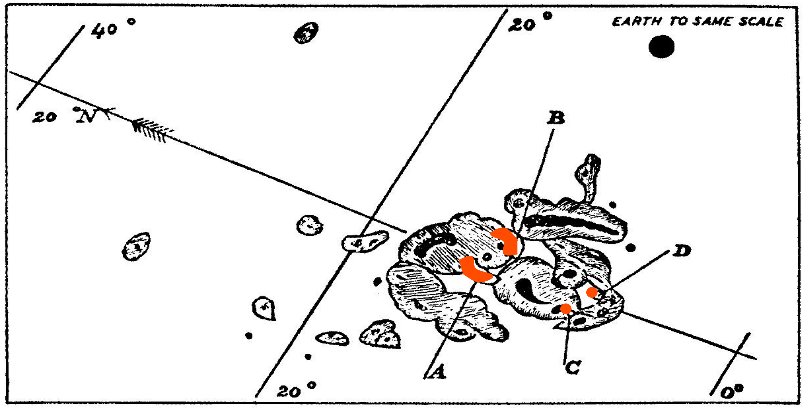


FIG. 36. Solar sketch, September 1, 1859, by R. C. Carrington

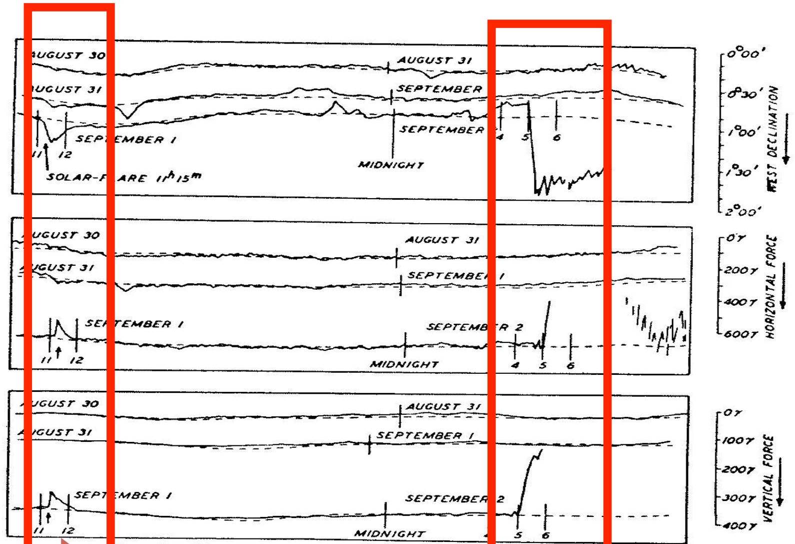


FIG. 35. Magnetograms, Kew, August 30 to September 2, 1859

First recorded flare – white light drawing by Carrington (1859)

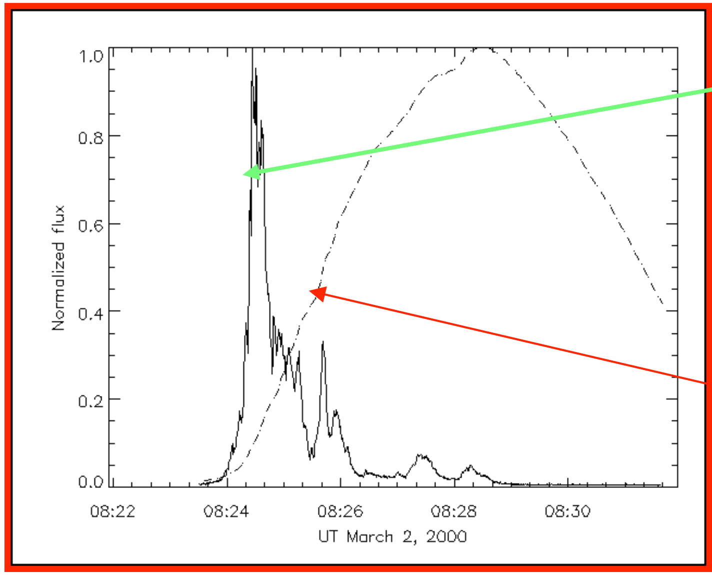
- Likened to the star α Lyrae, in brilliance and colour (bluish-white)

Magnetometer disturbances following Carrington's Flare :

(i) flare UV increases ionisation of ionosphere

(ii) CME arrives, disturbing geomagnetic field

Flare time profile



Impulsive phase - energy release

- Hard X-rays (10s of keV)
- Duration ~ 5 minutes to 1 hour
- Bursty time profile (t_{acc} ~ seconds)

Gradual phase - response

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

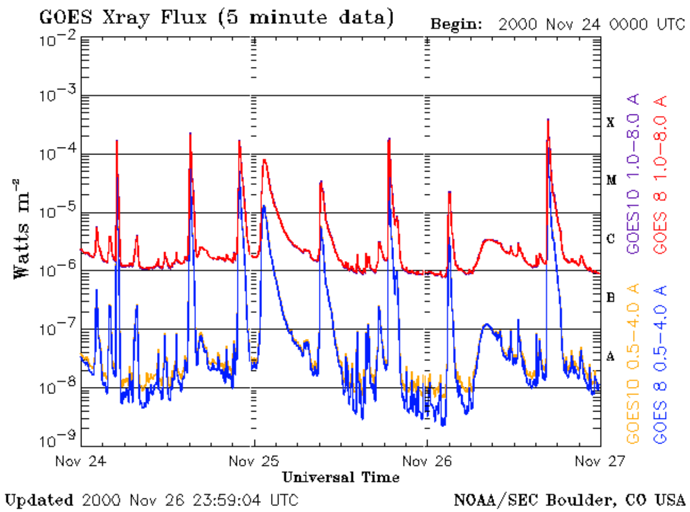
<u>GOES flare classification scheme</u>

Flux in the 1-8 Å band

C: more than 10^{-6} W m^{-2} at Earth
(e.g. C4.2 flare => 4.2×10^{-6} Wm^{-2})

M: more than 10^{-5} W m^{-2} at Earth

X: more than 10^{-4} W m^{-2} at Earth



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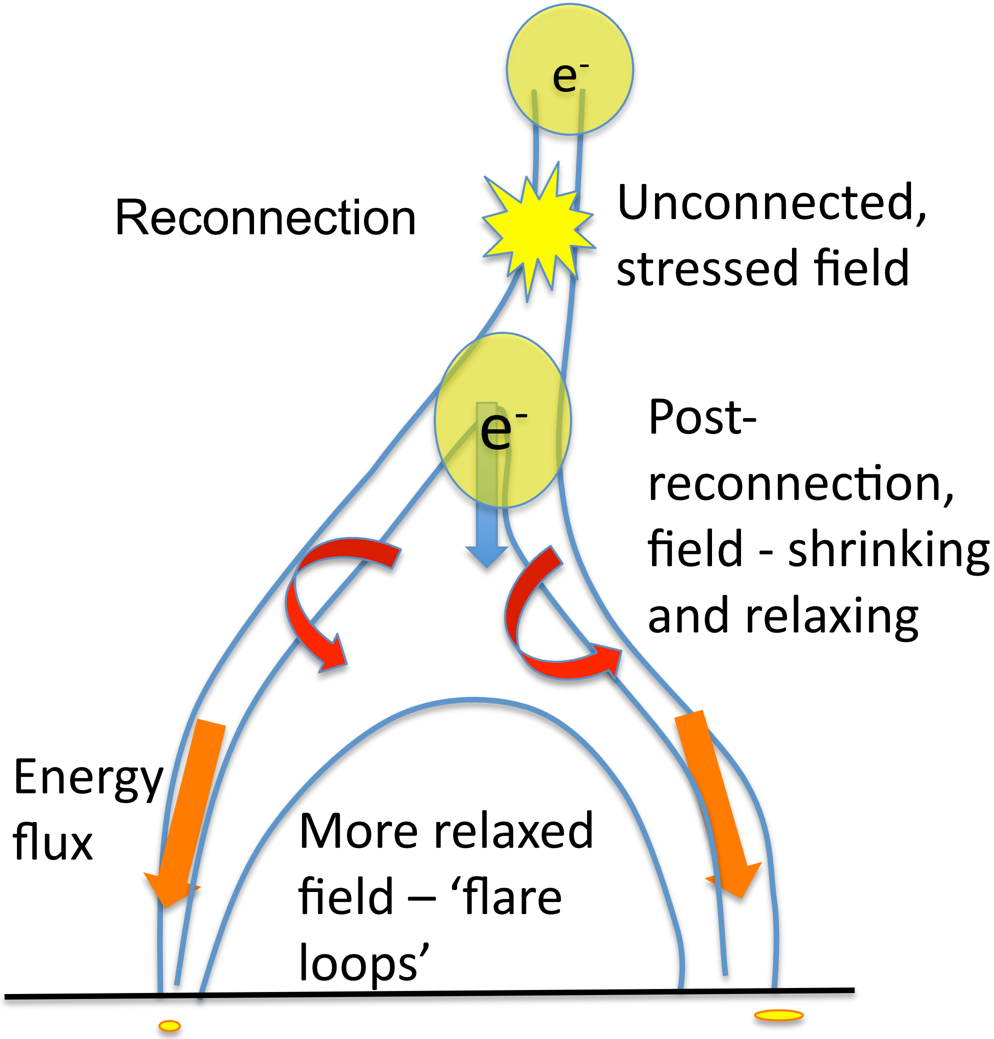
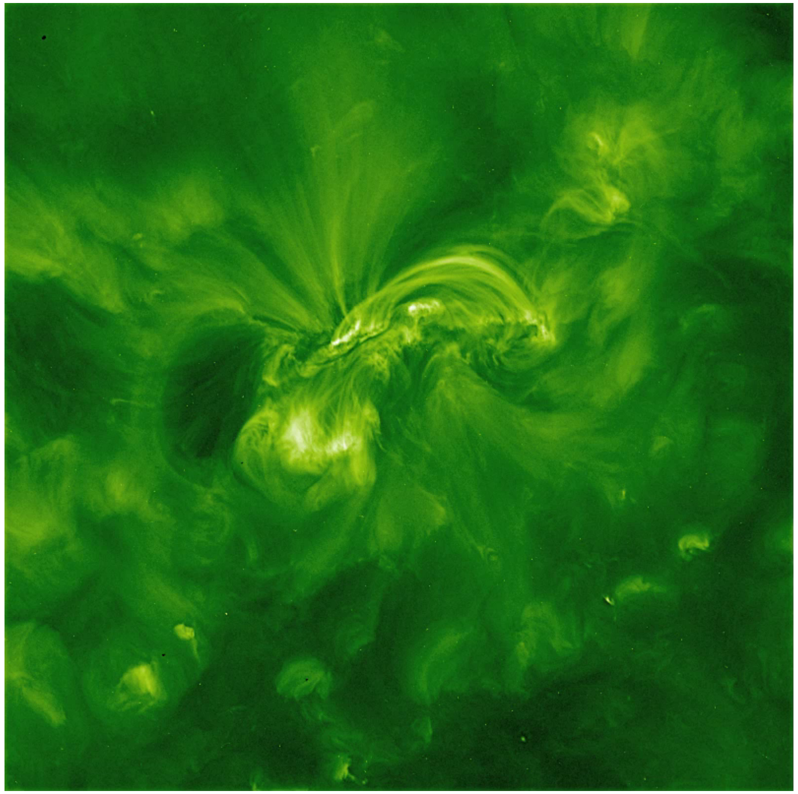
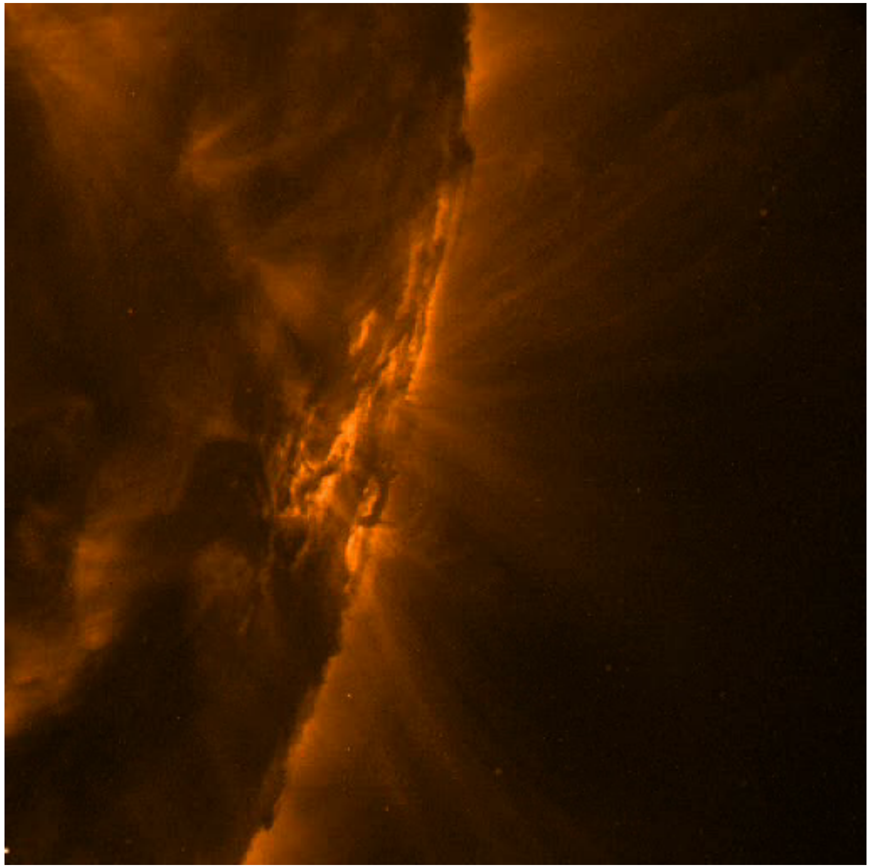
Flare ‘cartoon’



Footpoint UV/optical emission, fast electrons/ions (~50% of flare energy)

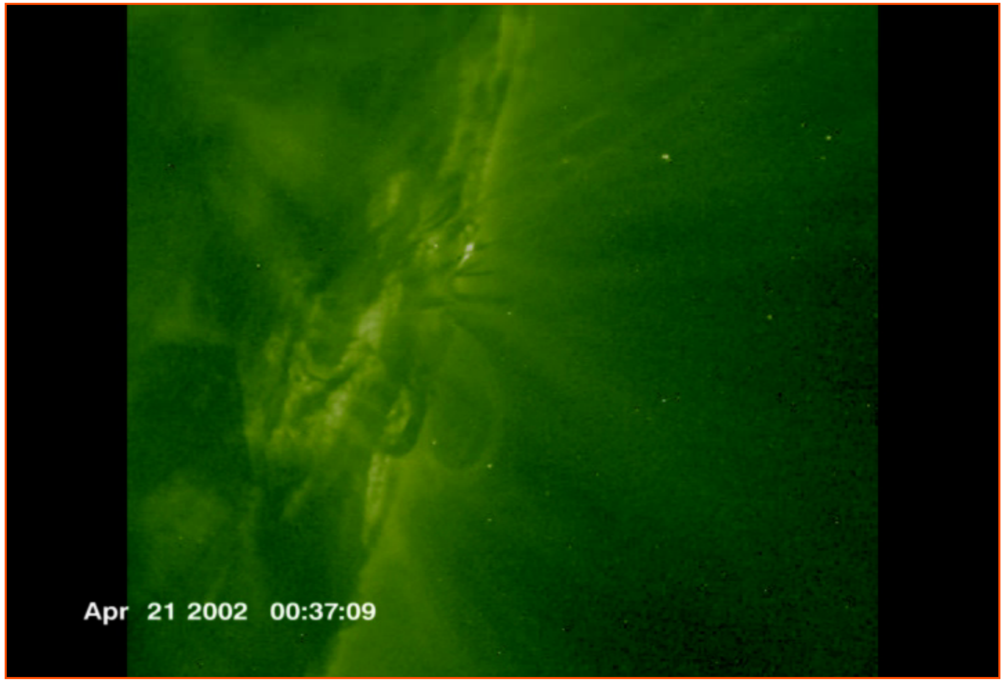


Thermal and non-thermal emission



Fe XII and Fe XXIV emission (TRACE)

T ~ 20 MK (~2keV)



Bremsstrahlung emission:

Red - 12-25 keV (RHESSI)

Blue - 25-50 keV – (RHESSI)

Green – thermal (TRACE)

Energetics

Total flare energy is rather poorly known

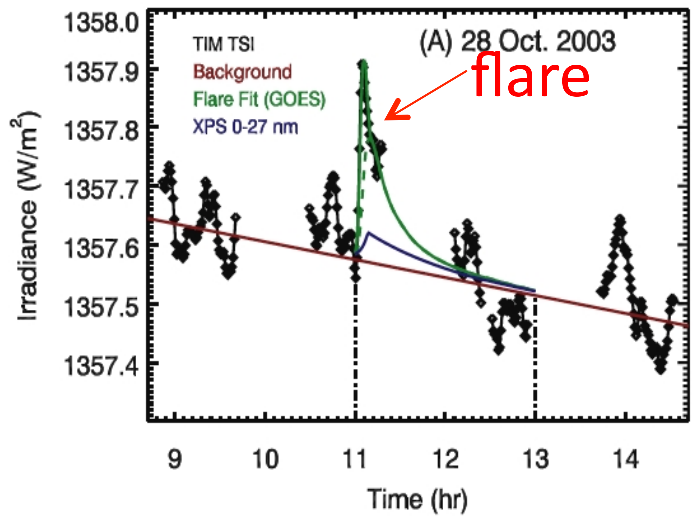
- Typically, most of the flare energy emerges in the UV to optical range
- Currently, this range is not well observed

(Can do much better for stellar flares which have great optical coverage)

Direct 'Sun as a Star' measurement gives X-flare power ~ 10^{29} erg s^{-1}
~ few x 10^{32} ergs total
(Woods et al 04, 05, Kretschmar et al 2010)

Comparable to power *inferred* for non-thermal electrons from hard X-rays.

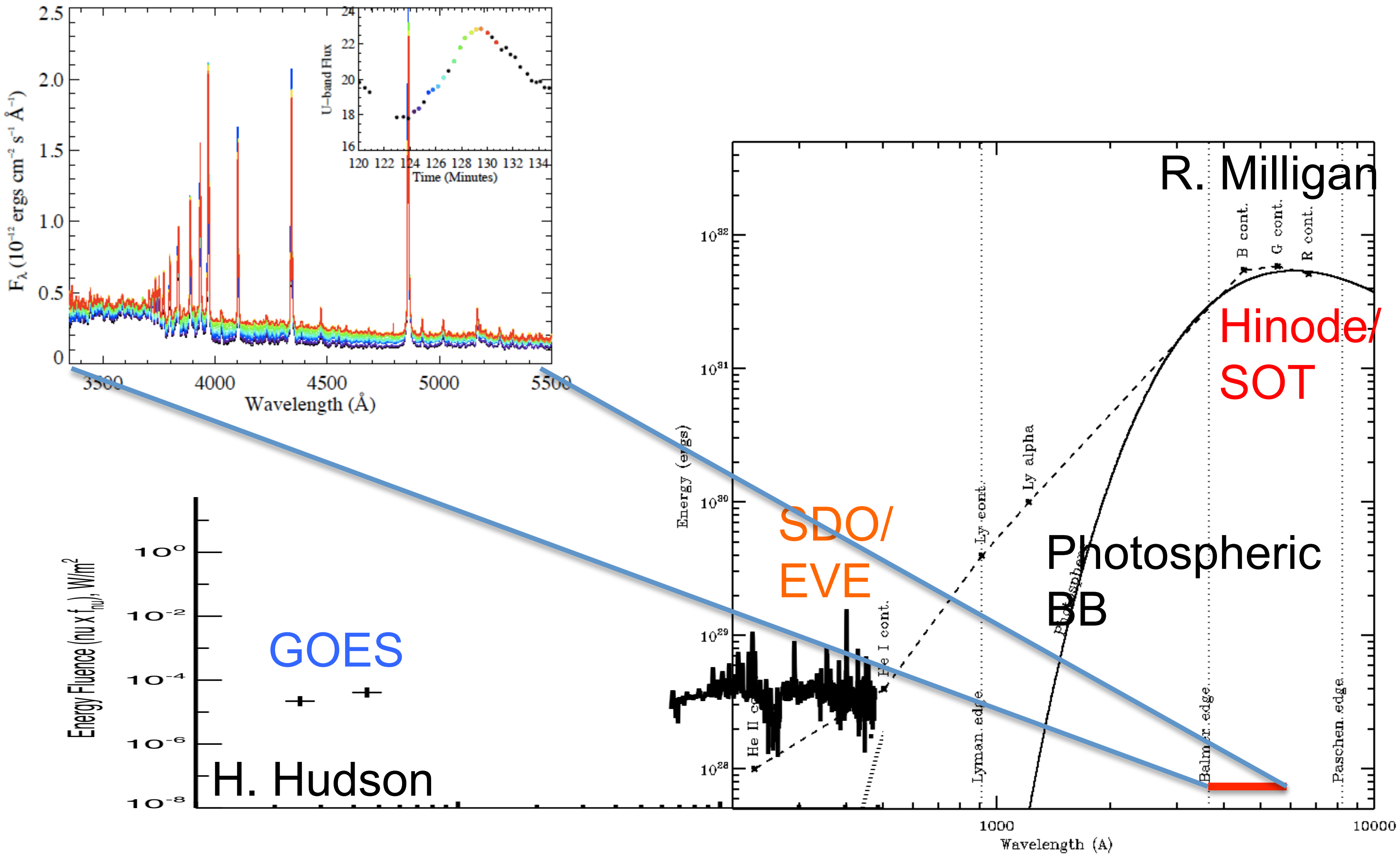
Flare total irradiance



Woods et al 2005

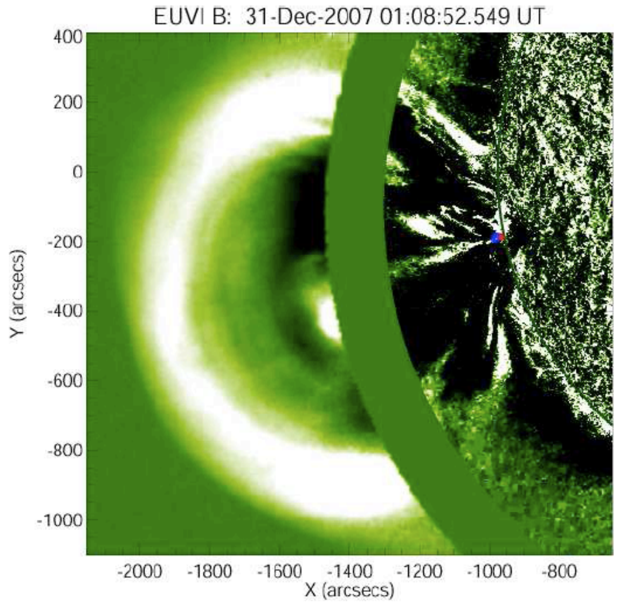
Solar flare spectral distribution

DMe flare (Kowalski et al 2010)

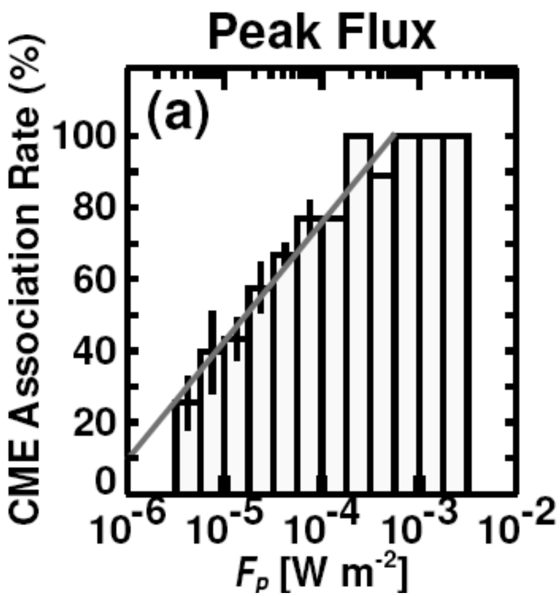


Flares and CMEs

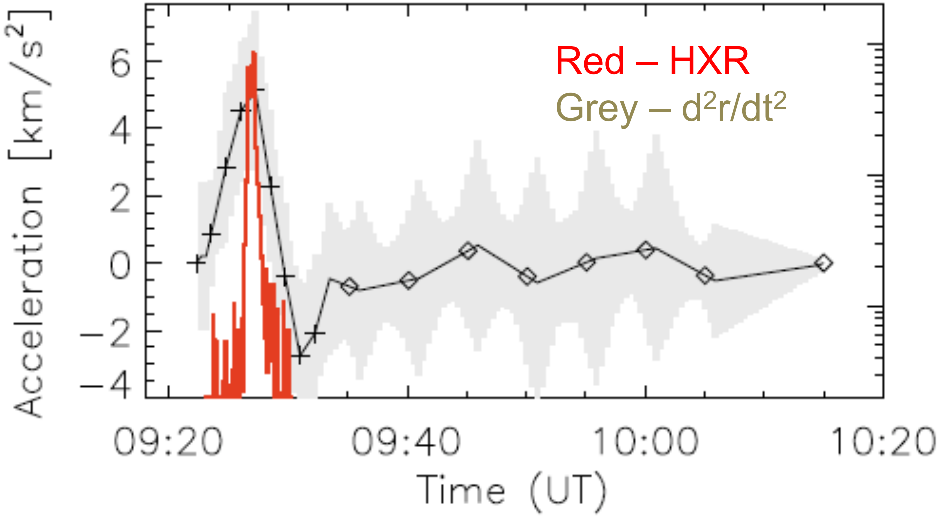
- 90% of GOES X-flares have a CME.
- Within instrumental time resolution, CME acceleration peaks simultaneously with hard X-rays
- Flare energy density >> CME energy density



Krucker et al. (2007)

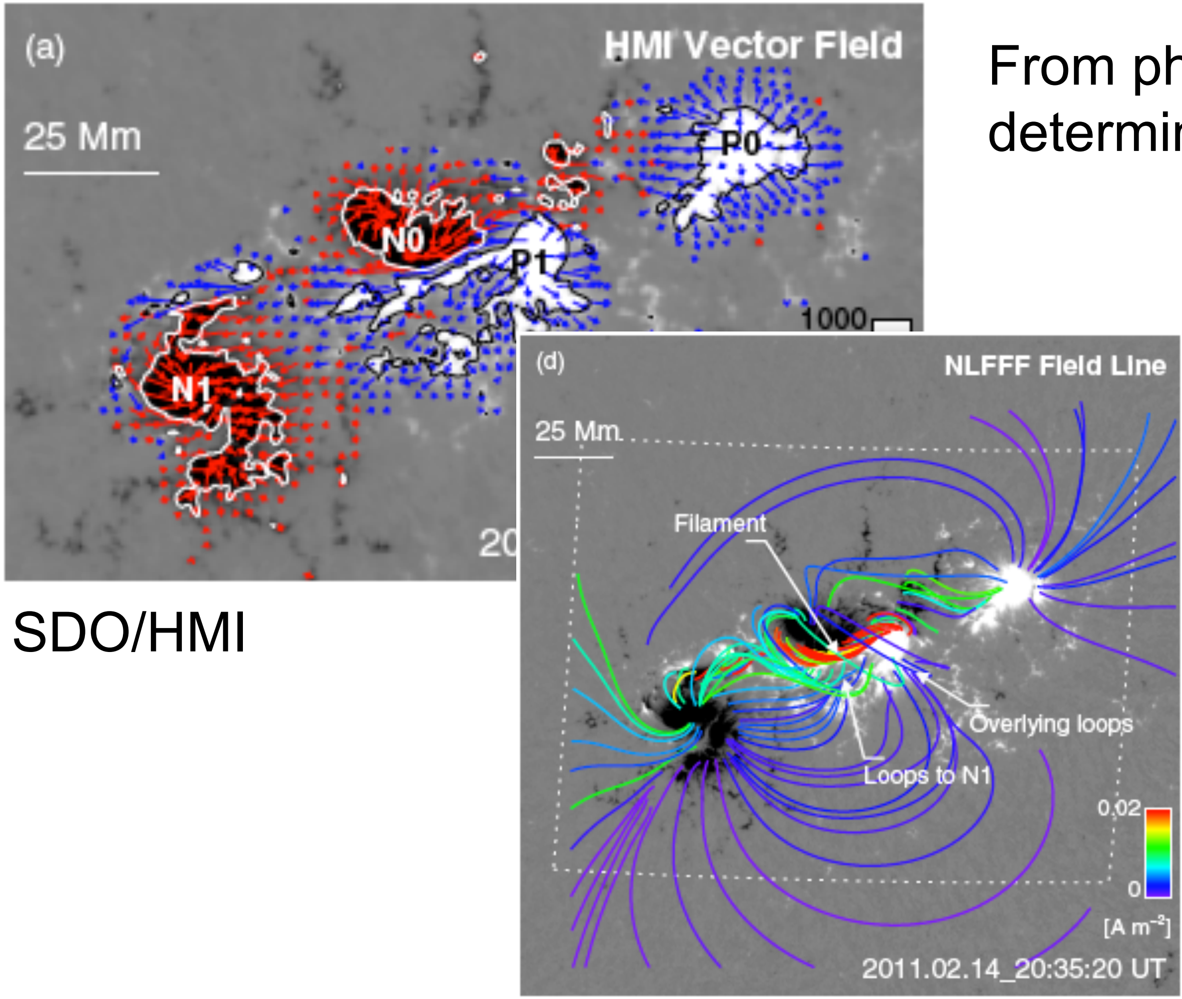


Yashiro et al. (2007)



Temmer et al. (2010)

Coronal energy storage



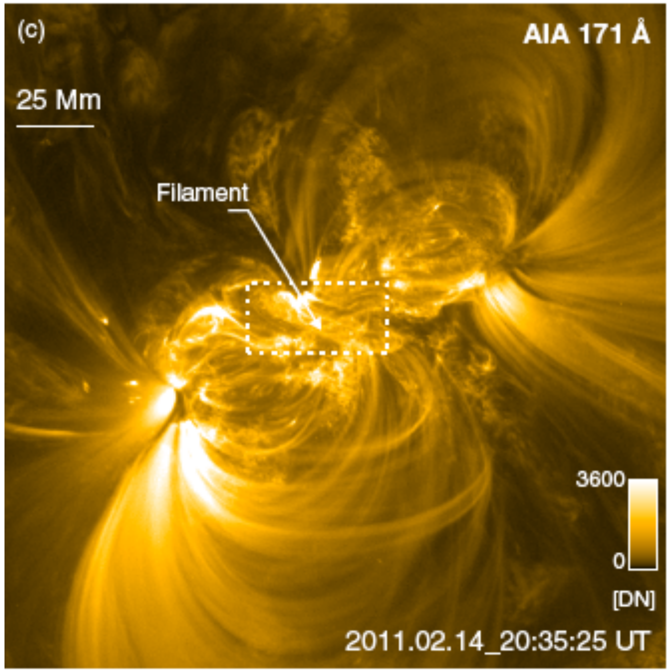
SDO/HMI

From photospheric vector field determine the coronal field

$$\nabla . \underline{B} = 0$$

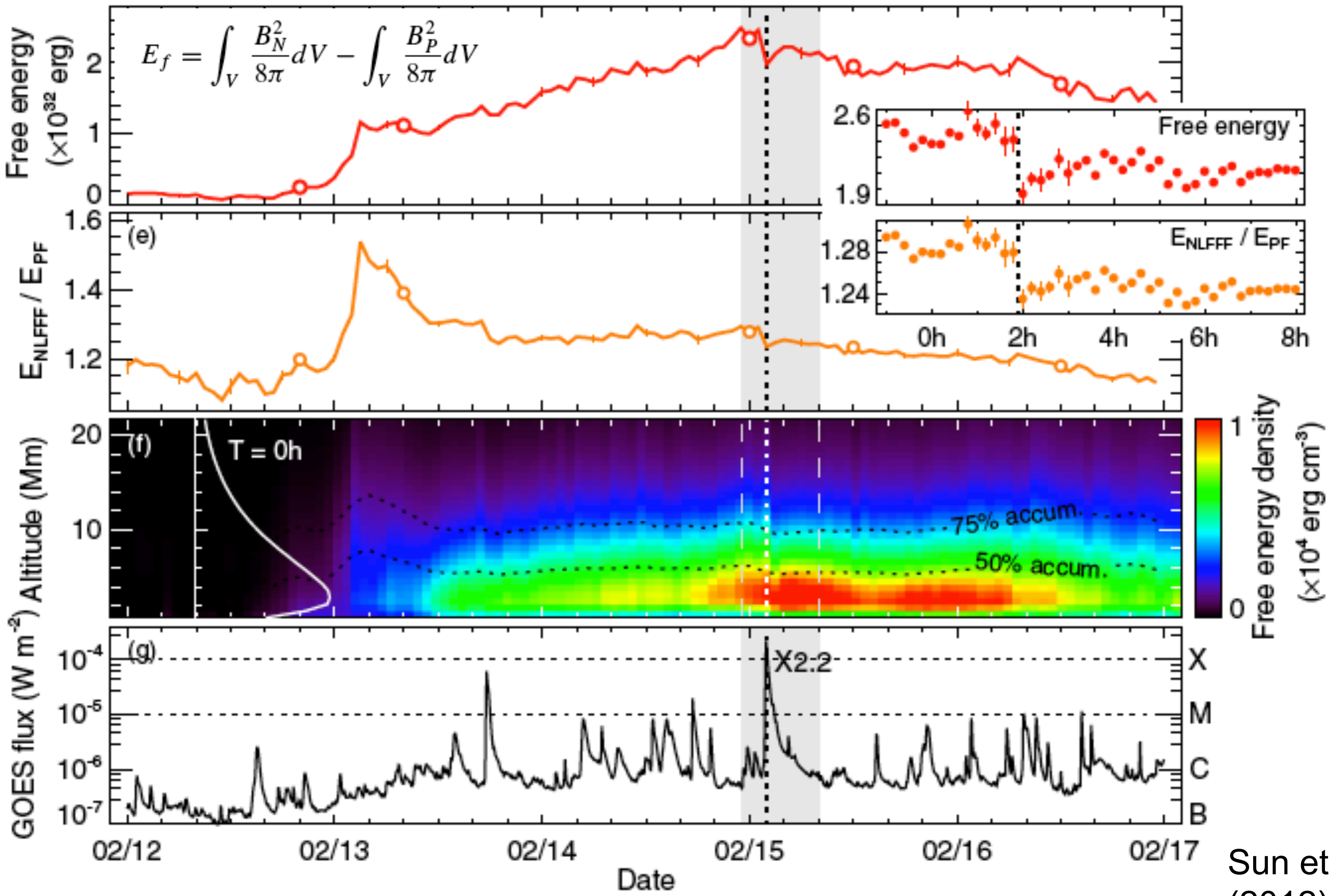
$$\nabla \times \underline{B} = \alpha \underline{B}$$

From B, compute j



(Sun et al. 2012)

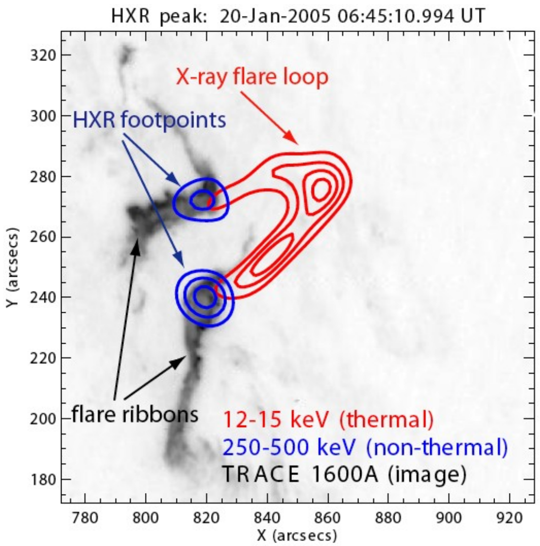
Coronal energy release



Sun et al. (2012)

Impulsive phase morphology

Krucker et al. 2008

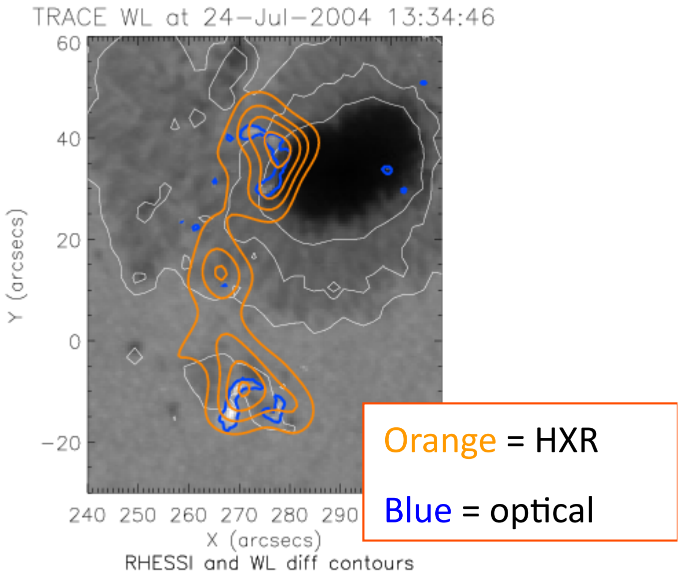


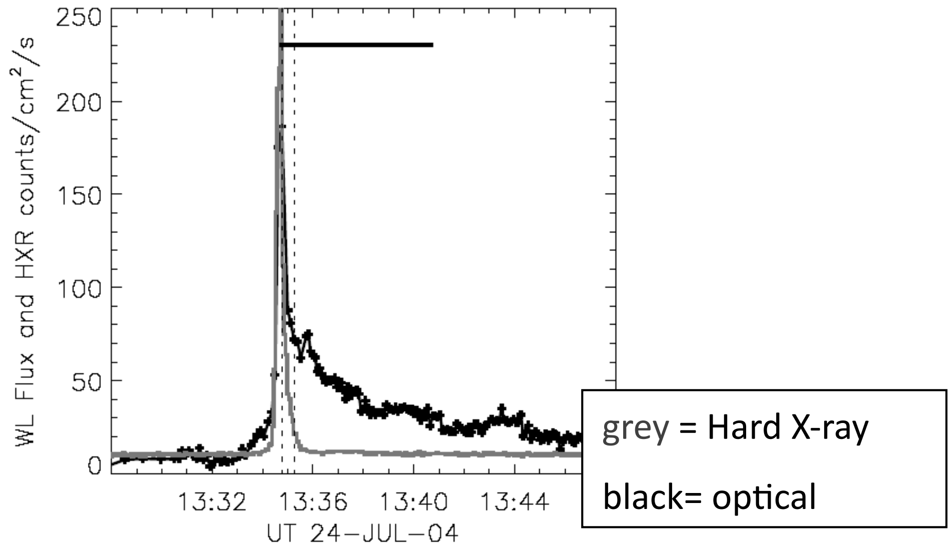
Typically a flare has ~2 strong hard X-ray 'footpoints' -> non-thermal electrons

Optical/UV/EUV emission is also produced at the footpoints.

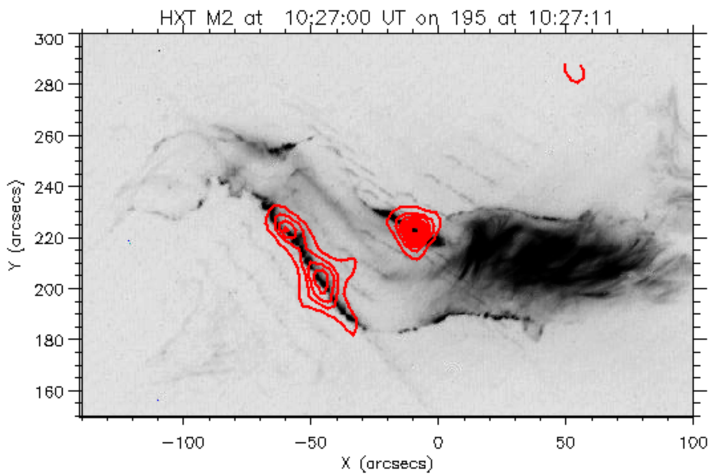
Power per unit area ~ 10^{11}-10^{12} erg s^{-1} cm^{-2}

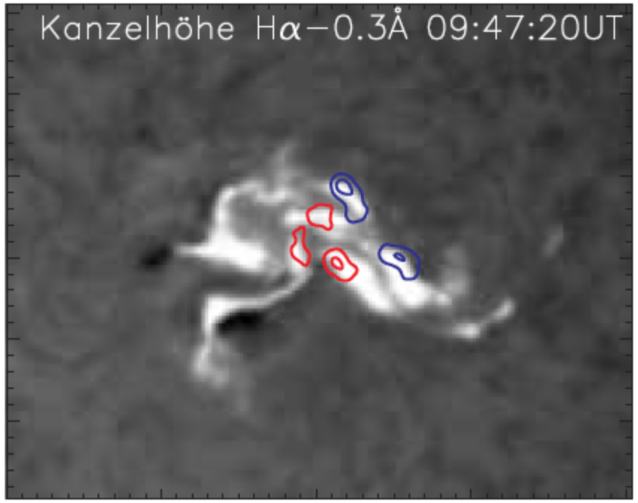
Fletcher et al. 2007





Impulsive phase morphology

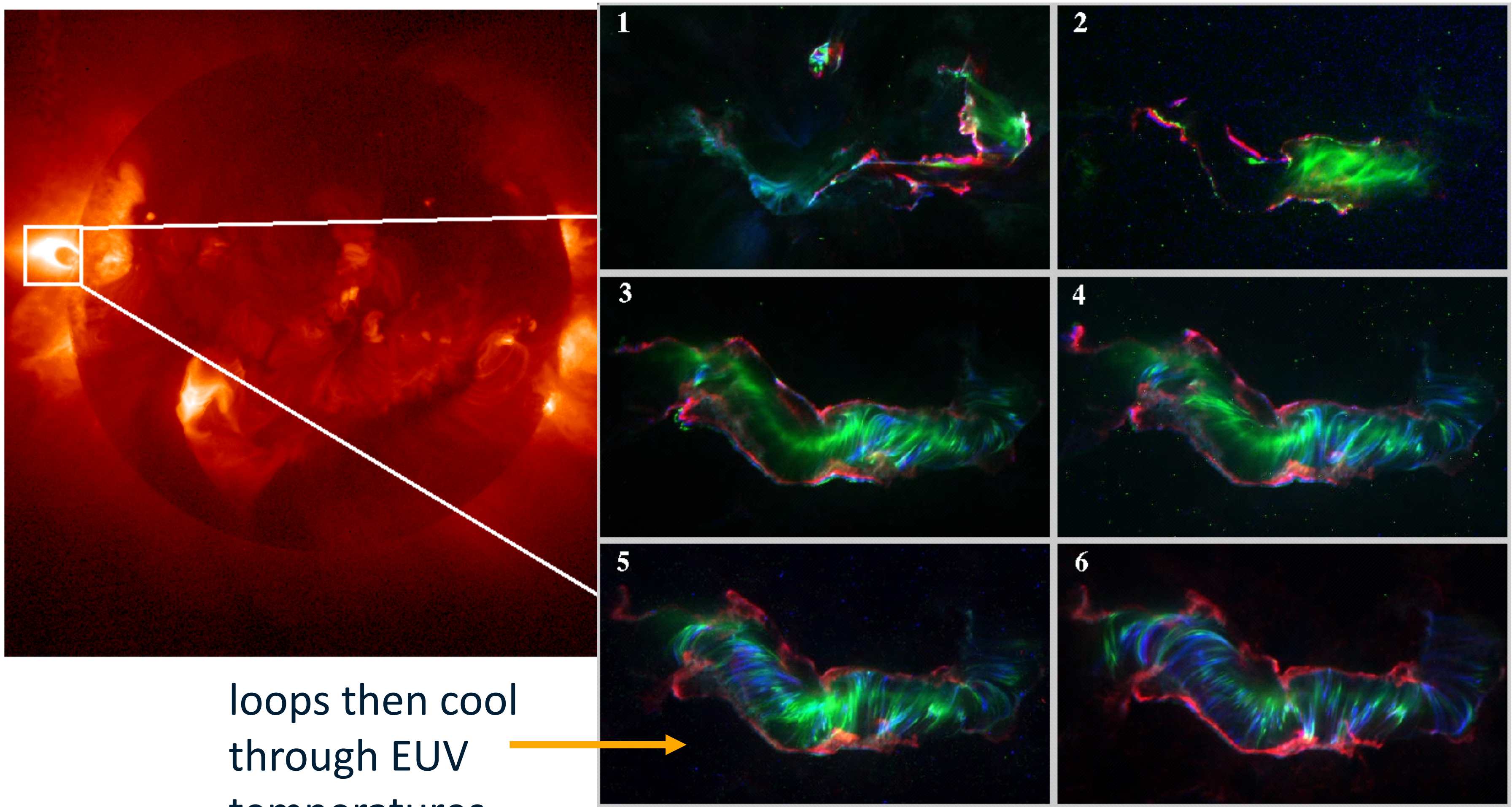




- Most flares organised into 2 main ribbons of emission, bright in Hα, UV, EUV
- Can be 4 ribbons in quadrupolar field geometries
- Hard X-ray and optical sources locations are a subset of the UV/Hα ribbon locations
- Indicates regions of stronger and weaker energy input
  - probably related to *magnetic topology*

Atmospheric response – SXR and EUV

Flare leads to brightening coronal loops, producing high fluxes of soft X-ray emission (0.1-1 keV).



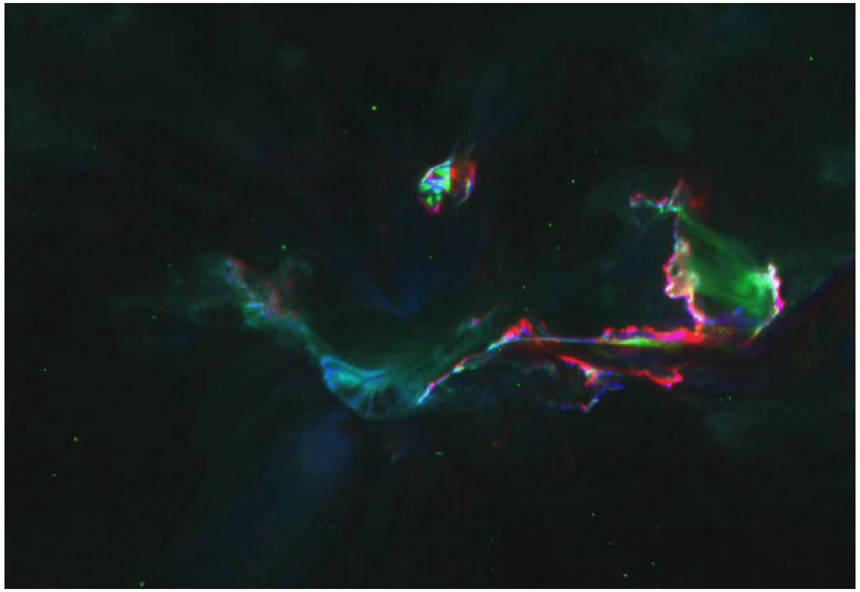
loops then cool through EUV temperatures

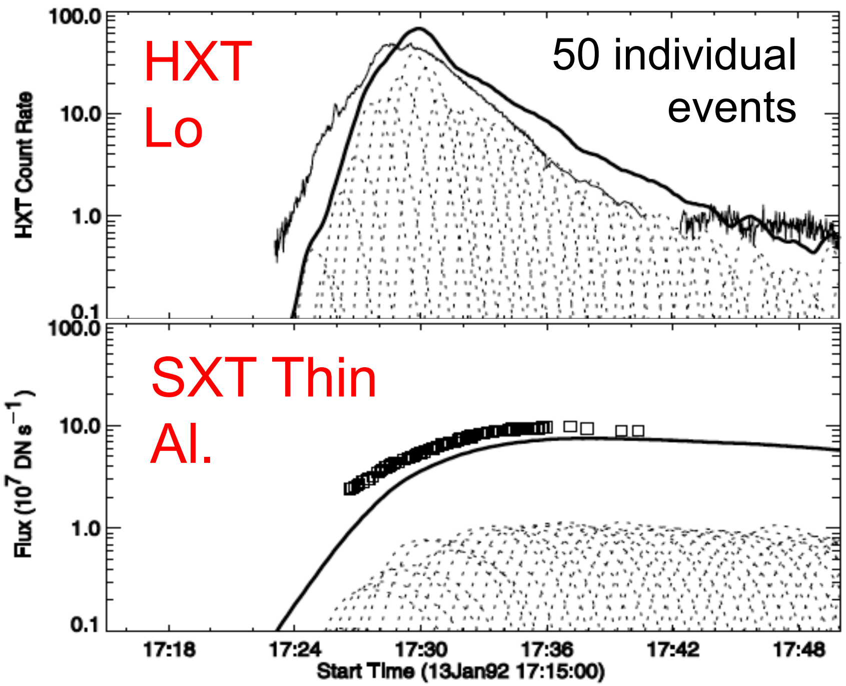
Multiple loops

Large solar flares can involve multiple resolvable loops, excited at different times.

A better agreement between flare EUV/SXR time profiles is obtained for multiple loops (e.g. Reale et al 2004., Warren 2006, Reale et al 2012, etc.)

Flare decay time is determined by single-loop cooling properties *and* overall loop excitation sequence

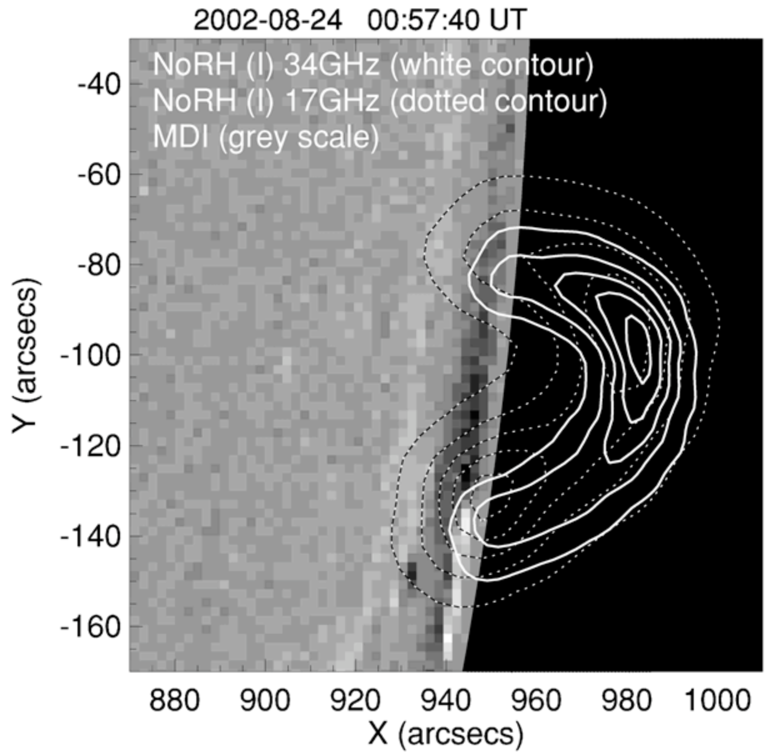


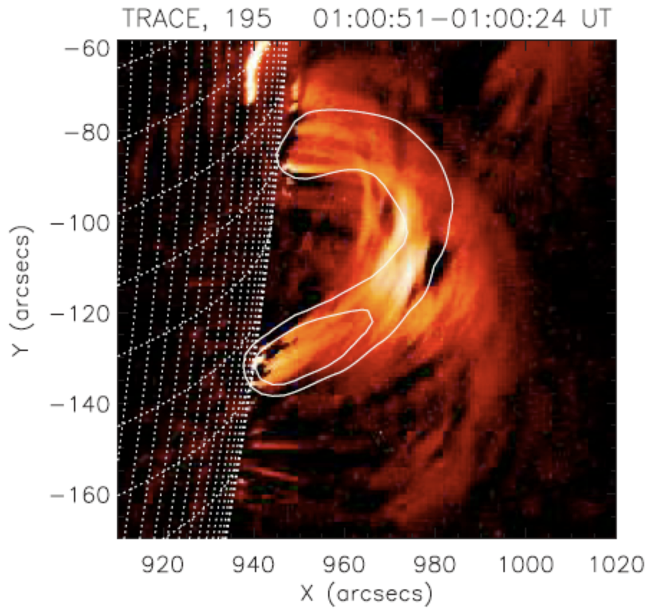


Warren (2006)

Flare gyrosynchrotron radiation

Flare coronal radio emission comes from accelerated electrons gyrating in magnetic fields, producing *gyrosynchrotron* emission.





Reznikova et al (2009)

Observed spectra/intensities/timing are consistent with gyrosynchrotron of electrons with energies of a few 100 keV in fields of ~ 100 G.

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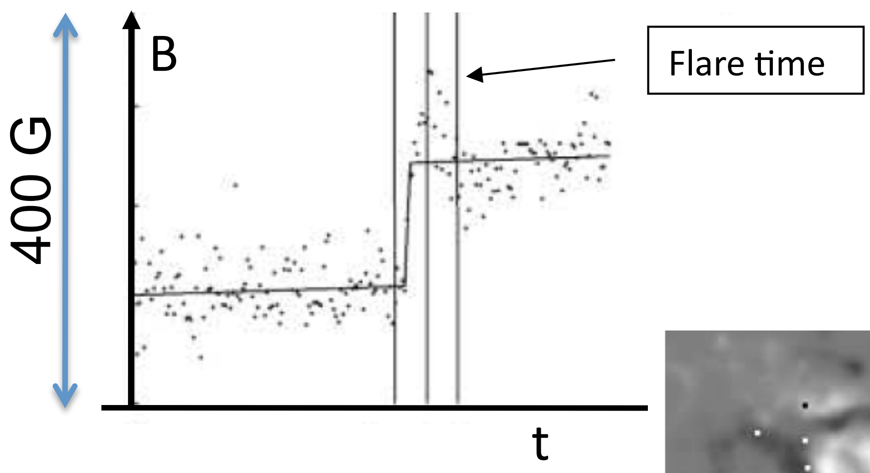
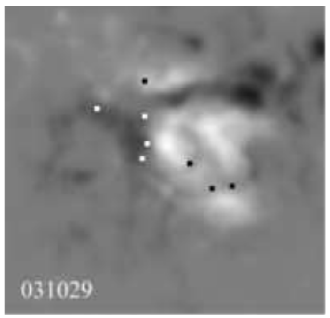
Flare effects on deep atmosphere

There is evidence that deep layers of the solar atmosphere are affected:

Non-reversing field changes

Photospheric LOS field changes of typically ~100 G coincident in space & time with impulsive phase

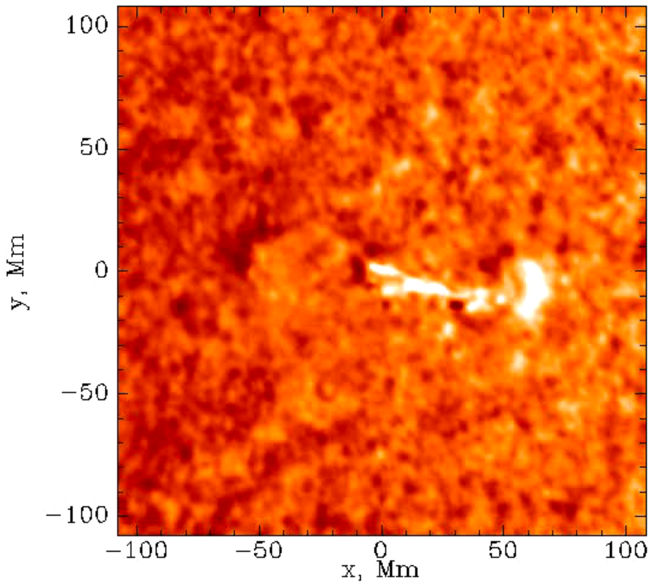




(Sudol & Harvey 2005)

Sunquakes

Requires ~ 0.1% of flare energy to penetrate photosphere



Kosovichev & Zharkova (1996)

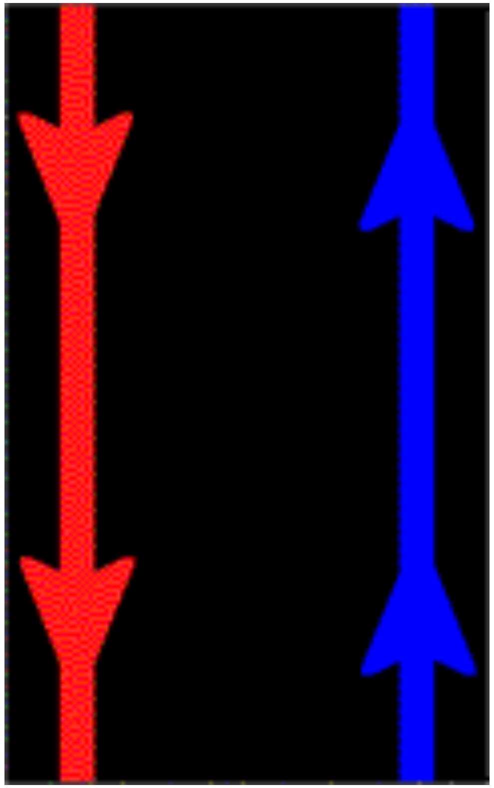
Reconnection in flares

Magnetic reconnection permits the magnetic field to restructure to a lower energy state;

Free energy is released which powers the flare;

The field restructuring generates propagating and standing MHD disturbances – waves – which transport and convert energy

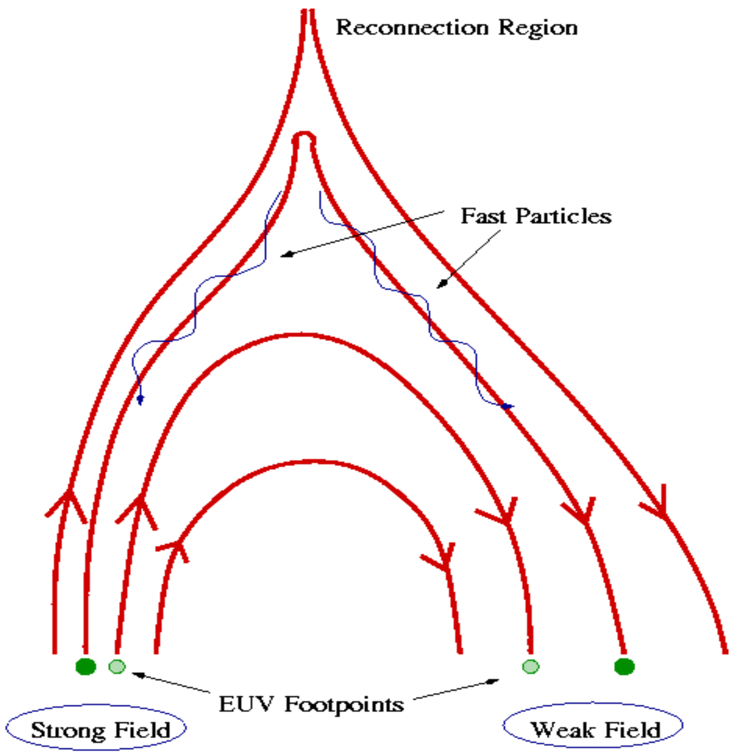
In the dissipation region a parallel field is generated that can accelerate charged particles.

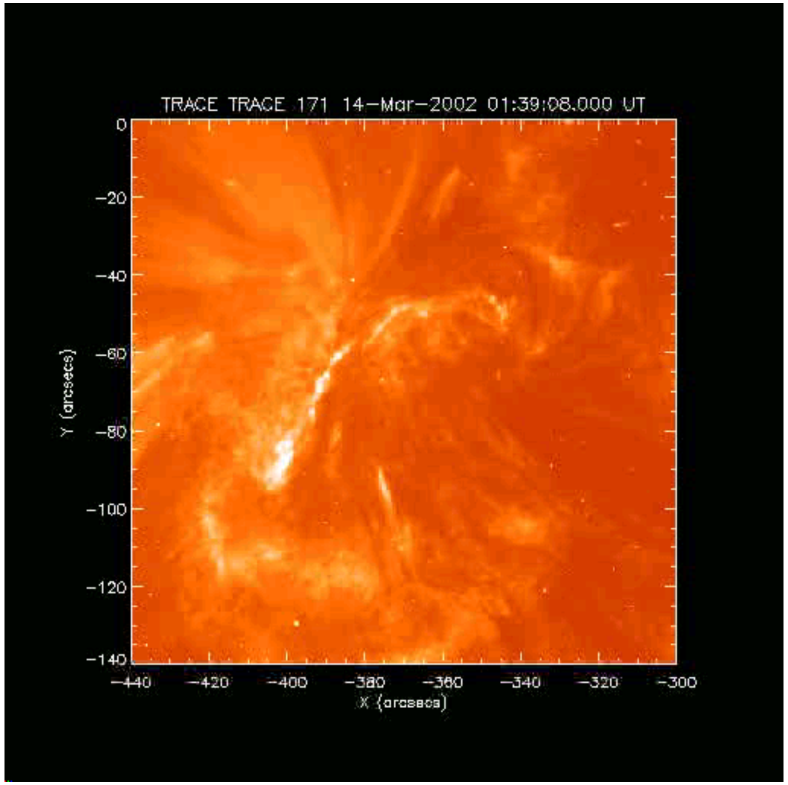


Reconnection and footpoint motion

As reconnection progresses in the corona, the footpoints of 'just reconnected' fieldlines are heated/excited by fast particles

This leads to footpoints (HXR) or flare ribbons (Hα, UV/EUV), which 'move' through the magnetic field as the flare proceeds





Coronal reconnection rate

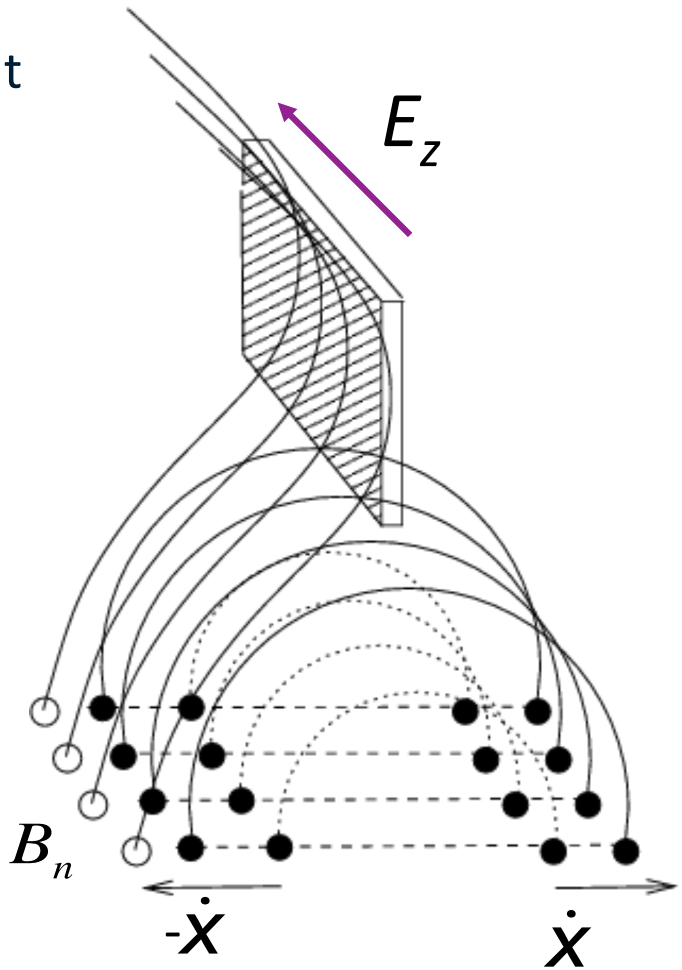
The reconnection rate is $$\frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial t}\left(\int B_{\mathrm{n}} da\right)$$

where B_n is the normal field and a is area swept out

Both can be determined from observations.

2-D configuration ⇒ $$\frac{\partial \Phi}{\partial t} = |E_{\mathrm{z}}| = B_{\mathrm{n}}\dot{x}$$

This E can accelerate particles, but for substantial acceleration need $E_{||}$.

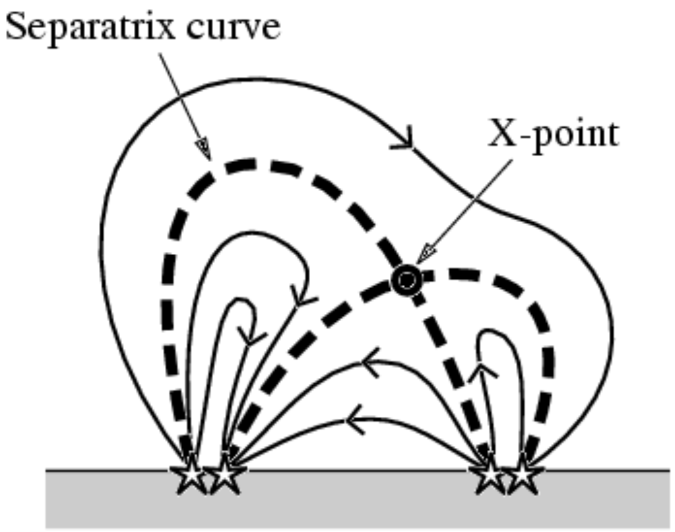


$d\Phi/dt$ is well-correlated with HXR and UV time profiles.

Separatrices and separators

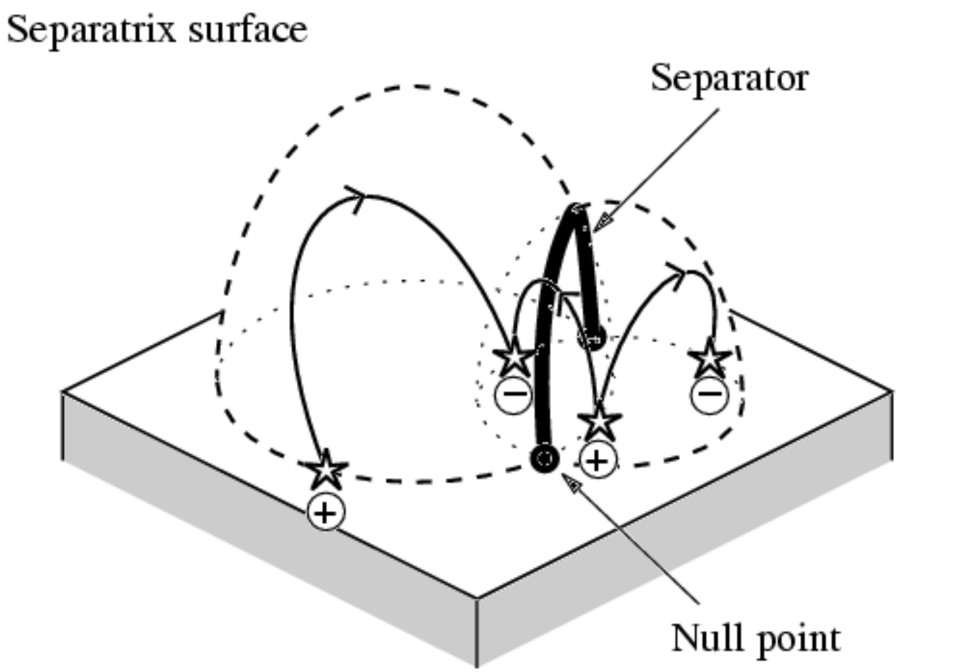
Separatrices are (curves)/surfaces separating domains of different magnetic connectivity in (2D)/3D

Flare radiation is produced at predicted separatrix sites, showing the importance of reconnection processes happening at magnetic domain boundaries



(a)

(Priest and Schrijver 1999)

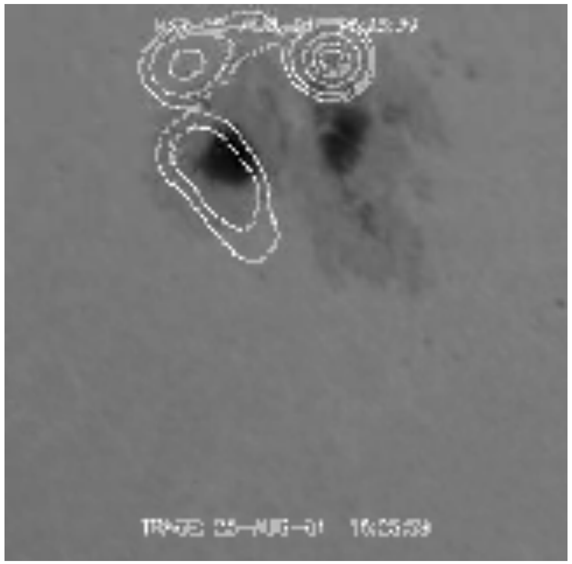


(Priest and Schrijver 1999)

(c)

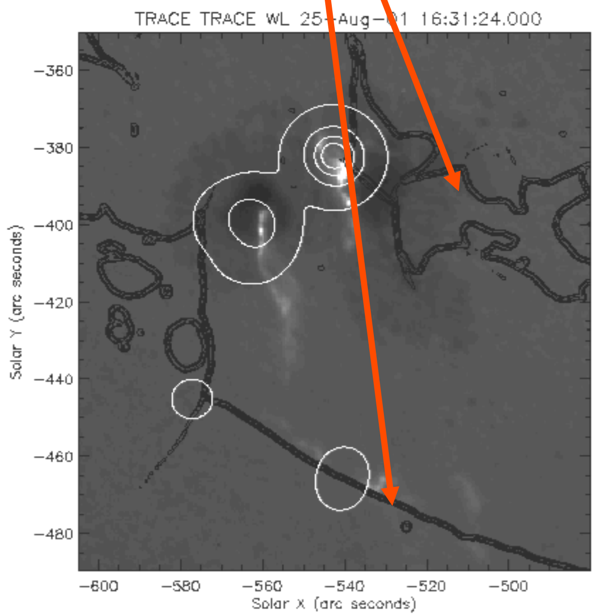
Separatrices in flares

Heating and radiation from non-thermal particles appears at the photospheric intersection of separatrix surfaces (eg Demoulin et al 1993, Masson et al 09).

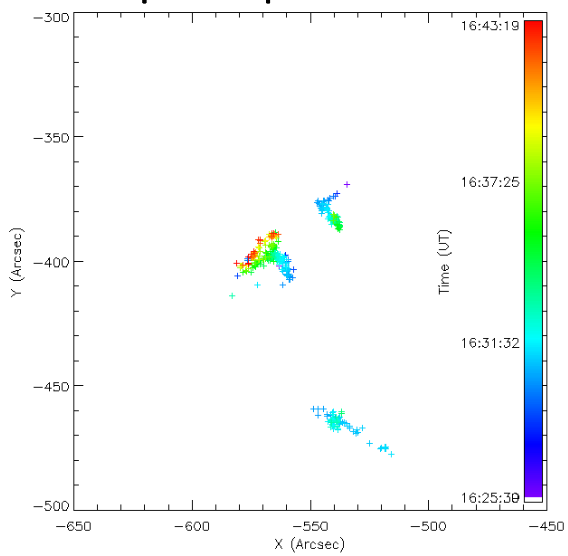


Metcalf *et al.* (2003)

Separatrix intersections



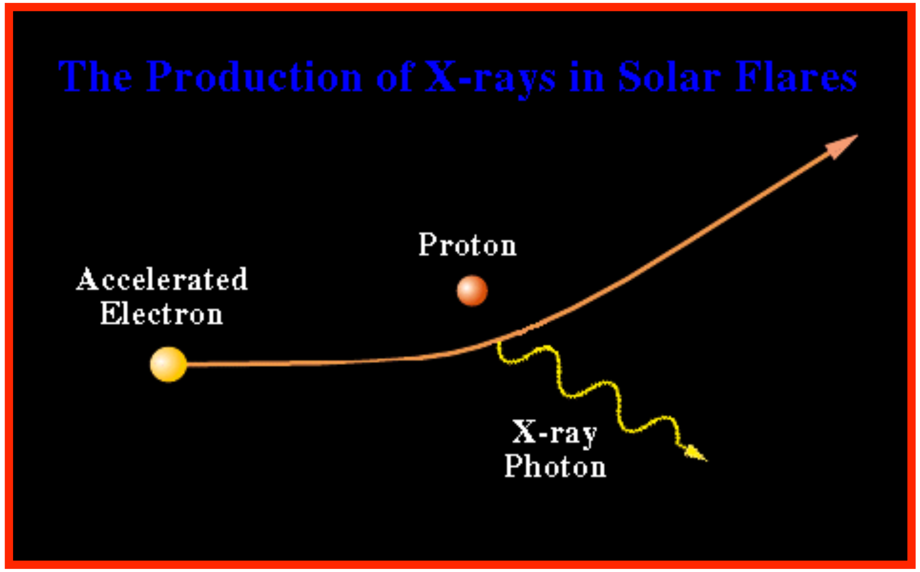
Time evolution of HXR footpoint positions



Hard X-rays

Hard X-rays observed by RHESSI are electron-proton bremsstrahlung from energetic electrons (> 25keV).

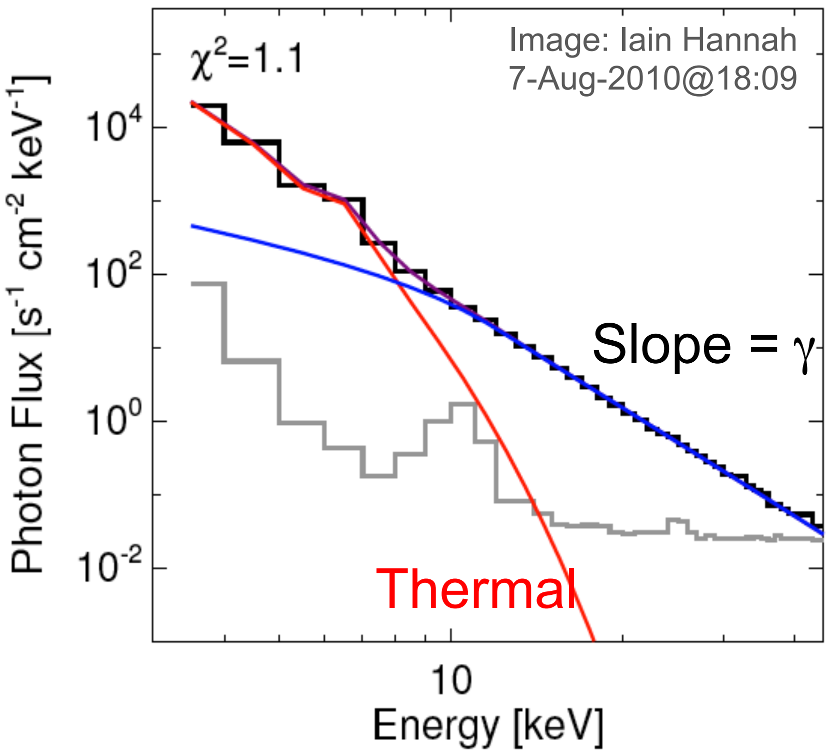
These are the primary diagnostic for flare electrons.



- Most high-energy bremsstrahlung is produced in the dense chromosphere.
- In the chromosphere, $E_{electron} >> E_{target}$, and bremsstrahlung is very inefficient.
- Only ~ 10^{-5} of the electron energy is radiated as HXRs

Non-thermal electron energy

Flare electrons produce collisional bremsstrahlung. The non-thermal electron energy and number budget is obtained from the bremsstrahlung spectrum



flare power = $$P(>E_{min}) = \frac{F_o}{\gamma - 1} E_{min}^{1-\gamma}$$

Assumptions:

- 2 distinct electron populations – thermal & non-thermal
- Non-thermal emission generated by collisionally-stopped electrons

Fit parameters from observations:

Nonthermal: F_o, γ, E_{min}

Typically, P ~ 10^{27}-10^{29} erg s^{-1}
and n ~ 10^{35}-10^{36} electrons s^{-1}

Electrons in the chromosphere: standard model

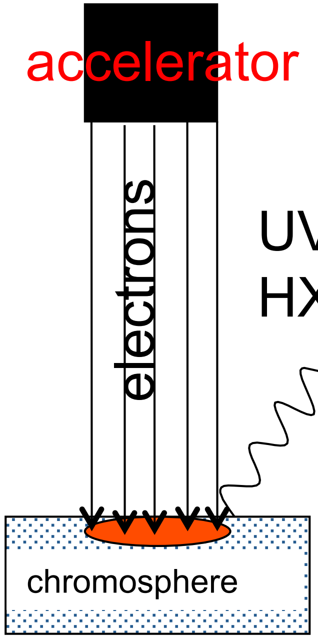
Accelerated electrons originate in corona.

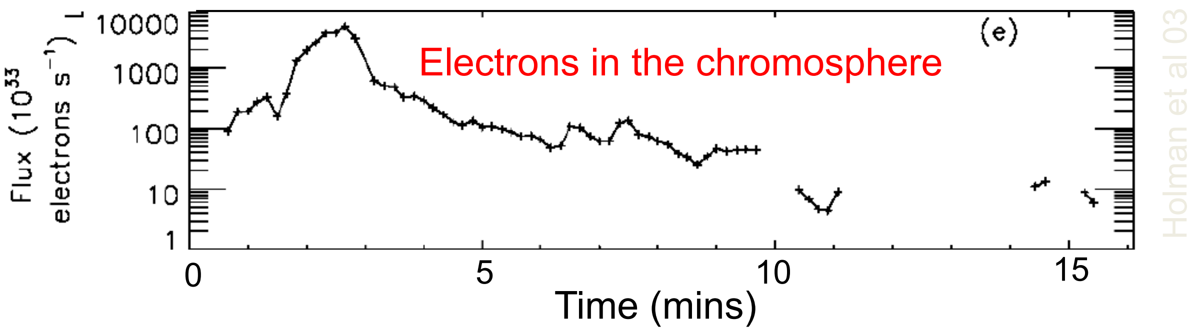
Electron beam travelling along coronal **B** carries flare energy to chromosphere

$$I(\epsilon) = \frac{\bar{n}V}{4\pi R^2}\int_{\Omega'}\int_{\epsilon}^{\infty} \bar{F}(E, \Omega')Q(\Omega, \Omega', \epsilon, E)dE\, d\Omega',$$

Photon spectrum

Source-averaged electron spectrum





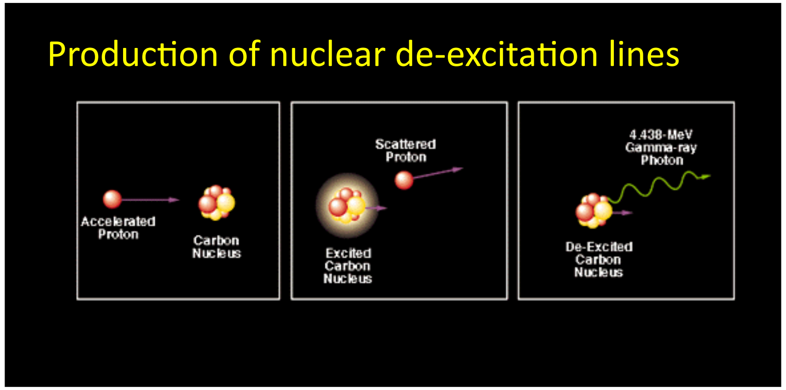
July 23 2003

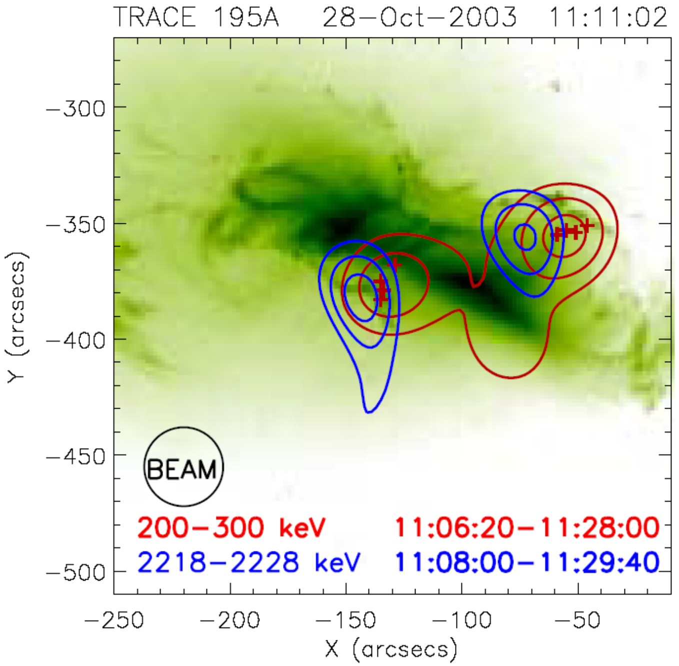
Problem: these electrons cannot penetrate deep enough to make much of the flare radiation.

Gamma rays

The presence of accelerated *ions* is revealed by gamma-rays

Nuclear de-excitation lines caused by bombardment of nuclei by > 30MeV protons





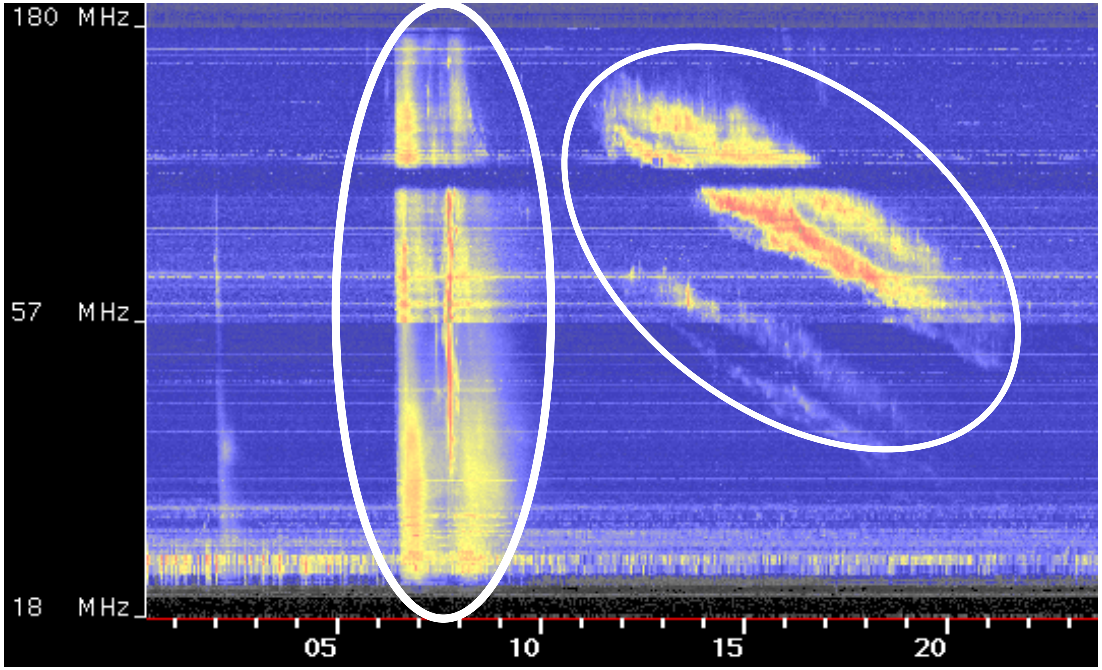
Neutron capture line at 2.23 MeV - n(p,γ)D

- shows location of 10s of MeV ions

Others: The positron annihilation line at 511keV

Continuum γ-rays by bremsstrahlung (~ 10MeV)

Coronal radio signature of flare beams and shocks



<u>Type III bursts</u> drift rapidly from high to low frequency.

-produced by flare-accelerated electron beams streaming into space which generate Langmuir waves. These mode-convert to EM radiation.

<u>Type II bursts are</u> produced by electrons accelerated at a super-Alfvenic coronal shock wave, driven by a coronal mass ejection.

Radio frequency = plasma frequency

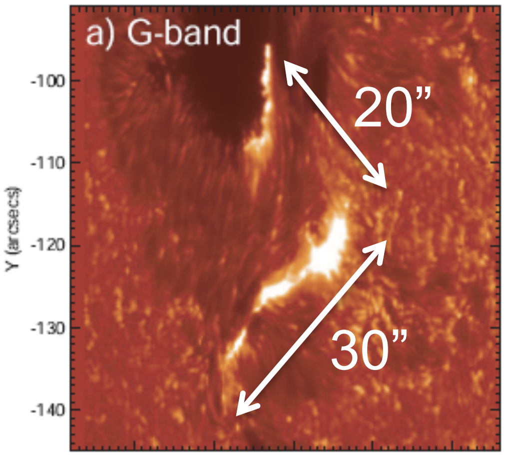
Energy Transport - electrons

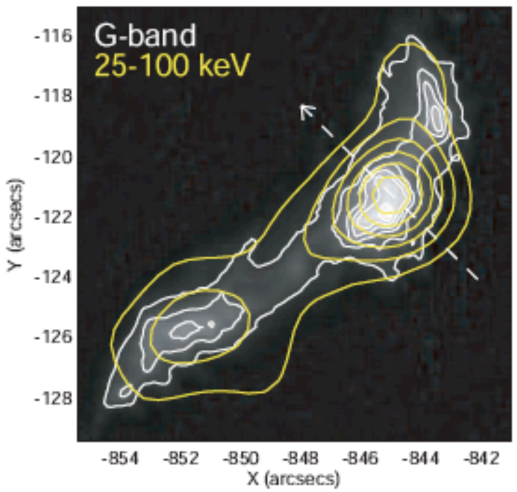
The transport of energy from corona to chromosphere is also uncertain

In the 'standard model', energy is carried by electron beams

Standard model implications:

- All electrons in the flare corona are accelerated and leave in 1-10s
- The resulting beam has a self-field of about 10^6 x ambient field
- A return current is generated that cannot flow stably with the beam





- e.g. 6-Dec-2012 X flare (Krucker et al 2011)
- Beam flux ~ 10^{36} electrons s^{-1}
- Beam intensity = 10^{20} electrons $cm^{-2}s^{-1}$
- Estimate volume = 30"x 20"x30"
- For $n = 10^9 cm^{-3}$, flare coronal volume empties in ~6 s

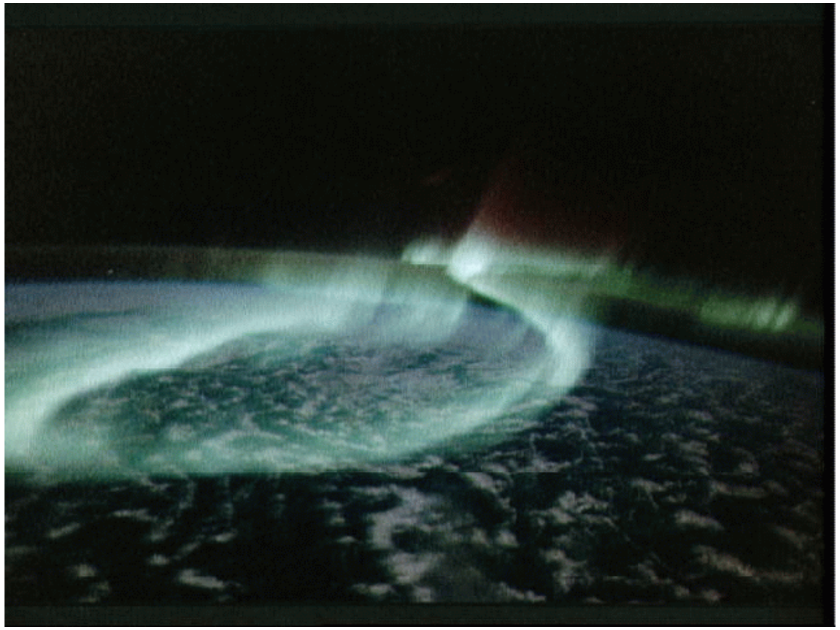
Energy transport - waves

Energy could also be transported from corona to photosphere by magnetic waves/pulses, as happens in magnetospheric substorms.

- Before the flare, energy is stored in twisted magnetic field.
- Field reconfigures, twist redistributes and energy is released
- Wave pulse carries energy as Poynting flux

$$S = v_{\mathrm{A}} \frac{(\delta B)^2}{4\pi}$$

- Electrons by turbulence or $E_{||}$ where wave dissipates



If dB/B ~ 5% in a 500G field, $n_e = 10^9$ cm^{-3} energy requirements are fulfilled.

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Particle acceleration in flares

Analysis of flare X-rays shows that around 10^{36}-10^{37} electrons per second must be accelerated to 10s of keV (and a similar number of ions).

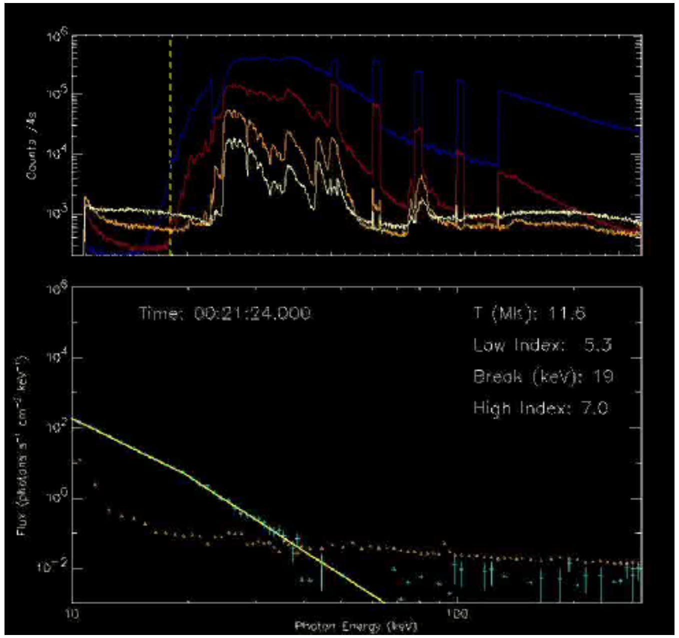
There are many theories for the origin of the accelerating electric field, including:

-due to changing B in or near reconnection ($\nabla\times E = -\partial B/\partial t$)

-generated by locally increased resistivity in a loop ($E = \eta j$)

-resulting from small-scale EM or electrostatic turbulence

- generated in an MHD shock (e.g. CME driven)



All of the above can produce electrons of a high energy in a short time, but none can easily maintain the *rate* (10^{36} e/s) implied by observations.

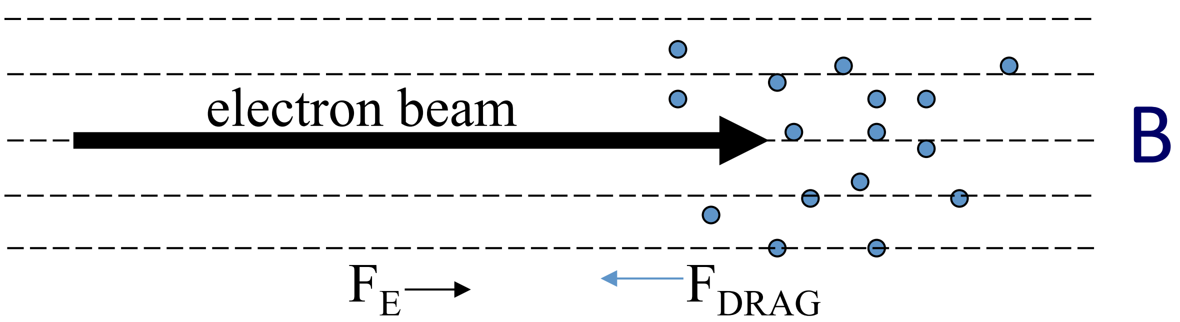
Field-aligned DC fields

- For example, a local increase in resistivity in a current loop leads to large potential drop (since huge inductance of circuit prevents rapid change in current)

- Electrons accelerated if this DC field is greater than the Dreicer field, $\mathcal{E}_d$ The Dreicer field is the value of the DC field such that the force exerted on the electrons exceeds drag force from e-e Coulomb collisions

- $\mathcal{E}_d$ typically 10^{-4} V/cm

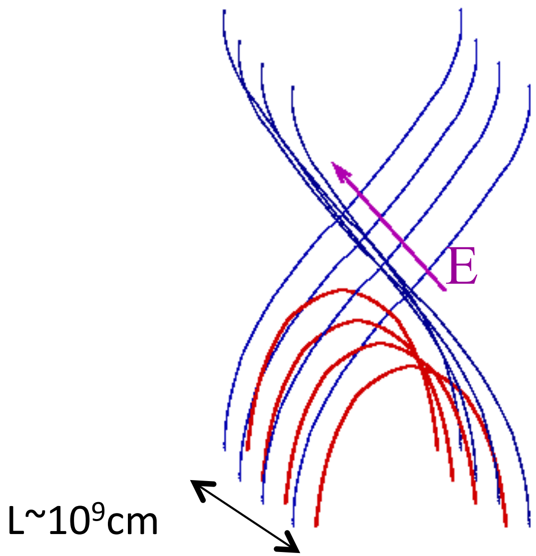
- Electrons with speeds greater than a critical speed $= v_{Te} (E_d/E)^{1/2}$ are freely accelerated → 'runaway' electrons



DC electric fields in a current sheet

Observations suggest that high electric fields occur in reconnection regions.

Inferred values of reconnection electric field are ~ 1 V/cm



total potential drop = 10^{10} V

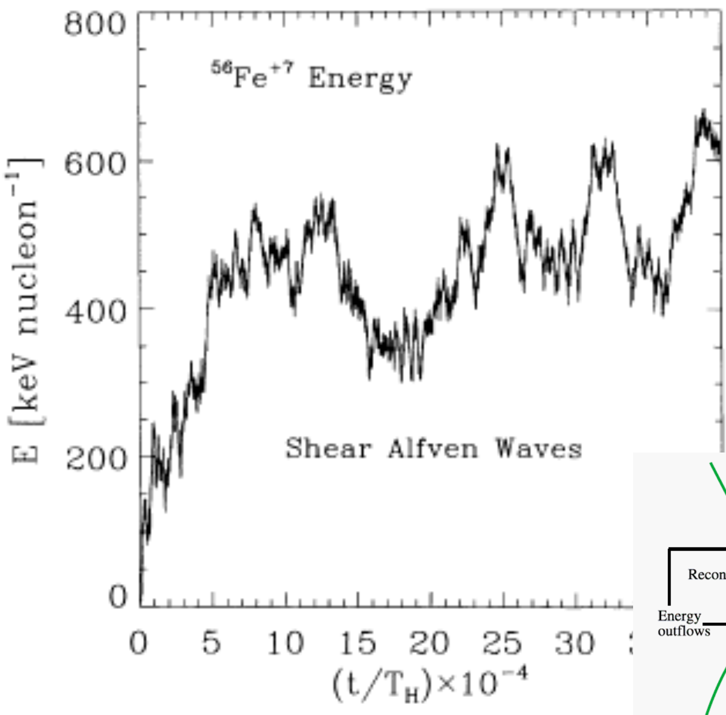
But E ⊥ B almost everywhere. Leads to drifts rather than acceleration

Near X-line or current sheet, there may be an 'unmagnetised' region B(x,y) → 0, or a component of E parallel to B

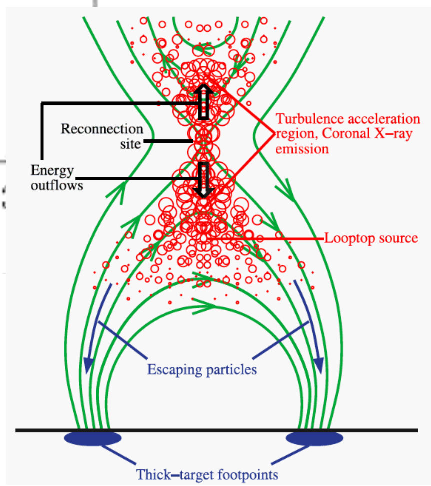
Here, efficient particle acceleration can occur – but only in a small volume (radius ~ r_L)

Stochastic resonant acceleration

Particle resonates with high-frequency wave. If a wave spectrum exists, it can 'hop' stochastically from one resonance to another



Miller & Viñas (1993)



Liu et al (2010)

Energy can be lost or gained in each interaction, but overall, energy of particle increases

In principle can operate throughout a large volume, and accelerate many particles.

But process is rather inefficient (~ 1 in 10^4 particles accelerated)

The smallest flares (micro/nano)

Observed flares span a large range in energies, from microflares (10^{24} ergs) to great flares (10^{32} ergs).

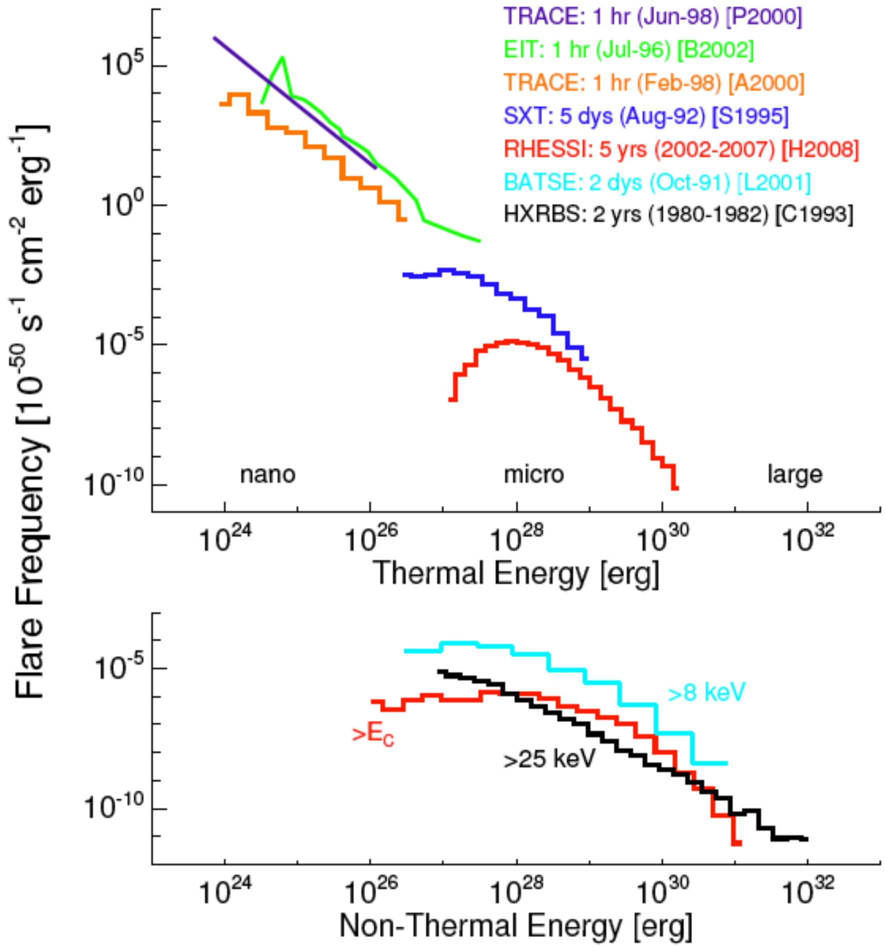
• Flares at 10^{23} erg have not been observed.

• Coronal heating requires a spectral index in flare frequency distribution of > 2 (Hudson 1991)

• Spectral index ranges from 1.5 to 2.1

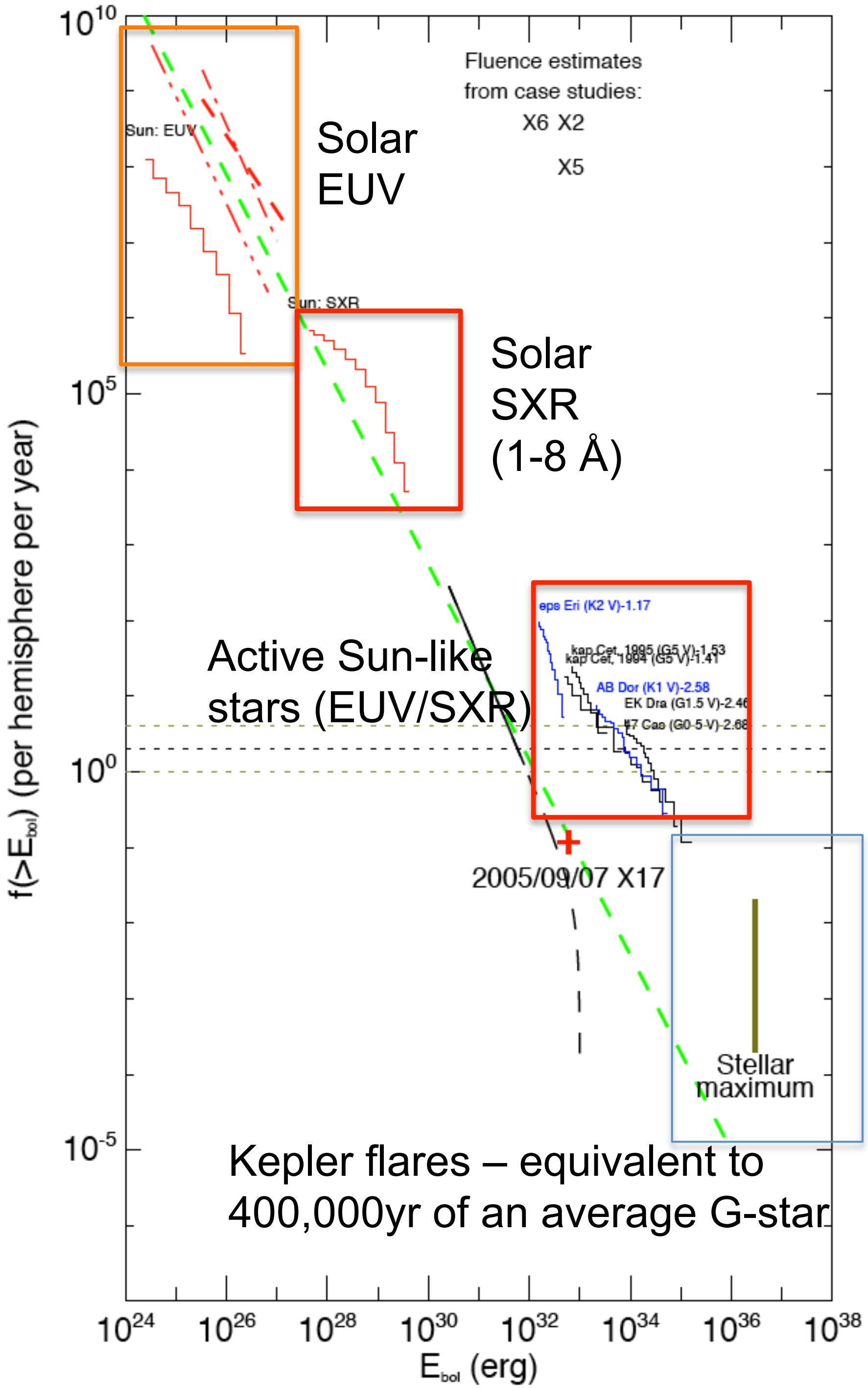
• Difficult counting very small events near the noise

• Not clear that the readily observable properties (e.g. EUV intensity) are very good proxies for total flare energy.



Hannah et al. 2008

The largest flares



The first flare ever observed (Carrington 1859) was probably the most geo-effective on record

From solar & stellar flare total energy estimates and occurrence rates, assess how often a 'deadly' event might occur (Schrijver et al 2012)

An upper cutoff energy for solar flares is known indirectly from proxies, but stellar flares can go well beyond this limit.

Can flares be forecast?

Folk Knowledge:

A complex, rapidly-evolving, large active region has highest probability of producing a flare, within a few days of its emergence.

More accurate forecast?

Prediction based on past X-ray activity (Bayesian statistics)

Moderately successful (Wheatland 2004)

Statistics of magnetic field parameters and their variations

Rather unsuccessful (Leka and Barnes 2006)

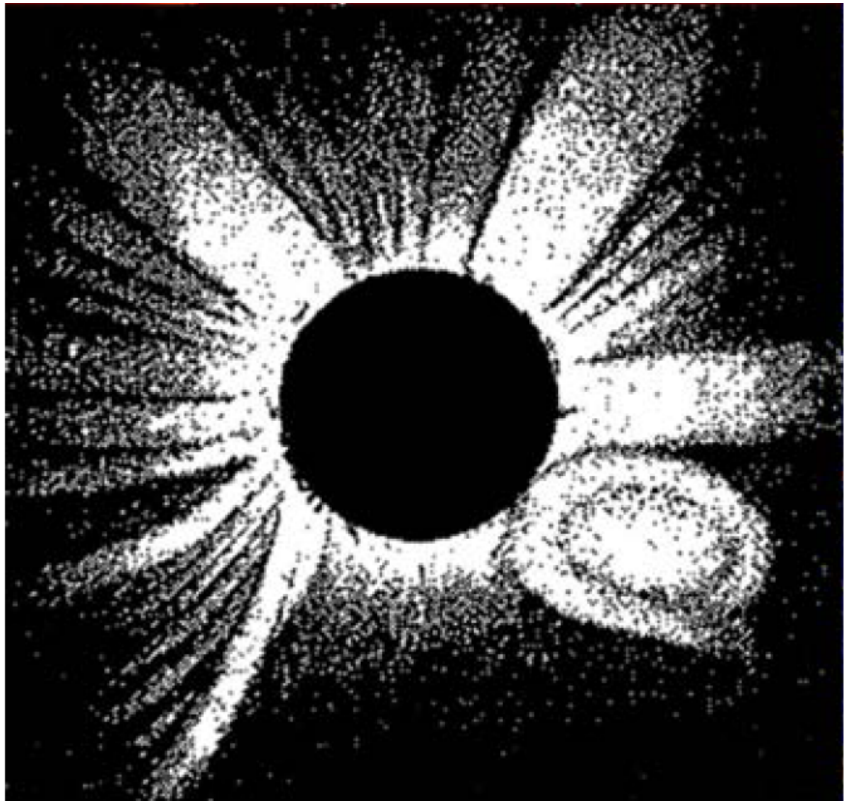
Neural net 'learning' of appearance of ARs about to flare

Underway

Best prediction so far…

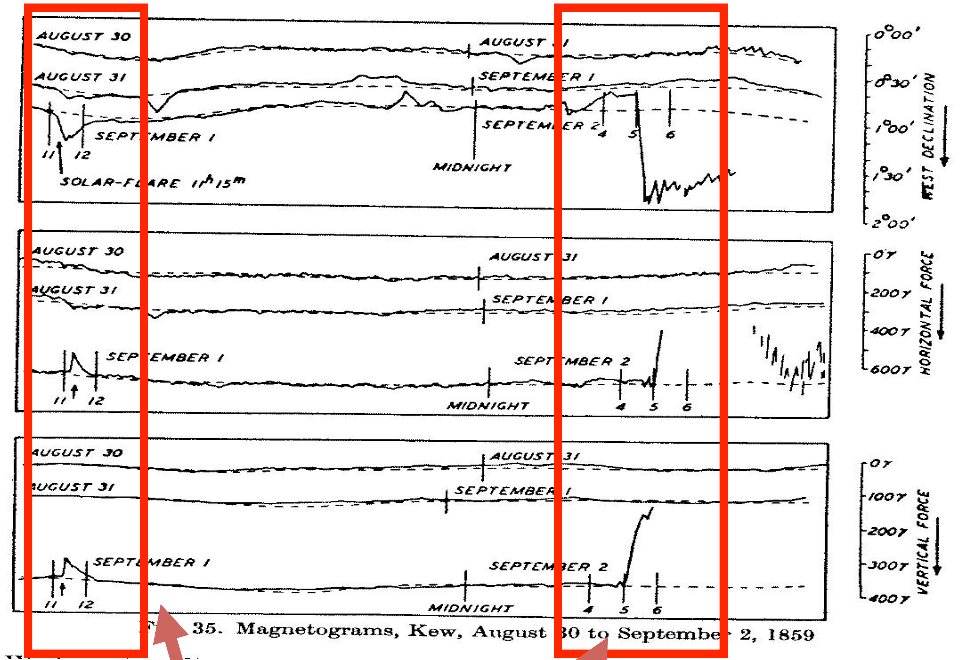
If total flux within 15 Mm of neutral line exceeds 2×10^{21} Mx, a major flare will occur within a day (Schrijver 2007)

Early CME observations



Drawing of white light corona

Tempel 1860, From Eddy (1974)



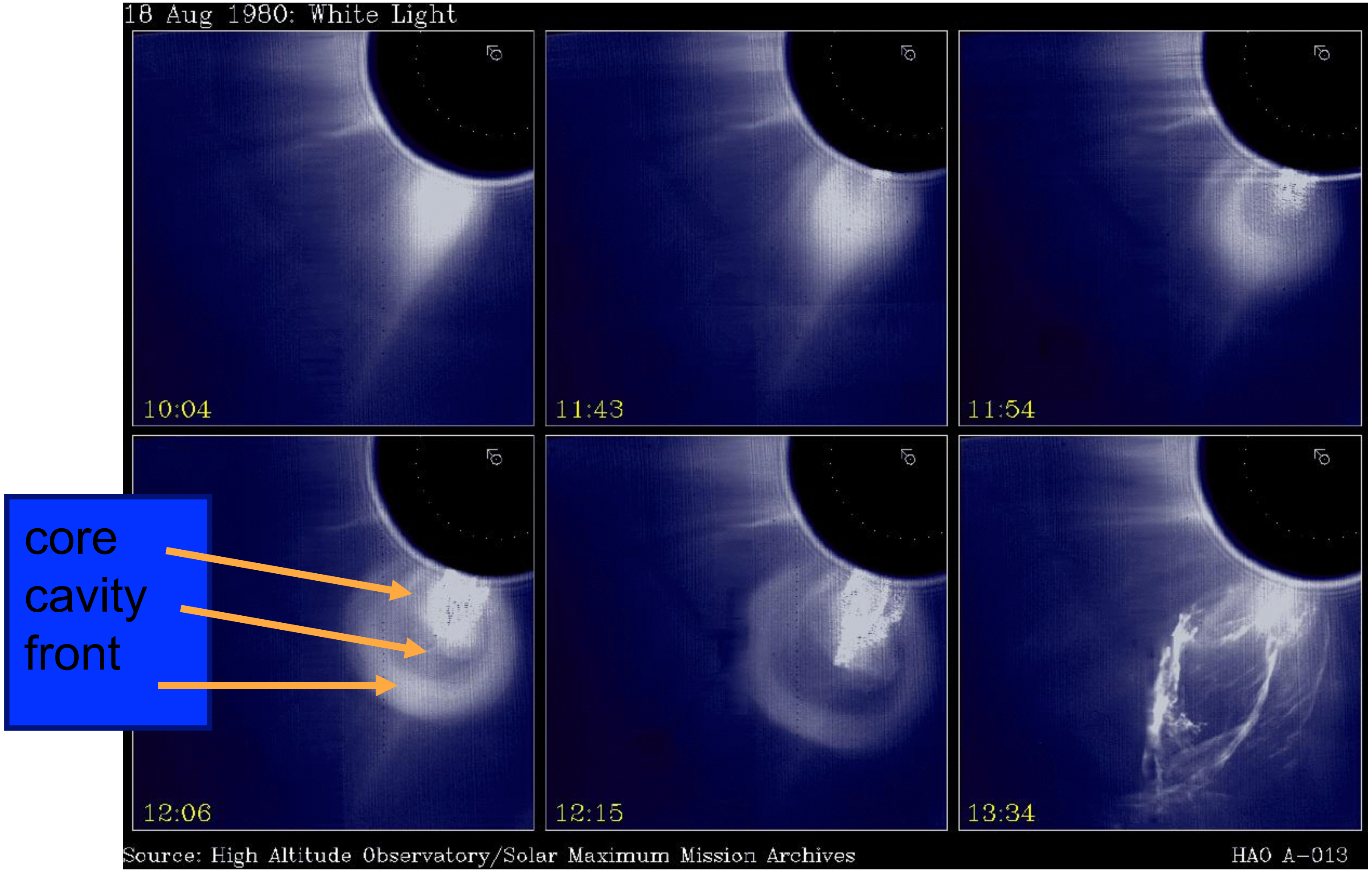
Magnetometer disturbances following 'Carrington's Flare (1859):

(i) ionospheric response to flare UV

(ii) CME hits

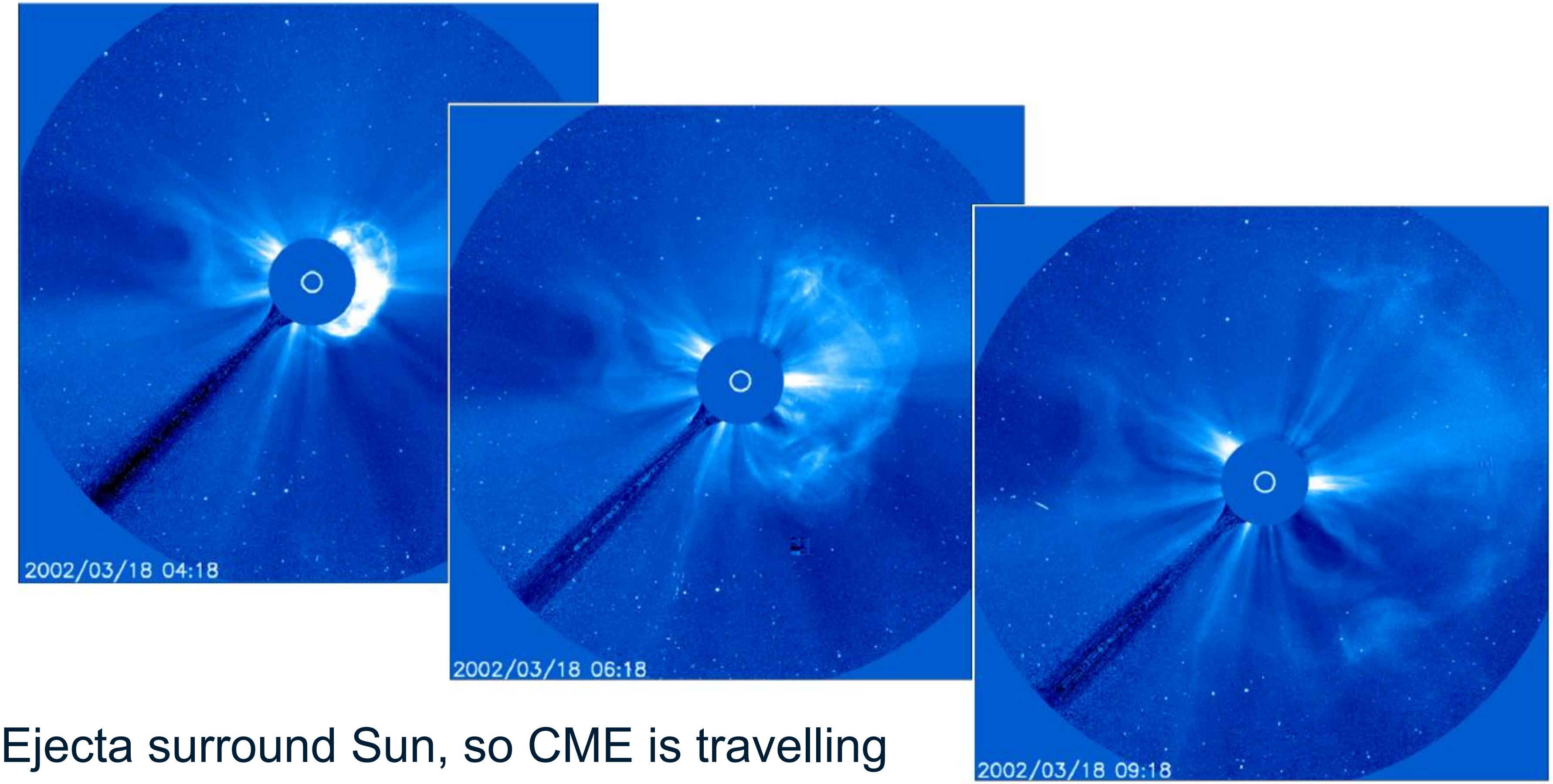
CME definition

"..an observable change in coronal structure that (1) occurs on a time scale of a few minutes [to] several hours, and (2) involves the appearance and outward motion of a new, discrete, bright, white light feature in the coronagraph field of view. " (Hundhausen 1986)



Halo CMEs

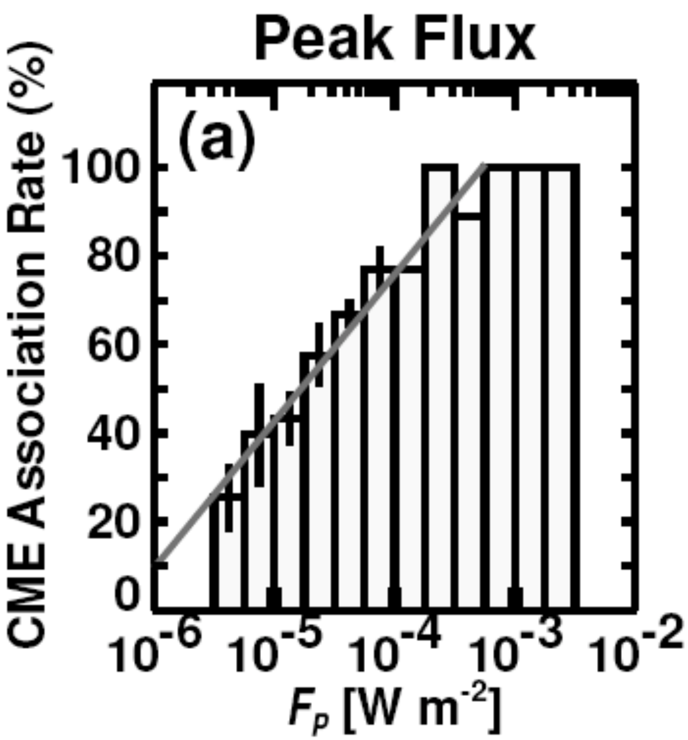
Discovered by Howard (1982). Known to be the CME type most responsible for terrestrial effects



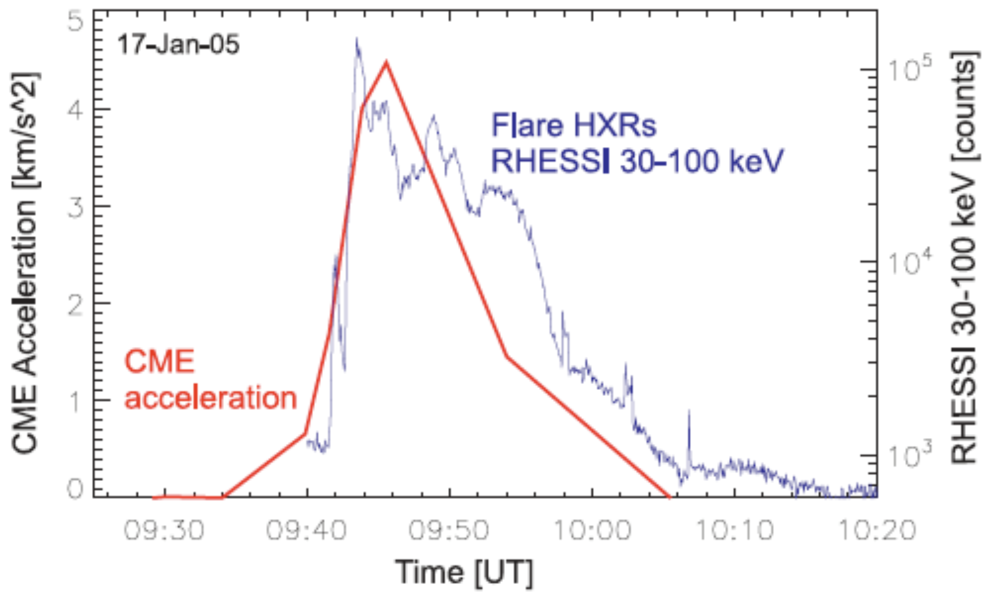
Ejecta surround Sun, so CME is travelling towards or away from Earth.

Flare/CME association

Every big GOES flare has a CME. Within instrumental time resolution, CME acceleration peak and hard X-ray peak happens simultaneously



Yashiro et al. (2007)

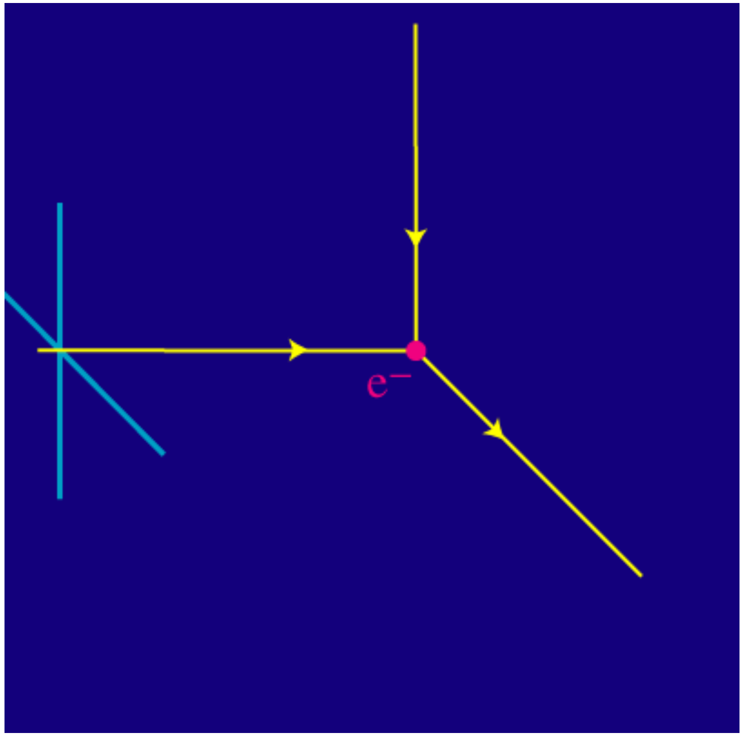


From Temmer et al. (2007)

CME white light measurements

CME white-light signal is produced by Thomson scattering of photospheric radiation by coronal electrons.

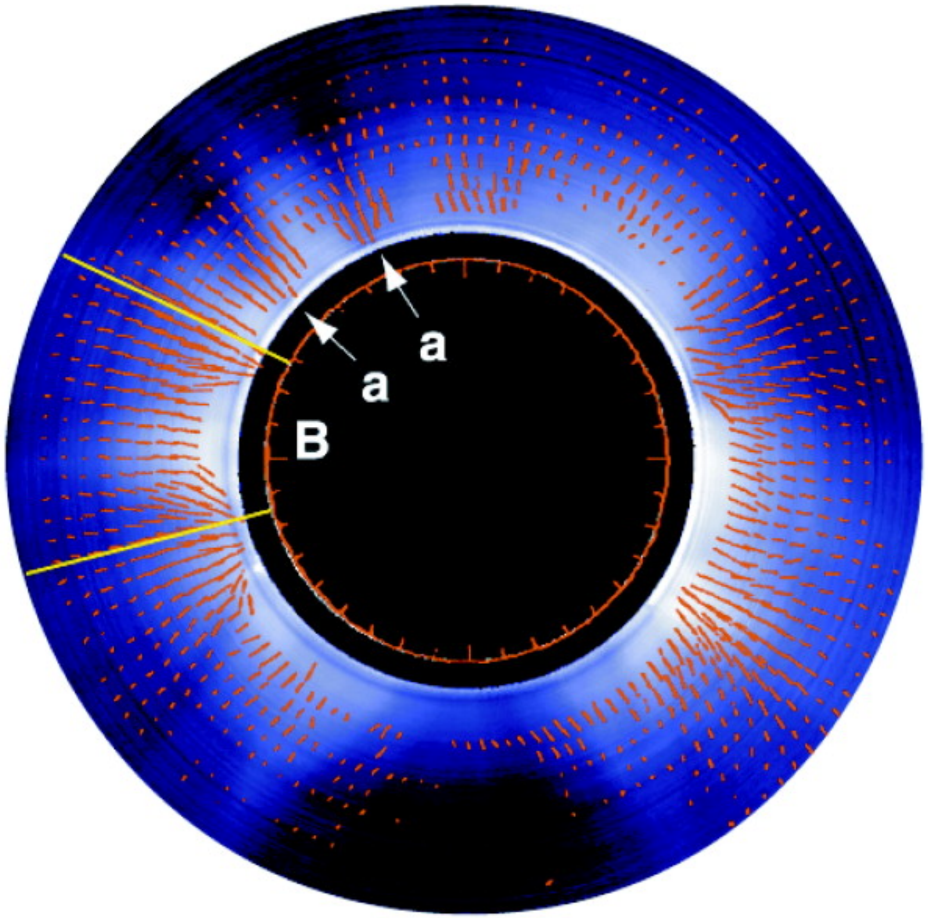
Scattered flux depends linearly on the number of electrons and the incident photospheric intensity - provides a direct way to estimate the CME mass.



However total scattered brightness includes all scattering sources, e.g. zodiacal dust, so need to look at polarized brightness

Polarized brightness

Dipole radiation from free electrons is strongest in the direction perpendicular to electron motion, so produces signal with linear polarization, p.



Polarized brightness image (blue) = electron distribution, integrated along line-of-sight.

Polarization vectors from resonance fluorescence of Fe XIII (Habbal et al), give field direction.

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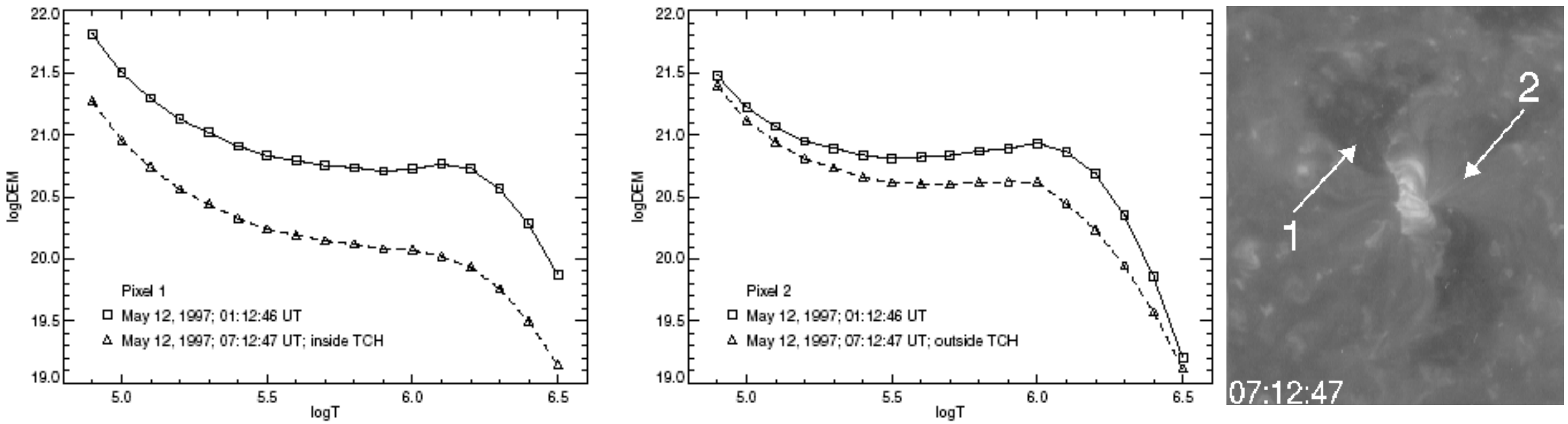
Soft X-ray and EUV

CMEs can be inferred from the loss of coronal material seen as a ‘dimming’ in SXR and EUV.

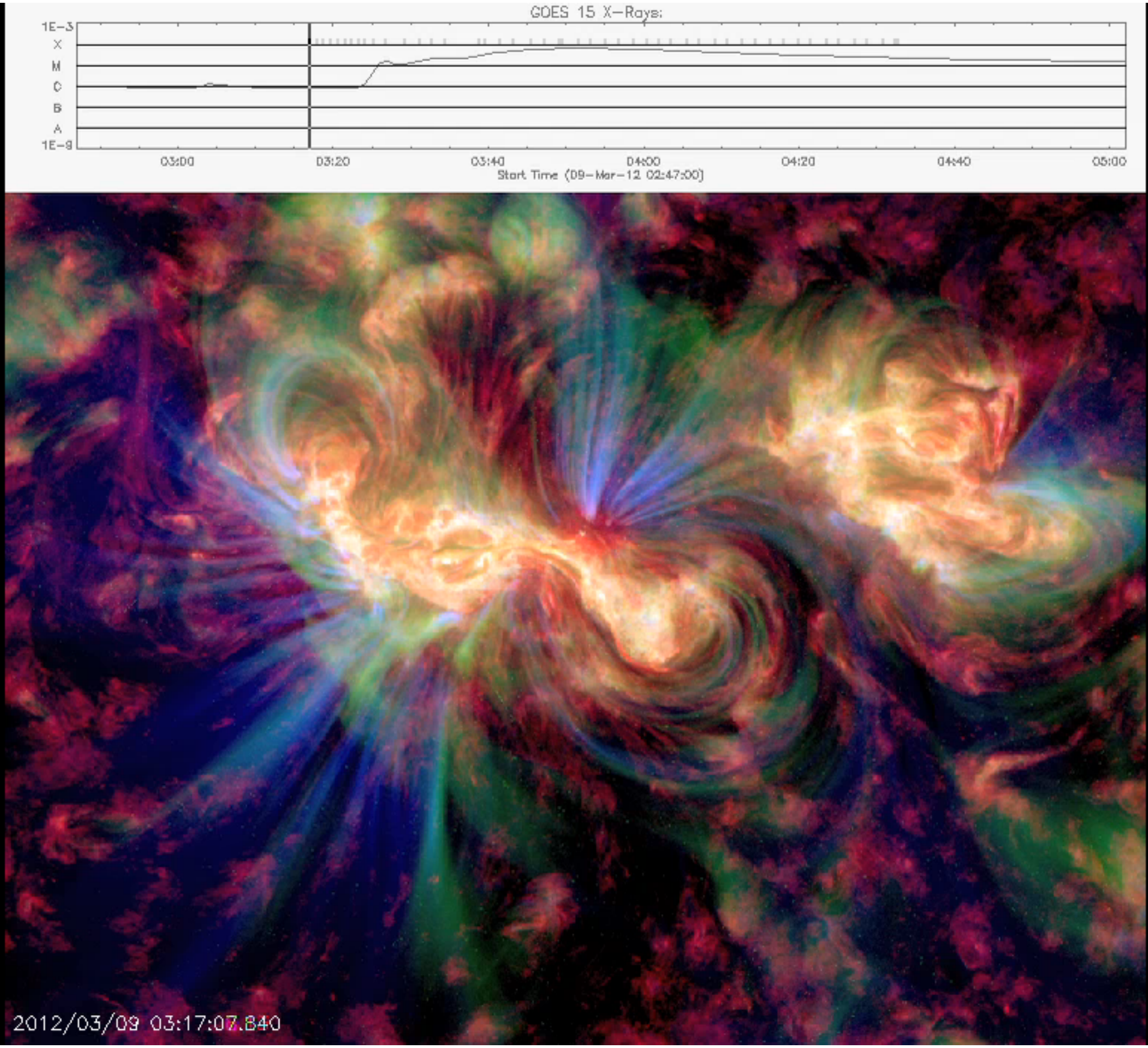


Zhukov & Auchère 2004

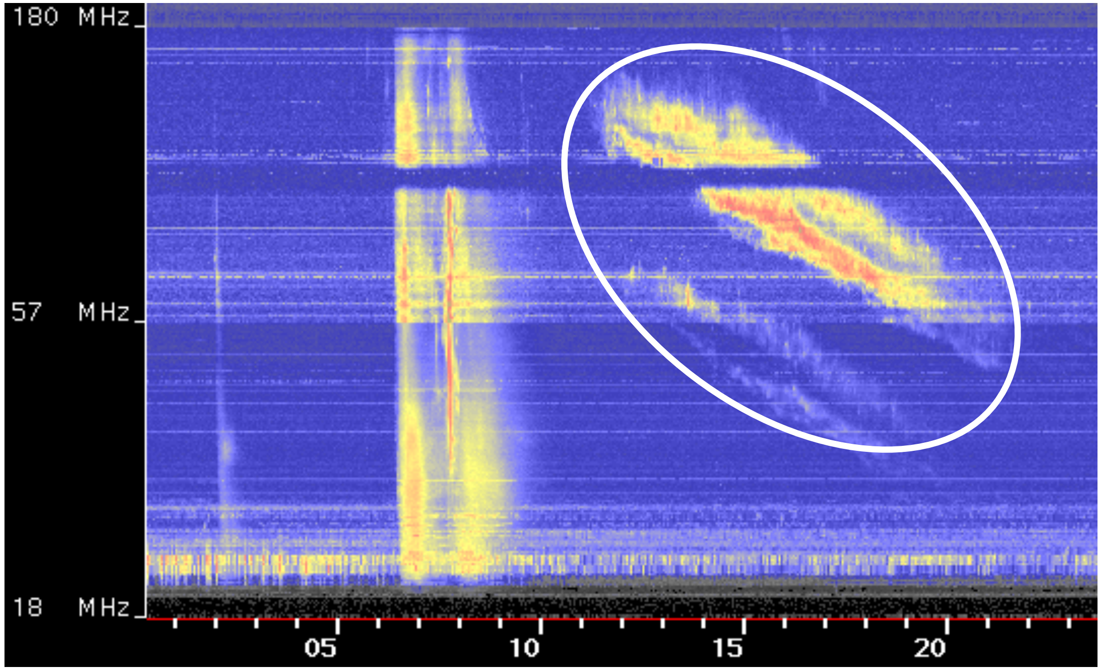
Dimming sometimes appears as a propagating wave-front

Mass removed is ~ same as average CME mass, but only 50% originates in the transient coronal holes.

Implosion and dimming



Coronal radio signature

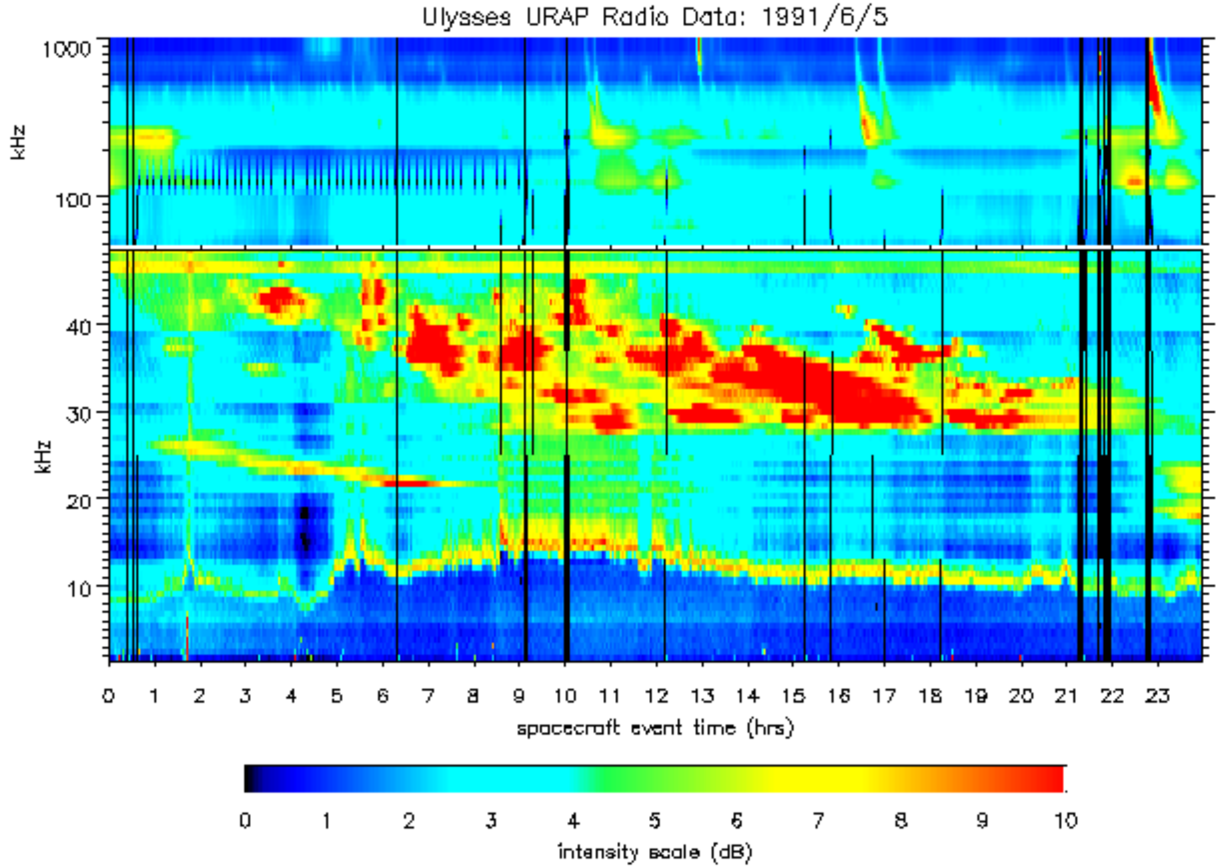


If CME front is super-Alfvenic, shock wave develops

Electrons accelerated at shock, stream away and produce Langmuir waves which convert to EM radiation.

Frequency = plasma frequency.

Interplanetary signature



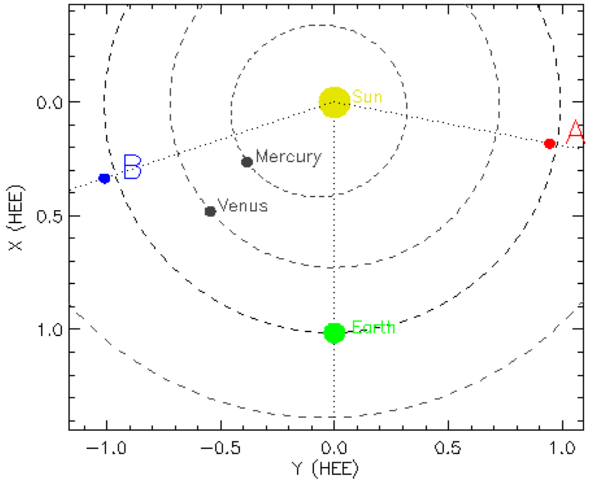
Low frequency CME radio emission is also observed directly in space.

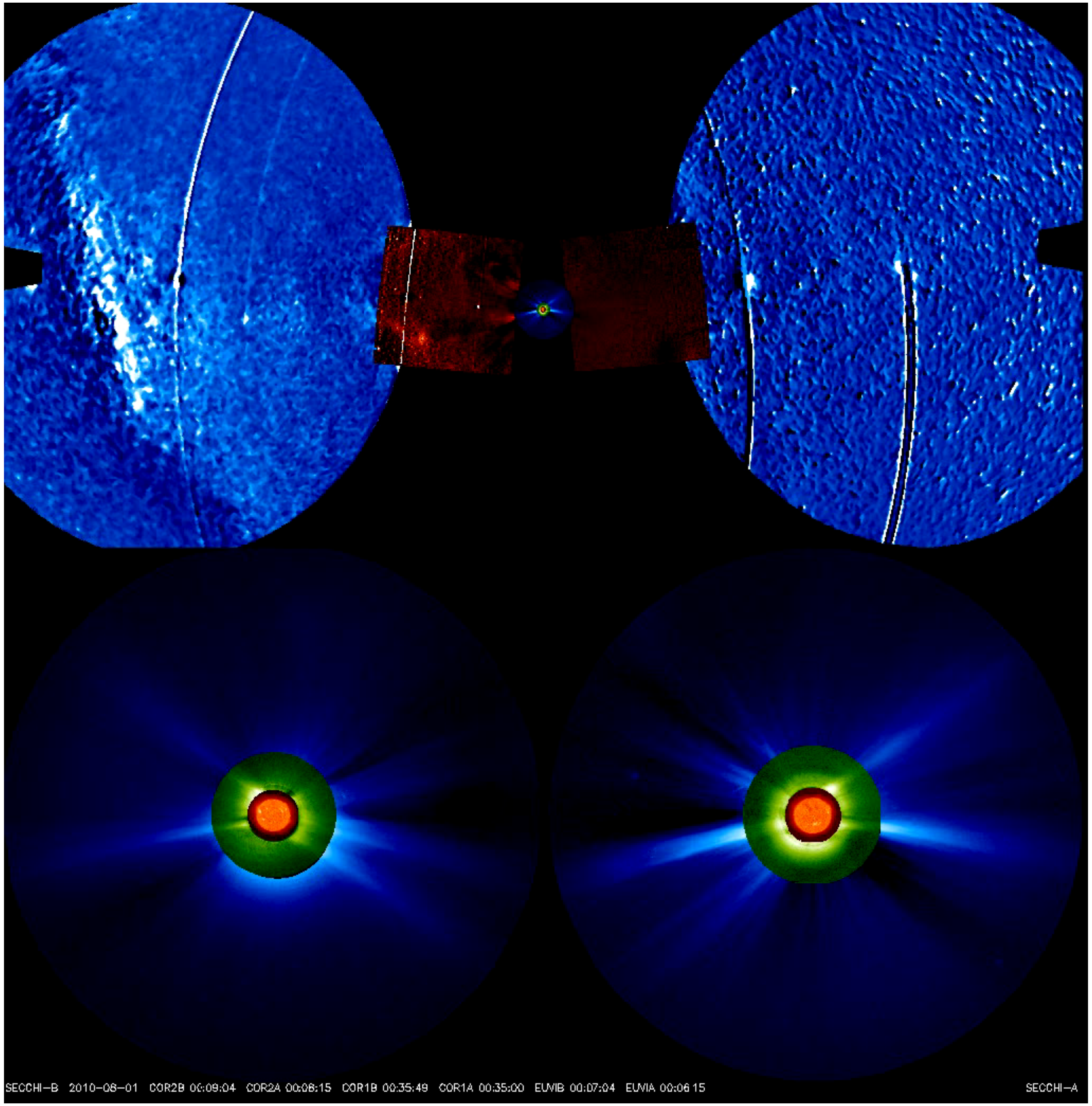
Effects on planets

Well-studied using in-situ field & particle data

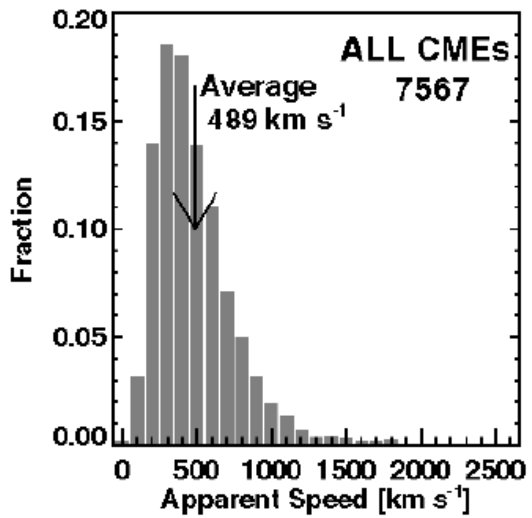
- Now with remote sensing too!

- STEREO A&B Heliospheric Imagers observe CMEs arriving at planetary orbits





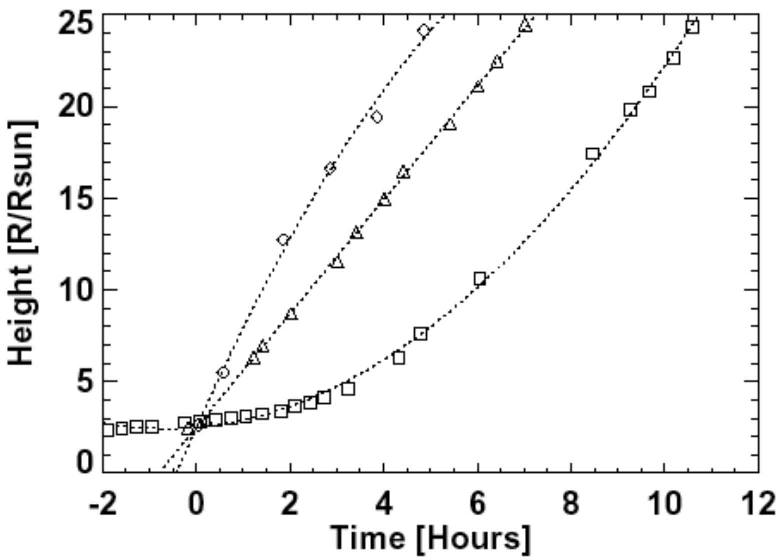
CME kinematics



Average speed ~ 500km/s

Faster CMEs (>1000km/s) always associated with flares

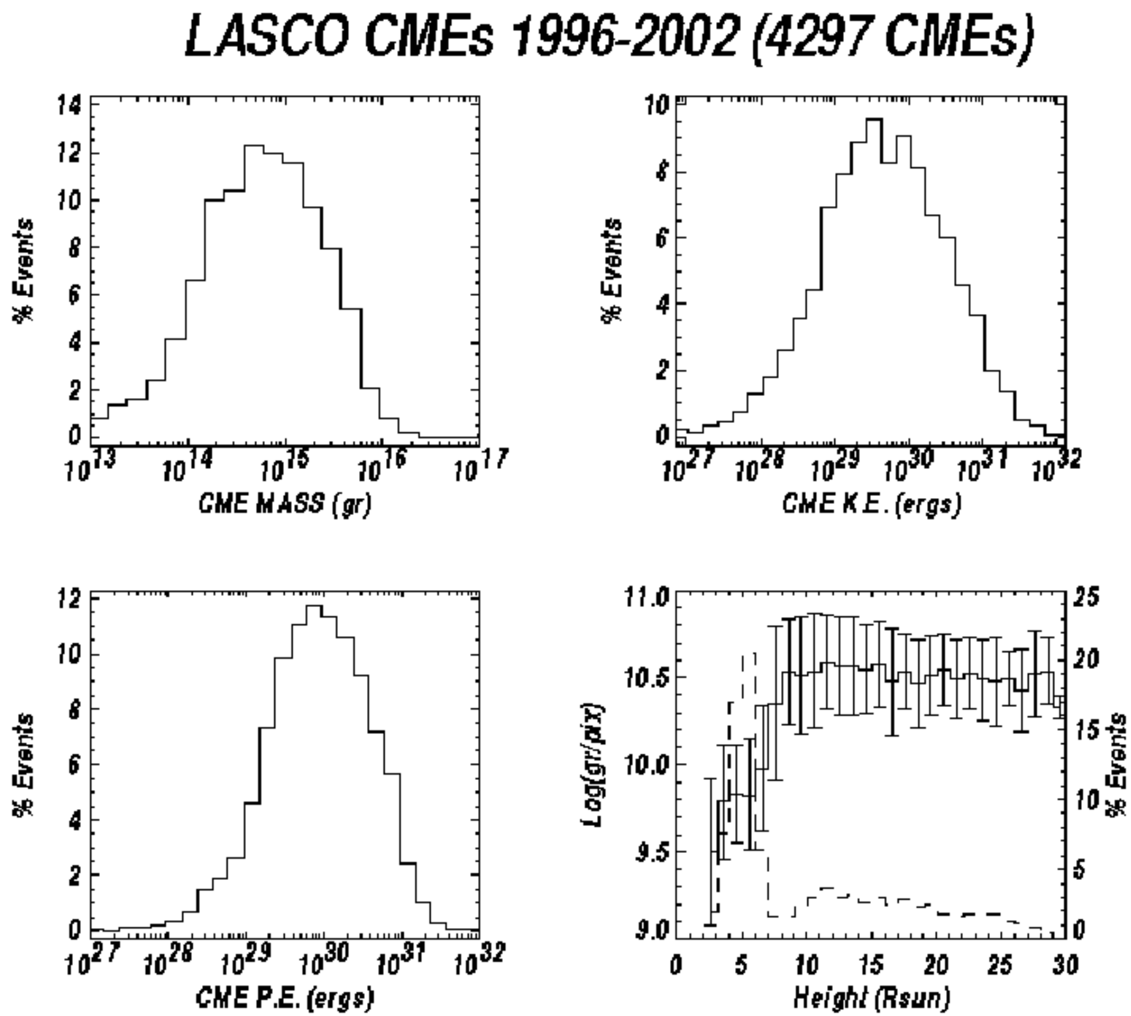
Gopalswamy et al. (2002)



Accelerating, decelerating and ~ constant velocity trajectories identified

- Slow CMEs accelerate
- Fast CMEs decelerate
- Due to drag of solar wind?

CME mass and energy



<u>Average quantities</u>:

mass ~ $10^{14} – 10^{15}$g

KE ~ 10^{29}-10^{30} ergs

PE ~ 10^{30} ergs

CME KE+PE is comparable to inferred particle and radiation energy of flare.

Energetics

Energy per component in units of $\log_{10}$ E (ergs)

	21 April 2002	23 July 2002
Primary Energy		
Magnetic	32.3 ± 0.3	32.3 ± 0.3
Flare		
Intermediate Energies (1)		
Electrons ($> E_{min}$)	31.3 ± 0.5	31.3 ± 0.5
Ions (> 1 MeV nucleon^{-1})	< 31.6	31.9 ± 0.5
Thermal Plasma ($T > 5$ MK)	$31.1^{+0.4}_{-1.0}$	$30.4^{+0.4}_{-1.0}$
Radiant Energy		
From *GOES* plasma	31.3 ± 0.3	31.0 ± 0.3
L_{total} (2)	32.2 ± 0.3	32.2 ± 0.3
CME		
Kinetic	32.3 ± 0.3	32.3 ± 0.3
Gravitational Potential	30.7 ± 0.3	31.1 ± 0.3
Energetic Particles at 1 AU	31.5 ± 0.6	< 30

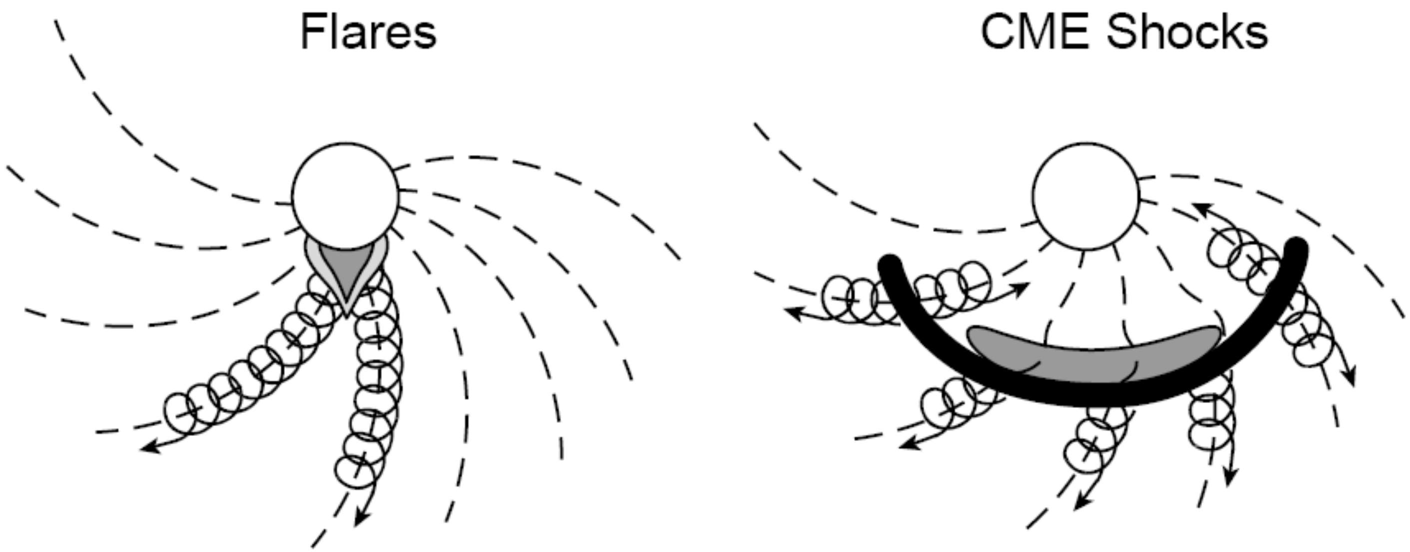
(1) E_{min} is largest value of low energy cutoff compatible with HXR spectrum.

(2) Assumes $L_{total}/L_x = 100$ (e.g. Kretschzmar 2011)

CMEs and solar energetic particles

Large solar eruptions producing high speed CMEs (1000-3000km/s) are the main source of energetic particles – protons, electrons and minor ions - in the solar system.

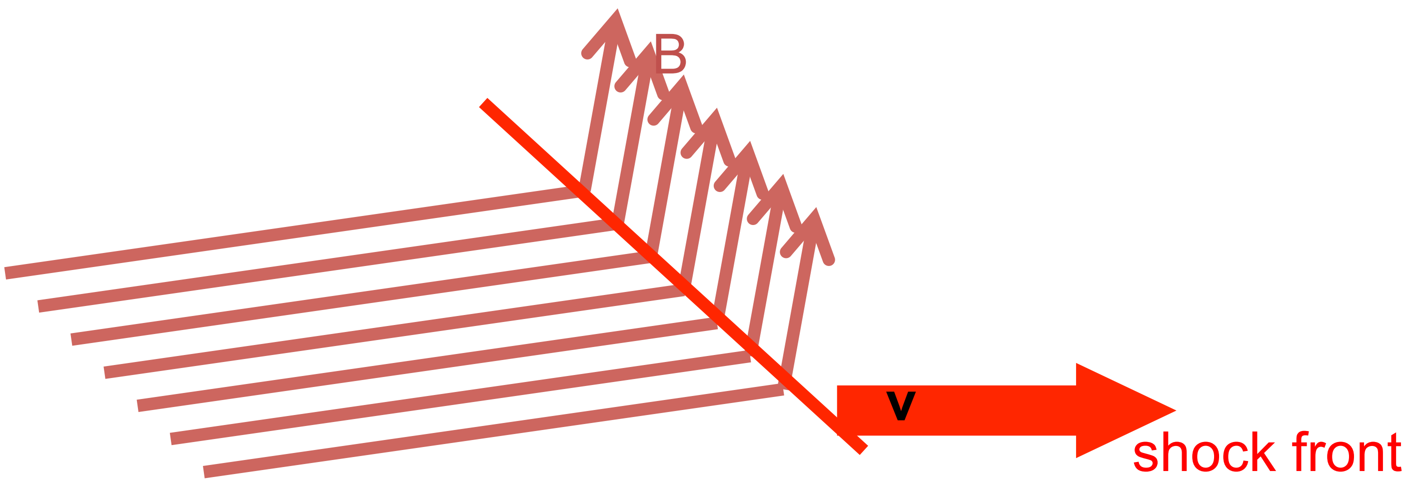
SEPs are accelerated both in flares (‘impulsive’ SEPs) and at CMEs (‘gradual’ CMEs)



Reames (1999)

Shocks

An MHD shock is essentially a bend in the magnetic field that is propagating faster than the upstream Alfven speed



The shock-jump conditions (Rankine-Hugoniot conditions) describe conservation of mass, momentum, energy across a (collisionless) shock

e.g.

$$\left[\rho v^2 + p + \frac{B_\perp{}^2}{2\mu}\right]_{upstream} = \left[\rho v^2 + p + \frac{B_\perp{}^2}{2\mu}\right]_{downstream}$$

(pressure continuity)

Particle acceleration at shocks

$$\left[\rho v^2 + p + \frac{B_\perp^{\ 2}}{2\mu}\right]_{upstream} = \left[\rho v^2 + p + \frac{B_\perp^{\ 2}}{2\mu}\right]_{downstream}$$

If fluid speed v is lower downstream, and gas pressure also lower (eg decreasing density medium) then $B_\perp$ is higher.

Also, $B_{||}$ constant across shock.

Conservation of first adiabatic invariant for particles crossing shock:

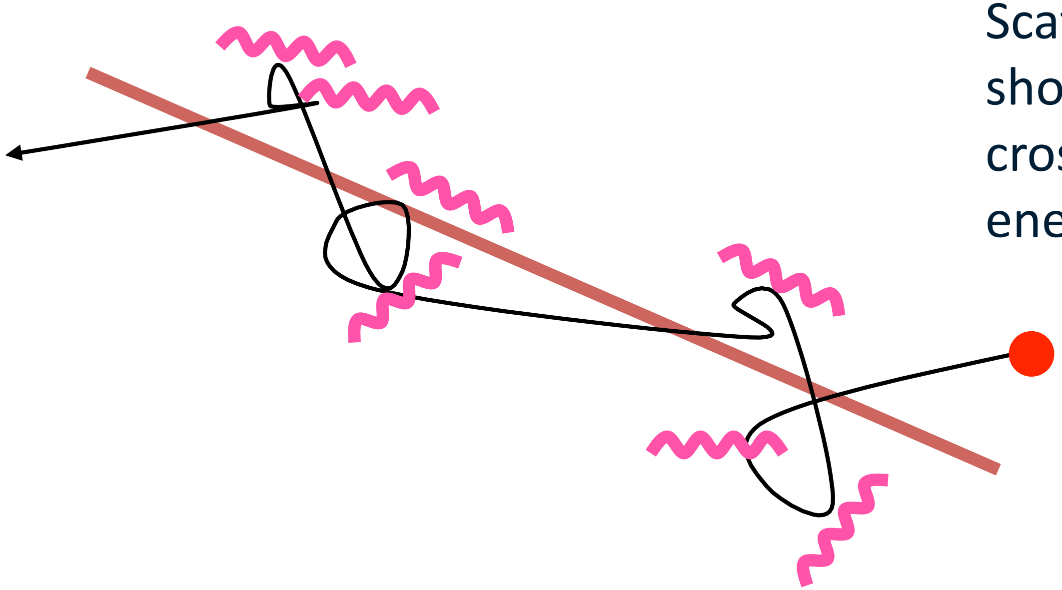
$$\frac{mv_\perp^{\ 2}}{B} = const$$

So particles crossing shock pick up perpendicular momentum. But not very much.

Diffusive shock acceleration

Ratio of magnetic field across a collisionless MHD shock < 4.

So particles don’t pick up much energy – unless they cross and recross field many times.



Scattering on each side of the shock front allows many shock-crossings, so particle picks up energy

Scattering is probably due to wave-particle interactions – acceleration can be described as a diffusion process.

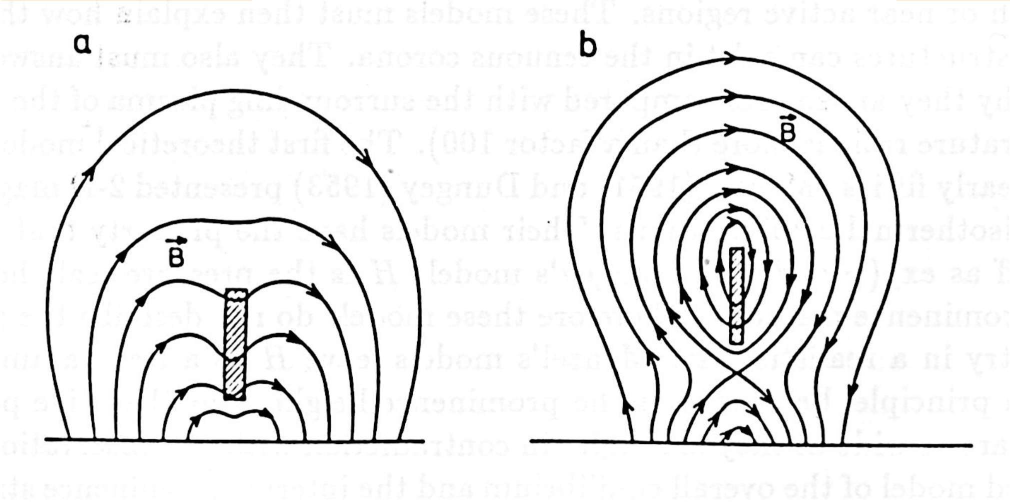
CMEs and flux ropes

CMEs are associated with the eruption of filament material, both in active region filaments and polar crown filaments.

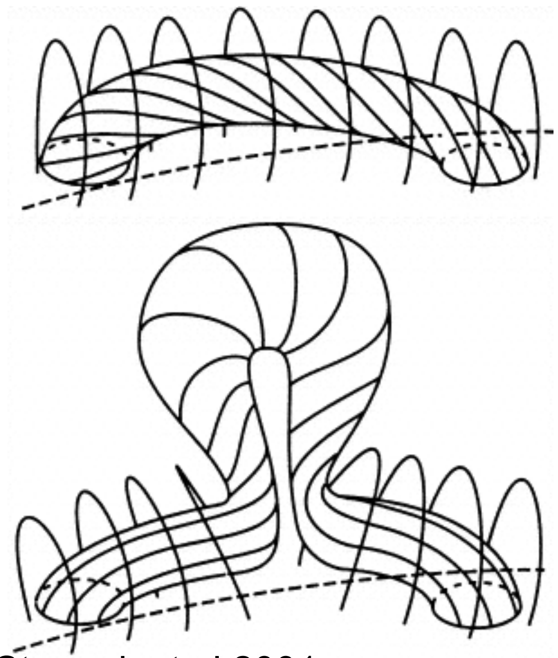
Support of cool, dense filament material in hot, tenuous corona calls for concave-up magnetic field

Two possibilities – ‘dipped’ or ‘twisted’ field lines (flux ropes)

2D-cut

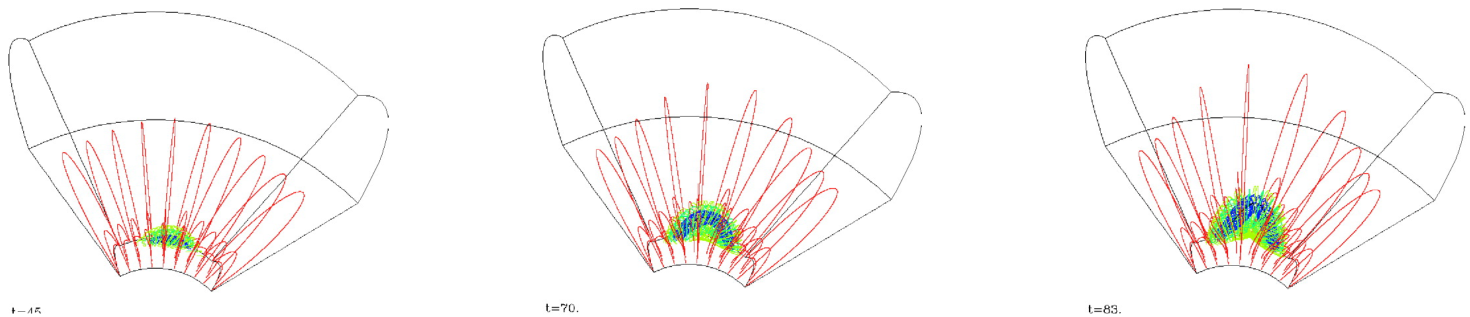


3D-sketch



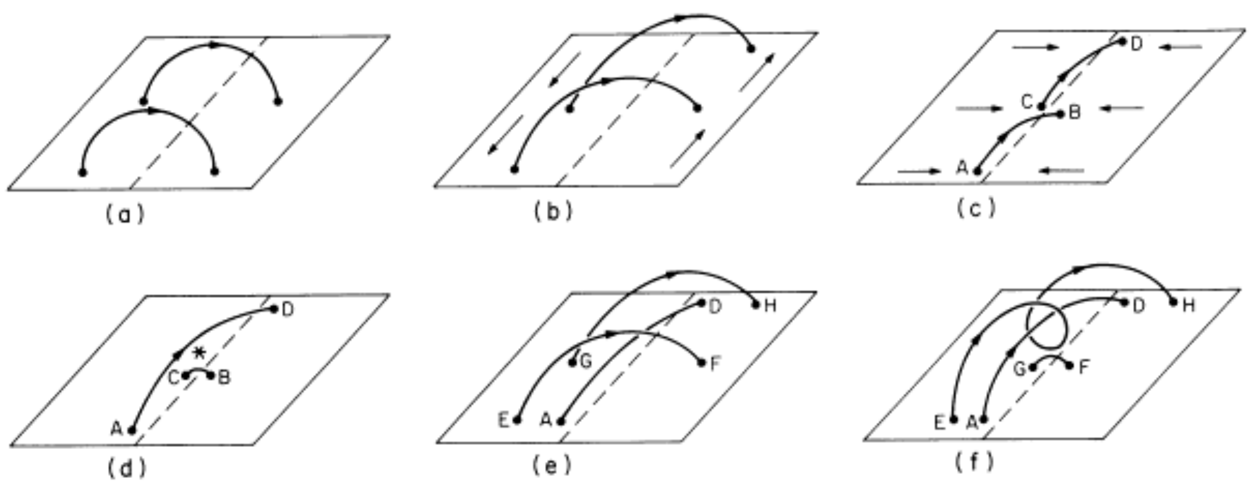
Sturrock et al 2001

Formation of coronal flux rope



Fan 2005

Alternatively – shearing of untwisted arcade could both generate and destabilise flux rope.

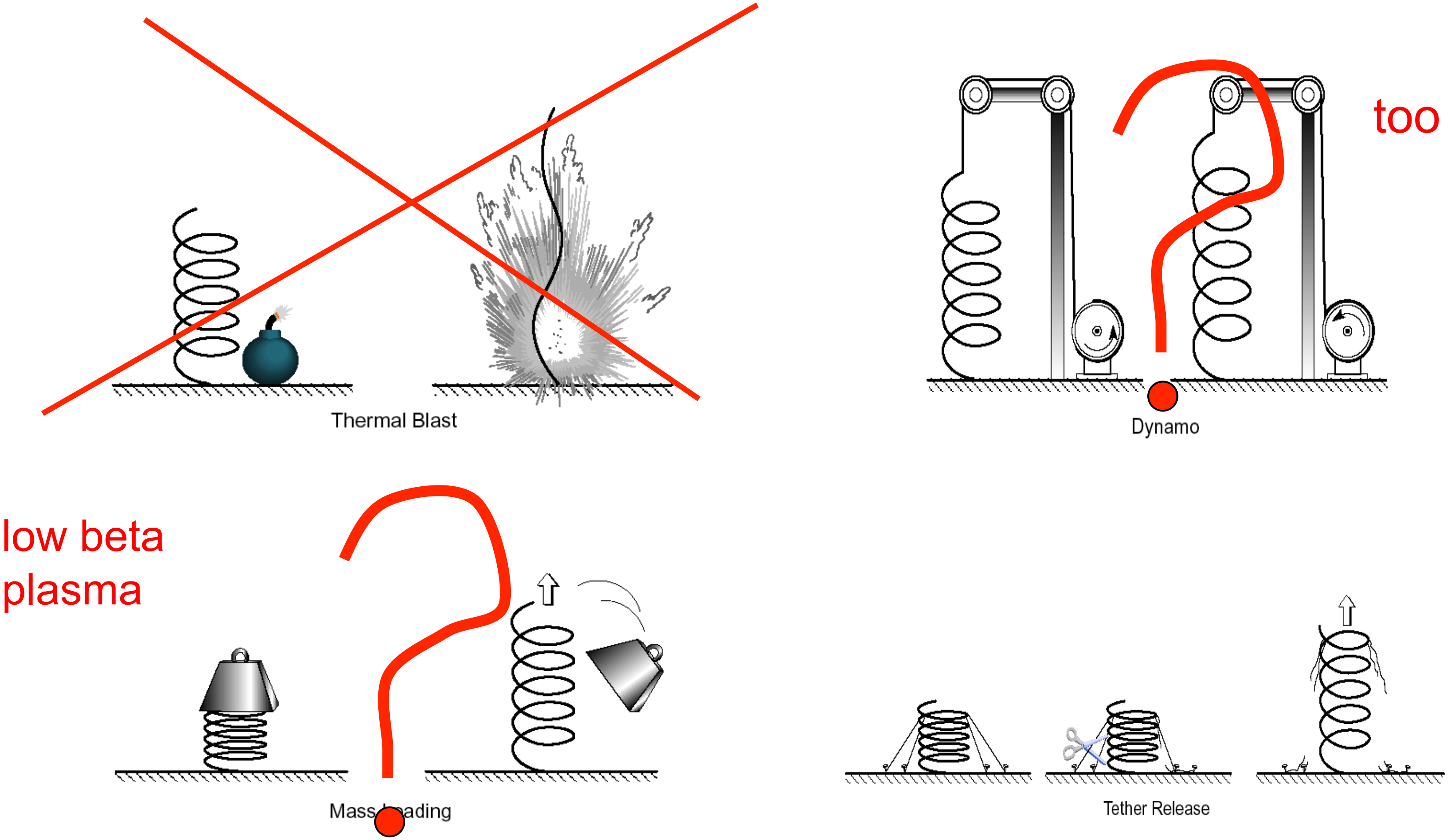


nb, not supported by active region measurements, but possible for polar crown filaments.

van Ballegooijen & Martens 1989

How is a CME eruption produced?

In a CME eruption the magnetised plasma (i.e. the magnetic field) explodes, 'inflates' or is stretched.



Mechanical analogues of CME theories - Klimchuk (2000)

University of Glasgow

Storage and loss of stability

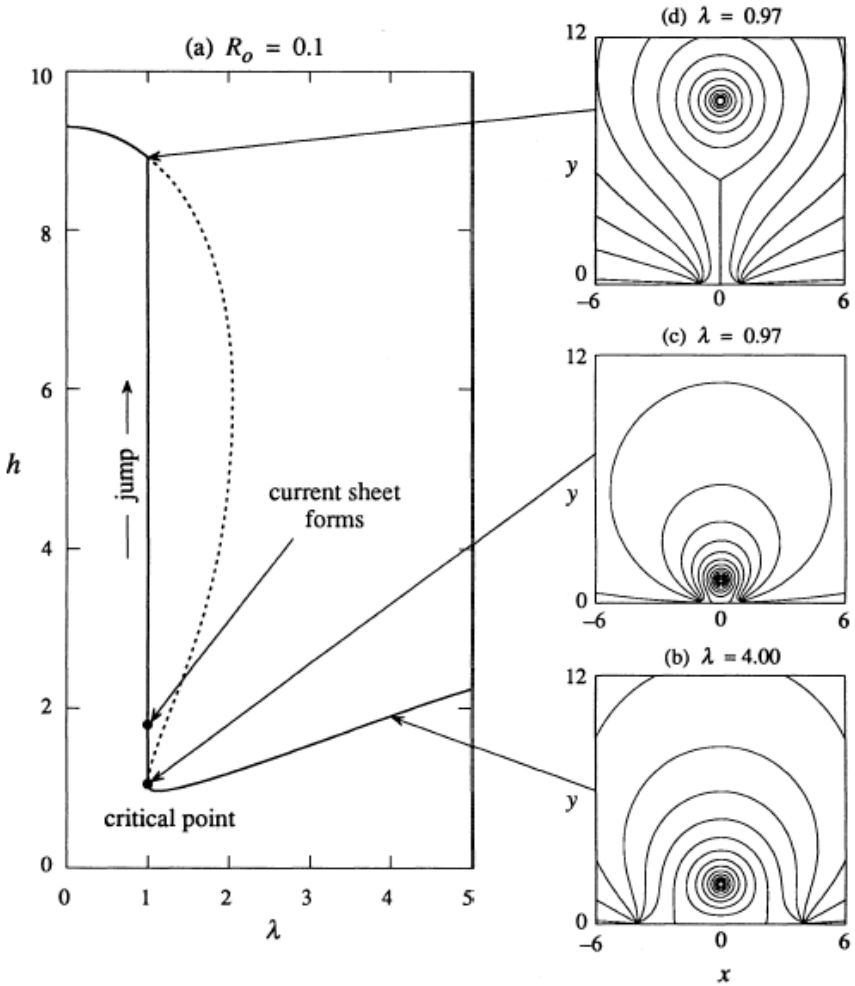
Balance between stored magnetic energy (twist) and external forces…

Hypothesis: energy is stored in the corona, in a twisted but stable configuration.

Loss of stability leads to CME - but there is no agreement about what leads to loss of stability.

- Purely ideal instability? (eg MHD kink, ballooning)
- Purely resistive? (e.g. reconnection)
- Hybrid – initially ideal and then resistive?
- Non force-free? (e.g. sudden draining of coronal mass?)

Ideal instability



Flux rope in corona, held down by overlying arcade.

Arcade footpoints driven together

At a critical value of the separation parameter l, the configuration jumps to a new equilibrium

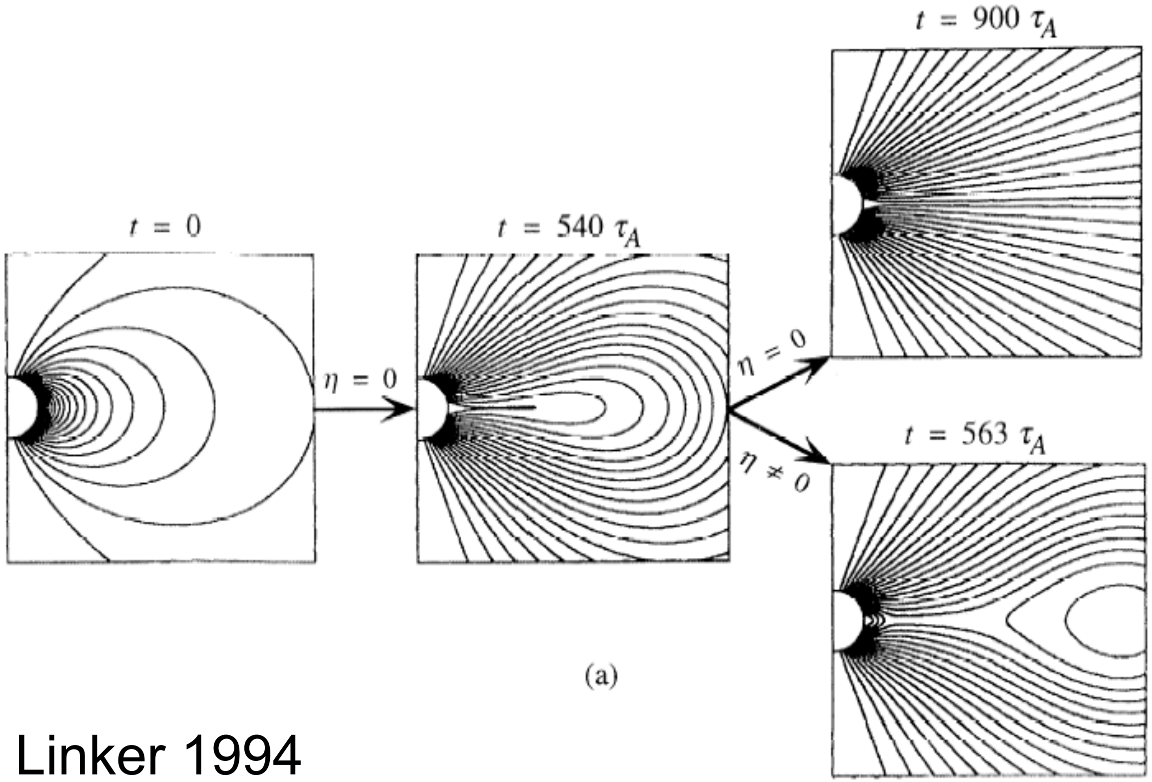
A current sheet forms – resistivity takes over.

Forbes & Priest 1995.

Resistivity

Resistivity must behave in a somewhat schizophrenic way

- η must be low and reconnection must be slow during driving phase.
- η must then suddenly increase to allow reconnection

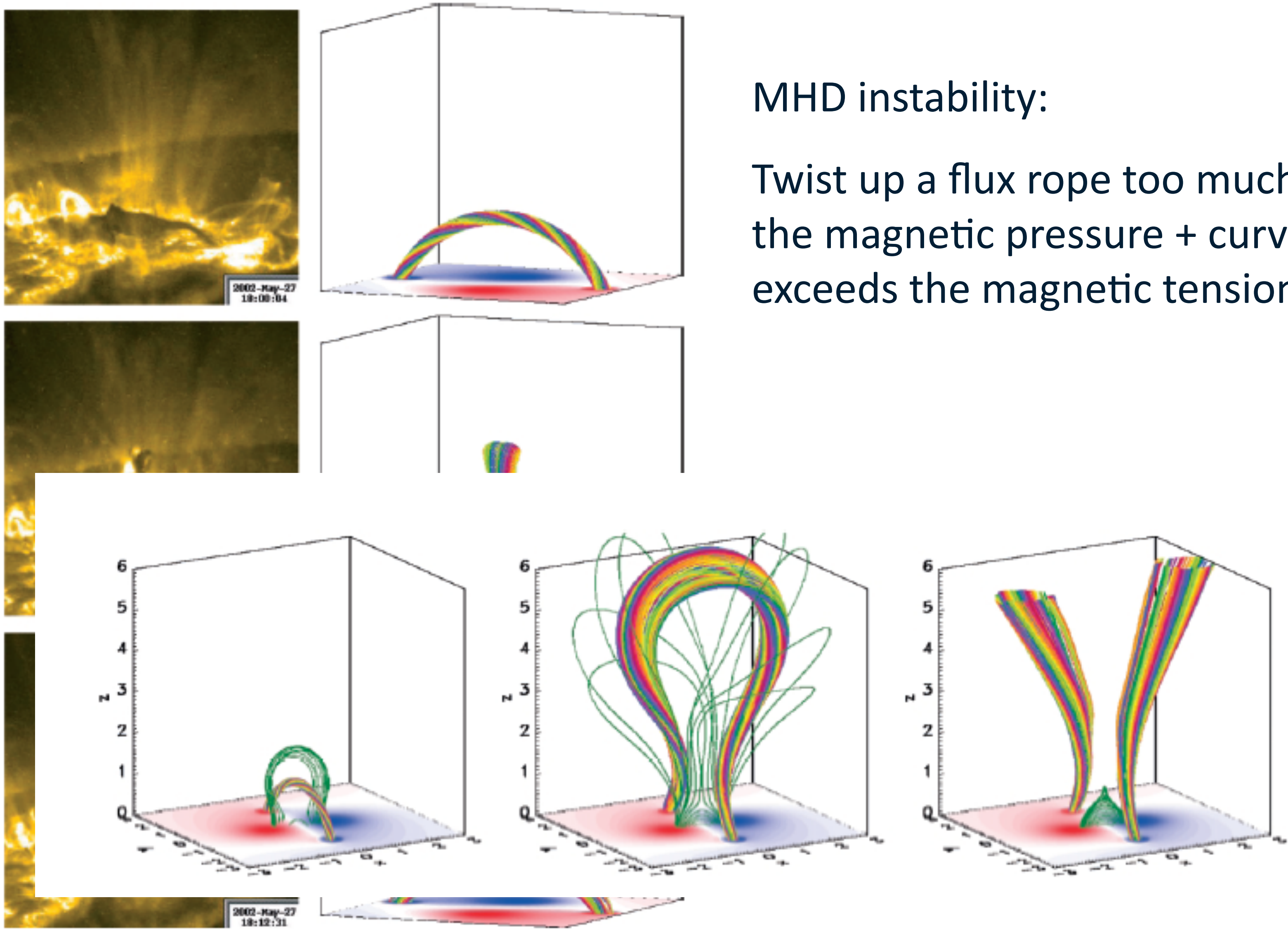


Resistivity stays low – no eruption

Resistivity increases - eruption

Mikić & Linker 1994

Kink instability



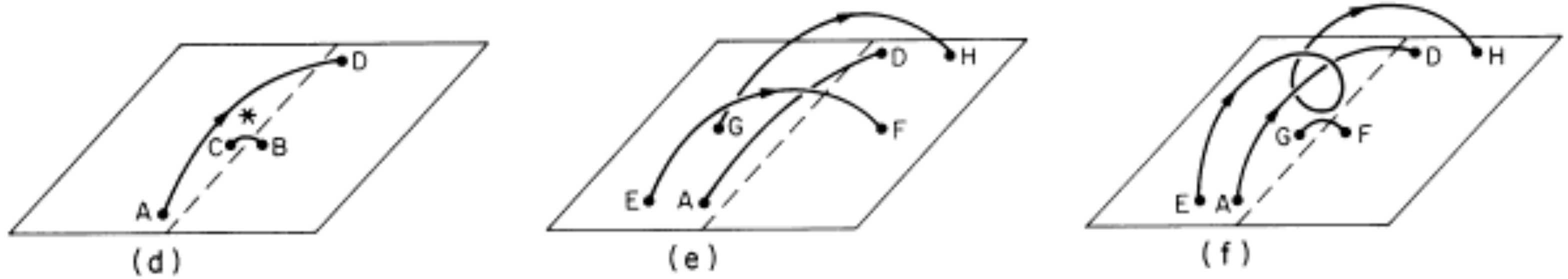
MHD instability:

Twist up a flux rope too much and the magnetic pressure + curvature exceeds the magnetic tension.

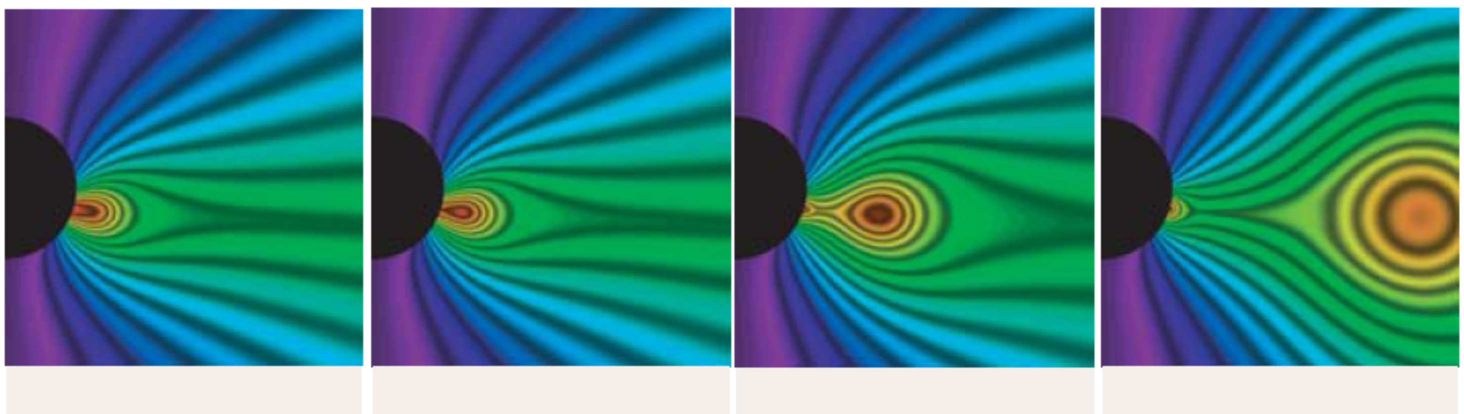
Török & Kliem 2005

Flux cancellation models

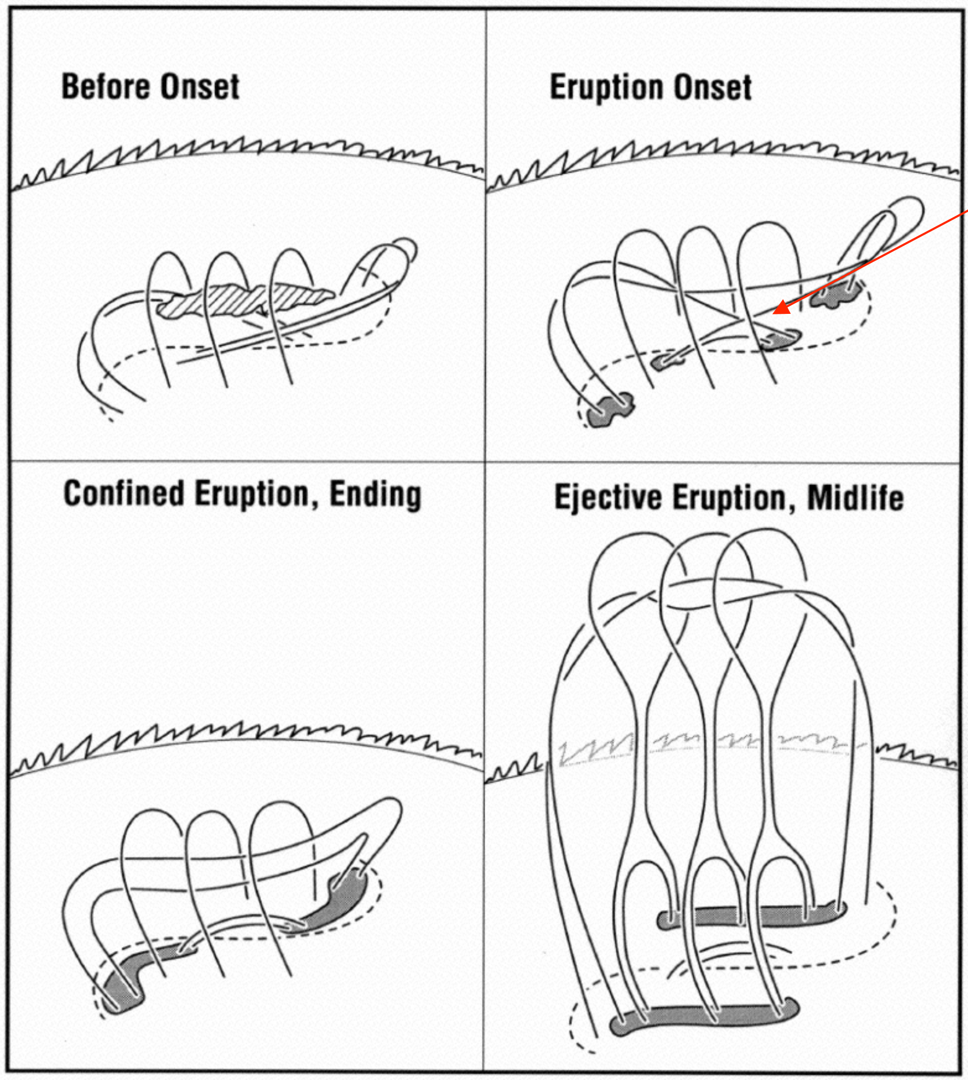
Flux cancellation is observed as the disappearance of magnetic flux near a magnetic neutral line, interpreted as reconnection.



Converts overlying 'restraining' field into twisted field of flux rope ⇒ external pressure decreases as flux rope expands.



Tether cutting models



Also proposes flux cancellation underneath filaments

This time filaments are part of an already twisted rope.

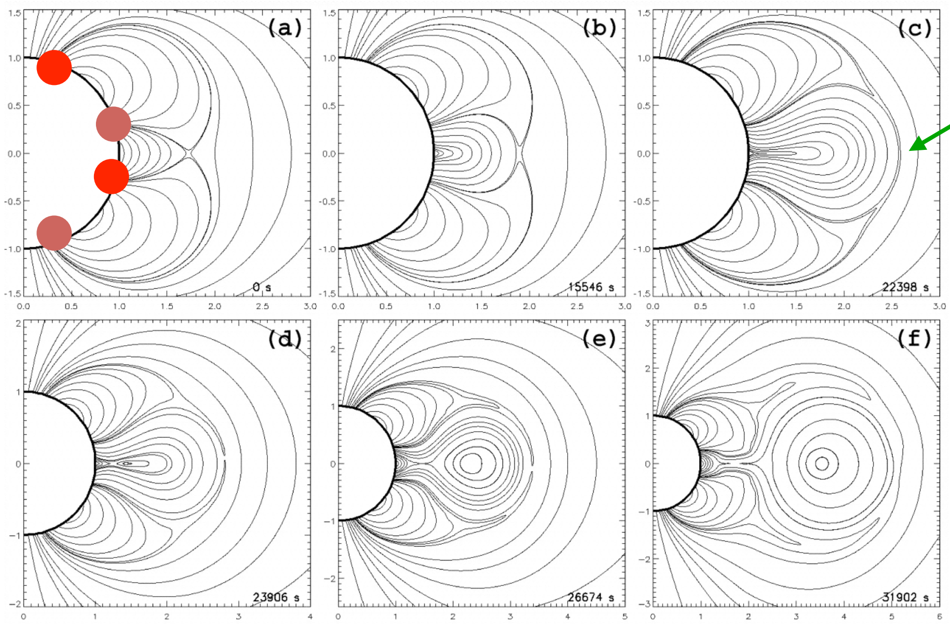
The reconnection cuts the restraining field, without adding significant twist to the configuration.

Moore et al.

‘Magnetic breakout’ model

This involves a quadrupolar field.

Shearing of an inner arcade causes it to expand and interact with overlying field, forming a current sheet.



reconnection occurs at sheet

removes overlying confining field.

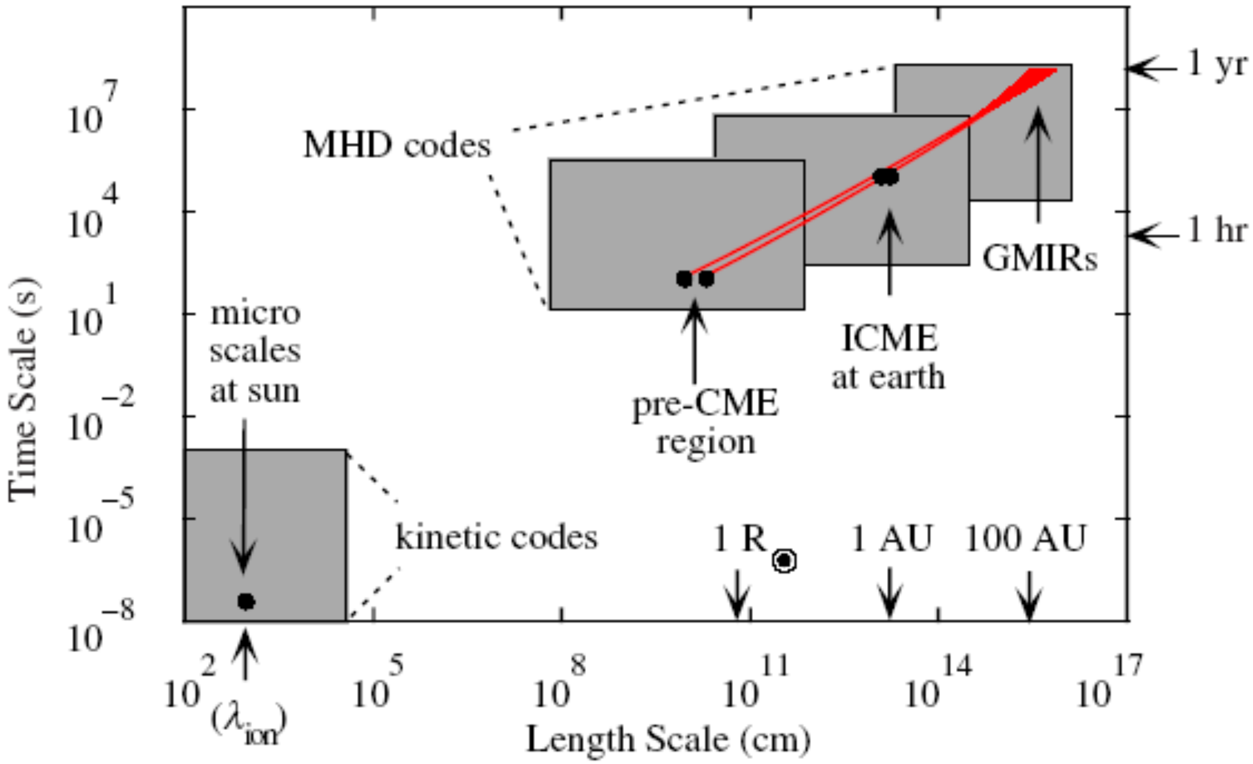
As inner field expands, sheet thins and elongates

So reconnection accelerates.

e.g. Antiochos 99, Lynch et al 2004

CME numerical modeling

Complete numerical modelling of the initiation and evolution of a CME requires a vast range of scales, and different modelling techniques.

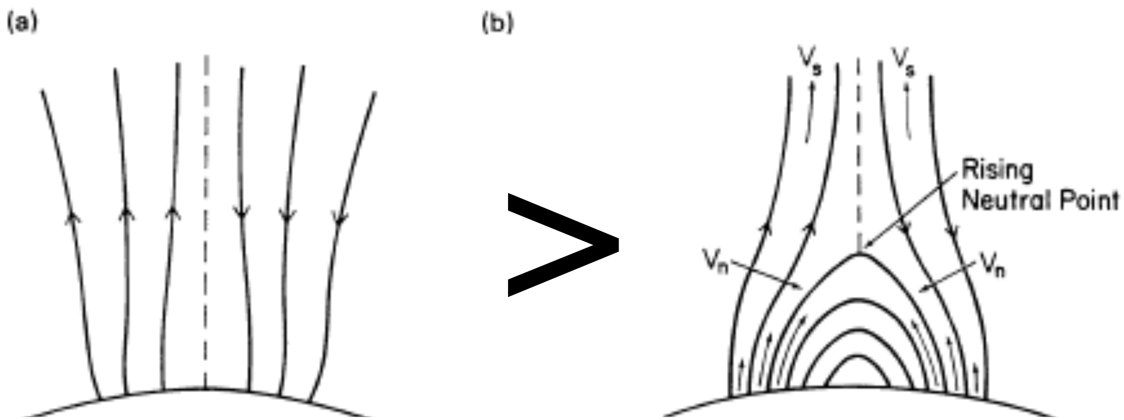


From Forbes et al. 2006.

The Aly-Sturrock Conjecture

CME hypothesis: energy to drive the CME comes from the free energy of the coronal magnetic field.

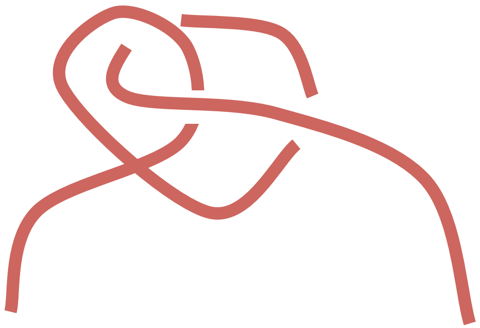
Aly+Sturrock: Fully open magnetic field, for a given lower magnetic boundary condition, always has higher energy than the corresponding (simply-connected) force free field.



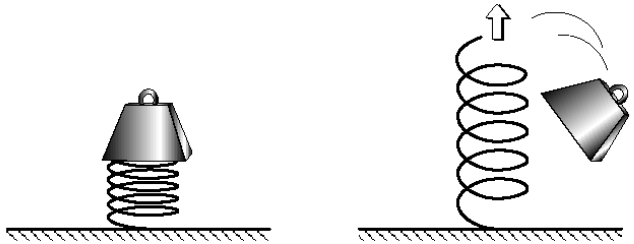
Problem: fully opening the field for a CME requires more energy than is stored in the pre-CME force-free field.

Possible solutions to the A-S puzzle

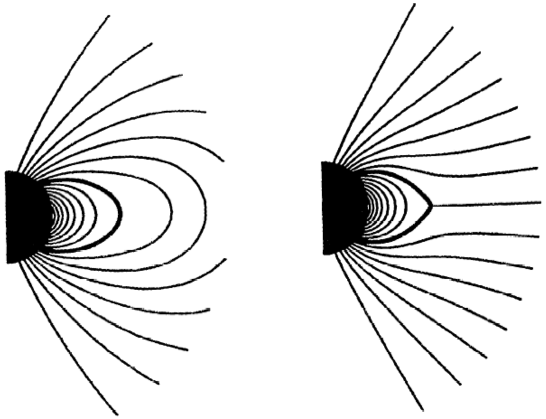
Pre-eruption field is not simply connected



Pre-eruption field is not force-free

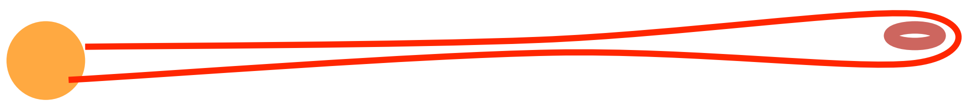


Field does not completely open



Wolfson + Low 1992

Field extends but does not open



The Jury is still out…

Closing thoughts

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Solar flares and CMEs affect all layers in the solar atmosphere and interplanetary space, and produce radiation and particles right across the spectrum.

Understanding them requires plasma physics at all scales, as well as nuclear and atomic physics, radiative transfer… etc

Some formidable general challenges ahead, e.g.:

- How do we use new, expensive facilities to answer our questions?
- How do we tie together the MHD (global) and kinetic (local) scales?
- How do we extend our mostly 2D 'cartoons' into realistic 3D models?

Answering these will also involve the detailed plasma physics which has been painfully learned in lab and magnetospheric plasmas

…take every opportunity to learn about these other fields!