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SOLAR FLARES AND CORONAL MASS EJECTIONS

Lyndsay Fletcher
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Big picture

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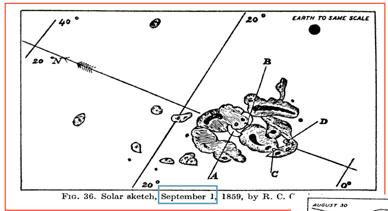
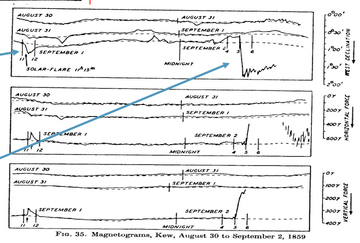
Historical flare observation



Carrington 1859

'White Light' flare



Prompt 'sudden ionospheric disturbance' (ionisation by flare UV radiation)

followed by CME arrival

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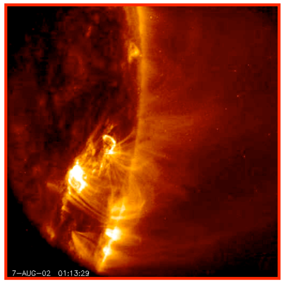
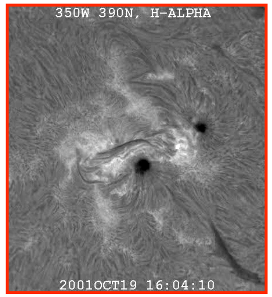
Two flares

Compact flare



TRACE 171A

2-ribbon flare



BBSO Hα

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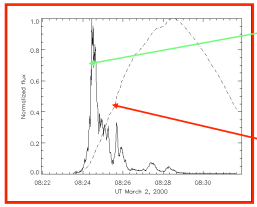
Flare time profile



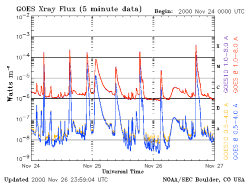
Impulsive phase - energy release
- Hard X-rays (10s of keV)
- Duration ~ 5 minutes to 1 hour
- Bursty time profile (t_{acc} ~ seconds)

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

GOES flare classification scheme

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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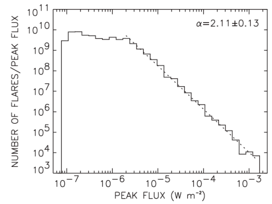
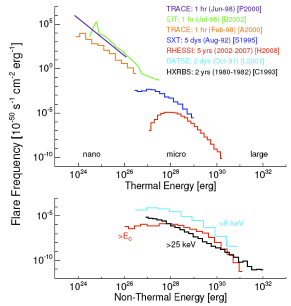
Distribution of flare sizes

Flare frequency as a function of peak GOES flux, and of energy is distributed as a power law.



Veronig et al. (2002), approx 49,000 flares (nb, GOES flux has not been background subtracted)

Q. Why do all these distributions flatten off?



From Hannah et al (2009), study of small flares.

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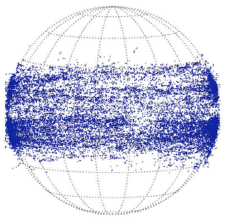
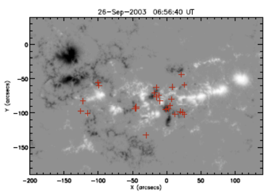
Distribution of flare locations

Solar flares occur almost exclusively in active regions, usually having sunspots (CMEs can occur outside active regions).





L: Distribution of RHESSI small flare locations across the Sun (Christe et al 2007) and R: locations of RHESSI microflares during one day (Stoiser et al)

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Flare energy budget

Estimates made by Emslie et al. (2004, 2005) show that a significant fraction of total flare energy appears in fast particles

Table 3. CME/Flare Energy Budgets for the 21 April 2002 and 23 July 2002 Events

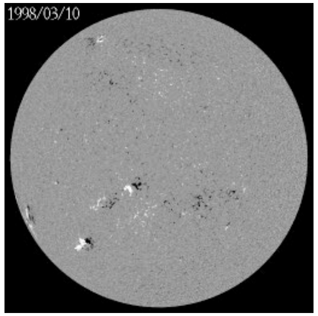
Mode	Symbol	$\log_{10}$ (Energy, erg) 21 April 2002	23 July 2002
Magnetic	U_B	32.3 ± 0.3	32.3 ± 0.3
Flare			
Thermal plasma, $T > 10$ MK	U_{th}	$31.3^{+0.4}_{-1}$	$31.1^{+0.4}_{-1}$
Nonthermal electrons	U_e	$31.3^{+?}_{-0.5}$	$31.5^{+?}_{-0.5}$
Nonthermal ions, >1 MeV $nucleon^{-1}$	U_i	<31.6	31.9 ± 0.5
CME			
Kinetic	U_K	32.3 ± 0.3	32.0 ± 0.3
Gravitational potential	U_Φ	30.7 ± 0.3	31.1 ± 0.3
Energetic particles at 1 AU	U_p	31.5 ± 0.6	<30

above 20 -40keV

Source of flare energy

Energy is imparted to the coronal magnetic field at or below photosphere.

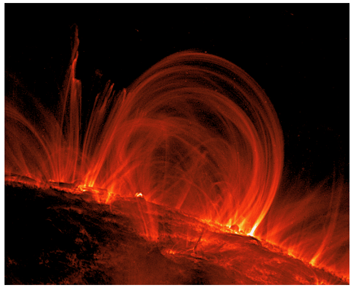
magnetic field evolution from SOHO/MDI



Photosphere is a high beta plasma, so gas pressure forces dominate.

Coronal loops

Coronal active region loops, on the other hand, are low beta structures in which the magnetic pressure dominates.



Each narrow strand can be considered as a mini-atmosphere (though probably not in hydrostatic equilibrium).

Q. Why do these loops look so narrow?

Energy storage as currents

MHD version of Ampère's Law

$$j = \nabla \times B / \mu$$

Twisting the field produces 'free energy' in the form of current.

MHD Force balance equation

$$-\cancel{\nabla p} + \vec{j} \times \vec{B} + \cancel{\rho \vec{g}} = \rho \cancel{\frac{D\vec{v}}{Dt}}$$

Assume ~ steady state, with negligible gravitational forces and pressure gradients (low beta corona). Then

$$\vec{j} \times \vec{B} = 0$$

Force-free condition, i. e. field and current are aligned

So $(\nabla \times \vec{B}) \times \vec{B} = 0$, meaning $\nabla \times \vec{B} = \alpha \vec{B}$

α constant along field lines

The source of current

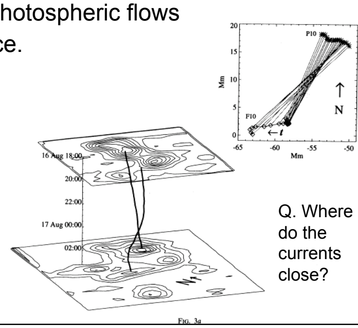
Does the magnetic field emerge already bearing free energy?

From vector B measurements, Leka et al. (1996) determined the curl of the magnetic field in an emerging active region

They also measured the photospheric flows during and after emergence.

AR twists too large to be generated by the photospheric flows.

So the field emerges from the convection zone *already carrying current*.



Q. Where do the currents close?

Extrapolations and 'free energy'

With the two equations for B,

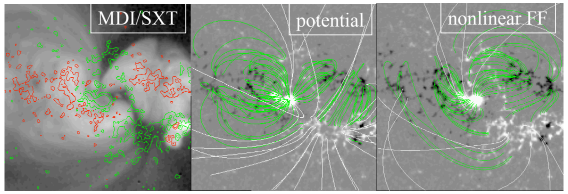
$$\nabla \cdot \vec{B} = 0 \qquad \nabla \times \vec{B} = \alpha(x, y)\vec{B}$$

and suitable boundary conditions, one can calculate B through the corona in different limits:.

$\alpha = 0$: 'potential' field. There are no currents

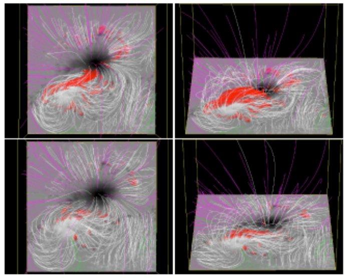
$\alpha = \text{const}$: linear force-free field. j= αB

$\alpha \neq \text{const}$: non-linear FFF



Location of free energy

Using Hinode vector magnetic data and the best available field extrapolation tools, the most likely location of the pre-flare currents can be calculated.



Schrijver et al 2008.

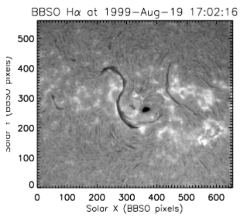
Result – pre - flare currents concentrated *low in the corona* (< 12000 km above photosphere) and *near to neutral line*

Q. Roughly what is the plasma beta in the corona of an active region?

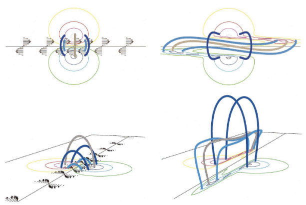
Filaments

Filaments (known as prominences on the limb) are cool, dense material overlying magnetic neutral lines.

Clearly seen in absorption in Hα line on disk (and in emission on limb)



Gibson et al. (2002)



DeVore & Antiochos (2000)

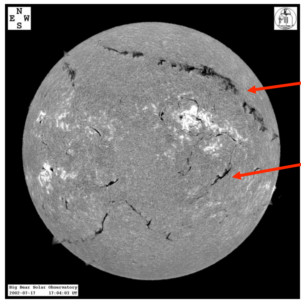
Dipped field lines may be formed by shearing magnetic field

Preflare activity

Most Reliable sign that a flare will happen - The rise/darkening/expansion of an AR Hα filament minutes to hours before flare (Svestka 1976, Martin 1980)

Filaments are dense, cool gas suspended in the corona.

The slow filament rise probably indicates the onset of an *MHD instability.*



polar crown filament

active region filament

movie movie

Q. What force supports a filament against gravity?

Can flares be forecast?

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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

Recently:

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

Flare precursors?

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Are there any other signs that a flare is going to happen?

Other pre-flare phenomena include:

- Small UV/EUV 'twinkles' (Moore & Sterling, Warren & Warshall)
- Small GOES events and preheating
- "Sigmoid" magnetic configuration (Hudson & Sterling)
- Early hard X-ray coronal sources (Lin et al.)
- Moving blueshifted Hα events (Des Jardins & Canfield 2003)

But none of these is unique to flares

Coronal sigmoids

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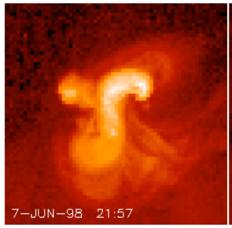
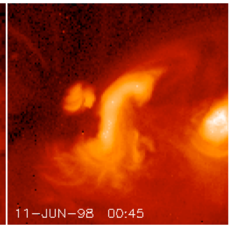
So-called for their 'S' shape (in the Northern Hemisphere)

Visible in soft X-rays (e.g. by Yohkoh/SXT and now GOES SXI)





pre-flare sigmoid observed by Yohkoh Soft X-ray Telescope

post-flare configuration – cusp shows that an eruption has happened.

RHESSI preflare sources

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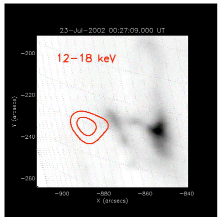
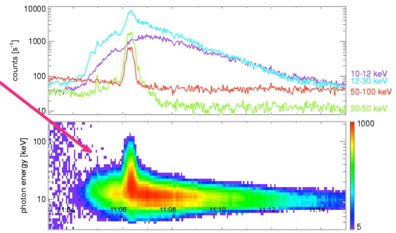
RHESSI often observes X-rays at ~ 10-20 keV, several minutes before the impulsive phase.





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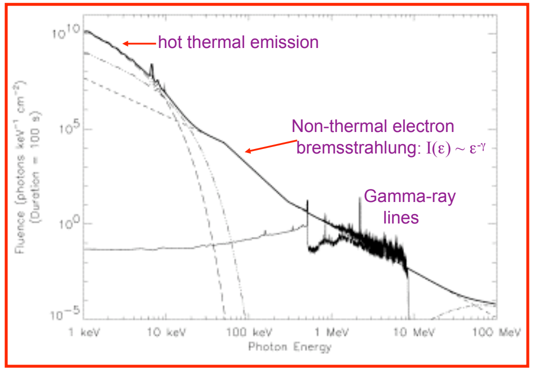
Impulsive phase high energy spectrum



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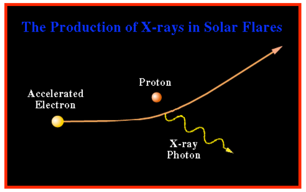
X-rays

X-rays observed are electron-proton bremsstrahlung from energetic electrons (> 15keV)



$$I(\epsilon) = \frac{1}{4\pi R^2}\bar{n}V\int_\epsilon^\infty \bar{F}(E)Q(\epsilon, E)dE,$$

Photon spectrum — electron spectrum

- Thermal bremsstrahlung: $E_{electron}$ ~ E_{target} and spectrum F(ε)~ $e^{-\epsilon/kt}$
  - Primarily coronal.
- Non-thermal bremsstrahlung: $E_{electron}$ >> E_{target} and spectrum F(ε)~$\epsilon^{-\gamma}$
  - Primarily chromospheric 'thick target' (electron slows as it radiates)
  - Very inefficient: ~ 10^{-5} of the electron energy radiated as X-rays.

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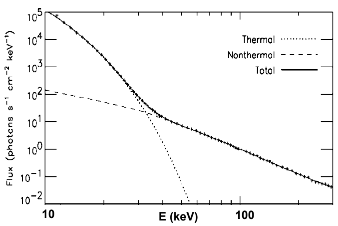
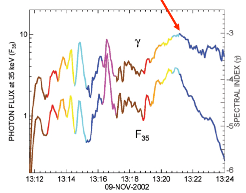
X-ray spectrum

- In impulsive phase, HXR spectrum can be fitted by a hot (20MK) or superhot (~60MK) thermal component plus a power-law $F(E)=F_o E^{-\gamma}$.
- Parameters of fit are correlated and vary during flare.
- *Microflares* also show thermal + power-law spectrum.



Typical spectral fit, Holman et al (2003)



Variation of fit parameters during a flare, Grigis & Benz (2005)

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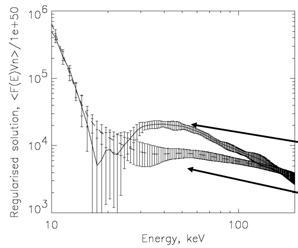
Alternative to fitting – spectral inversion

Photon spectrum I(ε) is integral of source-averaged electron spectrum

$$I(\epsilon) = \frac{1}{4\pi R^2}\bar{n}V\int_\epsilon^\infty \bar{F}(E)Q(\epsilon, E)dE,$$

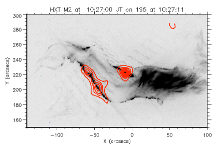
If Q is known, the integral can be inverted (i.e. differentiated) to recover source-averaged spectrum (Kontar et al. '03, '06).



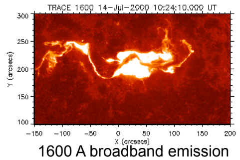
Inversion is model independent - allows subtle effects to be seen

Flare ribbons and footpoints

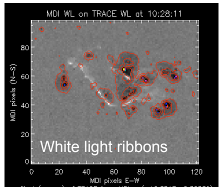
During the impulsive phase bursts of γ-rays hard X-rays, UV/EUV, H_α and (sometimes) optical emission show excitation of the low atmosphere



HXR footpoints on 195A emission



1600 A broadband emission

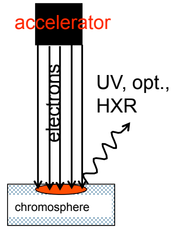


Optical/UV/EUV emission from heat deposition / ionisation / collisional / radiative excitation

Chromospheric electrons: standard model

Accelerated electrons originate in corona.

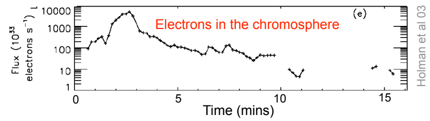
Electron beam travelling along coronal **B** carries flare energy to chromosphere



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

Photon spectrum

Source-averaged electron spectrum



July 23 2003

10^{35} - 10^{36} electrons/s accelerated. Coronal $n_e = 10^9$ cm^{-3}, so each second, all electrons in V = 10^{26} - 10^{27} cm^3 accelerated.

Electron current, and return current

Standard model **beam rate** is ~ 10^{36} el. s^{-1} (leaving corona)

Beam area from HXR and optical is < 10^{17} cm^2

Beam flux ~ 10^{19} el. cm^{-2} s^{-1}

Beam speed v_{beam} ~ 1-2 × 10^{10} cm s^{-1} (e^- at 30-100 keV)

Beam density n_{beam} ~ few × 10^8 cm^{-3} (large fraction of n_{corona})

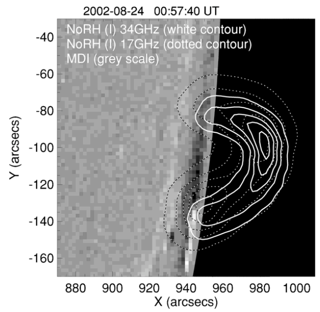
Self field ~ 10^8 G (~ 10^5 - 10^6 x ambient)

Return current $n_{beam}v_{beam} = n_{corona}v_{rc}$

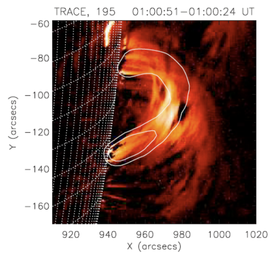
So v_{rc} ~ few × 10^9 cm s^{-1}

$c_s = 3\times10^7$ cms^{-1} and $v_{th,e}$ ~ 1.2 ×10^9 cm s^{-1} ➔ instability.

Flare gyrosynchrotron



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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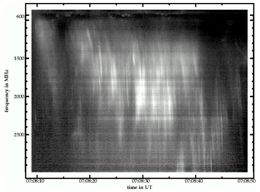
Coronal Radio Emission

Metric and decimetric Type III bursts are plasma radiation produced by electron beams (mode-conversion of Langmuir waves). Emission at plasma frequency:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}} = 2\pi\ 90\sqrt{\frac{n_e}{10^8 cm^{-3}}}\quad [MHz]$$

Upward and downward-going beams observed

Occur at peak time of HXR emission. Detailed radio/HXR burst-to-burst time-correlations improve at higher starting frequency (Benz et al '05)



Non-linear coherent emission ⇒ electron number estimates difficult.

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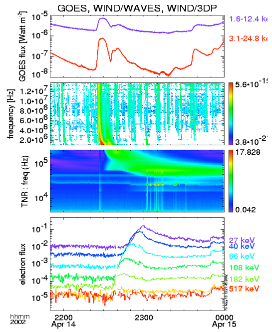
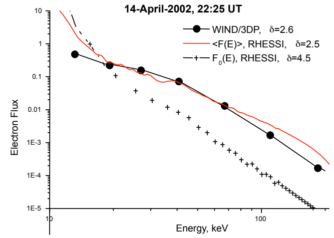
In situ measurements

Some hard X-ray events also have counterparts observed by particle detectors in space (e.g. 14 Apr 2002, Krucker et al, 2003)

In situ electron fluxes do not agree look like electron fluxes deduced from RHESSI





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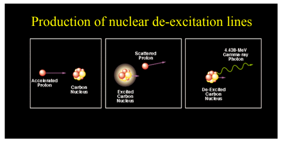
Gamma-rays

- Continuum γ-rays by bremsstrahlung (~ 10MeV)

- Nuclear de-excitation lines caused by proton bombardment;
  - 'prompt' radiation provides a diagnostic of protons above 30MeV



- The positron annihilation line at 511keV

- The neutron capture line at 2.23 MeV - n(p,γ)D
  - this is a delayed line, as neutrons must slow down before reacting.
    ⇒ formed low in the atmosphere, and after other emissions.

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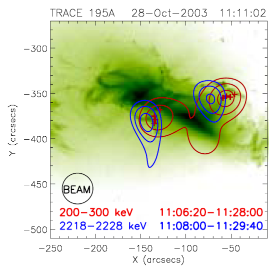
Gamma-ray footpoints

HXRs and gamma-ray lines have similar time profiles, implying related acceleration.

However, radiation produced by ions is *in a different location* from electron bremsstrahlung



Hurford et al. 2006

Neutrons produced by energetic ions (10s of MeV/nucleon).

The capture line is predicted to form within 500km of neutron production site.

But observed to be systematically offset from HXRs (electrons) by ~ 10,000km (15").

Still a mystery….

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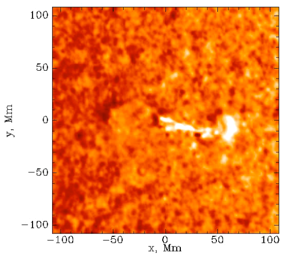
Flare quake

Flares produce photospheric disturbances at the time of the impulsive phase.

Flare quakes first detected by Kosovichev & Zharkova (1996)



Quake origin is approximately co-spatial with hard X-ray sources, and requires about 0.1% of flare energy.

Q. How do we get energy down to such deep layers of the atmosphere?

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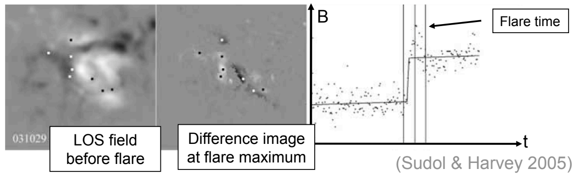
Changes to the magnetic field

In all large flares the line-of-sight B field at the photosphere changes suddenly by ~10% (0.01 – 0.02T, 100-200 G)

These changes occur are simultaneous with flare, co-spatial with flare ribbons/kernels and propagate at flare ribbon speed.



(Sudol & Harvey 2005)

Consistent with a 'jerk' of the magnetic field as it reconfigures?

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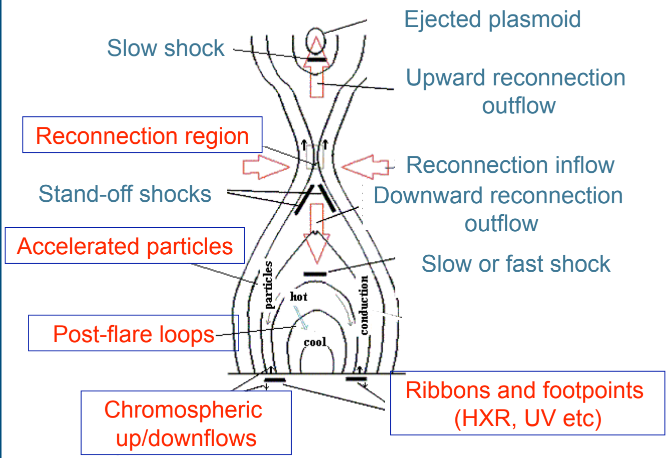
'Standard' flare cartoon



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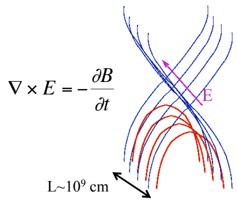
Electron acceleration in the corona

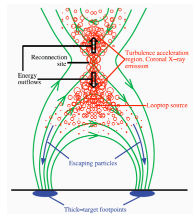
There are two main models for coronal electron acceleration:

1) Acceleration in reconnection E



High efficiency, low volume

2) Stochastic acceleration in turbulent E



Low efficiency, high volume

Liu et al 2008.

(nb – impulsive-phase shock acceleration of flare electrons is not likely)

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Reconnection and particle acceleration

Outside reconnection region:

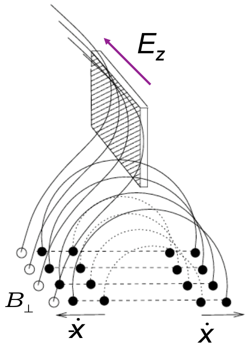
$$E + v \times B = 0$$

E given by rate of advection of B into reconnection region

2-D configuration $\Rightarrow$ $|E_z| = B_\perp \dot{x}$

The flare is clearly 3-D

However, we still expect high fluxes of fast particles at times of high reconnection rate



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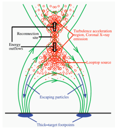
Stochastic acceleration

Particles gyrating in a magnetic field pick up energy from plasma waves if their gyration frequency is resonant with (multiples of) the wave frequency



Frequency matching condition:

$$\omega - k_{||} v_{||} - l\Omega/\gamma = 0$$

ω, Ω = wave and cyclotron frequencies
$k_{||}$ = parallel wave number
$v_{||}$ = parallel particle speed
l = integer

But as soon as a particle picks up some energy from a monochromatic wave, its gyration frequency changes and resonance is lost.

Particles in a wave spectrum can 'hop' stochastically from one resonance to another as their energy increases or decreases (e.g. Miller & Vinas 1993, Miller 1998)

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Ex. Acceleration of a single ion

Energy vs. time for a single Fe ion in isotropic, high frequency turbulence

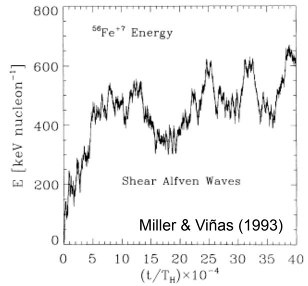

FIG. 9.—The kinetic energy per nucleon E of an initially thermal $^{56}Fe^{+7}$ ion as a function of dimensionless time t/T_H, where $T_H = \Omega_H^{-1}$. The charge state of +7 is the most probable one in a 10^6 K plasma. The particle is in the presence of 120 monochromatic shear Alfvén waves distributed over a range of frequencies and angles determined using Fig. 1, and each wave i has an electric field $E_i = 7.5 \times 10^{-4} B_0$.

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

Protons and ions mostly resonate with high-frequency Alfvenic waves

Electrons mostly resonate with electron cyclotron and whistler waves

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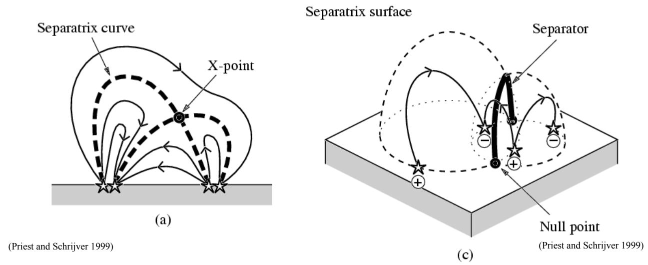
Separatrices and separators

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



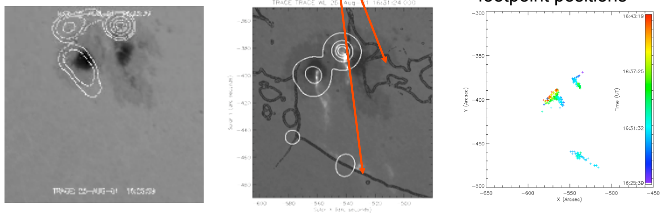
Flare footpoint locations

Radiation from non-thermal particles appears at the photospheric intersection of separatrix surfaces (eg Demoulin, Aulanier).

Motion of footpoints across magnetic field can be used to deduce a coronal magnetic reconnection rate.

Separatrix intersections

Time evolution of HXR footpoint positions



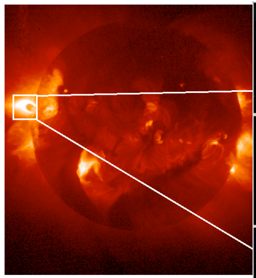
Metcalf *et al.* (2003)

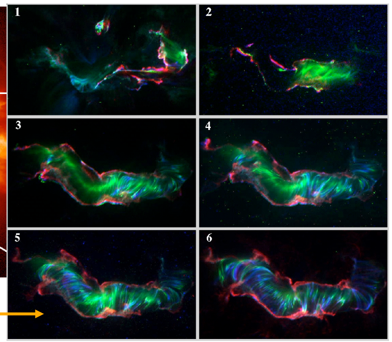
Impulsive phase - main points

- During the impulsive phase most of the flare energy is released.
- Energetic particles receive up to 50% of the total energy (rest goes to CME and heating).
- Most of the impulsive phase energy is focused into a few small sources.
- These sources are closely related to magnetic separatrices.
- Implication of 'standard model' is that up to 10^{36} electrons accelerated per second (i.e. all the electrons in $(10,000\text{km})^3$ at 10^9 cm^{-3}.
- Similar number of ions accelerated, but in a different place or following a different path.

Atmospheric response – SXR and EUV

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

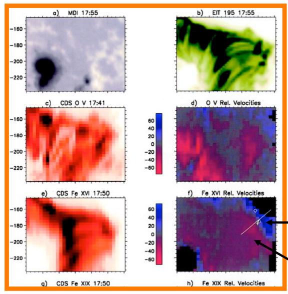




loops then cool through EUV temperatures

Atmospheric response – chromospheric flows

Energy input in the form of a beam heats the chromosphere rapidly and – if heating is strong enough - it expands upwards.



Chromospheric 'evaporation' has been observed spectroscopically in H_α (e.g. Antonucci et al 1984)

Also in UV/EUV using SoHO/CDS post-flare observations (e.g. Czaykowska et al 1999)

Blueshifts on outer part of arcade are evaporation

Redshifts on inner part of arcade are material cooling and draining.

Flare energy deposition

Assume energy input by beam with spectrum F(E,z) as a function of depth z in the atmosphere

$$\dot{E}(z) = -\int_0^\infty F(E,z)\frac{dE}{dz}dE$$

where dE/dz is the loss-rate of a single electron by Coulomb collisions.

What about energy loss?

By radiation: $\dot{E}_{rad}(z) = n_e^{\,2} P(T_e)$ — $P(T_e)$ is the radiative loss function

By conduction:

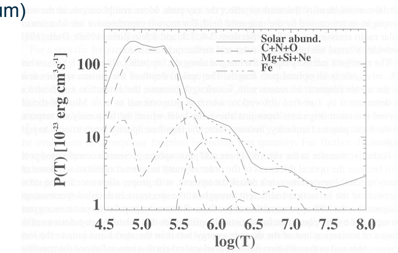
$$\dot{E}_c = -\nabla.(F_c) = -\nabla.\left(\kappa \frac{dT_e}{dz}\right) = -\nabla.\left(\kappa_o T_e^{5/2}\frac{dT_e}{dz}\right)$$

F_c = conductive flux, z = direction along magnetic field

Flare energy deposition

In non-flaring atmosphere, energy input, radiation and conduction balance.

Energy input is ultimately radiated away (mostly in hydrogen lines and continuum)



Radiative loss function

Rapid beam energy input means that the atmosphere may not be able to conduct or radiate all input energy (nb, $P(T_e)$ decreases as T increases)

So atmosphere moves (rapidly) towards new hydrostatic equilibrium – 'evaporation'

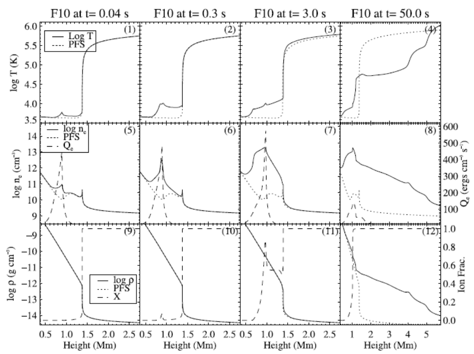
Evaporation simulations

Latest numerical simulations disagree somewhat with evaporation scenario

Coronal density increases, but temperature does not. The increasing ionisation, radiative losses and gas expansion absorb the energy

T

n_e

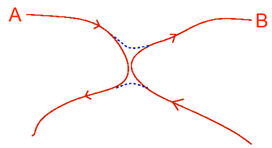


Allred et al 2006.

Reconnection - liberation of stored energy

Magnetic reconnection allows the coronal field to reconfigure, liberating magnetic energy

Reconnection is the process whereby two field lines, being frozen in and carried along by the fluid, break and rejoin in a different way.



So a particle that was on fieldline A can end up on fieldline B

Reconnection results from the local breakdown of flux conservation.

Breakdown of flux conservation

The induction equation – describes advection and dissipation of field

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B}) + \eta \nabla^2 \vec{B}$$

Define associated timescales :

$$\tau_a = L/v \quad \text{and} \quad \tau_d = L^2/\eta$$

where L is the typical length scale for variation in the magnetic field.
The ratio of τ_d to τ_a is called the Magnetic Reynolds number, R_M

$$R_M = \frac{\tau_D}{\tau_A} = \frac{vL}{\eta}$$

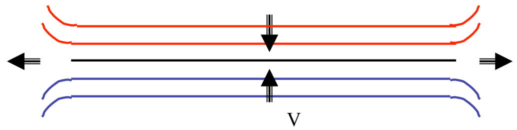
Normally in the corona, dissipation is much slower than advection (low collisional resistivity η, large v and L); so the field is frozen.

Magnetic field dissipation

τ_d in the corona is about 10^6 years. How do we speed up dissipation?

$\tau_d = L^2/\eta$ so must decrease the length scale L, or increase resistivity.

As field is advected by flow, it generates steep gradients - current sheets



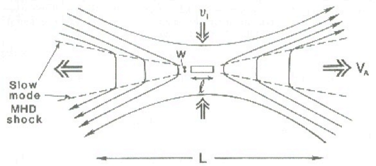
Field lines are advected in to the current sheet, reconnect, and plasma is advected out at the upstream Alfvén speed - Sweet-Parker reconnection.

Sweet-Parker reconnection is rather inefficient: the rate scales as $R_m^{-1/2}$
It is too slow (by ~ 5 orders of mag) to explain flare energy release.

Petschek reconnection

The Petschek model reduces the size of the diffusion region.

Reconnection rate increases as plasma is 'slingshotted' out



Outflow at ~ Alfvèn speed

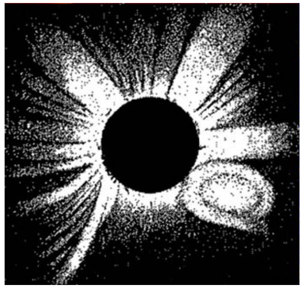
Vin/V_A $(\sim \pi/8 \ln Rm) \fallingdotseq 0.01 \sim 0.1$

- The reconnection rate is determined by the external conditions
- At slow shocks, energy conversion can occur
- May be fast enough to explain flare release if a high 'anomalous resistivity' is invoked.

Important points about reconnection

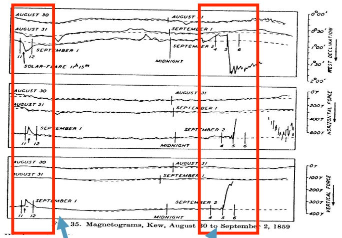
- Reconnection allows an energy-loaded magnetic field to *relax* to a lower energy state during a flare.
- Reconnection is a local process. *The local dissipation of flux does not lead to much energy release*. Energy is released by the field reconfiguration in the rest of the corona (and in shocks in Petschek-type geometries)
- Direct observational evidence for reconnection in the flaring corona is limited - however lab and magnetospheric/ionospheric experiments suggest that it happens all the time.
- Lab and space plasma experiments show evidence of collisionless reconnection. *Solar plasmas are probably also in the collisionless* - i.e. non-MHD – regime.

Early CME observations



Drawing of white light corona

Tempel 1860, From Eddy (1974)



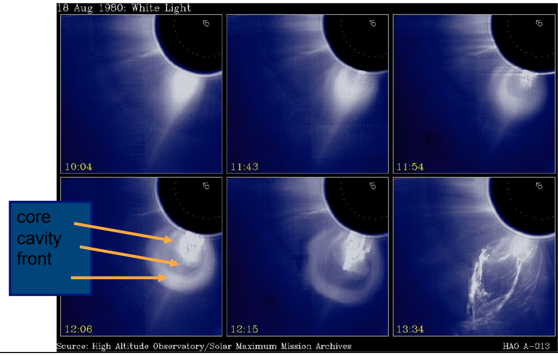
Magnetometer disturbances following 'Carrington's Flare (1859):

(i) ionospheric response to flare UV

(ii) CME hits

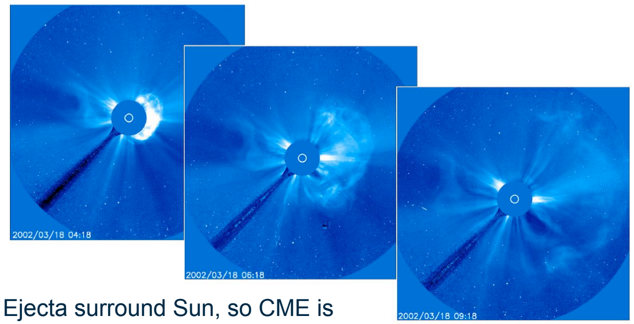
CME definition

"..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

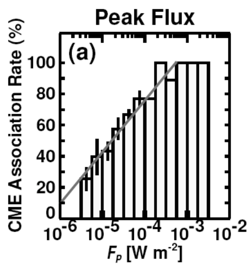
Discovered by Howard (1982). Known to be the CME type most responsible for terrestrial effects



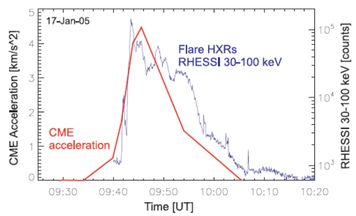
Ejecta surround Sun, so CME is travelling towards or away from Earth.

Flare/CME association

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



Yashiro et al. (2007)



From Temmer et al. (2007)

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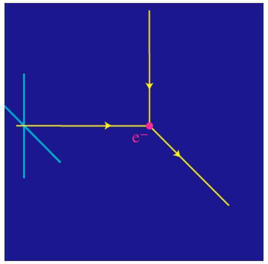
CME white light measurements

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 coronal mass.



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

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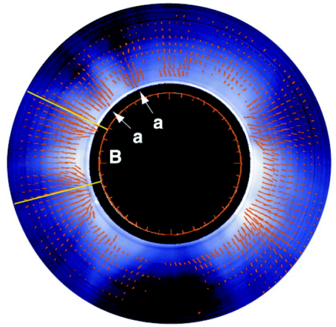
Polarized brightness

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



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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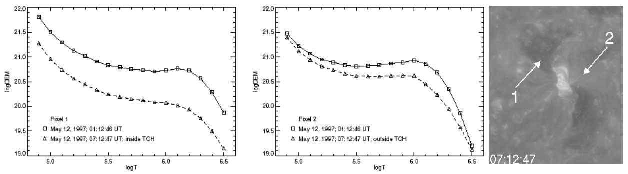
Soft X-ray and EUV

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.

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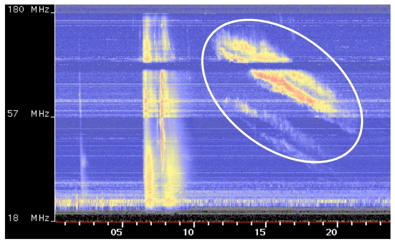
Coronal radio signature



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.

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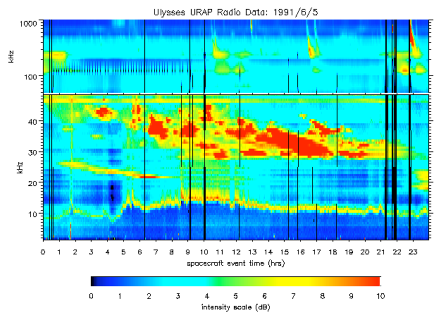
Interplanetary signature



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

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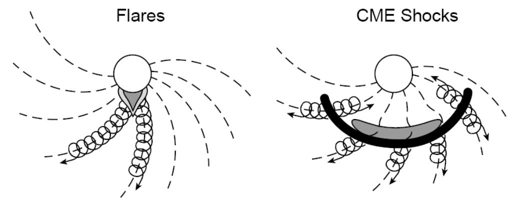
CMEs and solar energetic particles

Large solar eruptions producing high speed CMEs (1000-3000km/s) are the principal 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)

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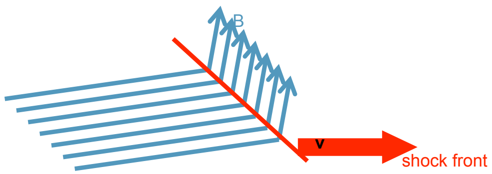
Shocks

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)

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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.

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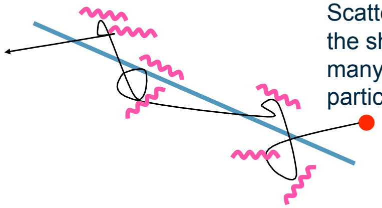
Diffusive shock acceleration

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.

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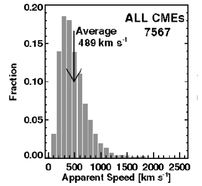
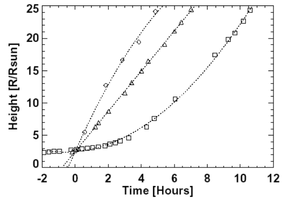
CME kinematics



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?

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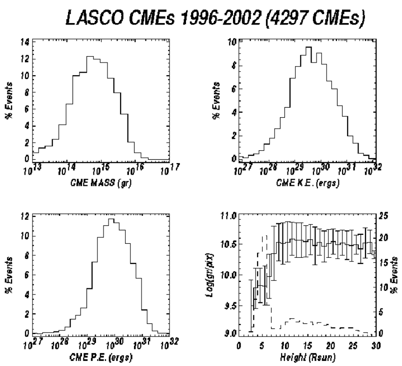
CME mass and energy



Average quantities:

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.

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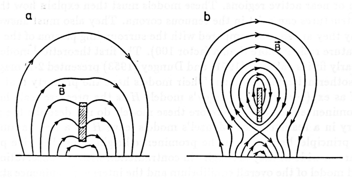
CMEs and flux ropes

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

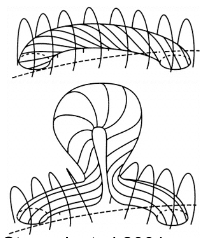
Support of cool, dense filament material in hot, tenuous corona calls for concave-up magnetic field

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

2D-cut



3D-sketch



Sturrock et al 2001

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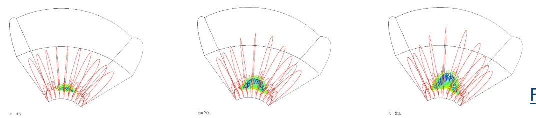
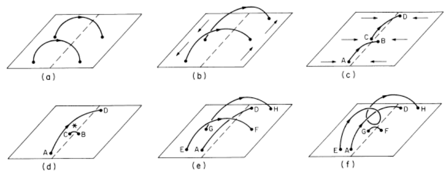
Formation of coronal flux rope



Fan 2005

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



nb, not supported by Leka *et al* AR measurements, but possible for polar crown filaments.

van Ballegooijen & Martens 1989

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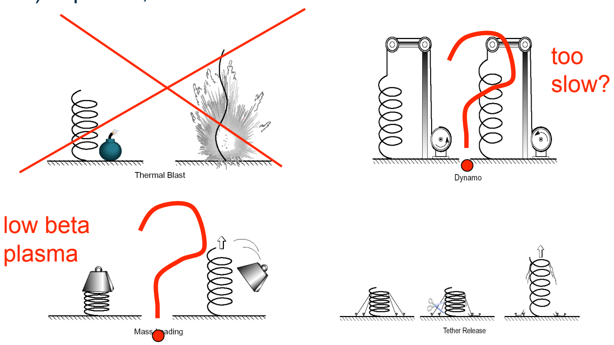
How is a CME eruption produced?

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



Mechanical analogues of CME theories - Klimchuk (2000)

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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 (linearly?-) stable, configuration.

Loss of stability leads to CME - but no concensus 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?)

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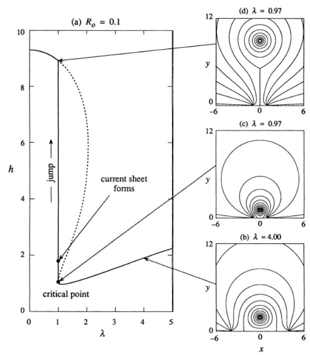
Ideal instability



Flux rope in corona, held down by overlying arcade.

Arcade footpoints driven together

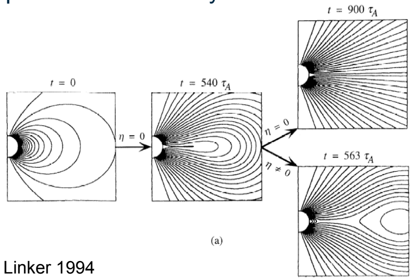
At a critical value of the separation parameter λ, the configuration jumps to a new equilibrium

A current sheet forms – resistivity takes over.

Forbes & Priest 1995.

Resistivity must behave in a somewhat schizophrenic way

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

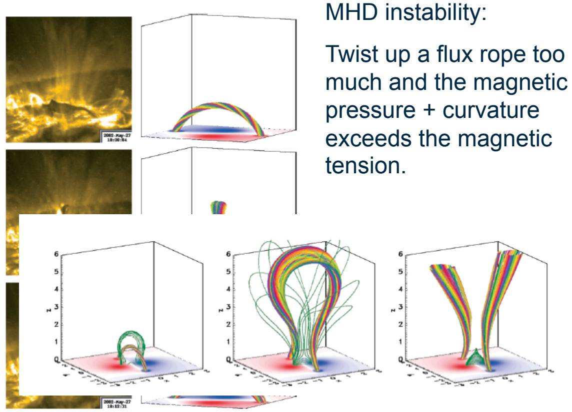


Resistivity stays low – no eruption

Resistivity increases - eruption

Mikić & Linker 1994

Kink instability



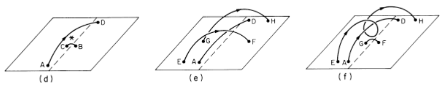
MHD instability:

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

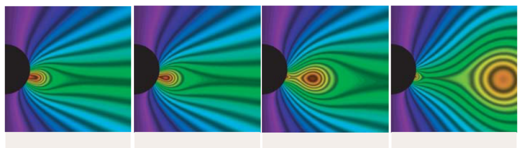
Török & Kliem 2005

Flux cancellation models

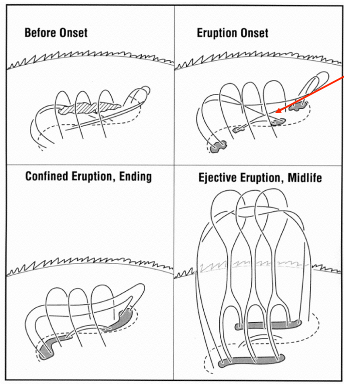
Flux cancellation (observationally the disappearance of magnetic flux) interpreted as reconnection at a neutral line.



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



Tether cutting models



Also invoking flux cancellation underneath filaments, but this time filaments are part of an already twisted rope.

The reconnection just cuts the restraining field, rather than adding significant twist to the configuration.

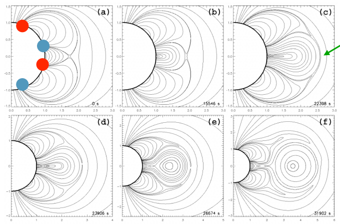
Moore et al.

University of Glasgow

'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, removing overlying confining field.

As inner field expands, sheet thins and elongates

So reconnection accelerates.

e.g. Antiochos 99, Lynch et al 2004

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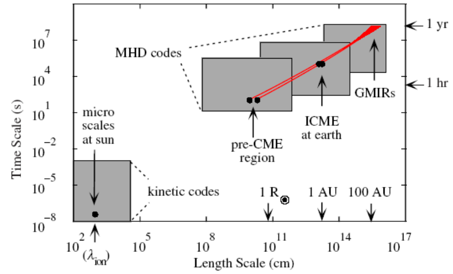
CME numerical modeling

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 (in prep).

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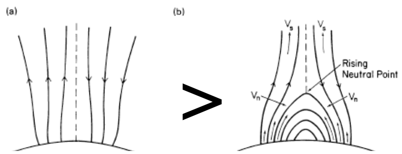
The Aly-Sturrock Conjecture

CME working 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.

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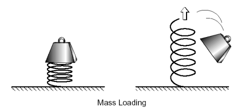
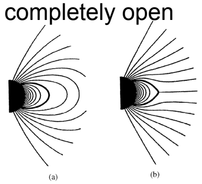
Possible solutions to the A-S puzzle

Pre-eruption field not simply connected

Pre-eruption field not force-free



Field does not completely open



Wolfson + Low 1992

Field extends but does not open

The Jury is still out…