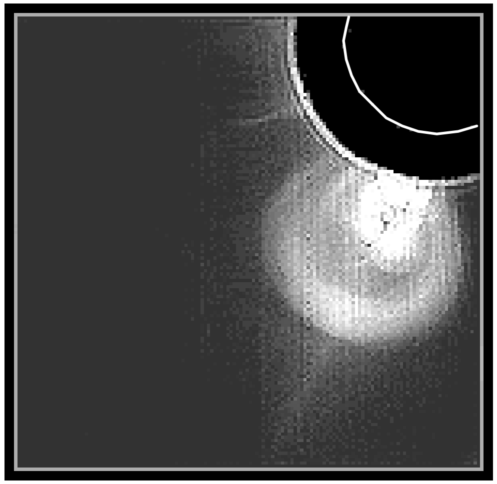
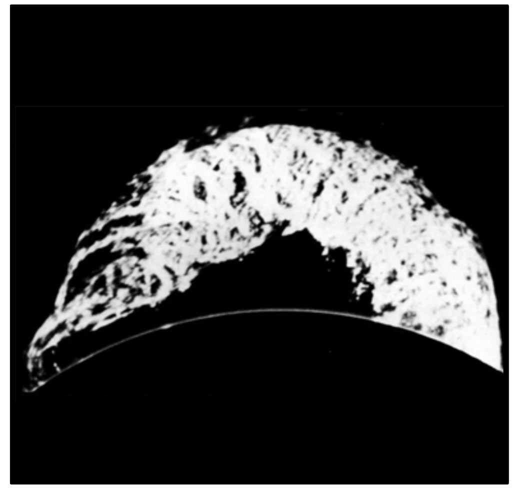
Different Aspects of Solar Eruptions

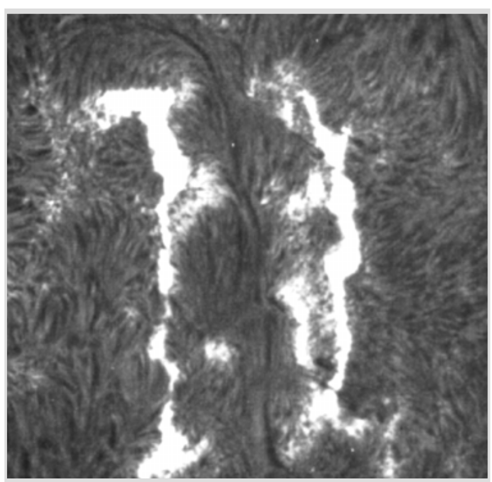
CME



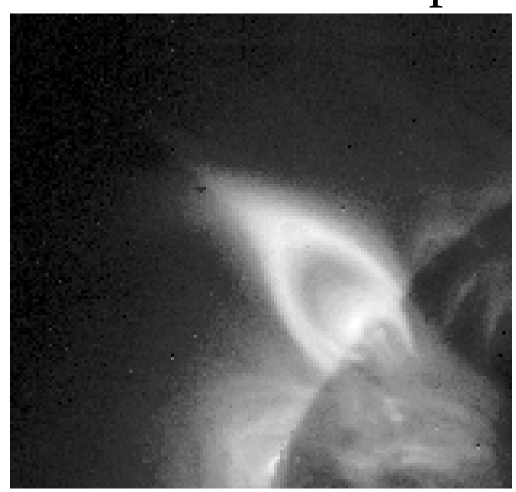
Erupting Prominence



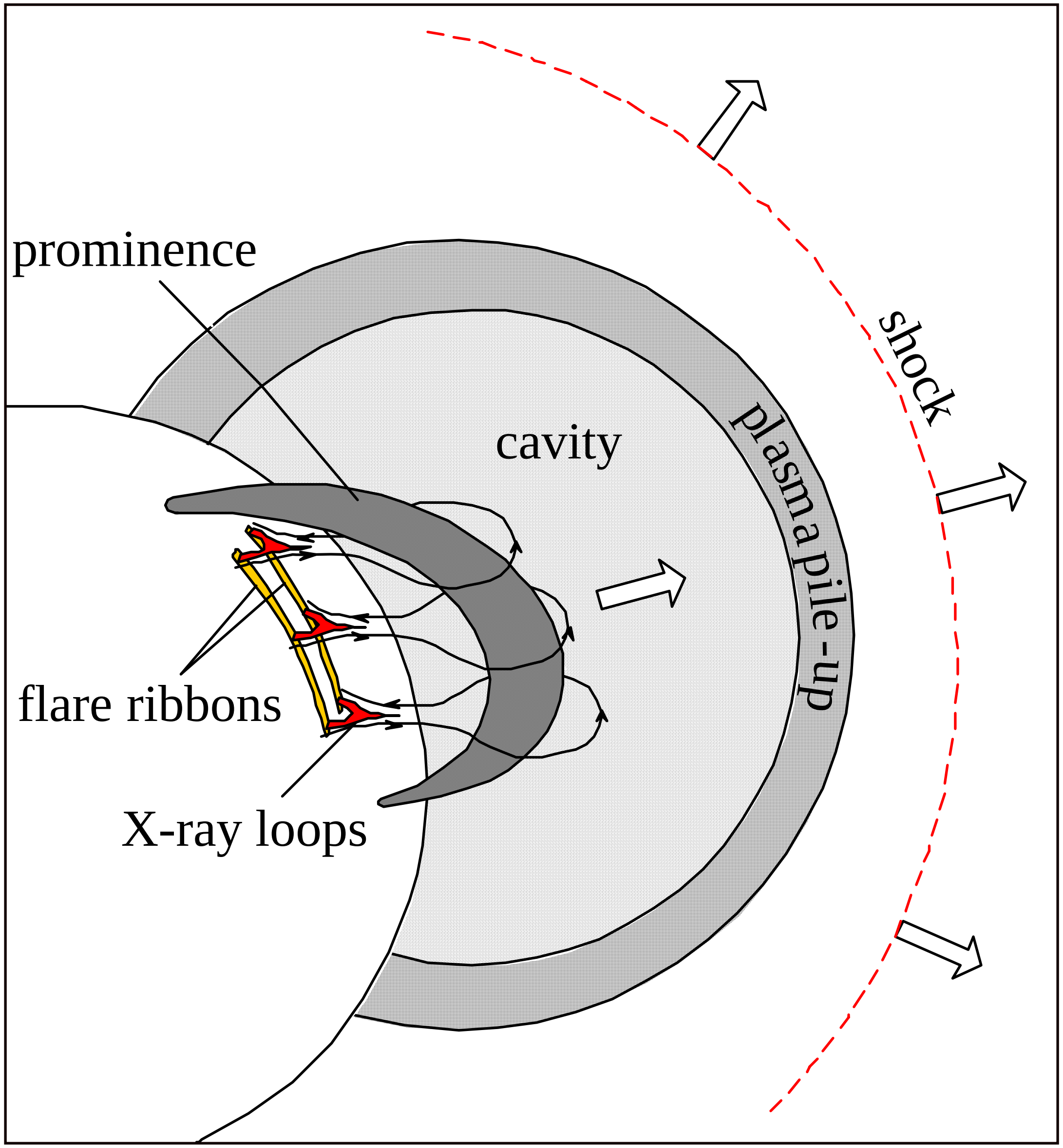
CME/Flare Ribbons



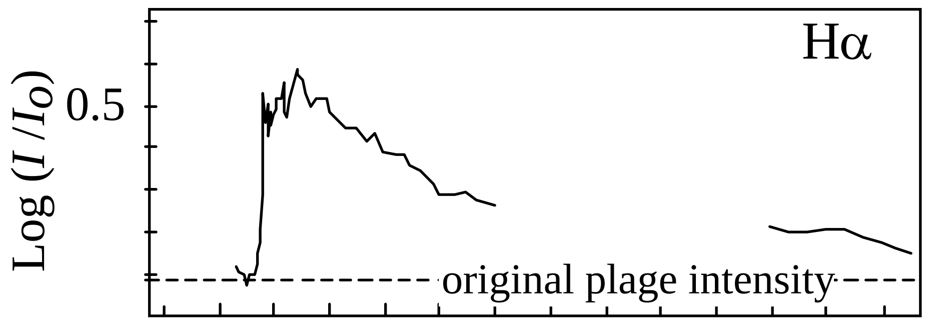
CME/Flare Loops

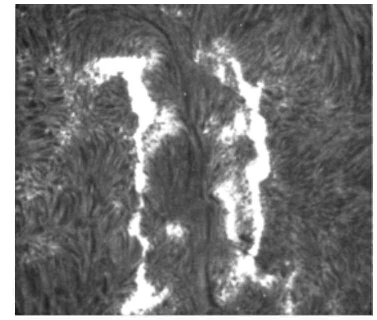


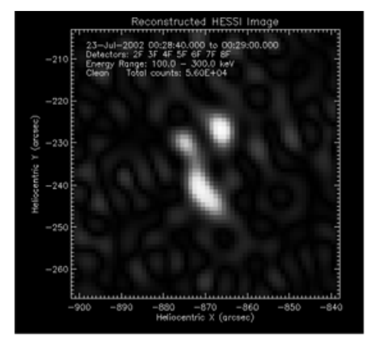
Large Solar Eruptions



QuickTime™ and a
Video decompressor
are needed to see this picture.

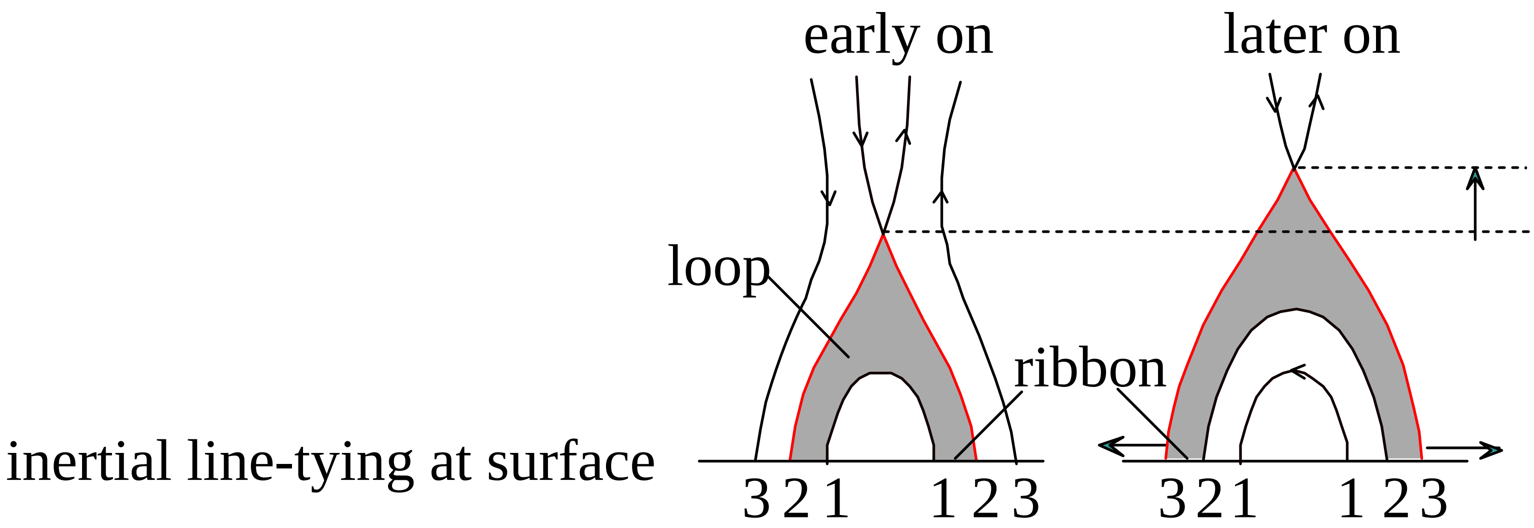

Hα
Log (I / I_O)
0.5
original plage intensity

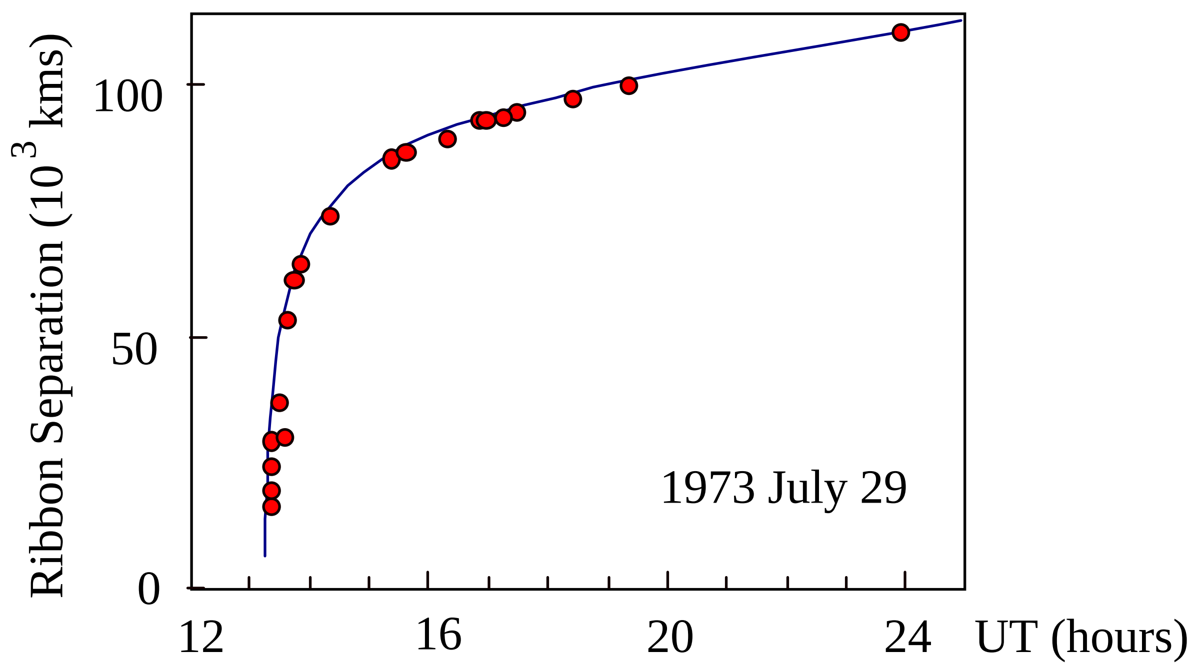



Reconstructed HESSI Image
23-Jul-2002 00:28:40.000 to 00:29:00.000
Detectors: 2F 3F 4F 5F 6F 7F 8F
Energy Range: 100.0 - 300.0 keV
Clean Total counts: 5.60E+04
Heliocentric Y (arcsec)
Heliocentric X (arcsec)

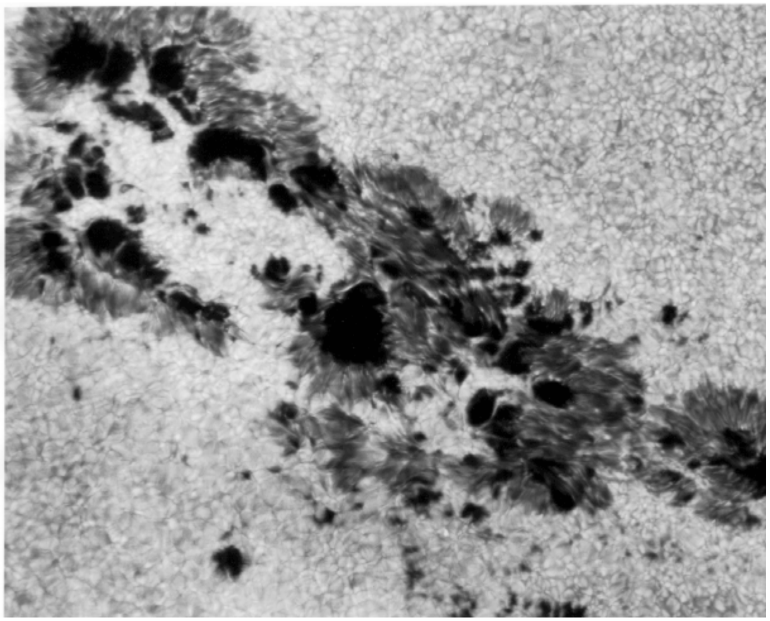
QuickTime™ and a
Photo decompressor
are needed to see this picture.

Apparent Motion of Loops & Ribbons





Inertial Line-Tying



Photospheric boundary condition:

$$\mathbf{E} = -\mathbf{V} \times \mathbf{B} = \mathbf{0}\,.$$

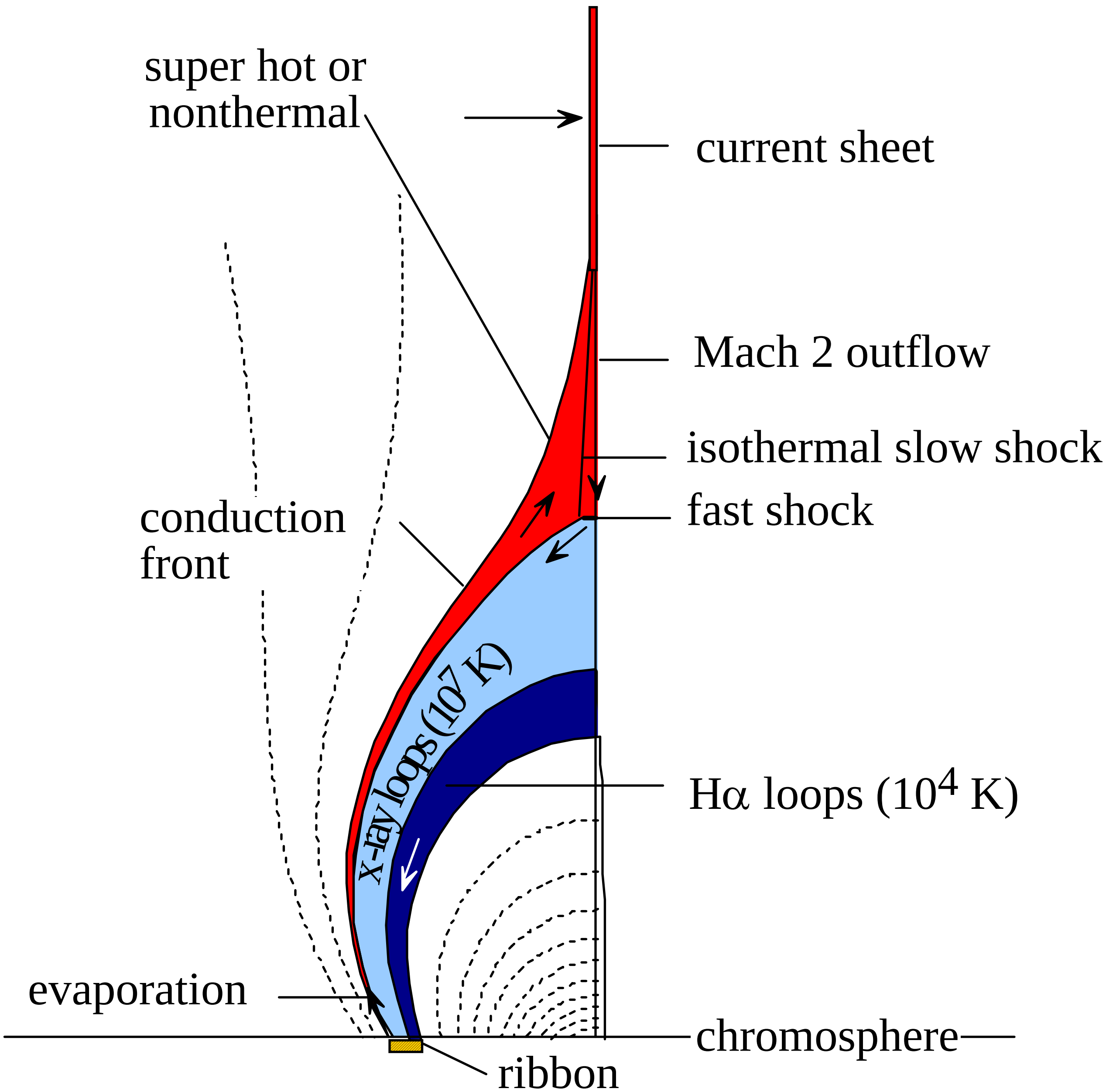
Photospheric convection is negligible

Plasma below the photosphere is both massive and a good conductor.

B normal to surface is fixed.

Evolution of the photosphere is slow compared to time scale of eruptions.

CME/Flare Loop Structures

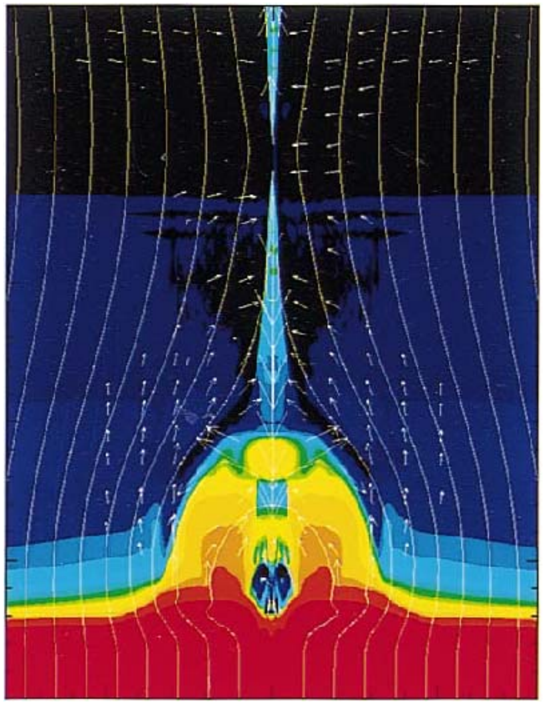


QuickTime™ and a
Animation decompressor
are needed to see this picture.

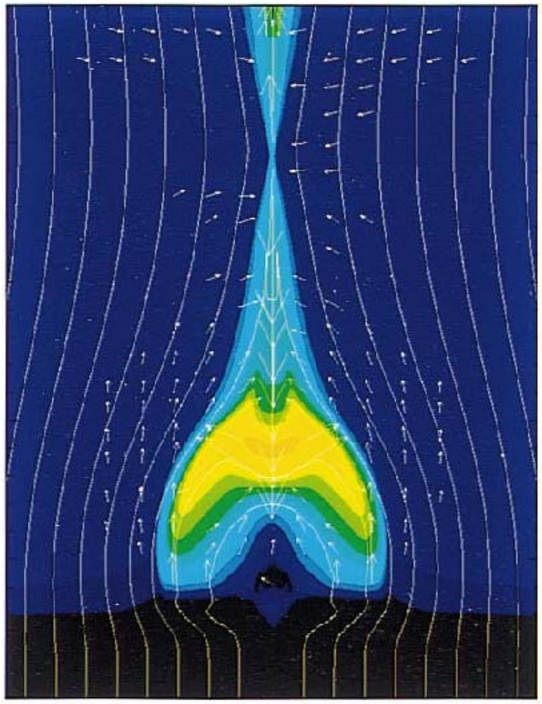
Flare-Loop Simulations

Yokoyama & Shibata (2001)

Density



Temperature

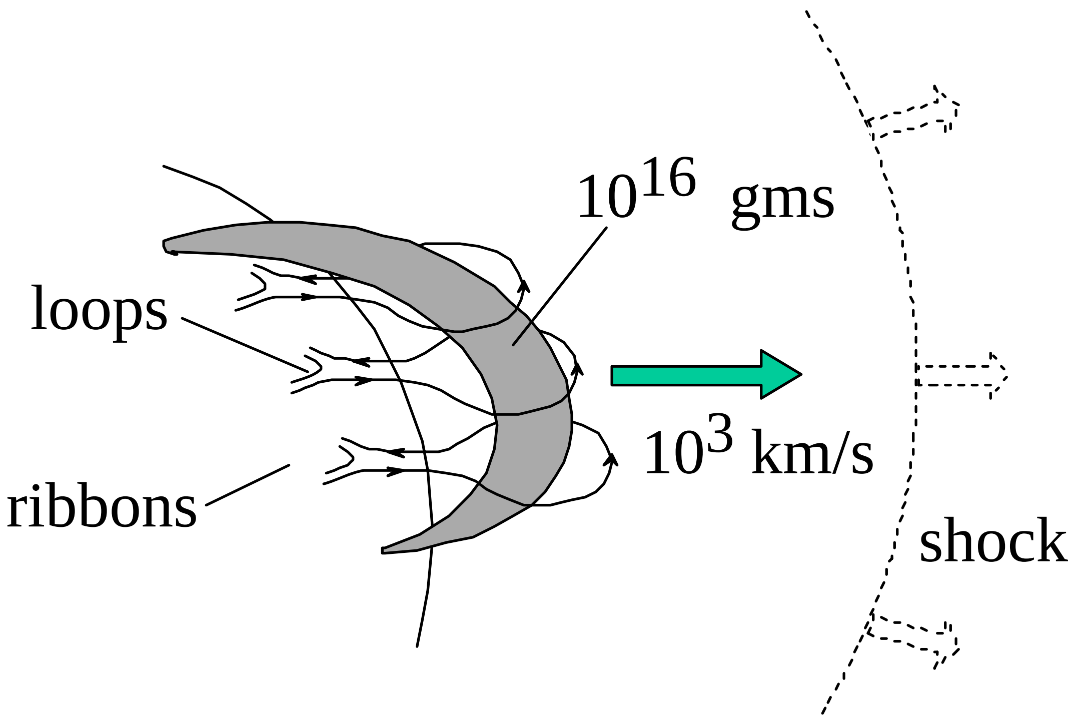


CME/Flare Energetics

kinetic energy of mass motions: $\approx 10^{32}$ ergs

heating / radiation: $\approx 10^{32}$ ergs

work done against gravity $\approx 10^{31}$ ergs



volume involved:
$\gtrsim (10^5 \text{ km})^3$

energy density:
$\lesssim$ 100 ergs/cm^3

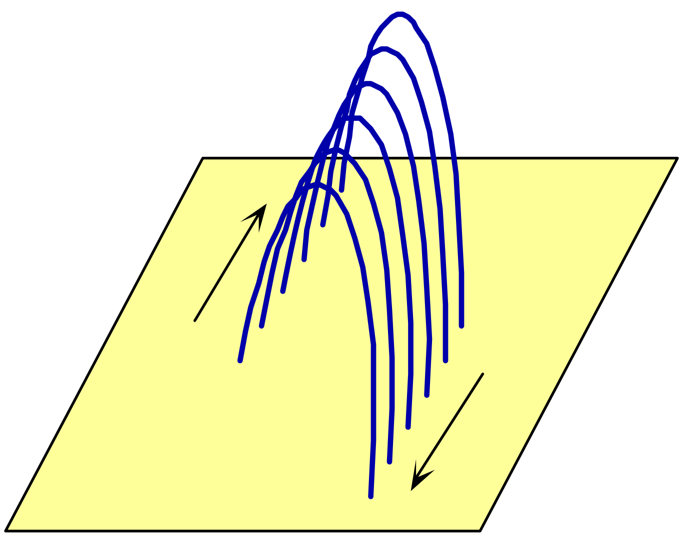
Nature of Energy Source: Required: ≈ 100 ergs/cm^3

Type	Observed Values	Energy Density
kinetic $(m_p n V^2)/2$	$n = 10^9$ cm^{-3} $V = 1$ km/s	10^{-5} ergs/cm^3
thermal nkT	$T = 10^6$ K	0.1 ergs/cm^3
gravitational $m_p n g h$	$h = 10^5$ km	0.5 ergs/cm^3
magnetic $B^2/8\pi$	$B = 100$ G	400 ergs/cm^3

How is Energy Stored?

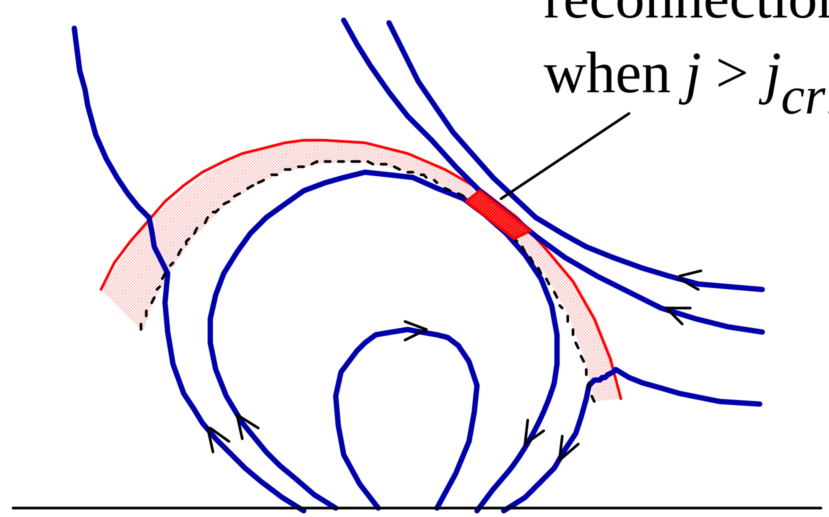
$\beta = 10^{-3}$ $\nabla p \approx 0$ $\mathbf{j} \times \mathbf{B} \approx 0$

Force-free fields: $\mathbf{j} \parallel \mathbf{B}$



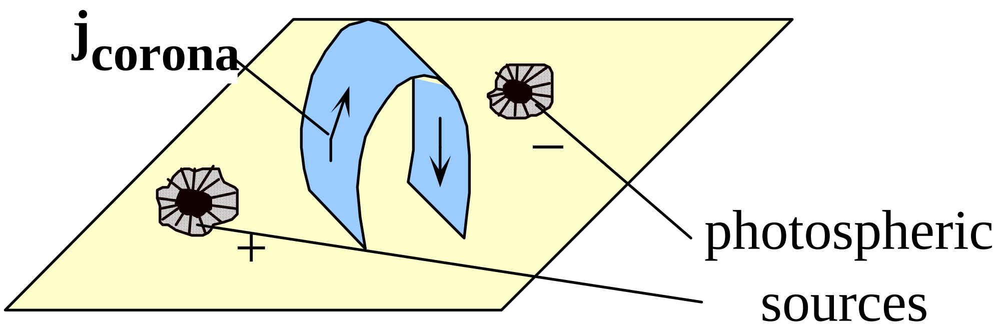
sheared magnetic fields

Current sheets:

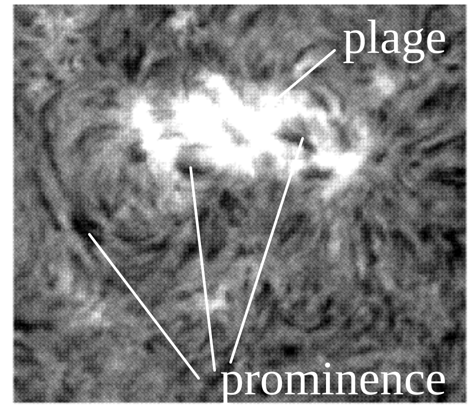


emerging flux model

How Much Energy is Stored?



Hα image

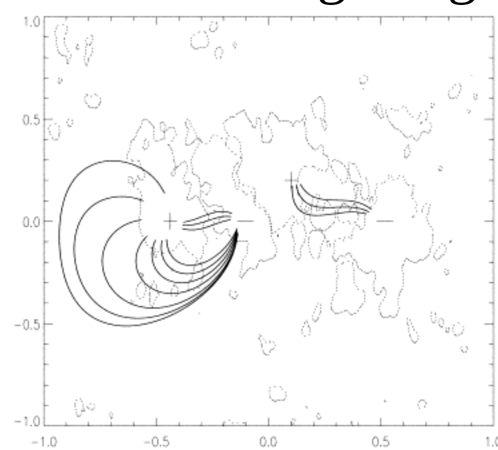


$$\mathbf{B} = \mathbf{B}_{\substack{\textbf{photospheric}\\ \textbf{currents}}} + \mathbf{B}_{\substack{\textbf{coronal}\\ \textbf{currents}}}$$

invariant during CME (photospheric currents)

source of CME energy (coronal currents)

model with magnetogram

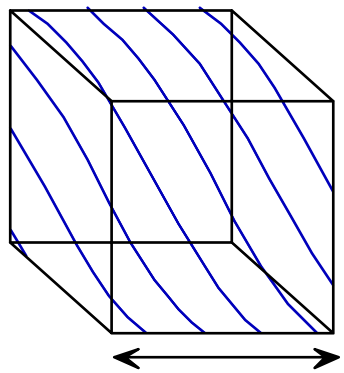


from Gaizauskas & Mackay (1997)

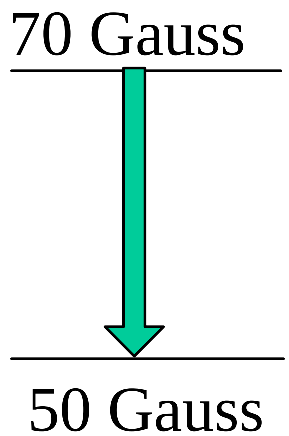
$$B_{from\ corona} \approx B_{from\ photosphere}$$

free magnetic energy ≈ 50% of total magnetic energy

Magnetic Energy Conversion:



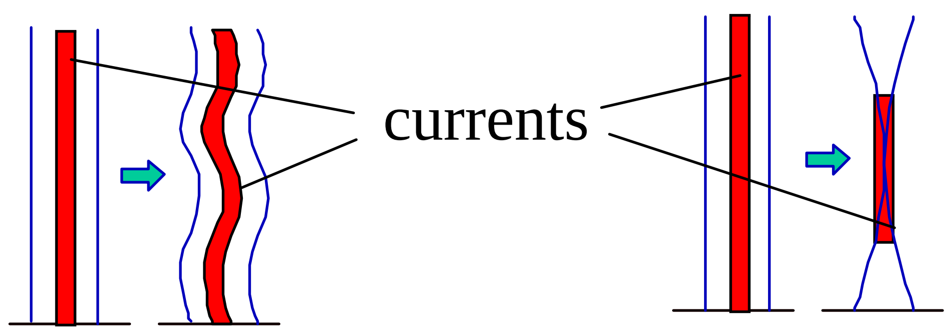
$L \; = \; 6 \times 10^4 \text{ km}$



$W_B \; = \; 10^{32} \text{ ergs}$

ideal MHD

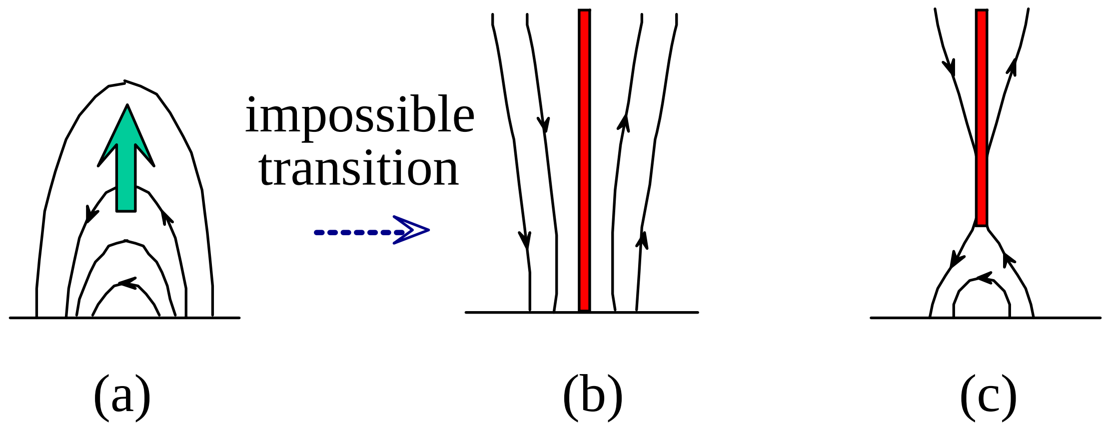
reconnection

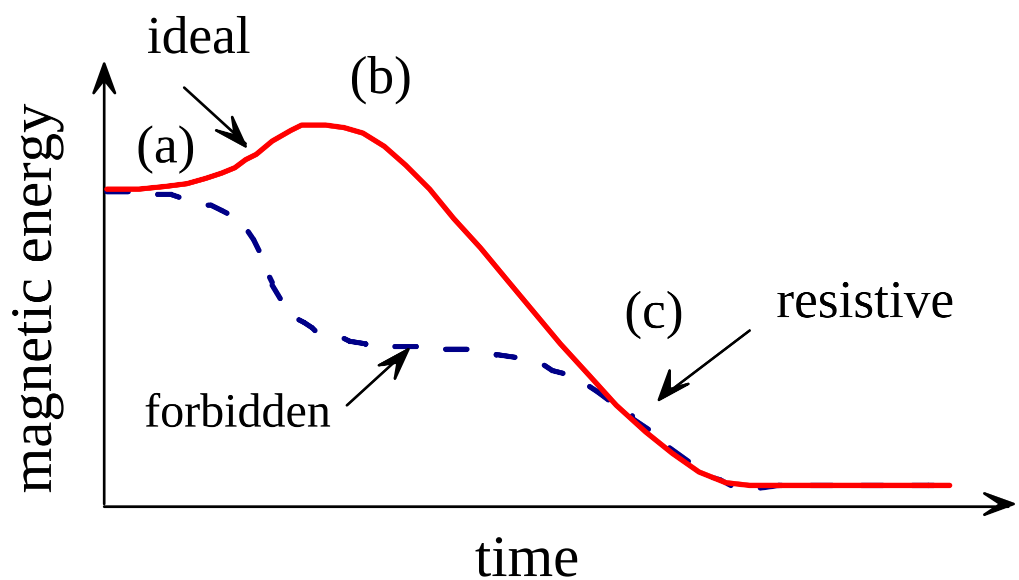


inefficient (< 10%)
fast

efficient (100%)
slow

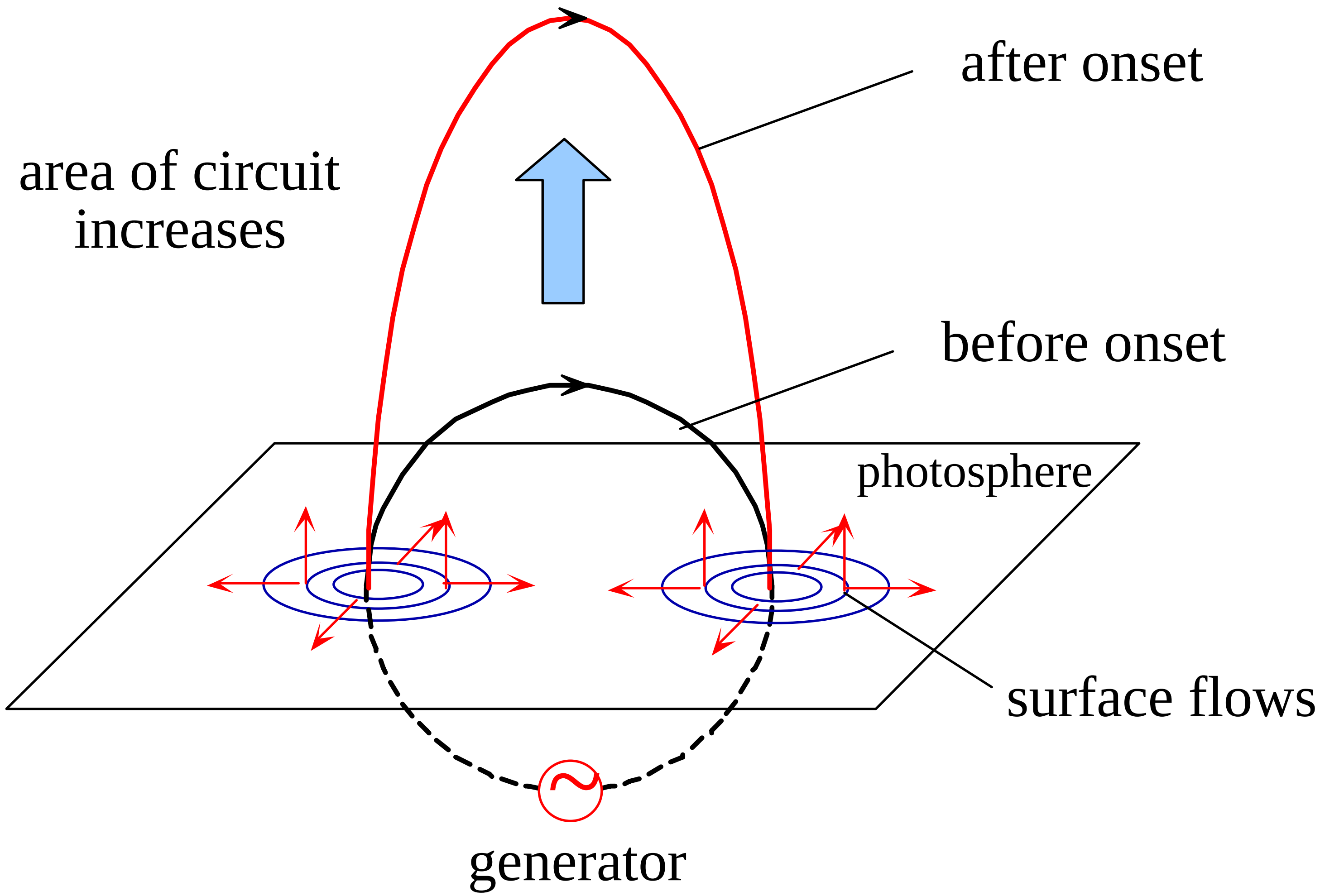
Aly - Sturrock Paradox



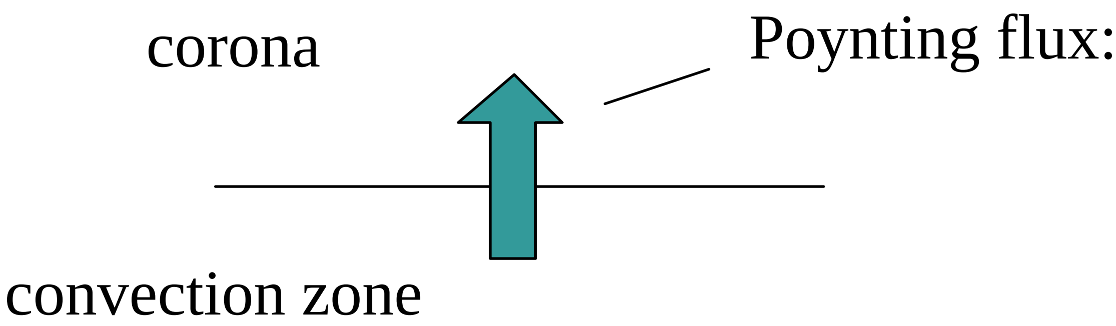


Flux Injection Models

(e.g. Chen 1989)



During injection energy flows through photosphere.



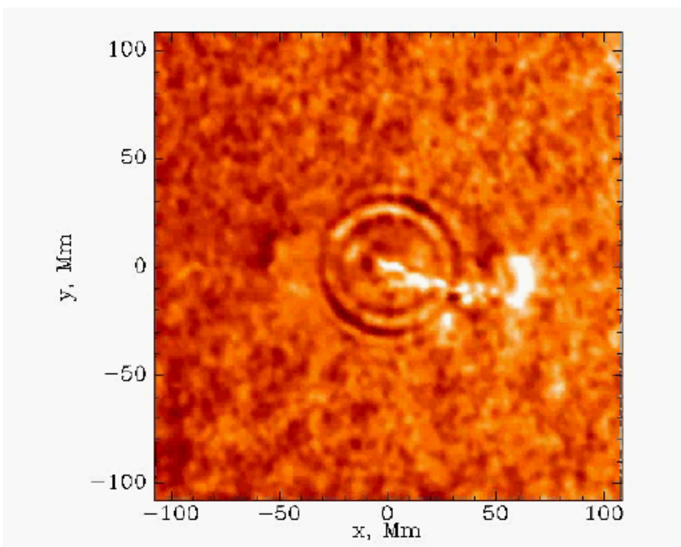
$$\mathbf{S} = c\,\mathbf{E} \times \mathbf{B} \,/\, (4\pi)$$

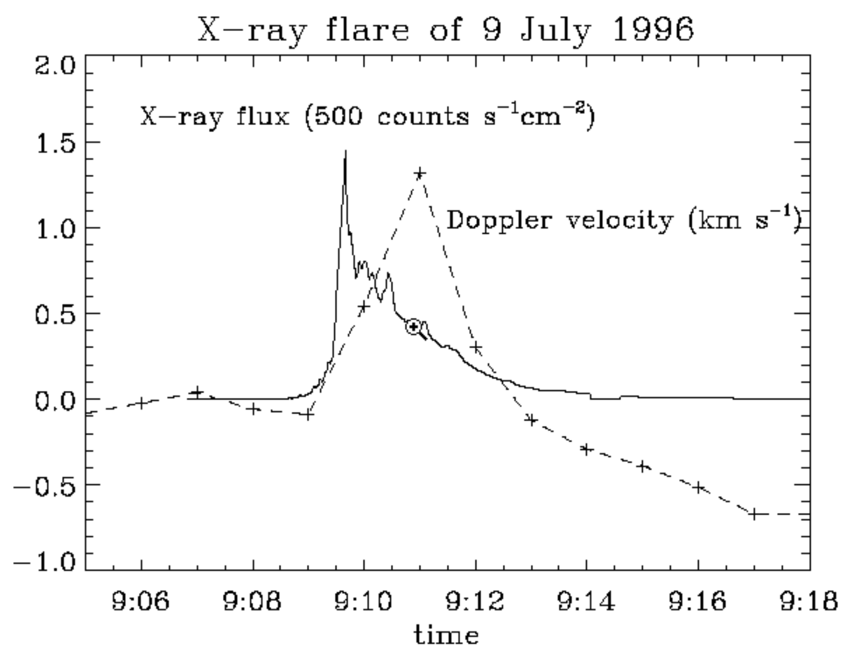
(ergs/cm/sec)

$$\mathbf{E} = -(\mathbf{V} \times \mathbf{B}) \,/\, c$$

> 10 km/sec for > 10 minutes

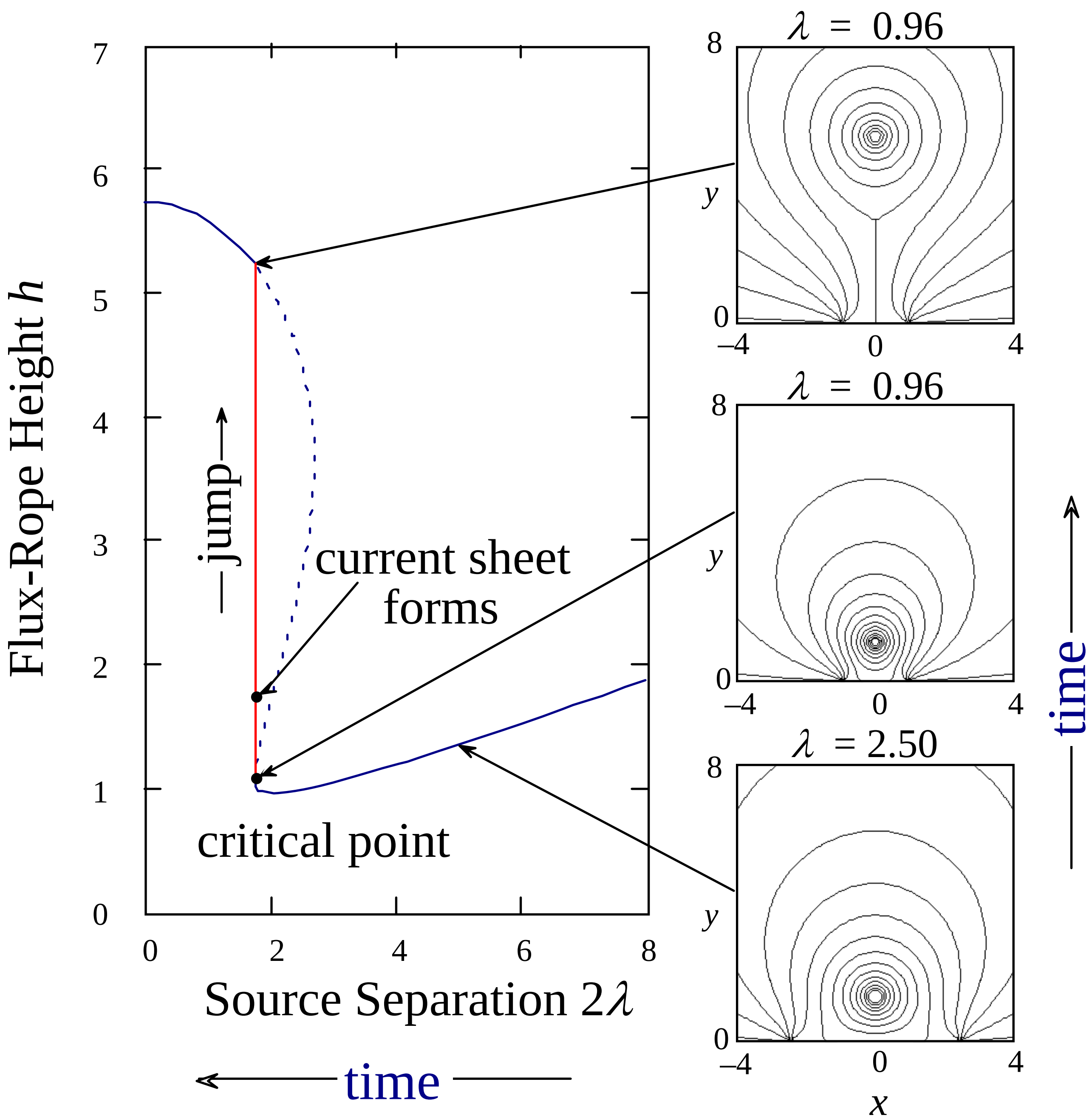
Kosovichev et al. 1998



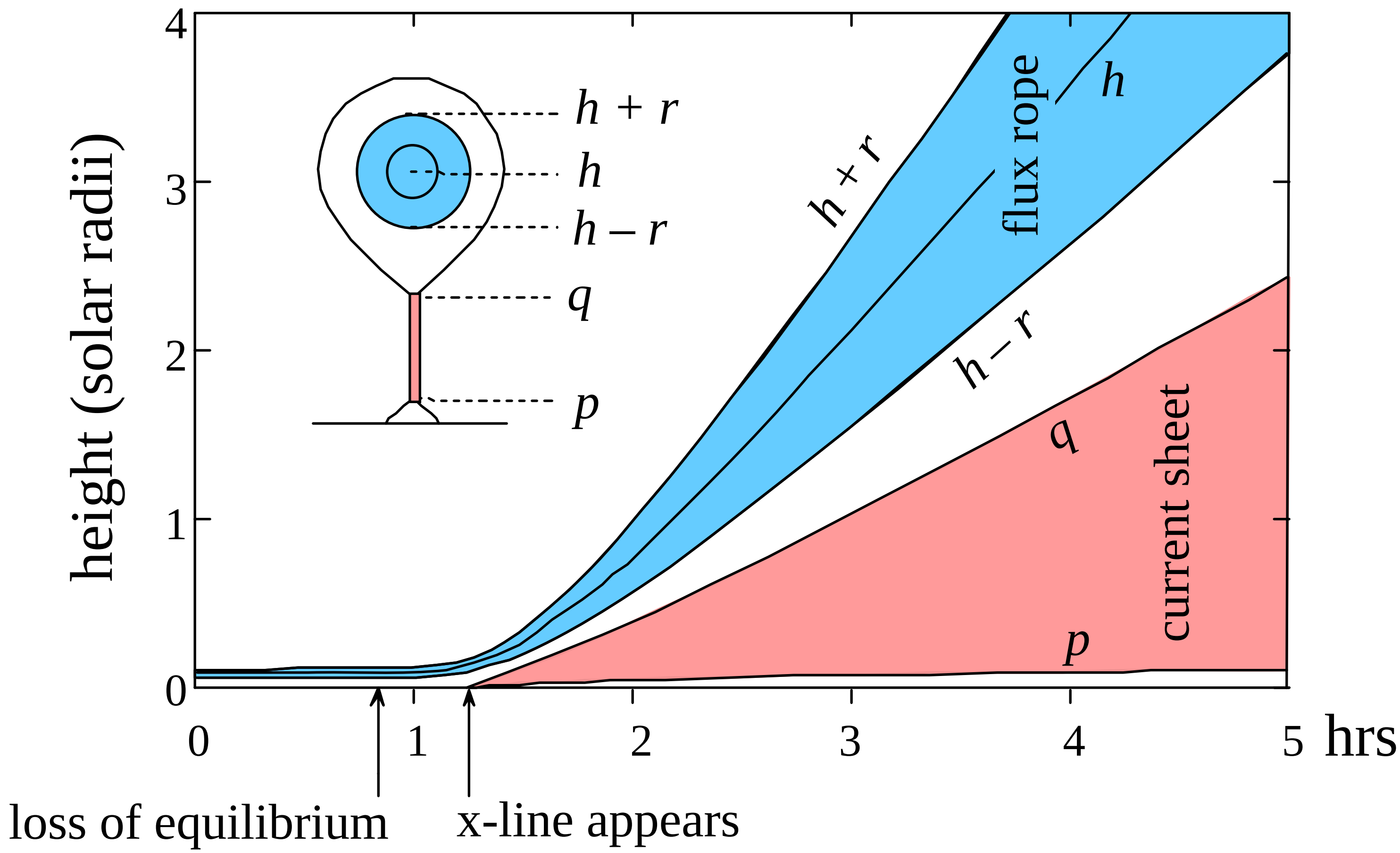


Injection models predict large surface flows which are never observed.

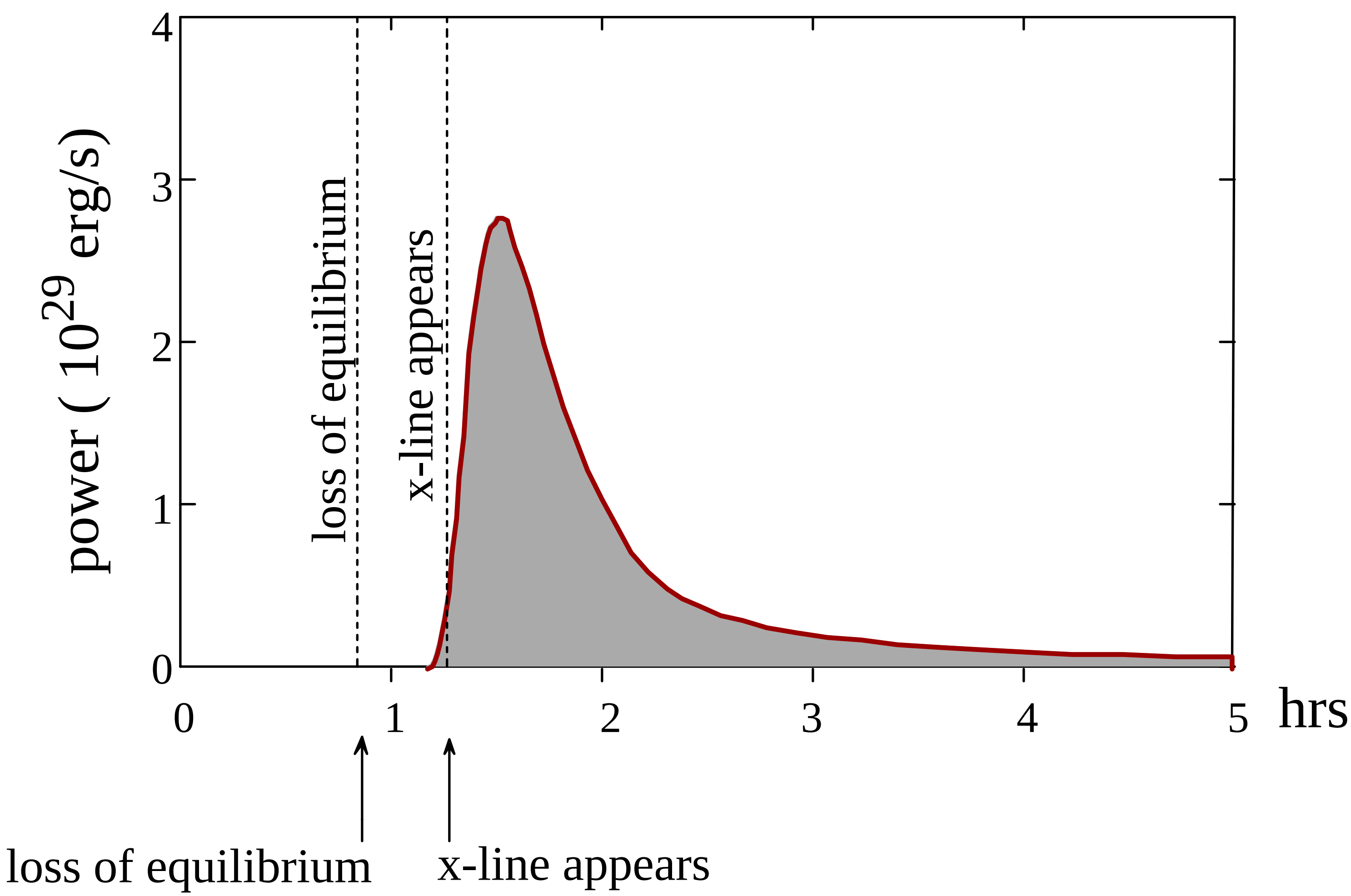
A Storage Model



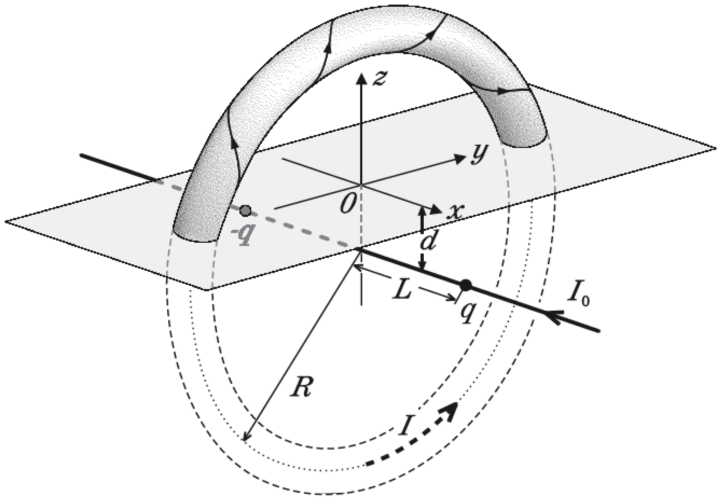
Trajectories



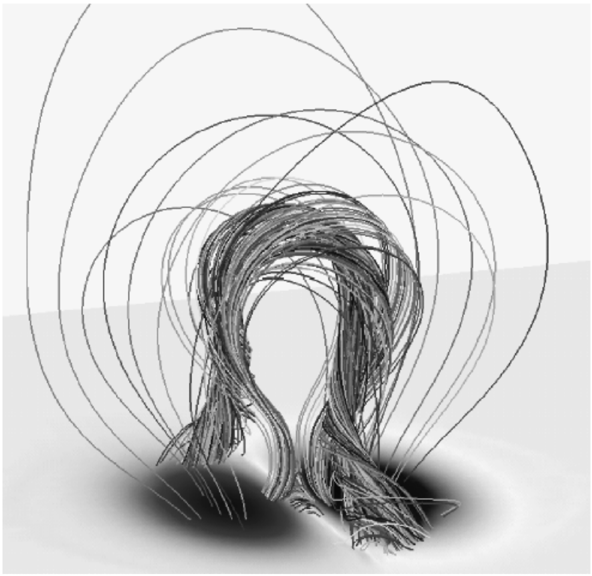
Power Output



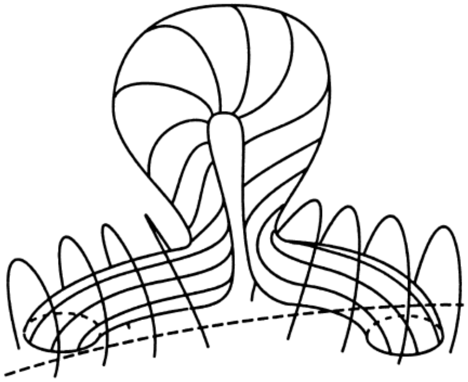
Three-Dimensional Storage Models



Titov & Démoulin 1999

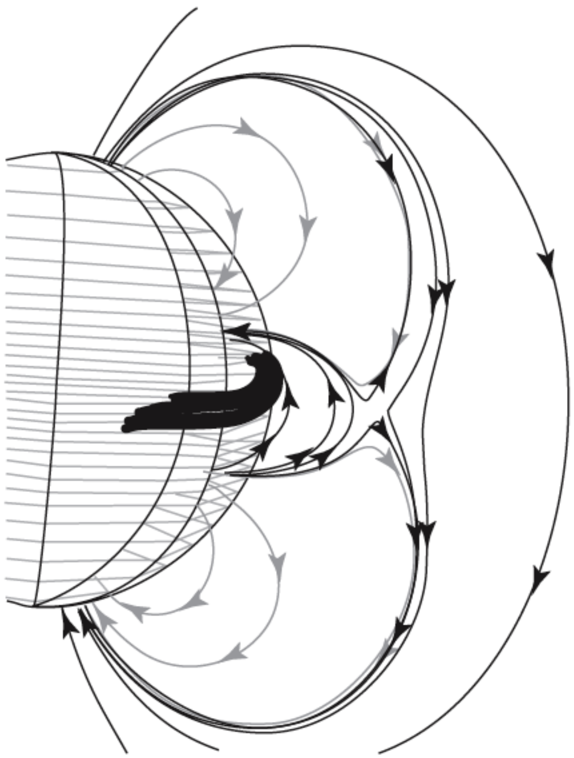


Amari et al. 2000



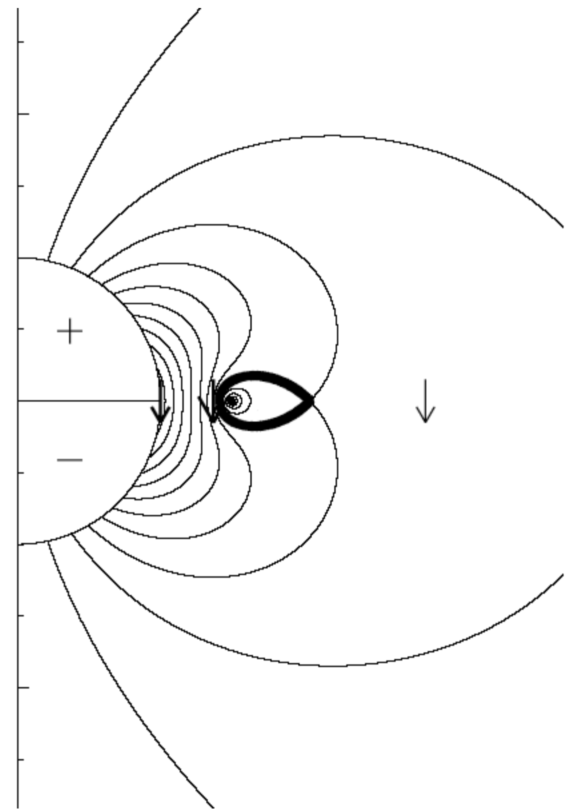
Sturrock et al 2001

Other Storage Models



breakout model

(Antiochos et al. 1999)

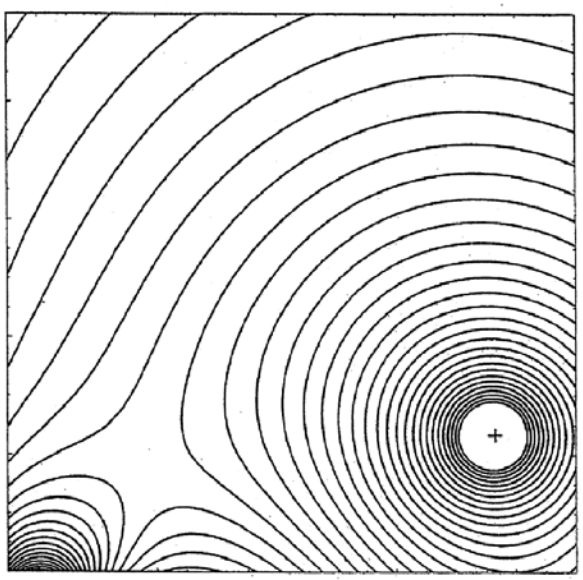


flux rope with normal polarity

(Low & Zhang 2002)

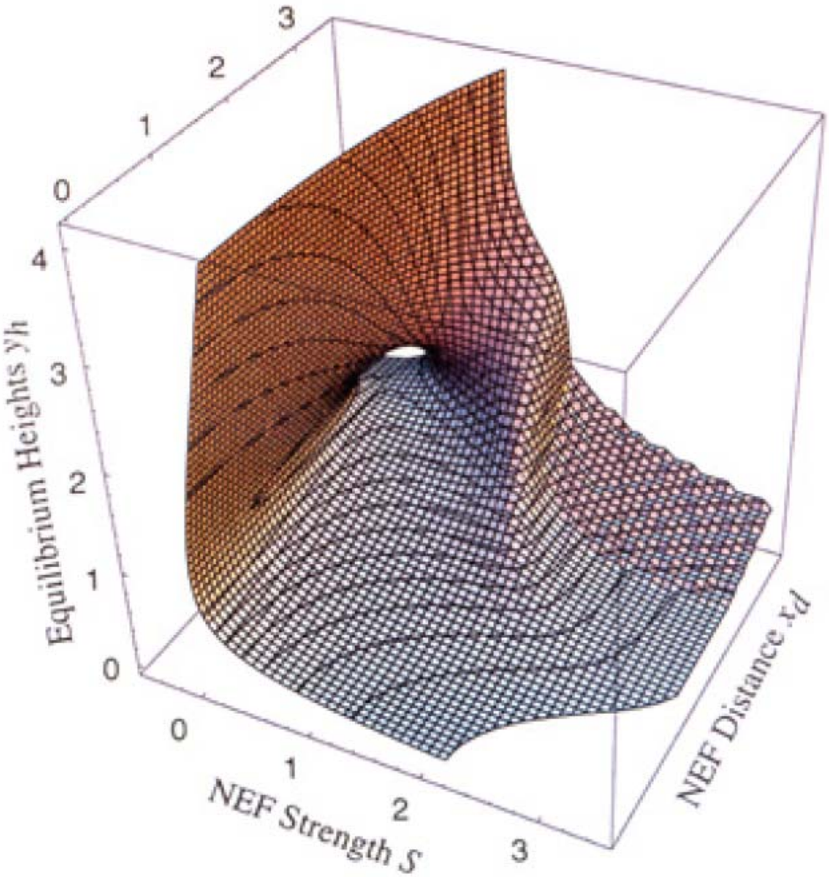
Hybrid Storage Models:

"tether cutting" model



Ideal + Non-Ideal Processes

equilibrium manifold

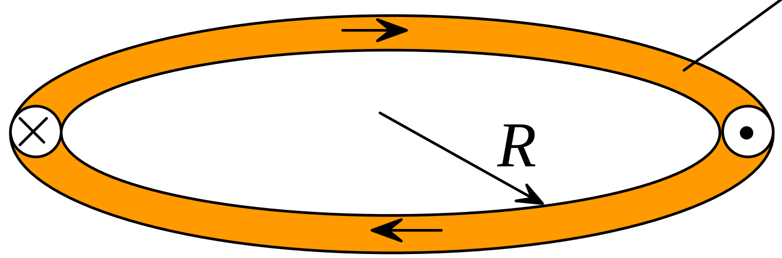


NEF: New Emerging Flux

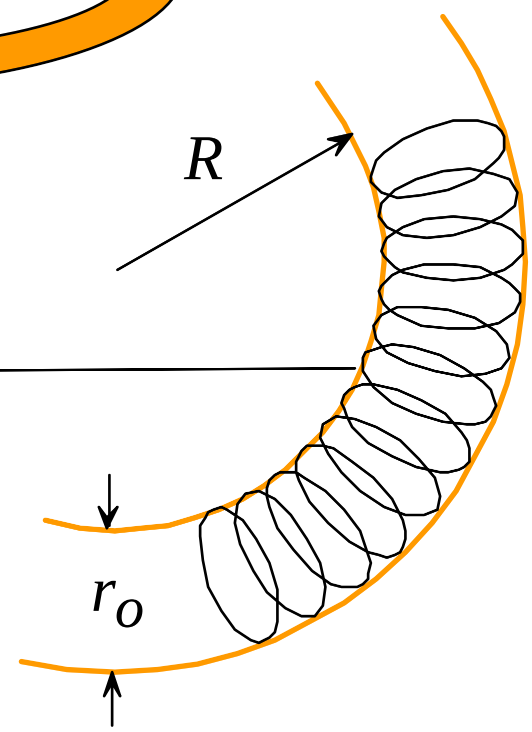
Basic Principles I

Driving Force:

ring with current I



inner edge is pinched by curvature of rope

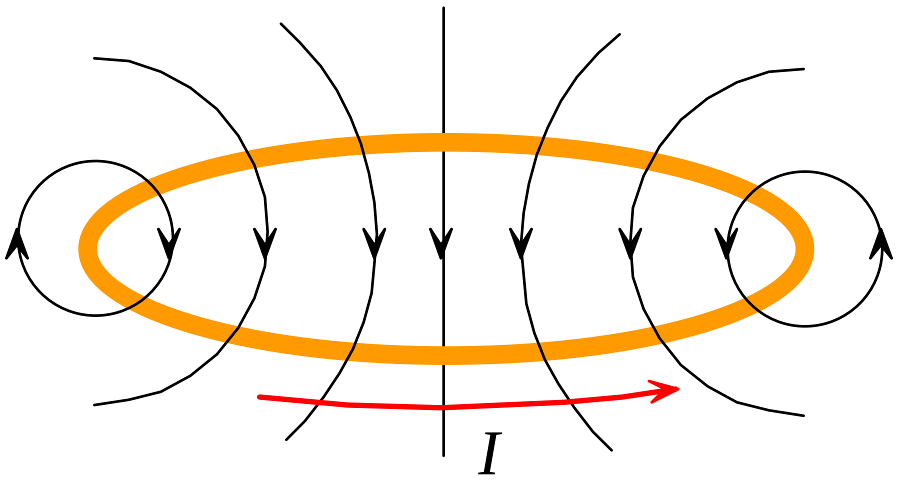


repulsive force:

$$F \propto \frac{I^2}{R} \ln (R / r_o)$$

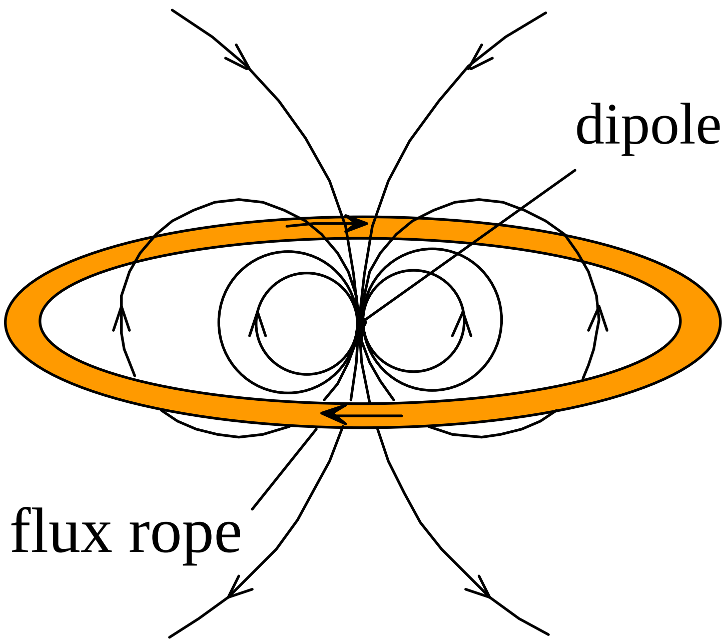
Basic Principles II

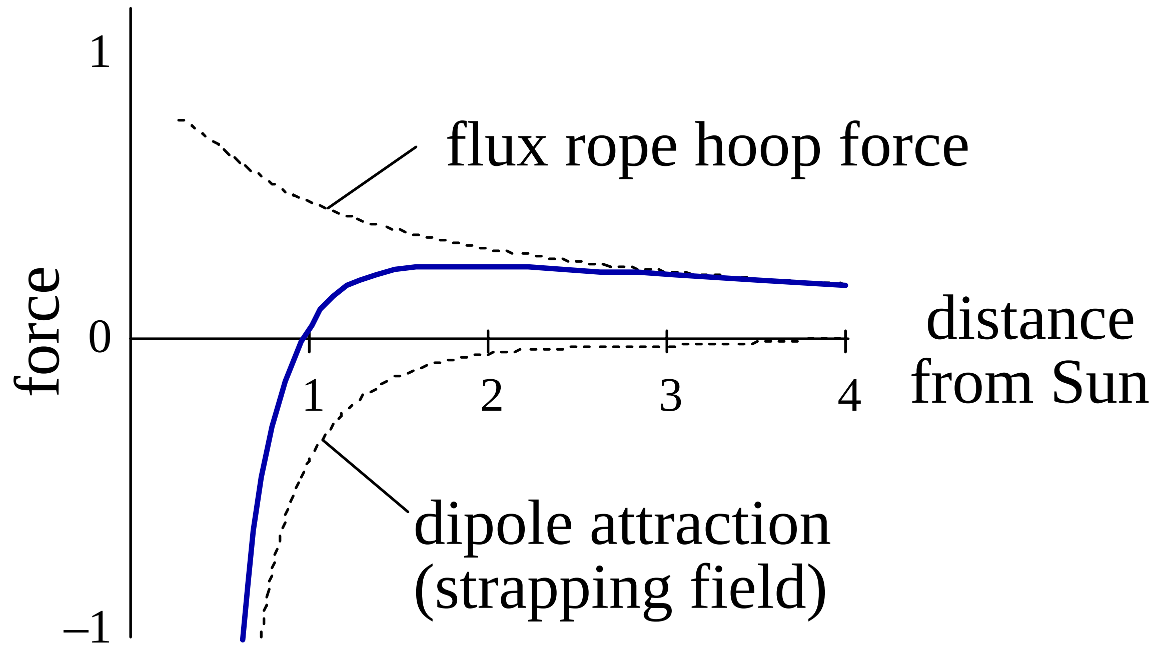
Flux Conservation:



$$I \propto 1/[R \ln(R/r_0)]$$

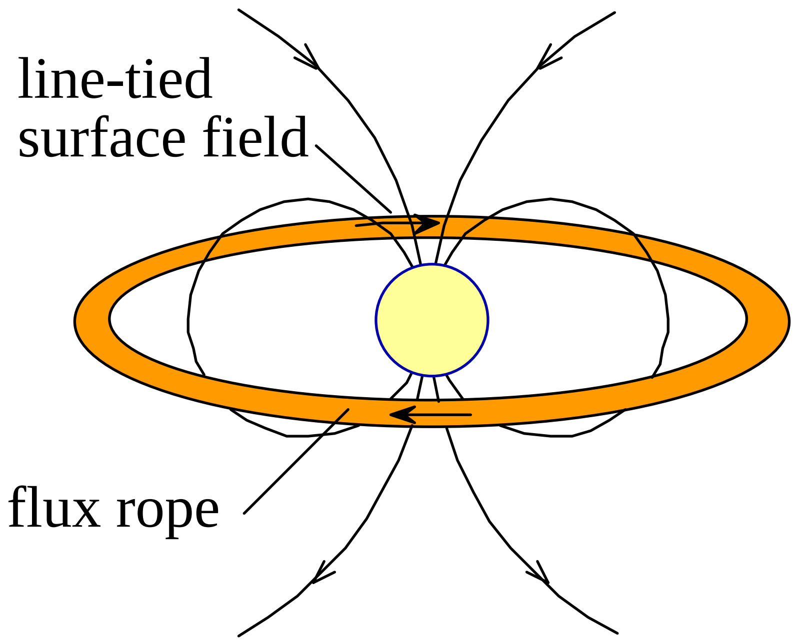
How to Achieve Equilibrium



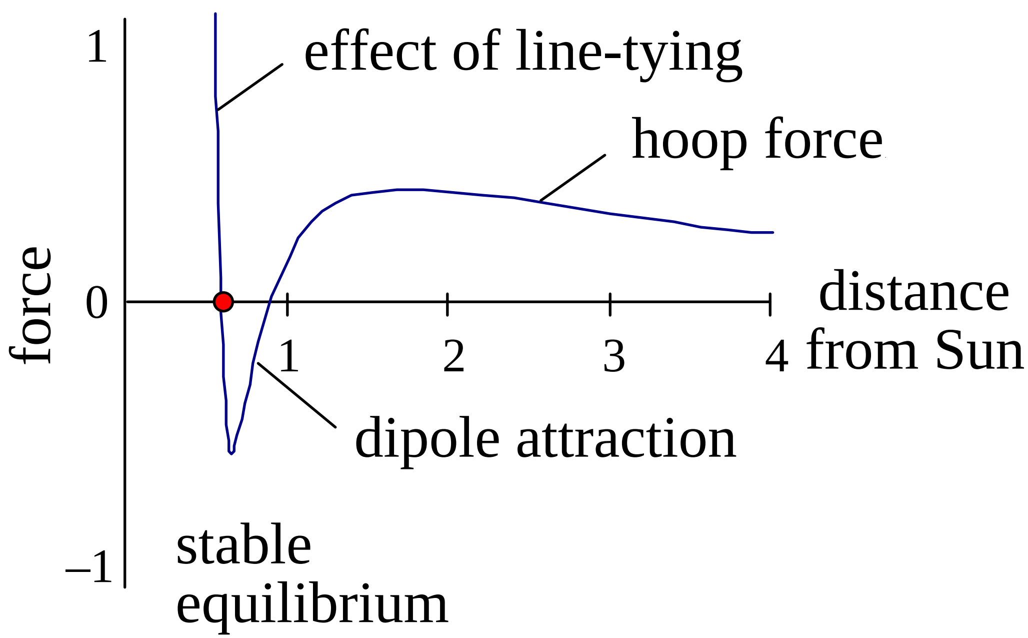


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium



Key factor: Line-tying



Line-tying creates a second, stable equilibrium

3D Loss-of-Equilibrium Model

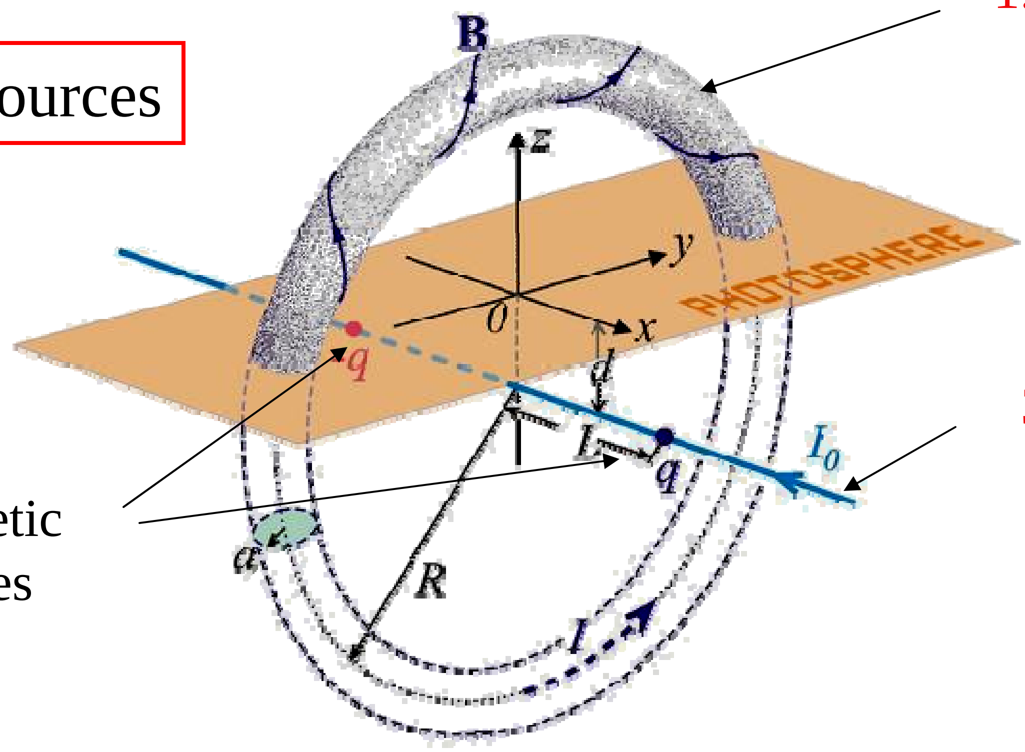
Titov & Démoulin (1999)

3 field sources

1. flux rope

2. magnetic charges

3. line-current



Simulation of “Torus*” Instability

QuickTime™ and a
GIF decompressor
are needed to see this picture.

1. no subsurface line current
2. subcritical twist for helical kink
3. torus center near surface

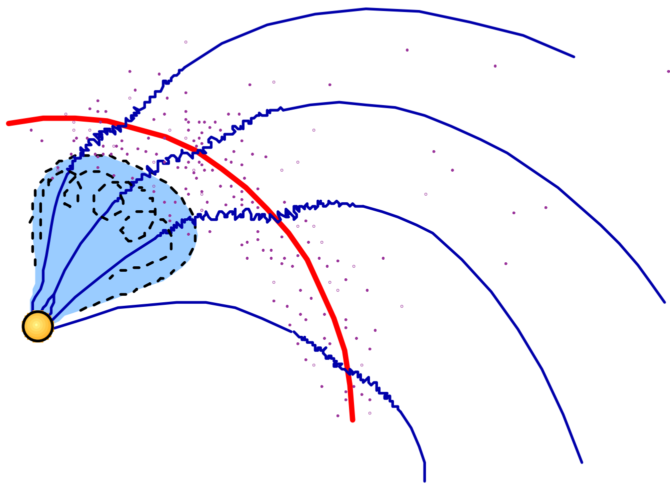
*nonhelical kink
(see Bateman 1973)

QuickTime™ and a
GIF decompressor
are needed to see this picture.

QuickTime™ and a
Photo decompressor
are needed to see this picture.

Energetic Particles

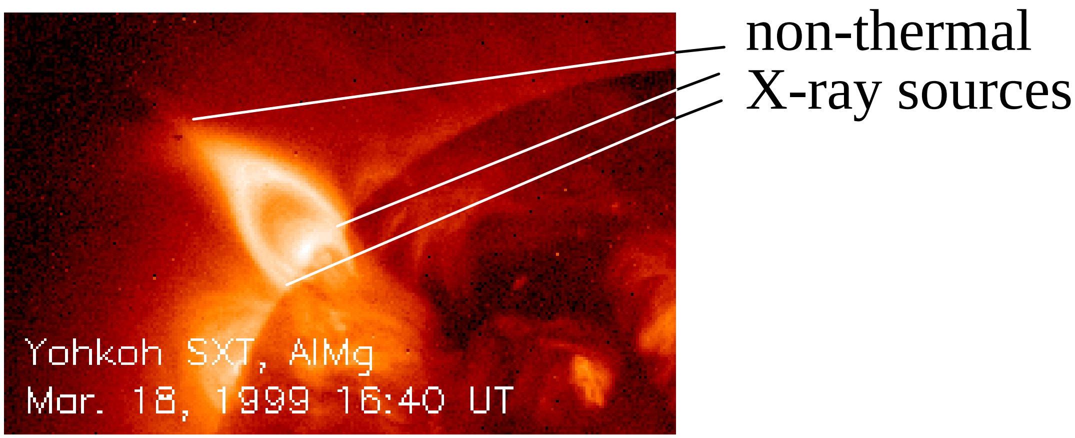
(1) CME driven shock acceleration



(a) shock properties at earliest times?

(b) elemental abundances?

(2) surface and lower corona



(a) turbulent fluctuations ?

(b) reconnection shocks ?

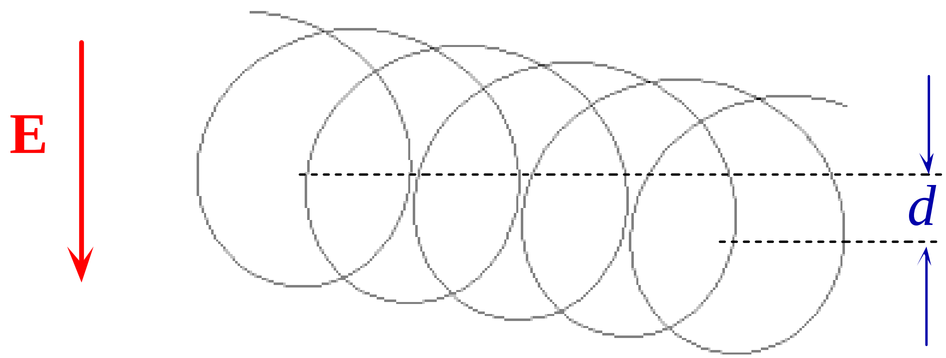
(c) reconnection *E* field?

Key Particle Acceleration Parameters

energy gain / particle: $q\,E\,d$

electric
field

distance
traveled



Electric field for reconnection driven processes should be of order $V_A\,B$.

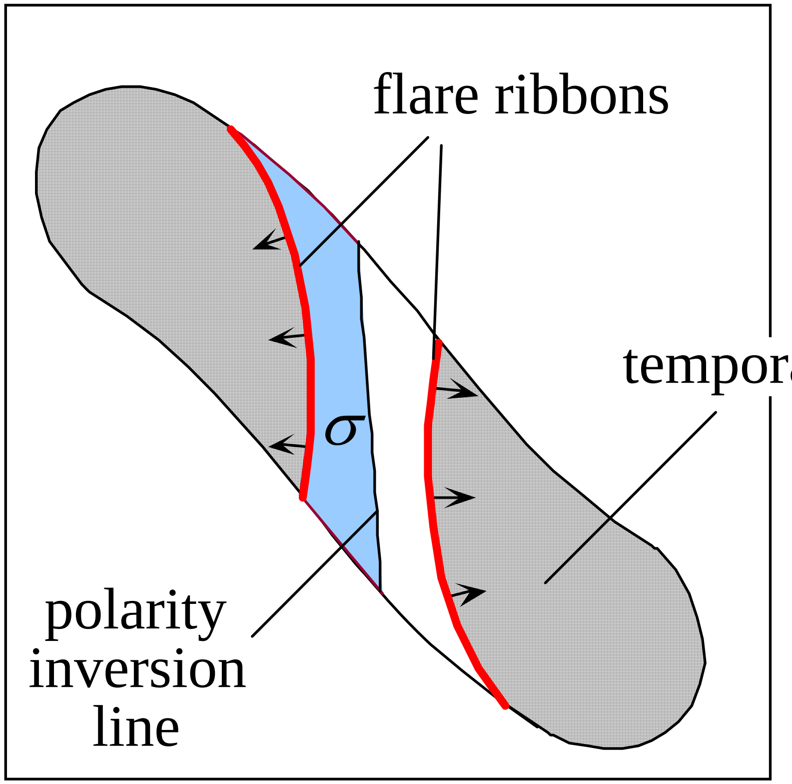
turbulence with $\Delta B/B \approx 1$

fast-mode shocks with $M_{fm} \approx 2$

- number accelerated
- acceleration time
- life time

Other parameters are key to determining efficiency of a particular mechanism.

Reconnection Electric Fields



newly reclosed flux:

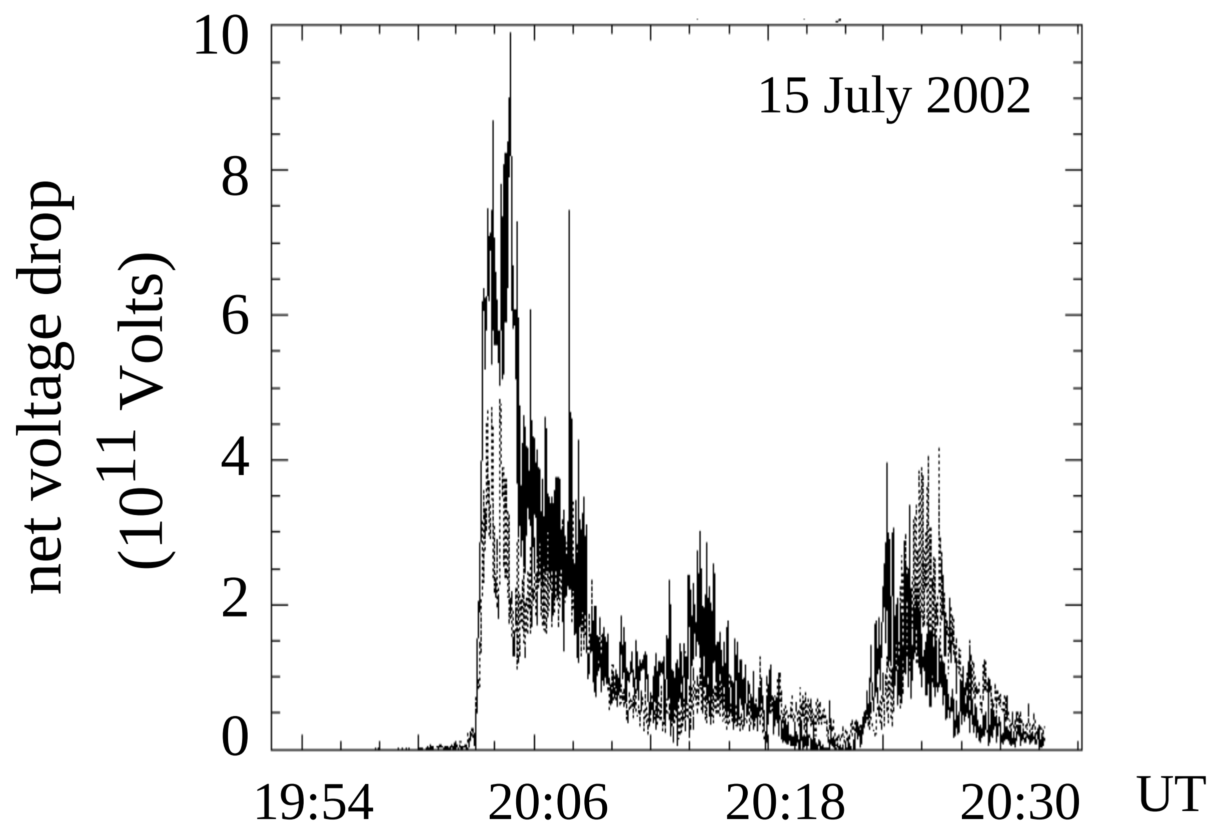
$$\Phi_B = \iint_\sigma B_z \, dxdy$$

global reconnection rate:

$$\int \mathbf{E} \cdot \mathbf{dl} = \frac{d\Phi_b}{dt}$$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Observed Reconnection Rate for X3 Flare

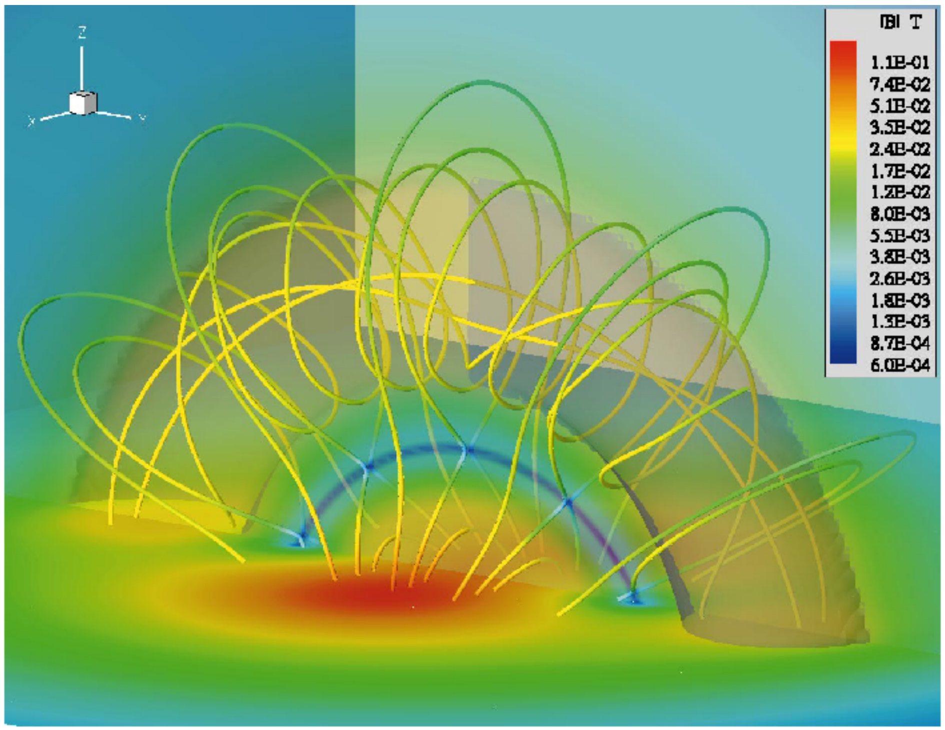


for estimated separator length of 2×10^5 km:

$E \approx 20$ Volts / cm

3D Flux Rope Simulation

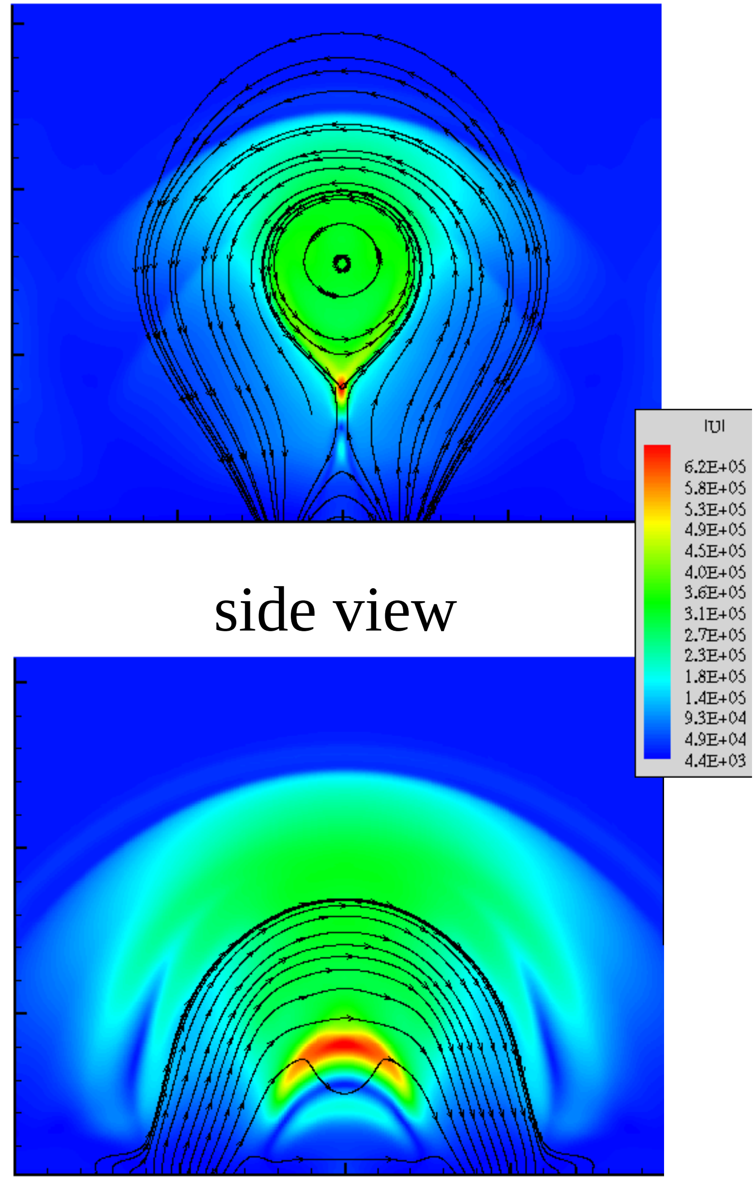
initial configuration



Roussev et al. (2003)

end-on view

side view



cross sections during eruption

QuickTime™ and a
BMP decompressor
are needed to see this picture.

QuickTime™ and a
YUV420 codec decompressor
are needed to see this picture.

Summary

1. Sudden onset of solar eruption is suggestive of an ideal-MHD process.

2. Magnetic reconnection accounts for about 90% of total energy release.

3. No consensus exists as to what triggers an the magnetic field to erupt.