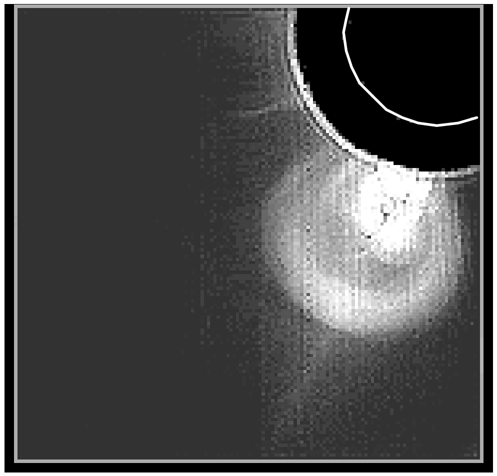
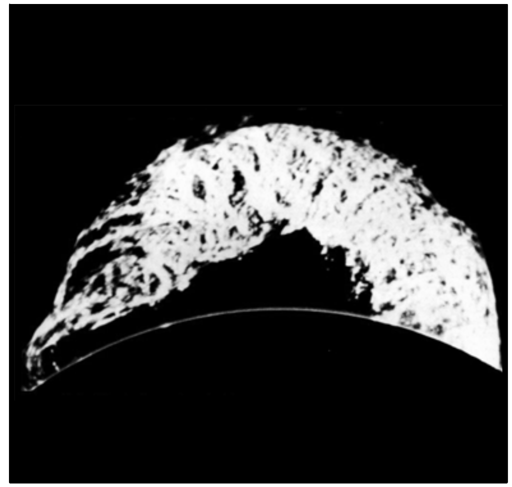
CME's and Flares

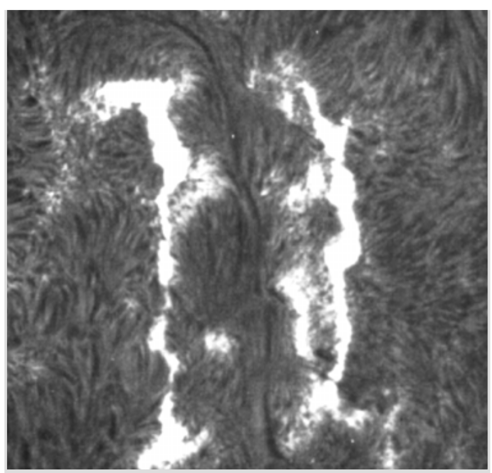
coronagraph (CME)



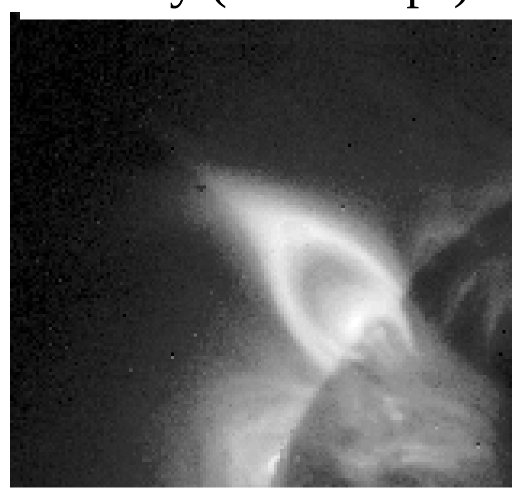
Hα limb (prominence)



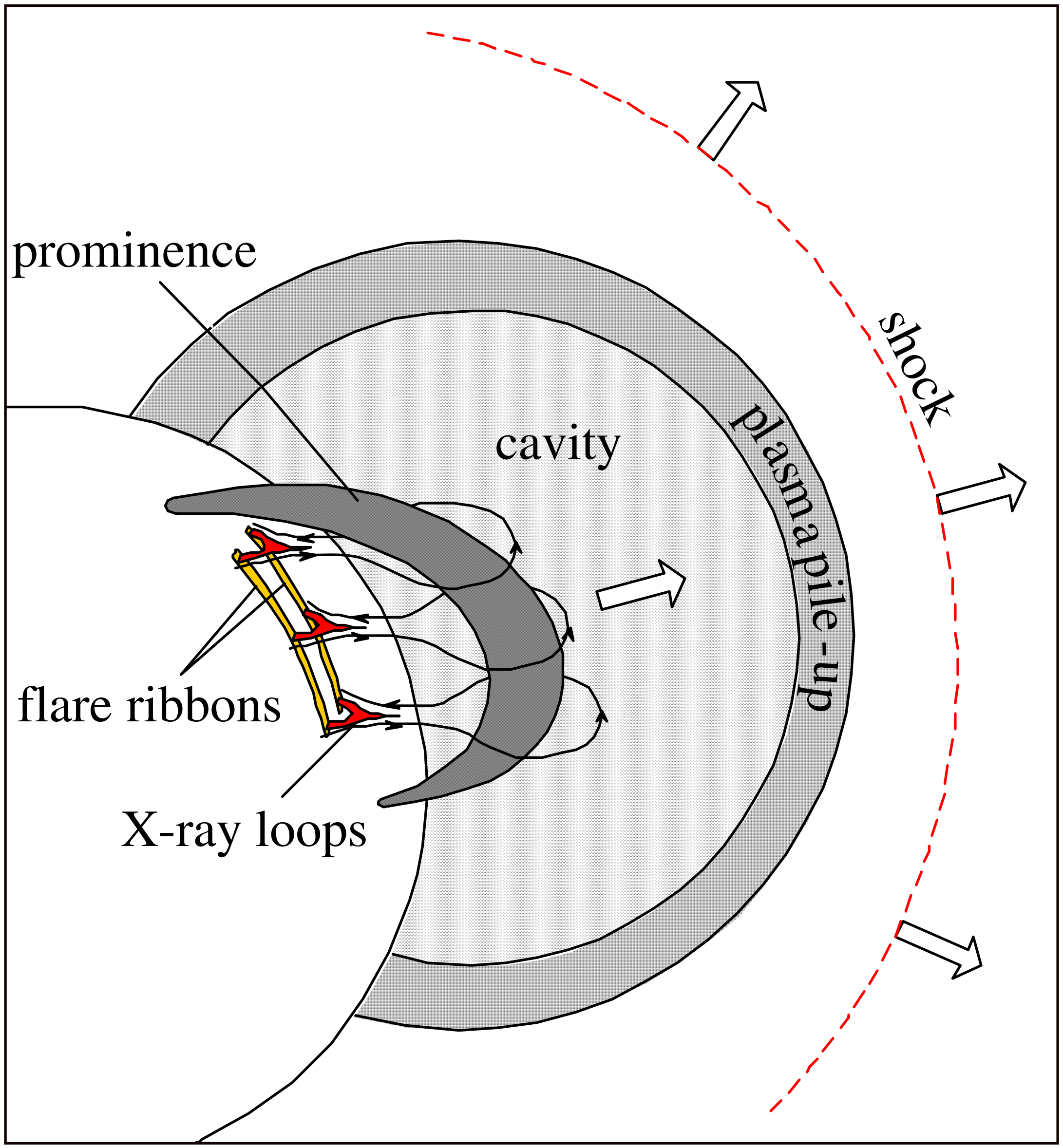
Hα disk (flare ribbons)



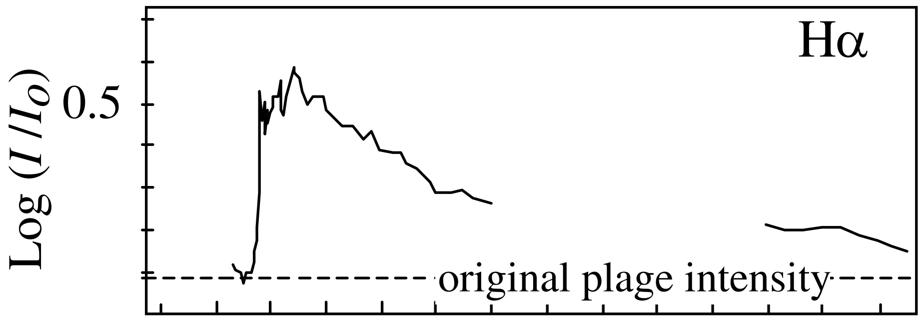
X-ray (flare loops)

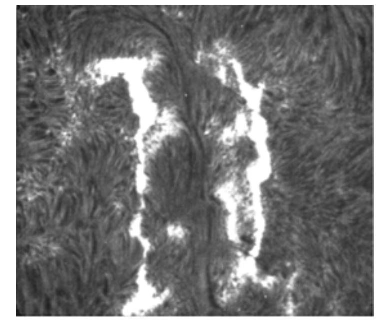


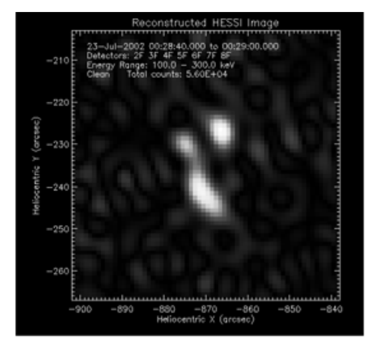
Large Solar Eruptions



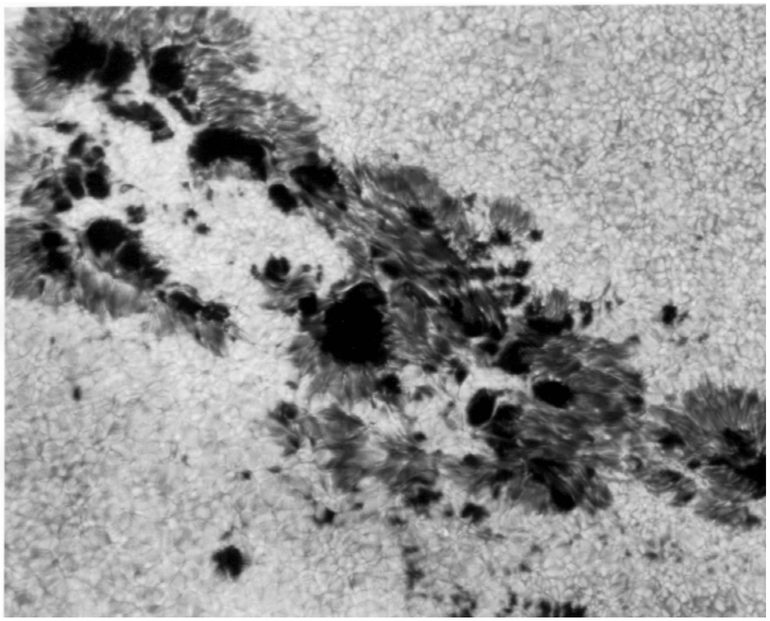
QuickTime™ and a
Video decompressor
are needed to see this picture.


Hα
0.5
Log (I /I_O)
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
-210
-220
-230
-240
-250
-260
Heliocentric Y (arcsec)
-900 -890 -880 -870 -860 -850 -840
Heliocentric X (arcsec)

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.

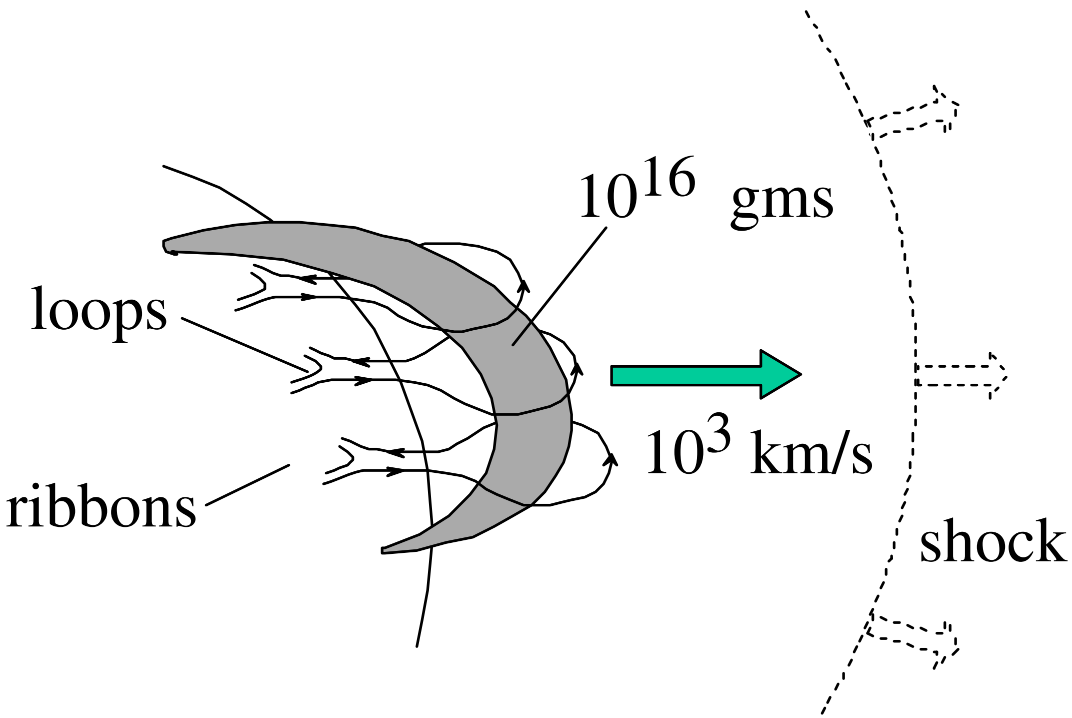
Evolution of the photosphere is slow compared to time scale of eruptions.

CME/Flare 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

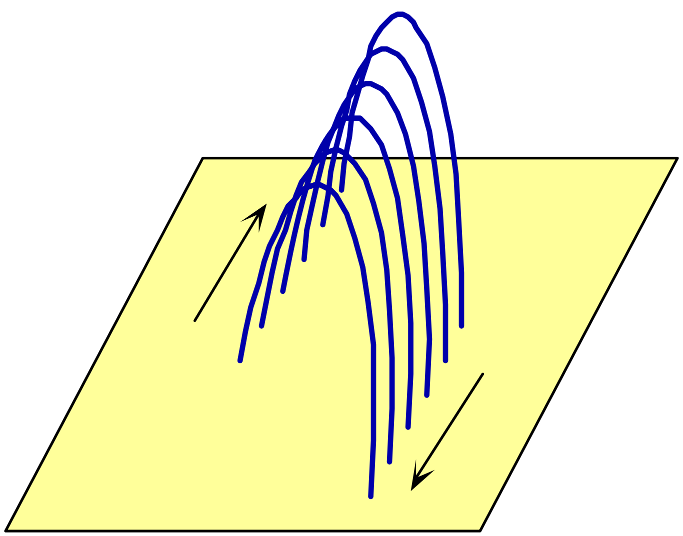
Type	Observed Values	Energy Density
kinetic $(m_p n V^2)/2$	$n = 10^9$ cm^{-3} $V = 1$ km/s	10^{-5} ergs/cm^3
thermal nkT	$T = 10^6$ K	0.1 ergs/cm^3
gravitational $m_p n g h$	$h = 10^5$ km	0.5 ergs/cm^3
magnetic $B^2/8\pi$	$B = 100$ G	400 ergs/cm^3

How is Energy Stored?

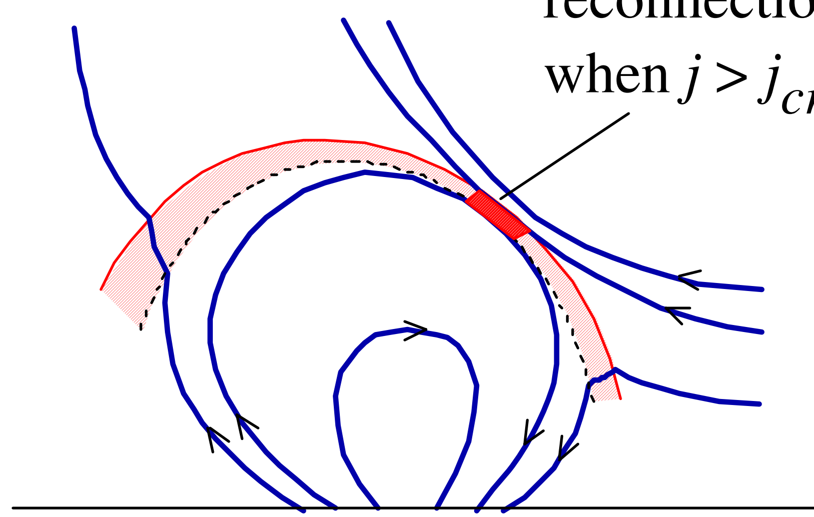
$\beta = 10^{-3}$ $\nabla p \approx 0$ $\mathbf{j} \times \mathbf{B} \approx 0$

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

Current sheets:

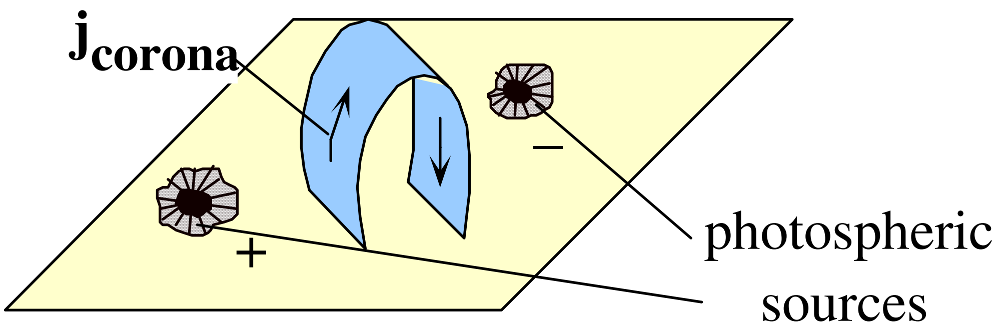


sheared magnetic fields

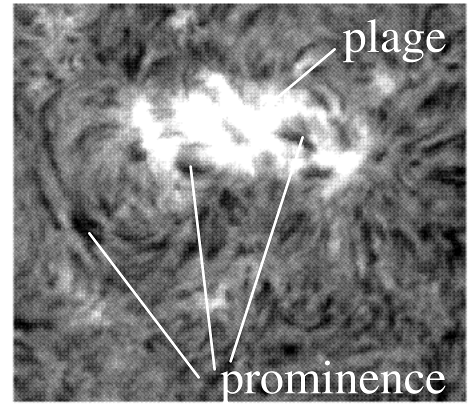


emerging flux model

How Much Energy is Stored?



Hα image



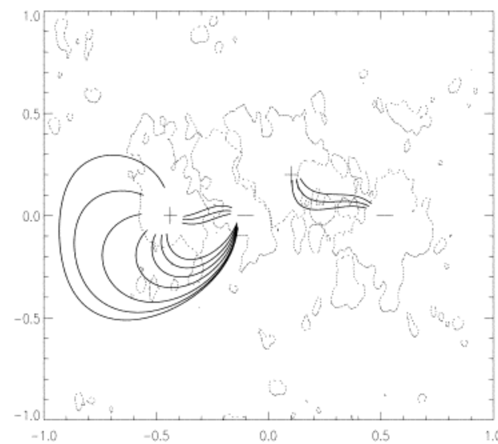
$$\mathbf{B} = \mathbf{B}_{\substack{\text{photospheric}\\ \text{currents}}} + \mathbf{B}_{\substack{\text{coronal}\\ \text{currents}}}$$

invariant during CME

source of CME energy

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

model with magnetogram

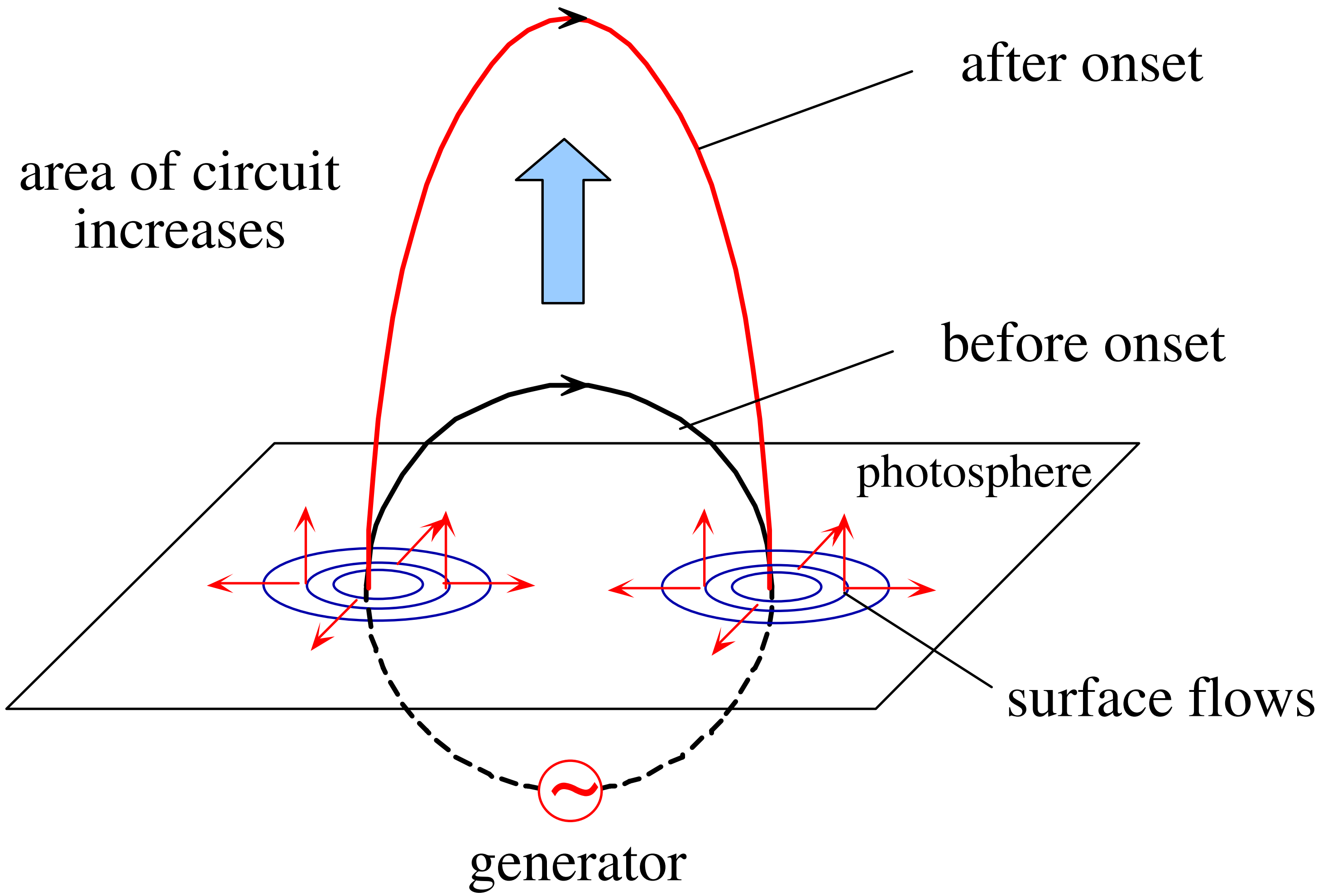


from Gaizauskas & Mackay (1997)

free magnetic energy ≈ 50% of total magnetic energy

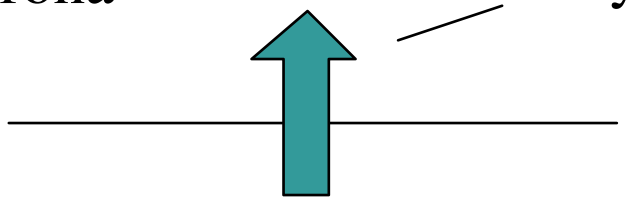
Flux Injection Models

(e.g. Chen 1989)



During injection energy flows through photosphere.

corona



convection zone

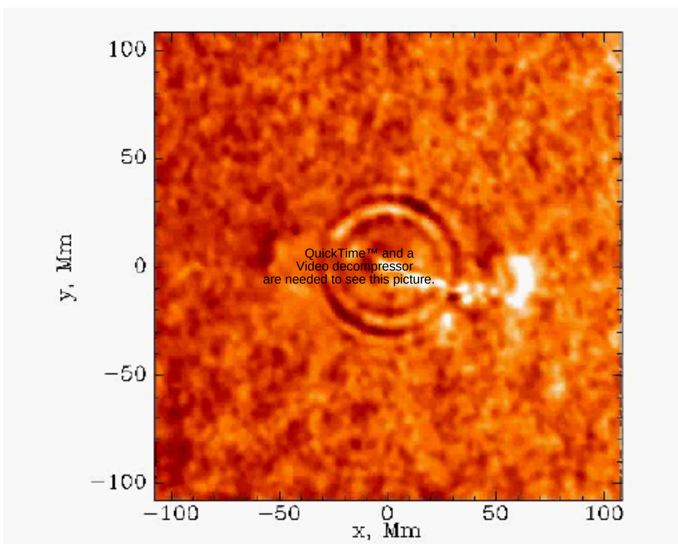
Poynting flux: $\mathbf{S} = c\, \mathbf{E} \times \mathbf{B} / (4\pi)$

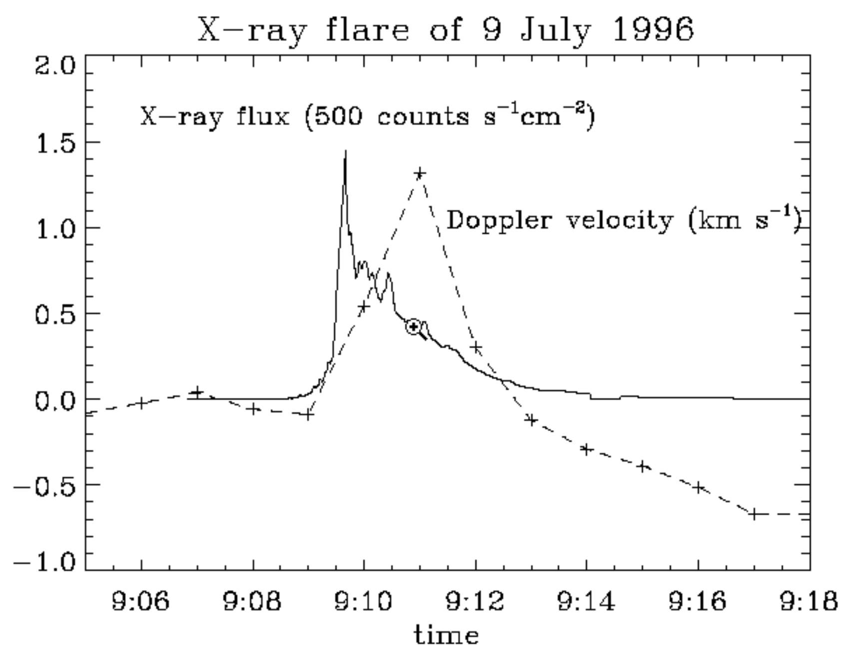
(ergs/cm/sec)

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

> 10 km/sec for > 10 minutes

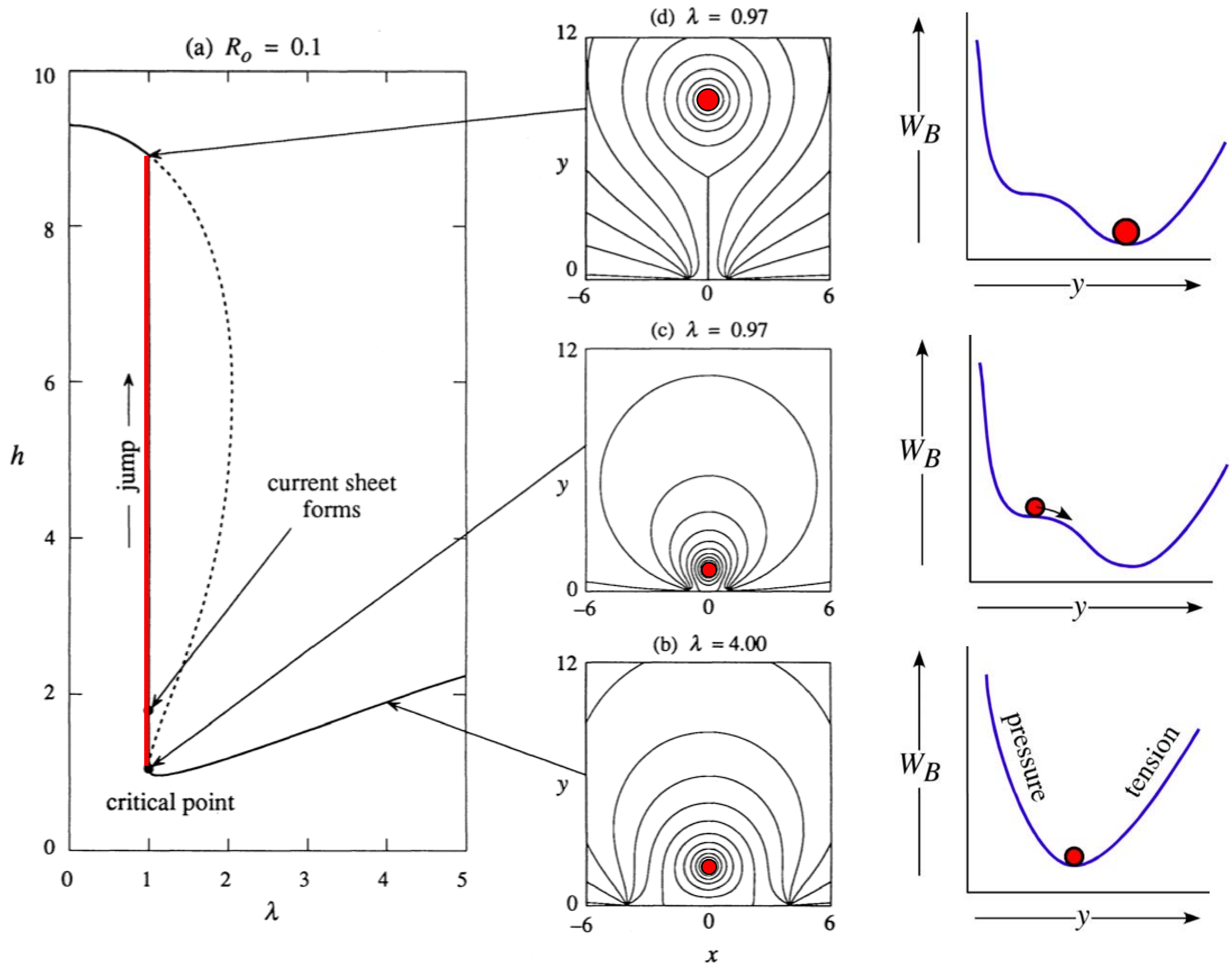
Kosovichev et al. 1998



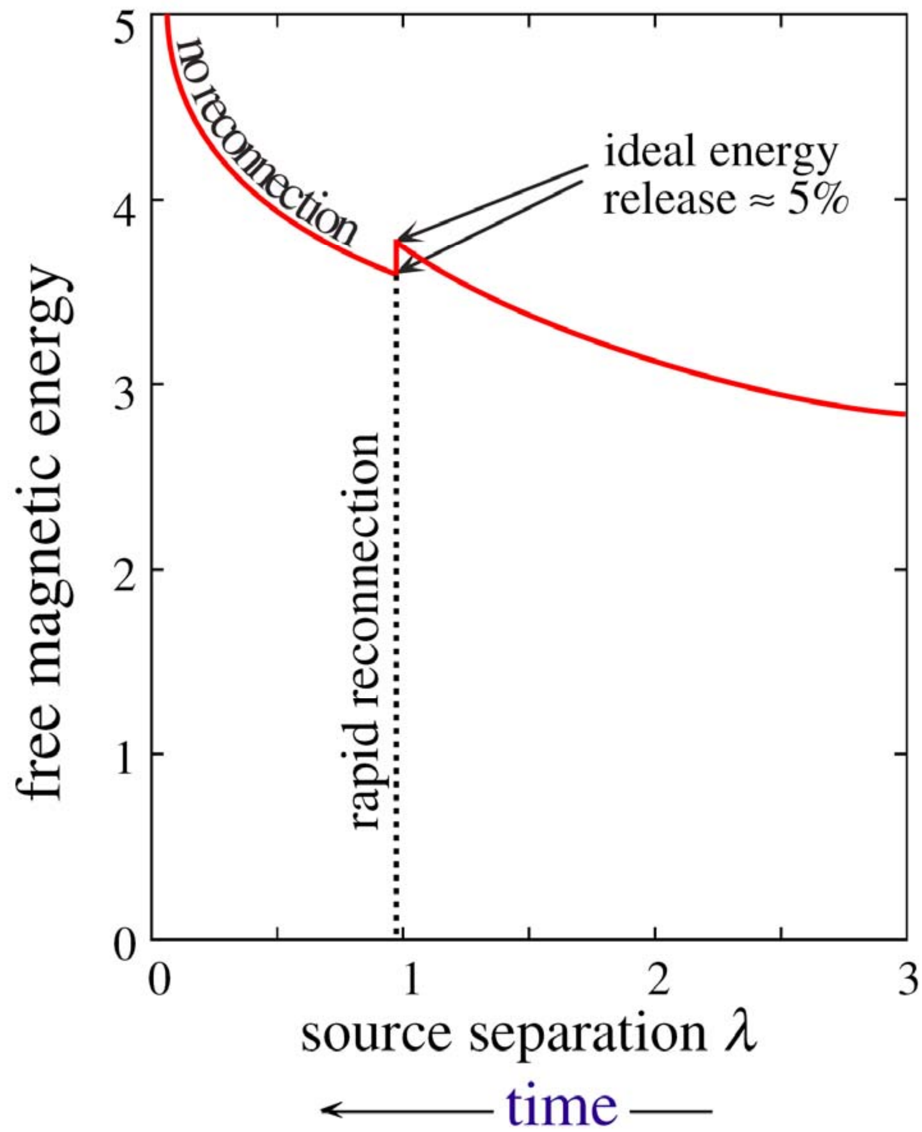


Injection models predict large surface flows which are never observed.

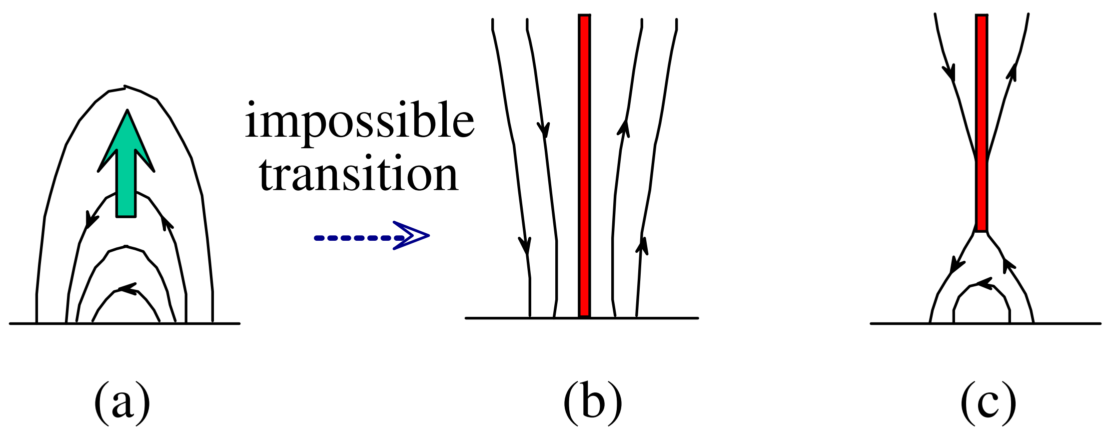
Loss of Equilibrium Model

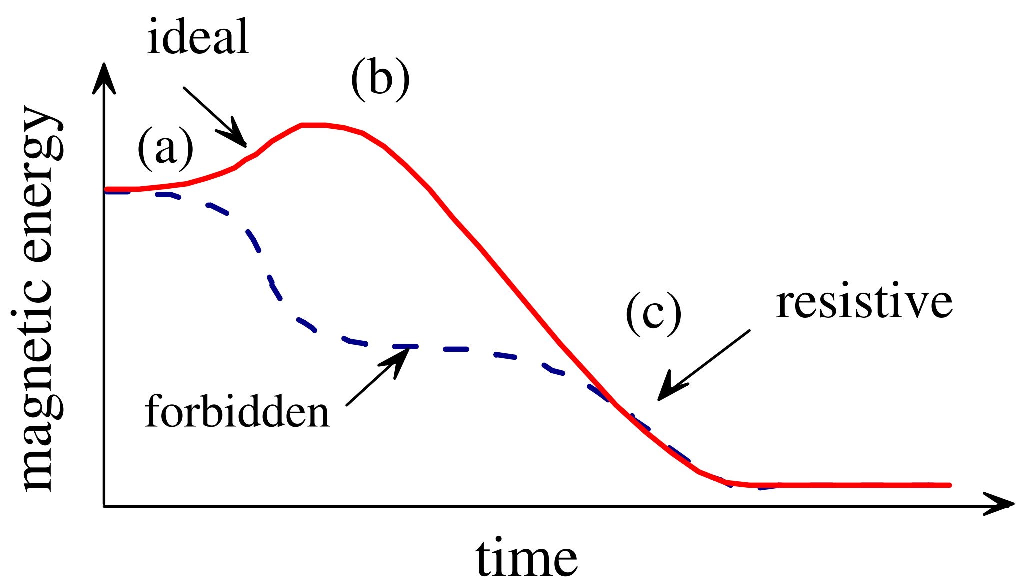


Energy Release in 2D Model

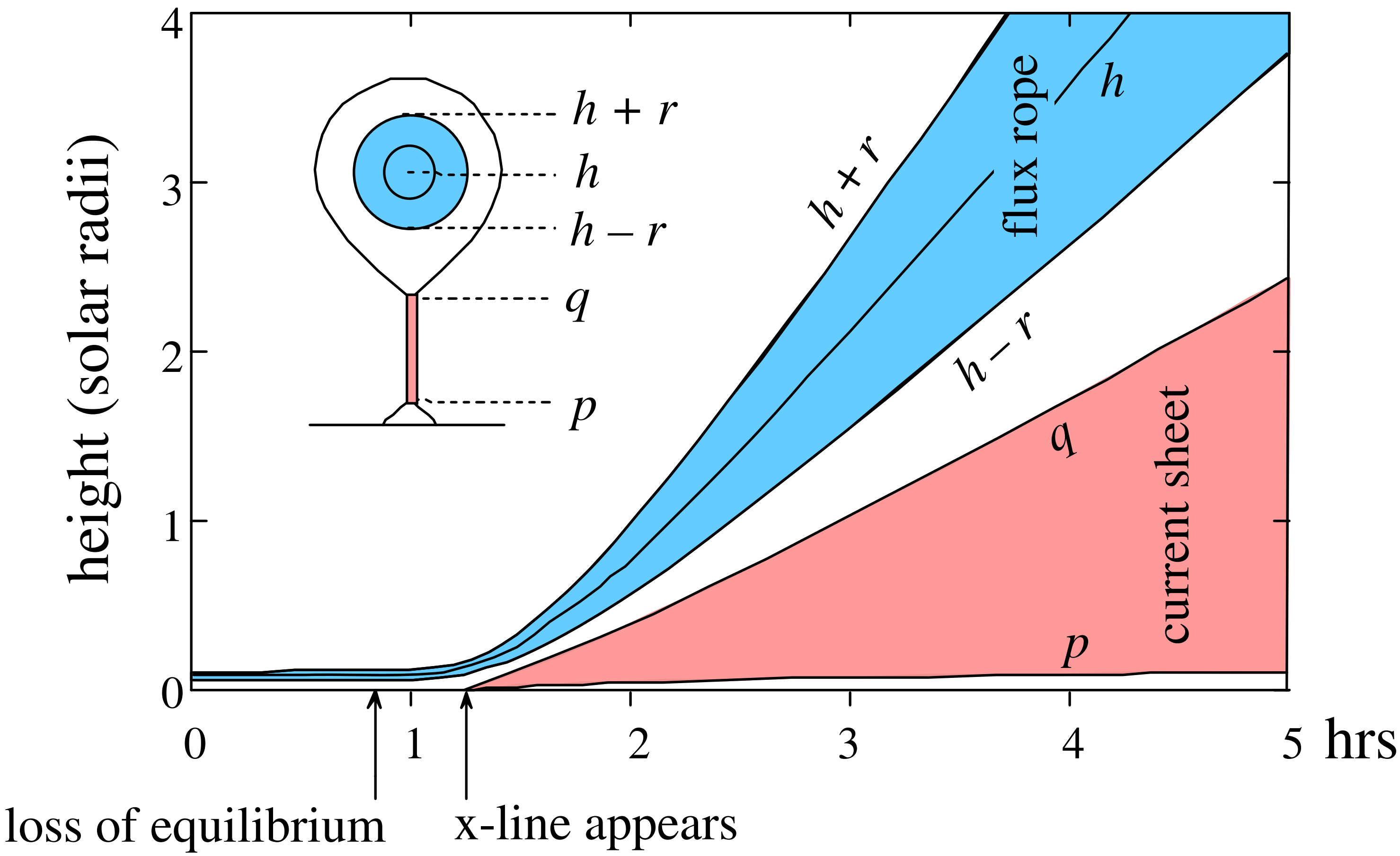


Aly - Sturrock Paradox

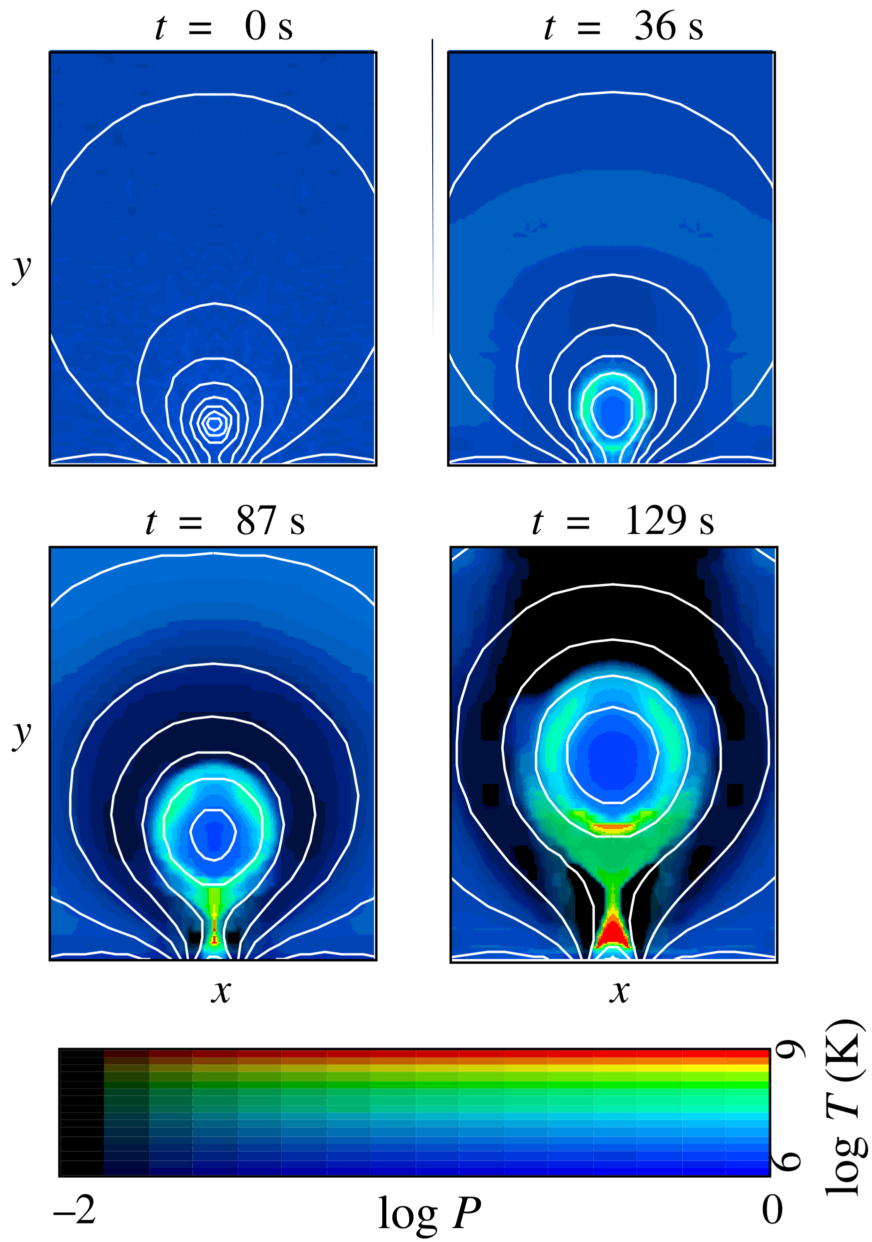




Trajectories



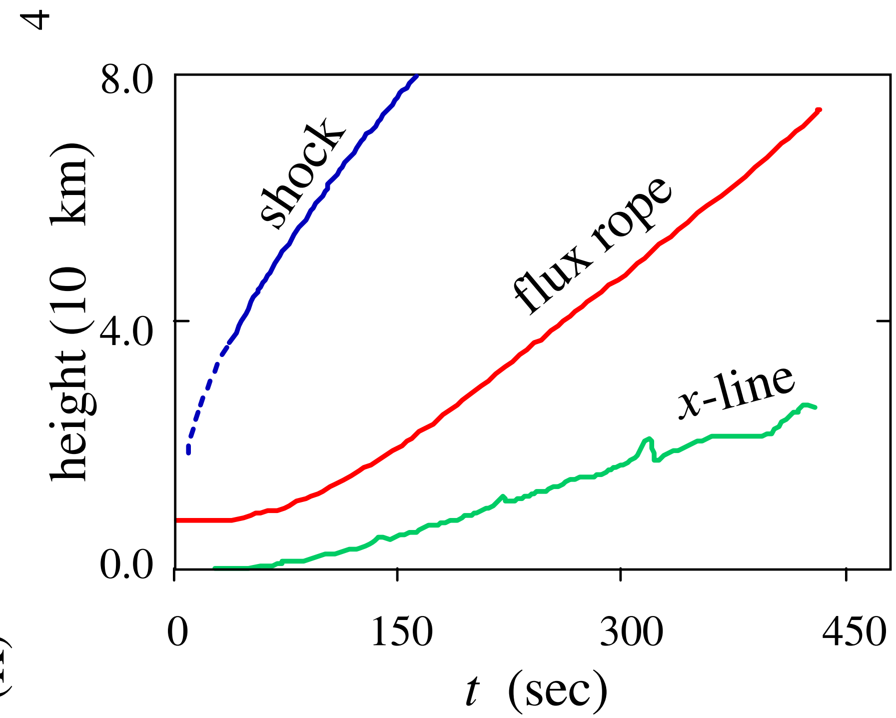
Numerical Simulation of Critical Point Configuration



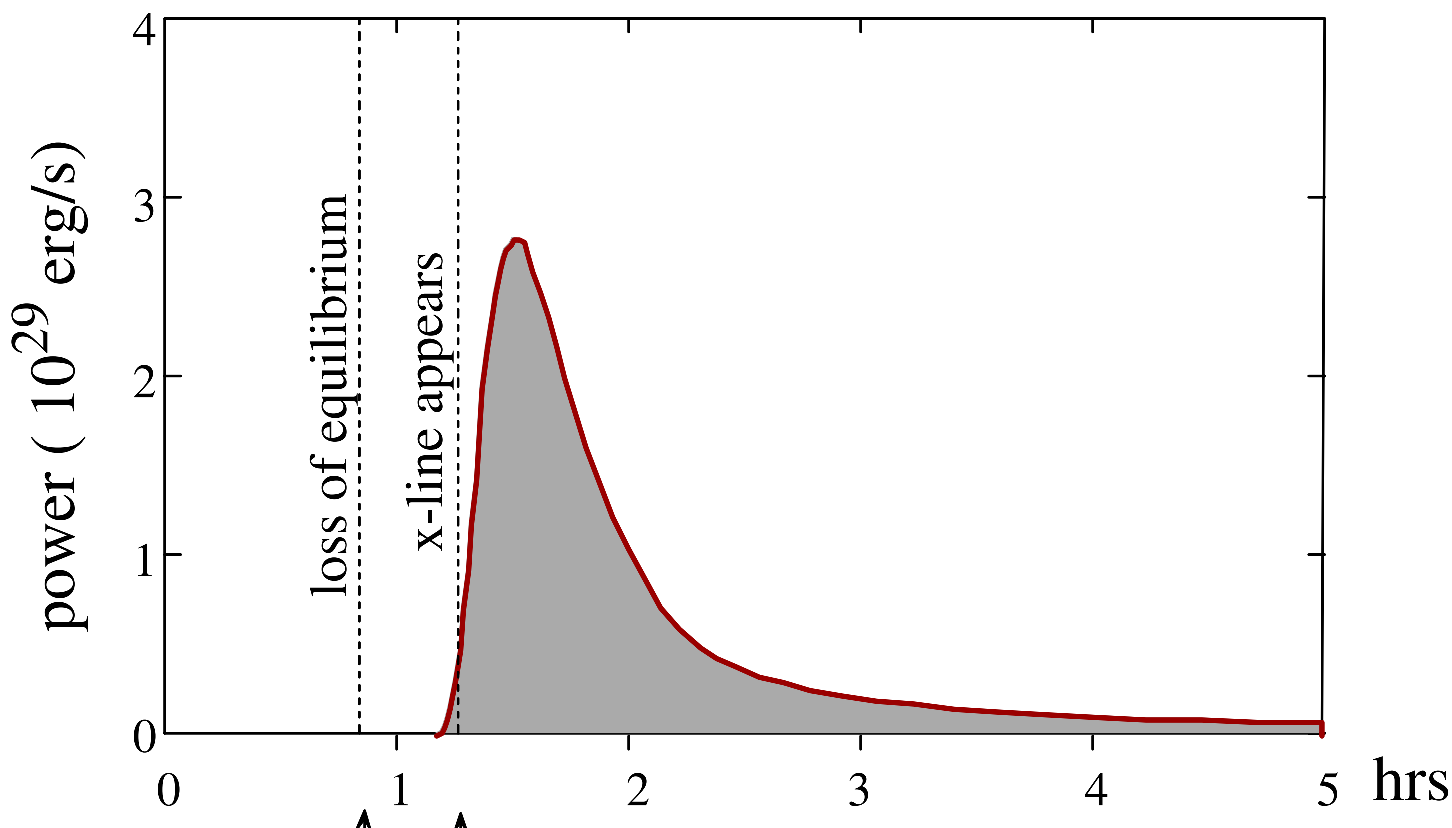
initial condition: **V** = 0

energy equation: Ohmic heating
no cooling

resistivity: uniform, S = 500

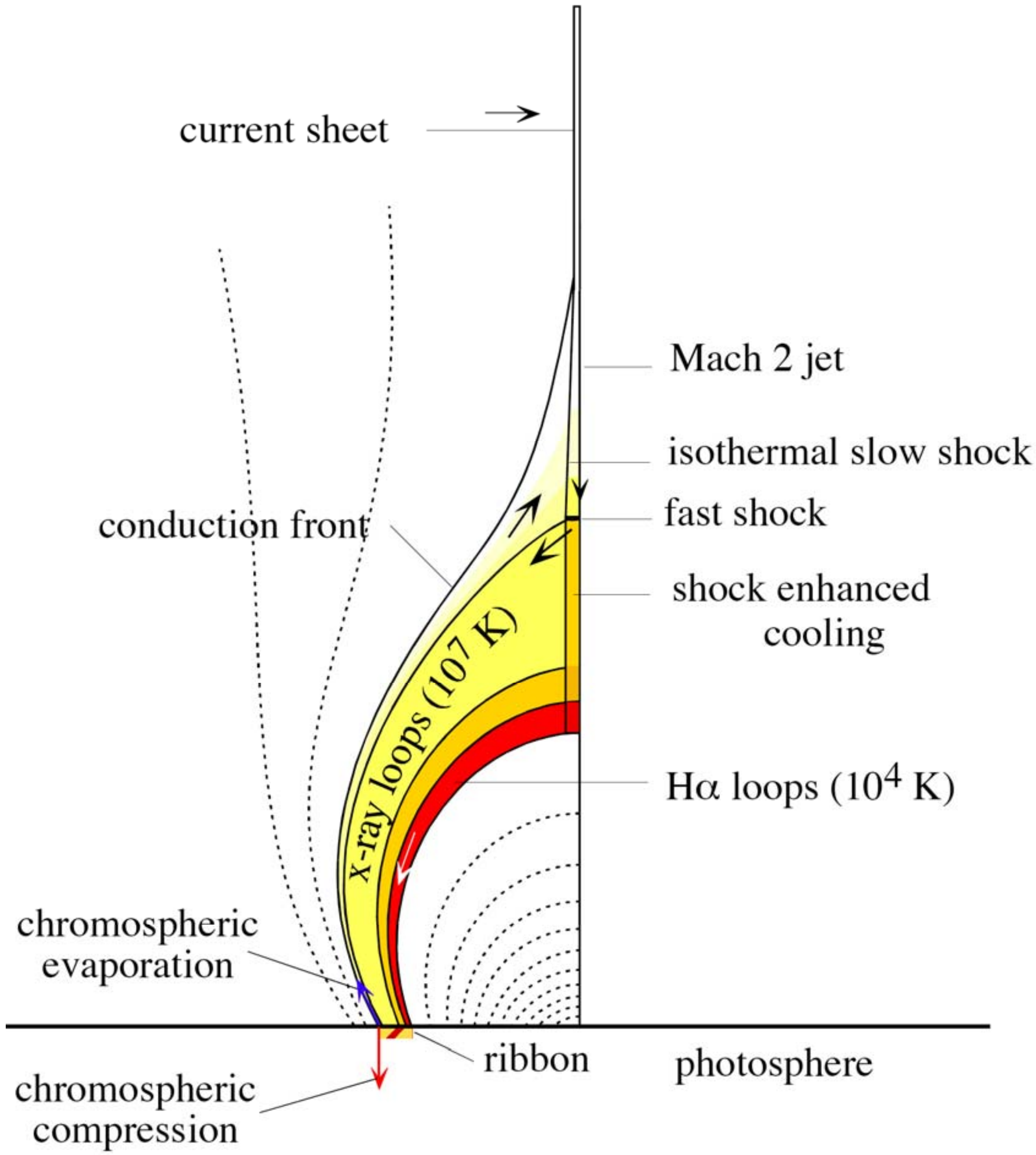


Power Output



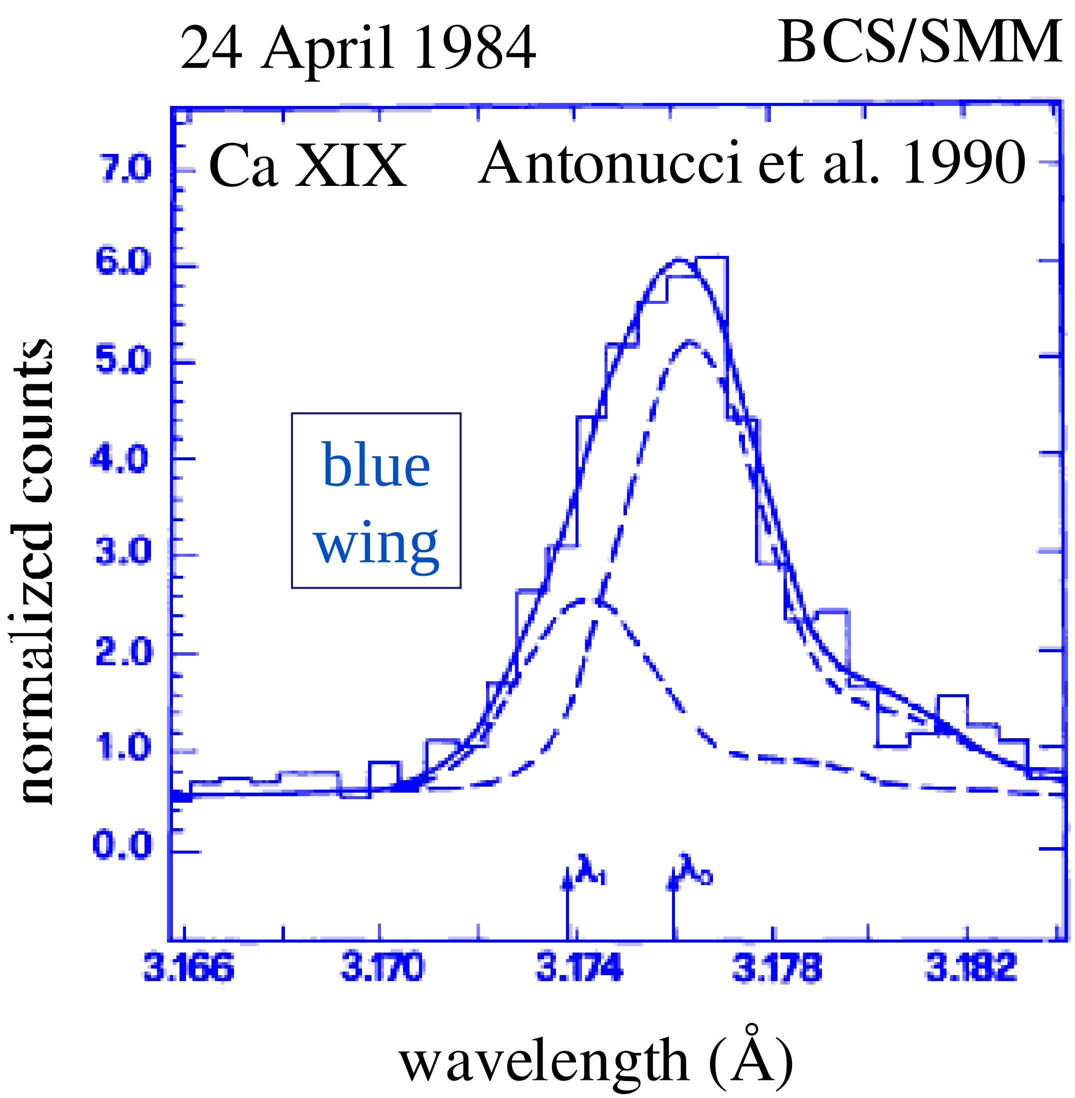
loss of equilibrium x-line appears

Chromospheric Evaporation



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

Evaporation Doppler Shift Puzzle

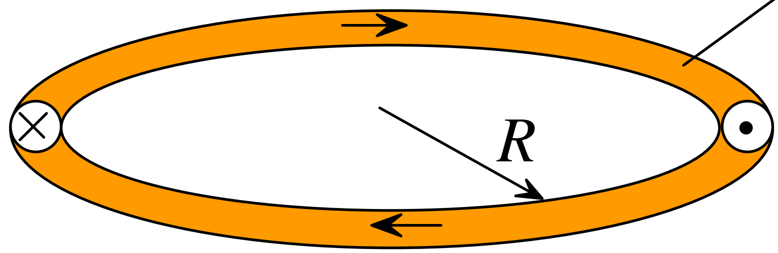


QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

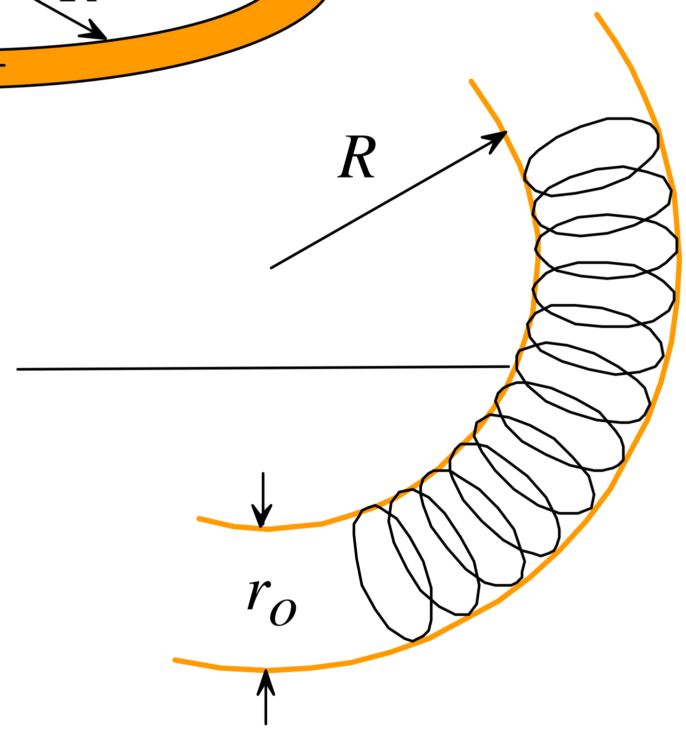
Basic Principles I

Driving Force:

ring with current I



inner edge is pinched by curvature of rope

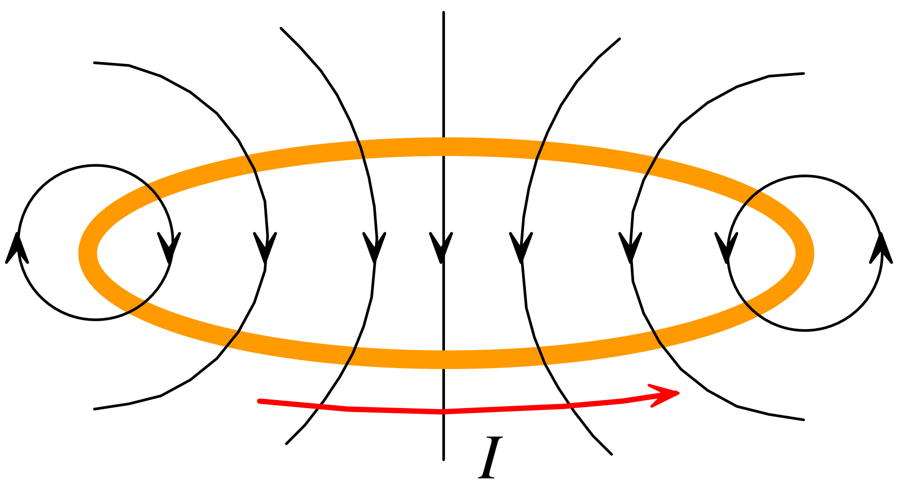


repulsive force:

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

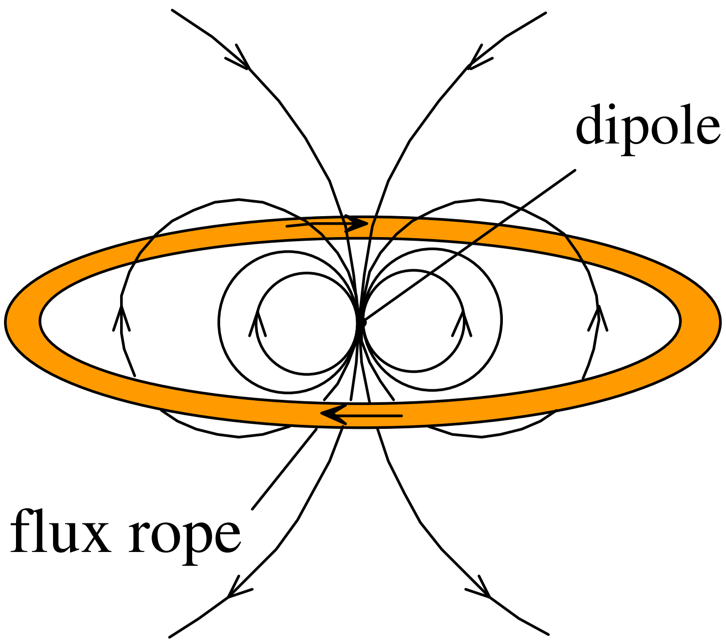
Basic Principles II

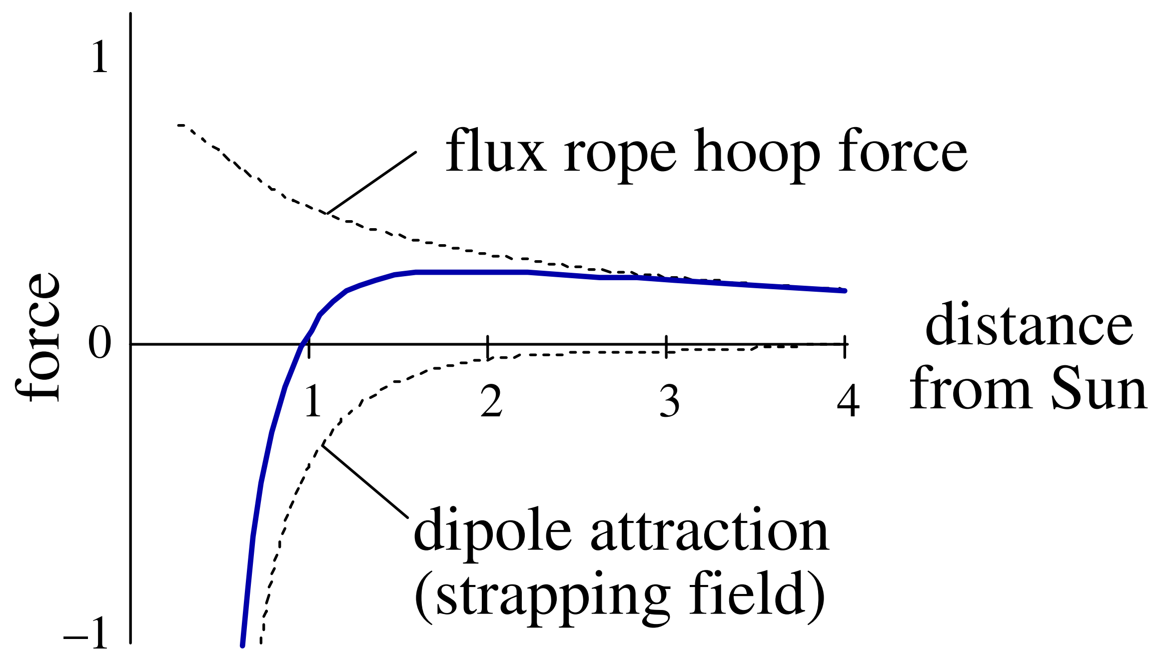
Flux Conservation:



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

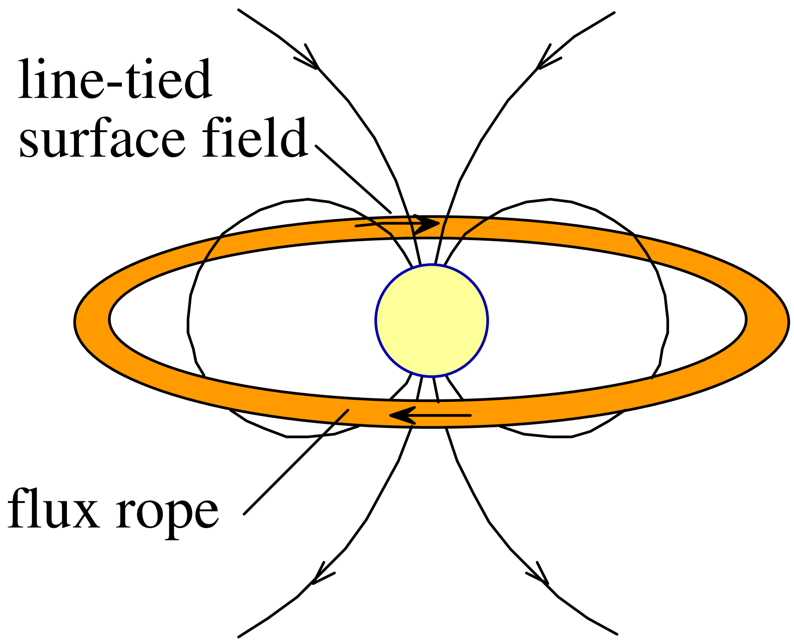
How to Achieve Equilibrium



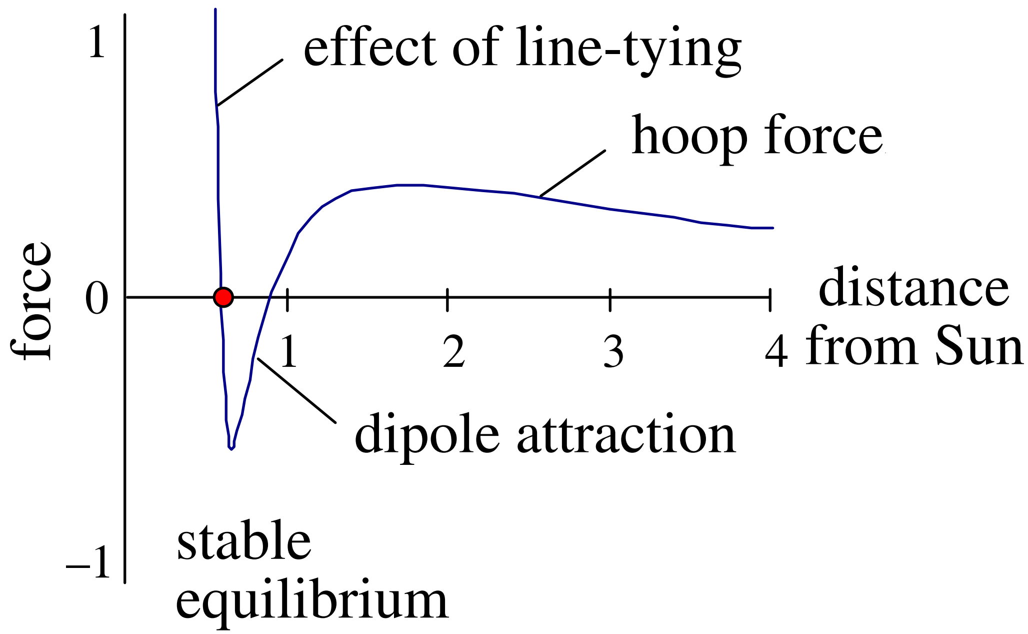


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium



Key factor: Line-tying

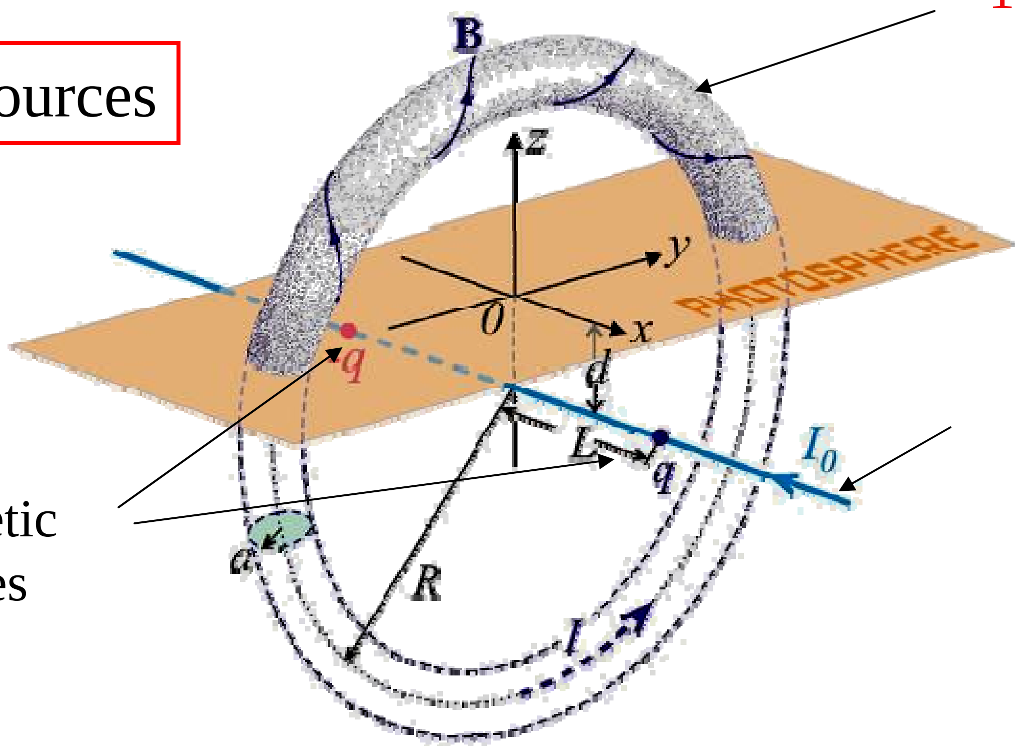


Line-tying creates a second, stable equilibrium

3D Loss-of-Equilibrium Model

Titov & Démoulin (1999)

3 field sources



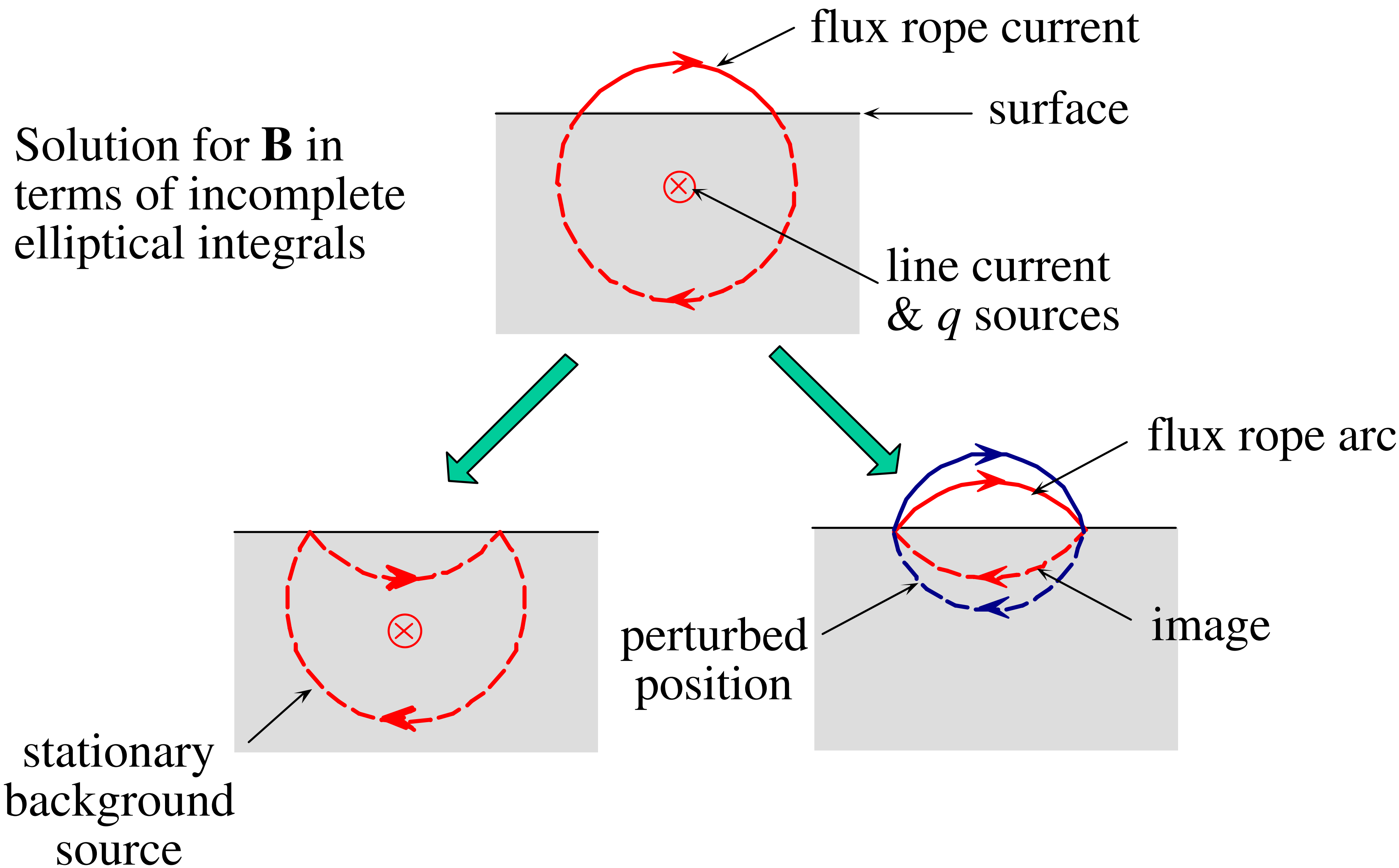
1. flux rope

2. magnetic charges

3. line-current

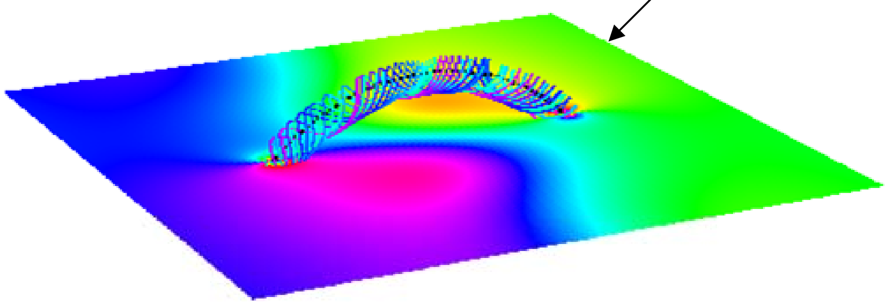
3D Line-Tied Solution by Method of Images

Solution for **B** in terms of incomplete elliptical integrals

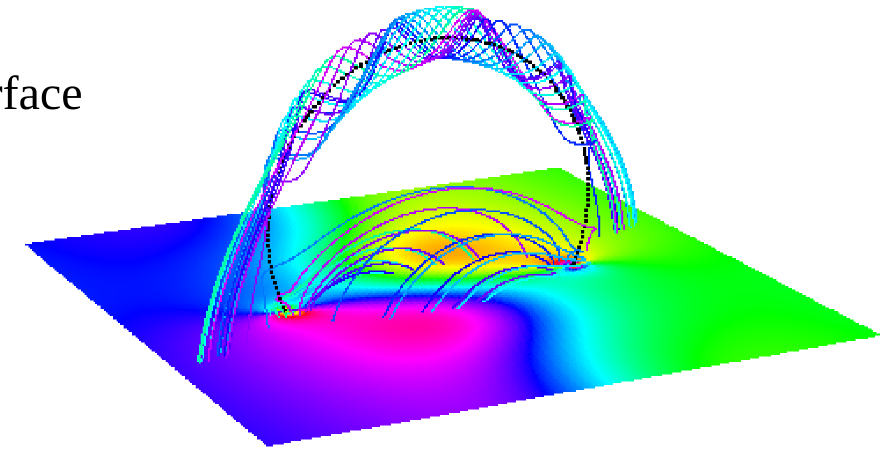


Line-Tied Evolution

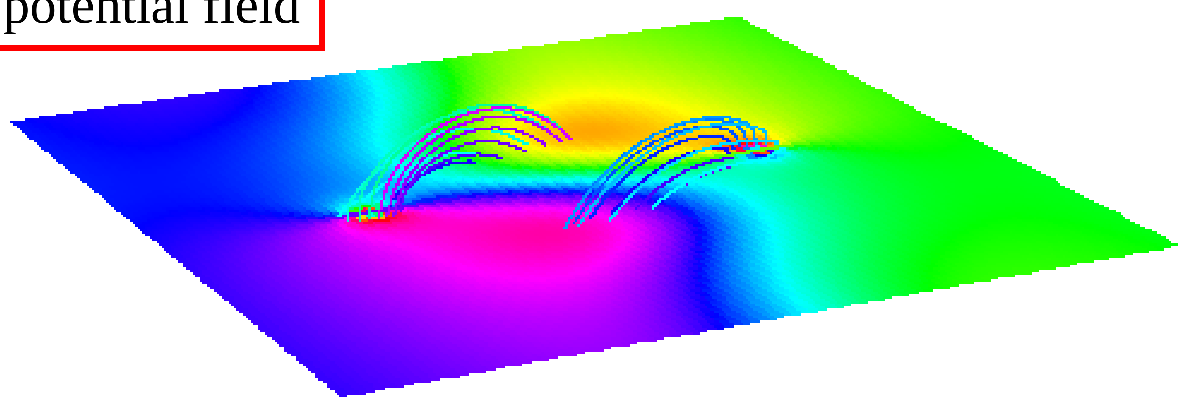
initial configuration



erupted configuration



potential field



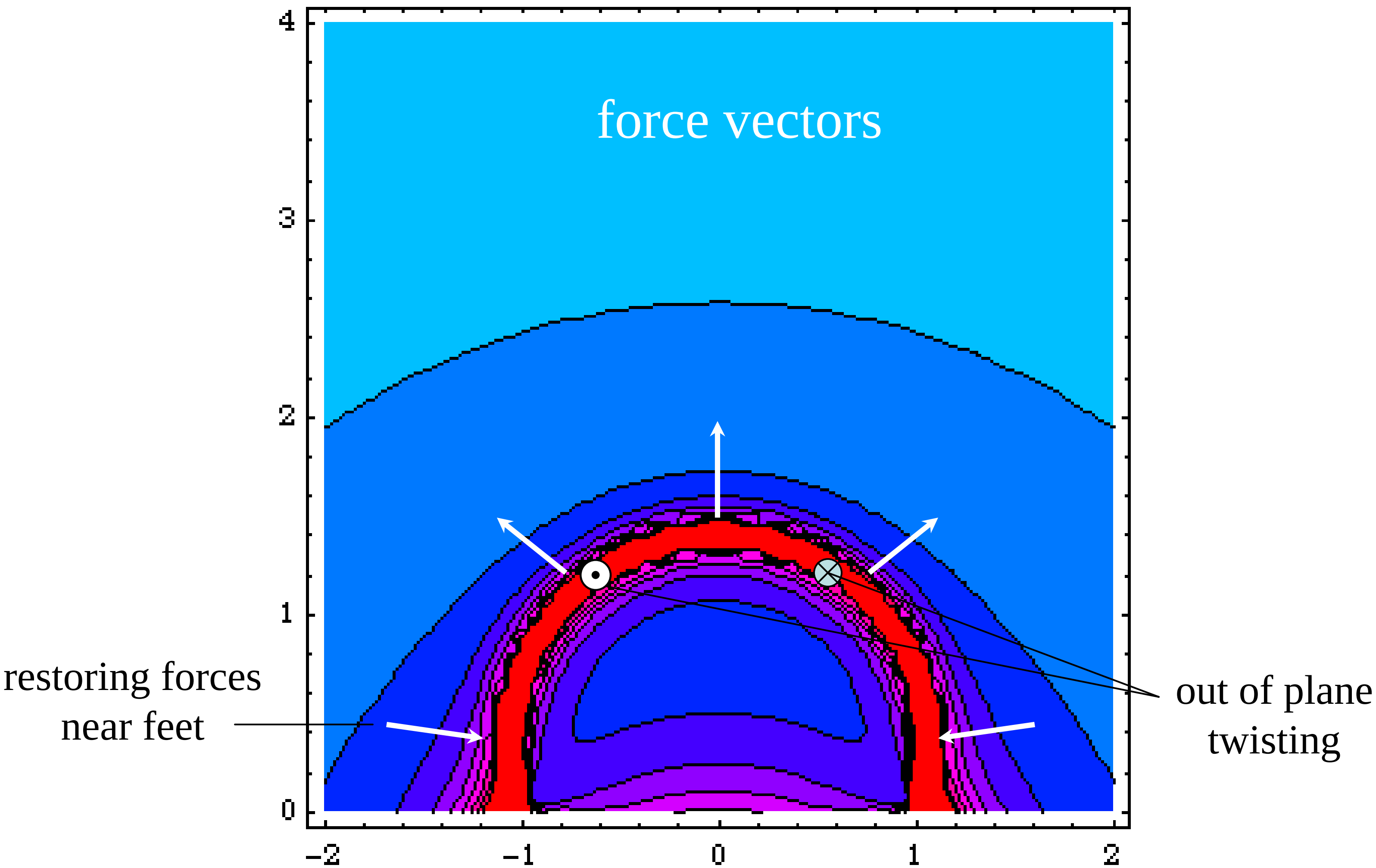
Transient Coronal Holes as Seen by EIT

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

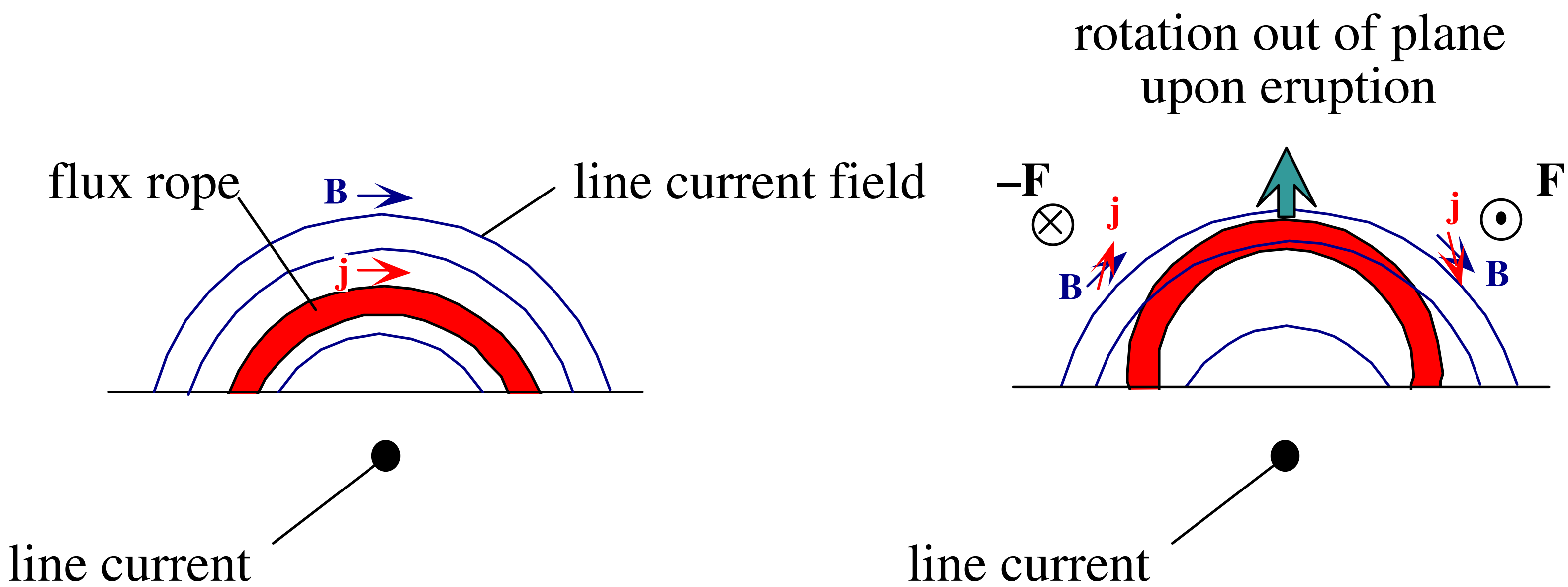
Transient Coronal Holes as Seen by TRACE

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

Forces Acting on Flux Rope



Effect of Line Current on Twist



current density

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

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

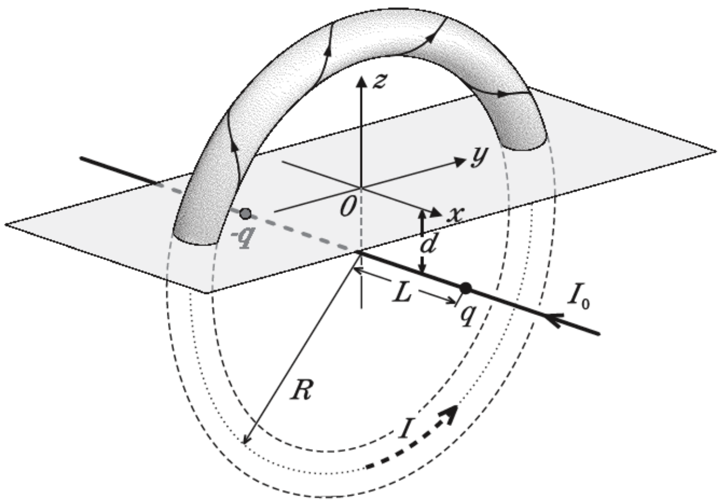
Kliem & Török (2004)

Simulation of Kliem & Török

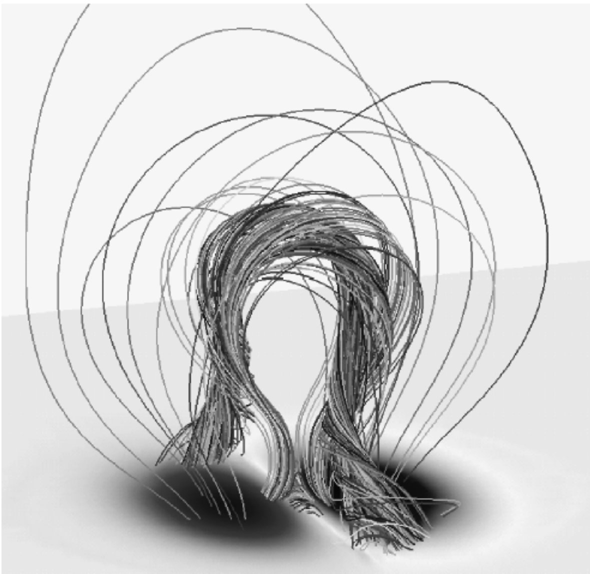
QuickTime™ and a
GIF decompressor
are needed to see this picture.

1. line current replaced by quadrupole
2. subcritical twist for helical kink
3. torus center near surface

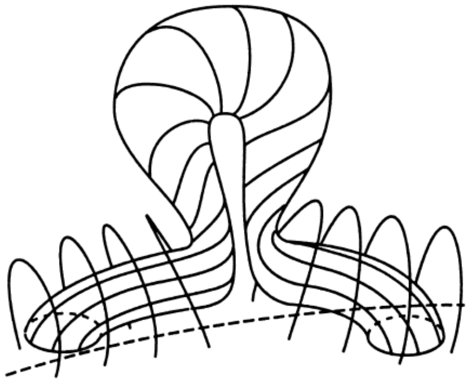
Three-Dimensional Storage Models



Titov & Démoulin 1999

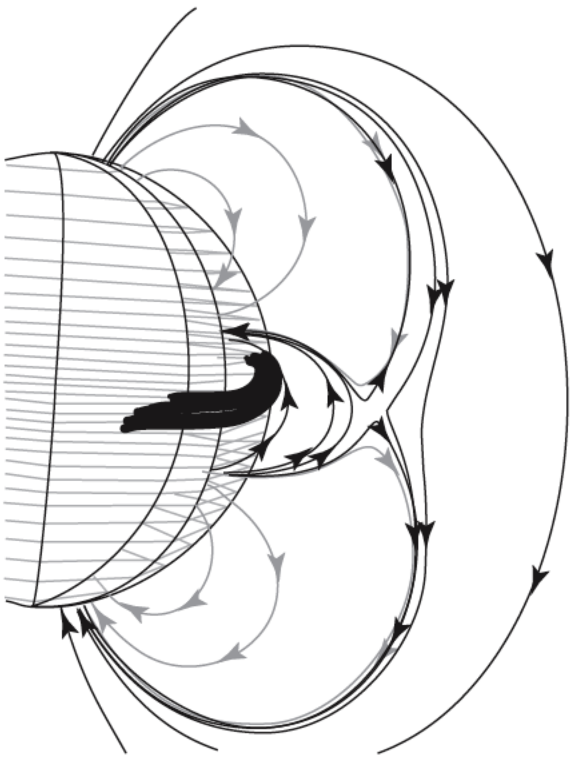


Amari et al. 2000



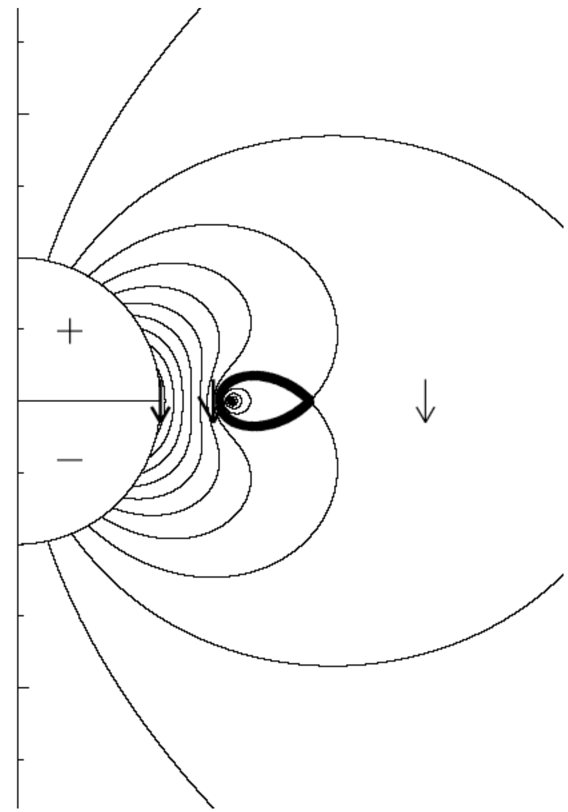
Sturrock et al 2001

Other Storage Models



breakout model

(Antiochos et al. 1999)



flux rope with normal polarity

(Low & Zhang 2002)

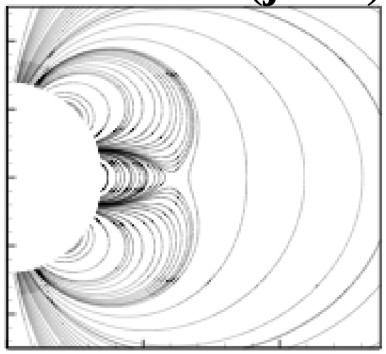
Role of Reconnection in the Breakout Model

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

What is the Trigger Mechanism in the Breakout Model?

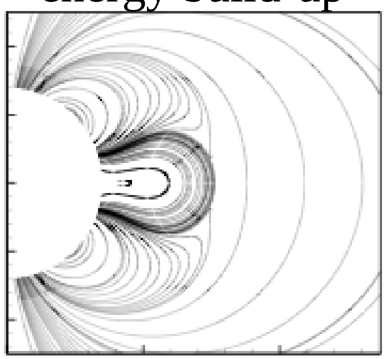
initial state (**j** = 0)

1.



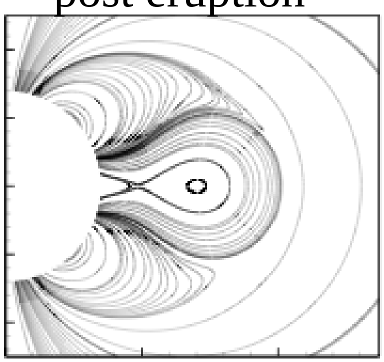
energy build-up

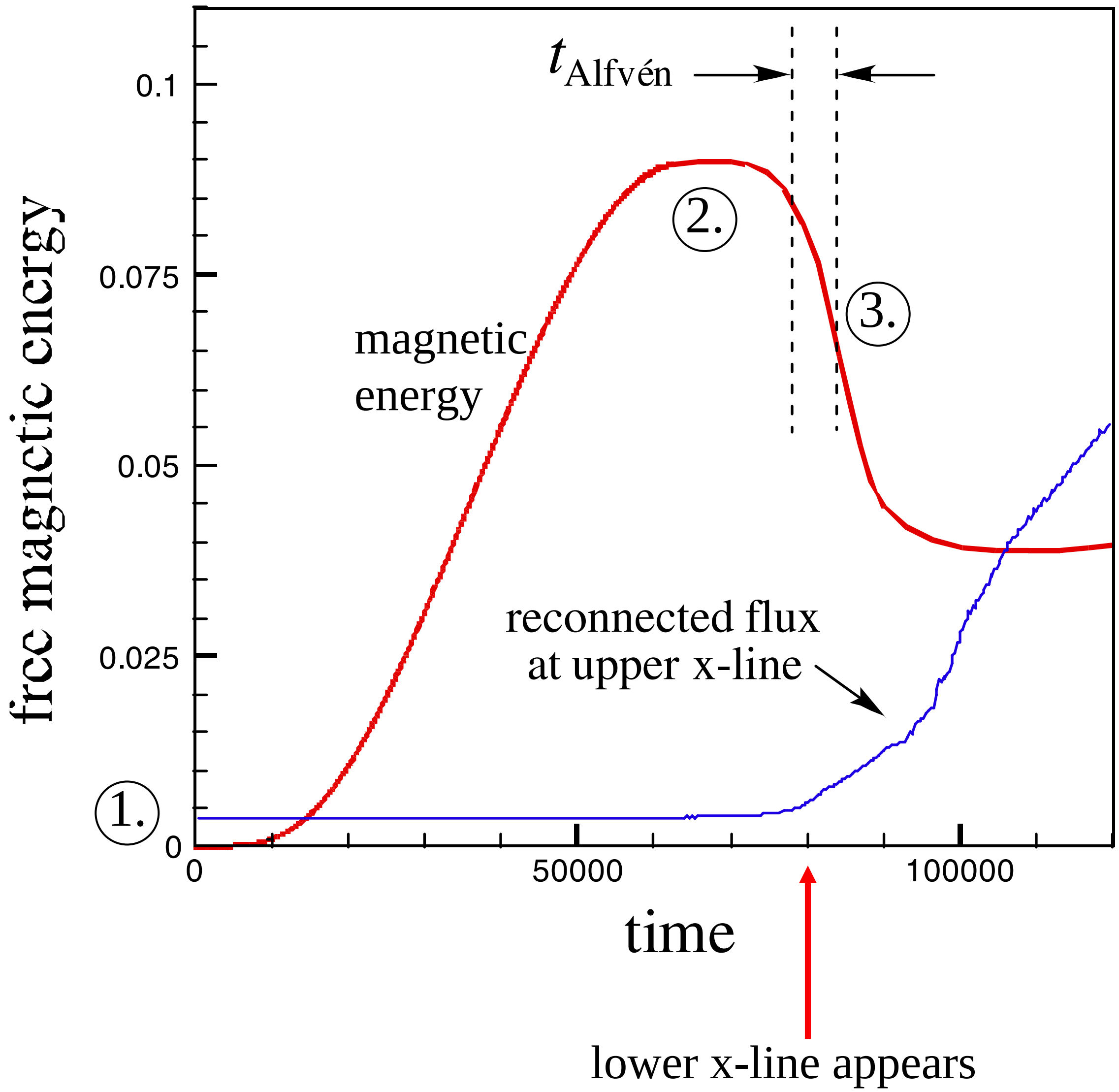
2.



post eruption

3.





Some Unanswered Questions

1. How are stressed magnetic fields formed?

   — issue of reverse currents —

2. What determines the rate of reconnection?

   — kinetic processes –
   — turbulence —

3. To what extent are flares & CMEs predictable?

   — complexity –