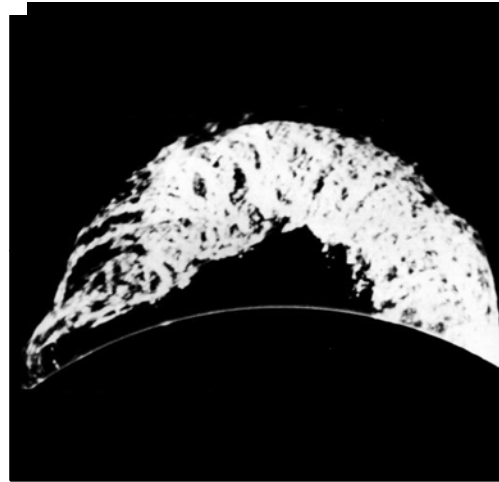
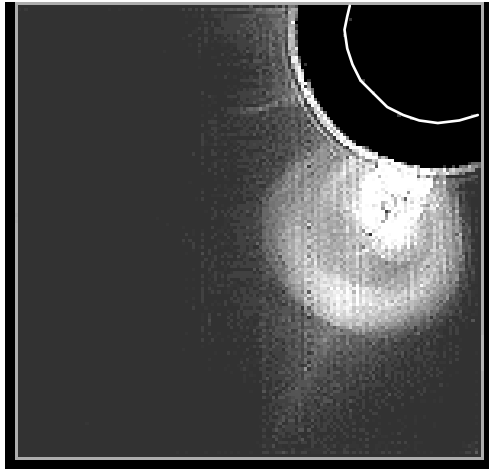
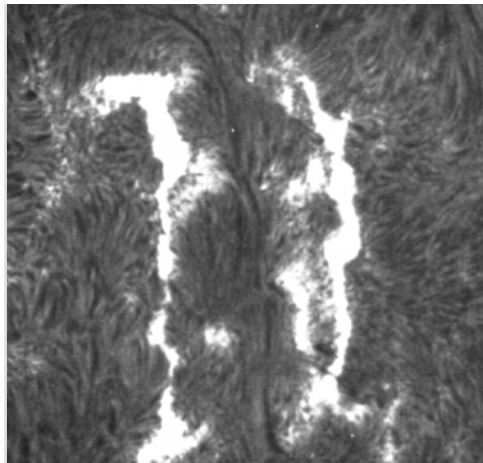


Theory & Modeling of Solar Eruptions

coronagraph (CME) H α limb (prominence)



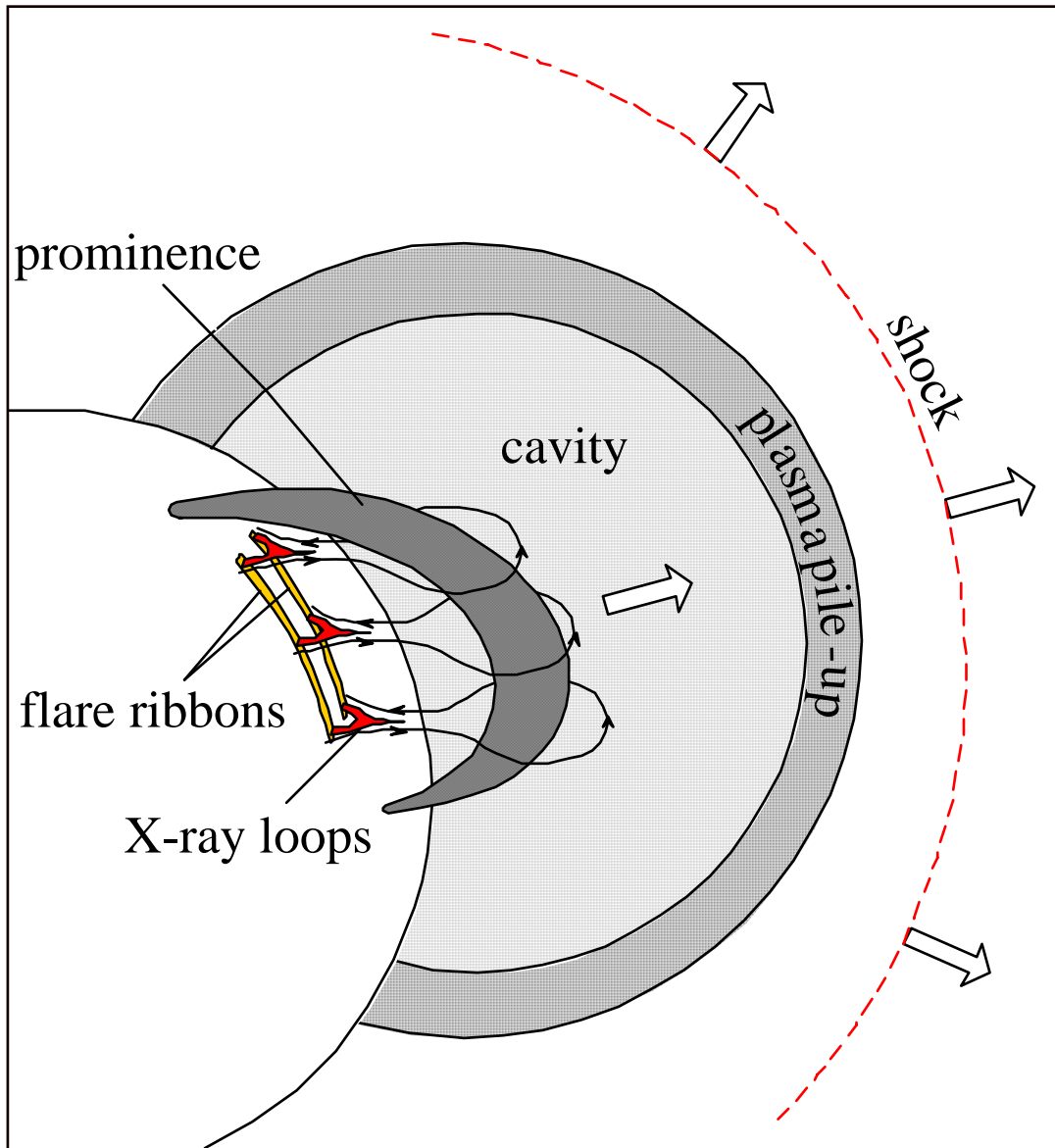
H α disk (flare ribbons)



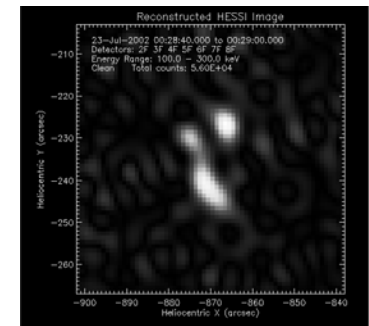
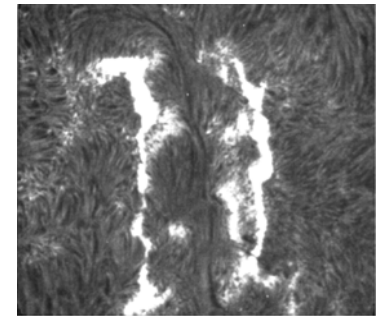
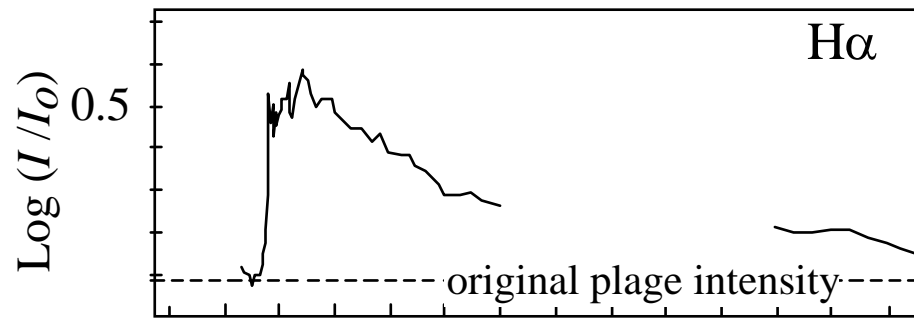
X-ray (flare loops)



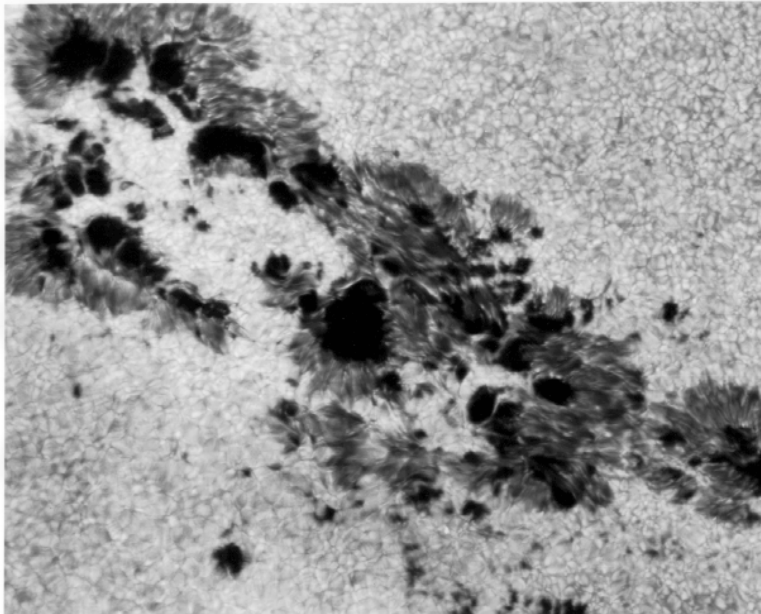
Large Solar Eruptions



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



Inertial Line-Tying



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

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

Photospheric boundary condition:

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

Photospheric convection is negligible

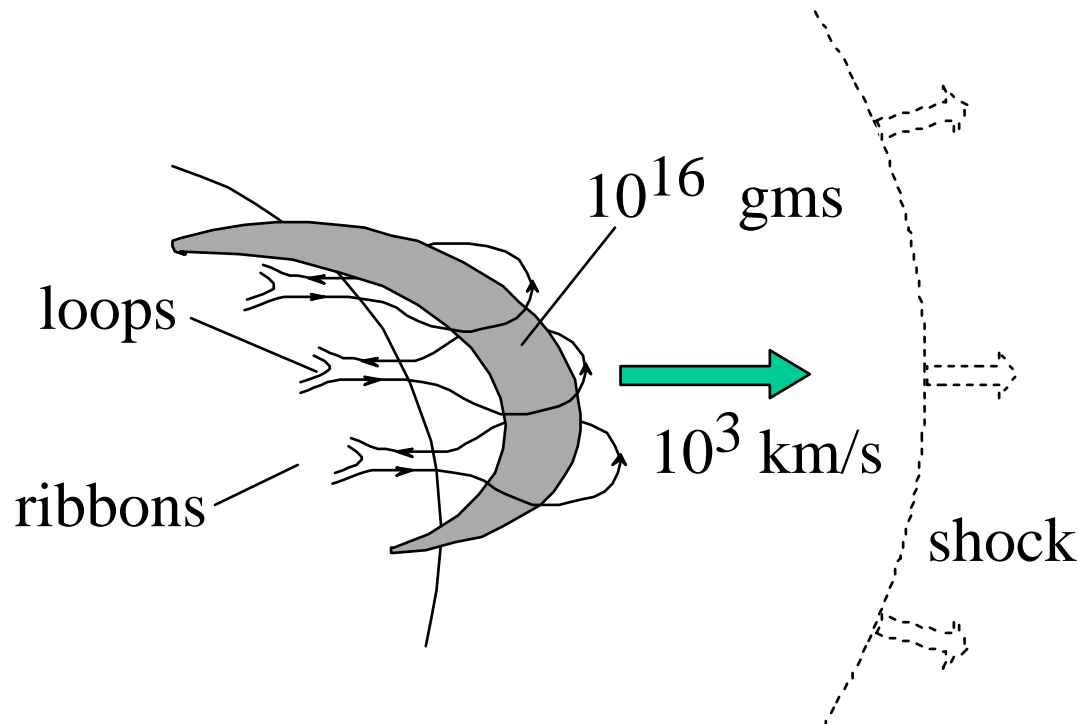
\mathbf{B} normal to surface is fixed.

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:
 $\lesssim 100 \text{ ergs/cm}^3$

Nature of Energy Source: Required: $\approx 100 \text{ ergs/cm}^3$

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

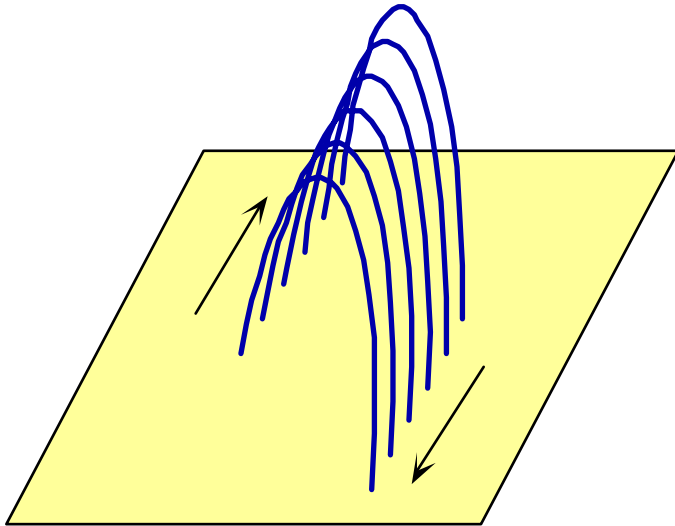
How is Energy Stored?

$$\beta = 10^{-3}$$

$$\nabla p \approx 0$$

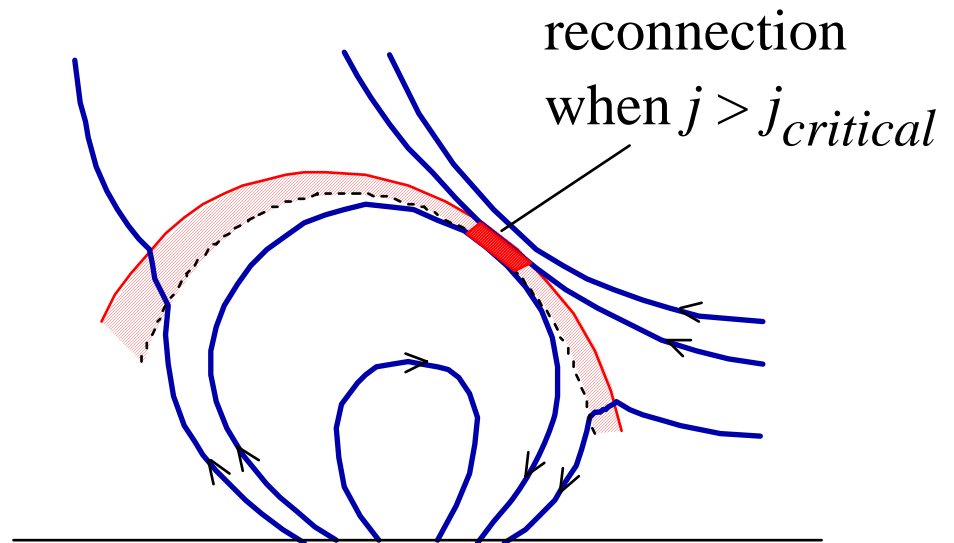
$$\mathbf{j} \times \mathbf{B} \approx 0$$

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



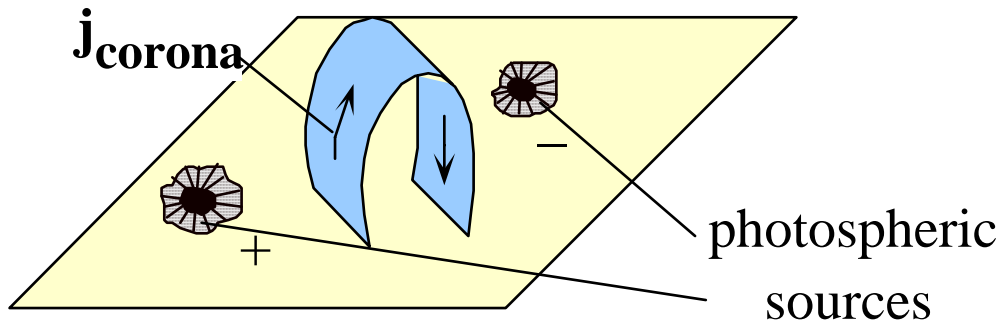
sheared magnetic fields

Current sheets:

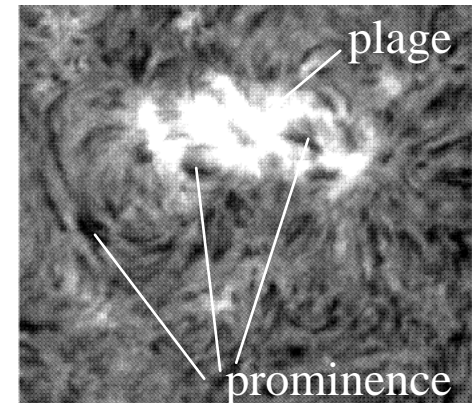


emerging flux model

How Much Energy is Stored?



H α image



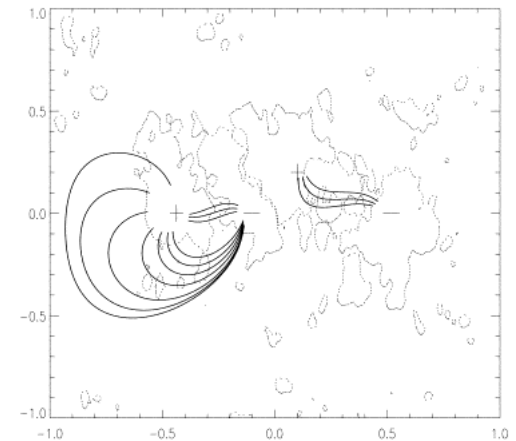
$$\mathbf{B} = \mathbf{B}_{\text{photospheric currents}} + \mathbf{B}_{\text{coronal currents}}$$

invariant
during CME

source of
CME energy

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

model with magnetogram

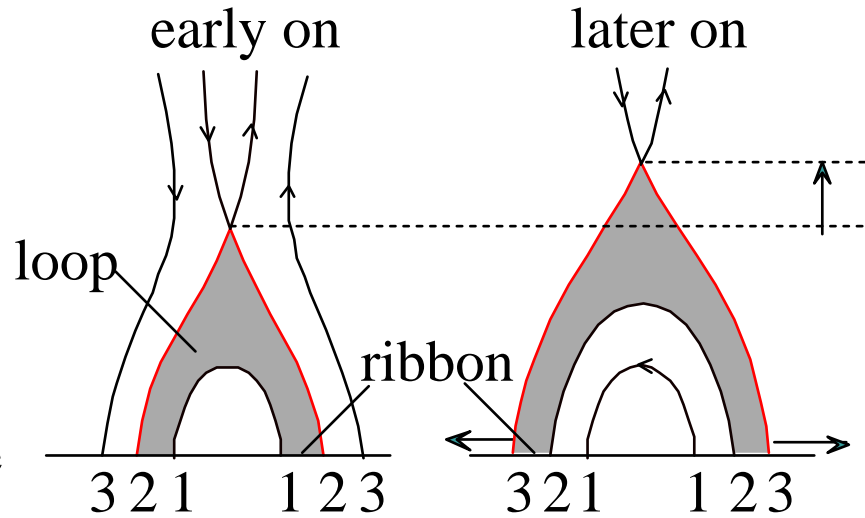


from Gaizauskas & Mackay (1997)

free magnetic energy \approx 50% of total magnetic energy

Apparent Motion of Loops & Ribbons

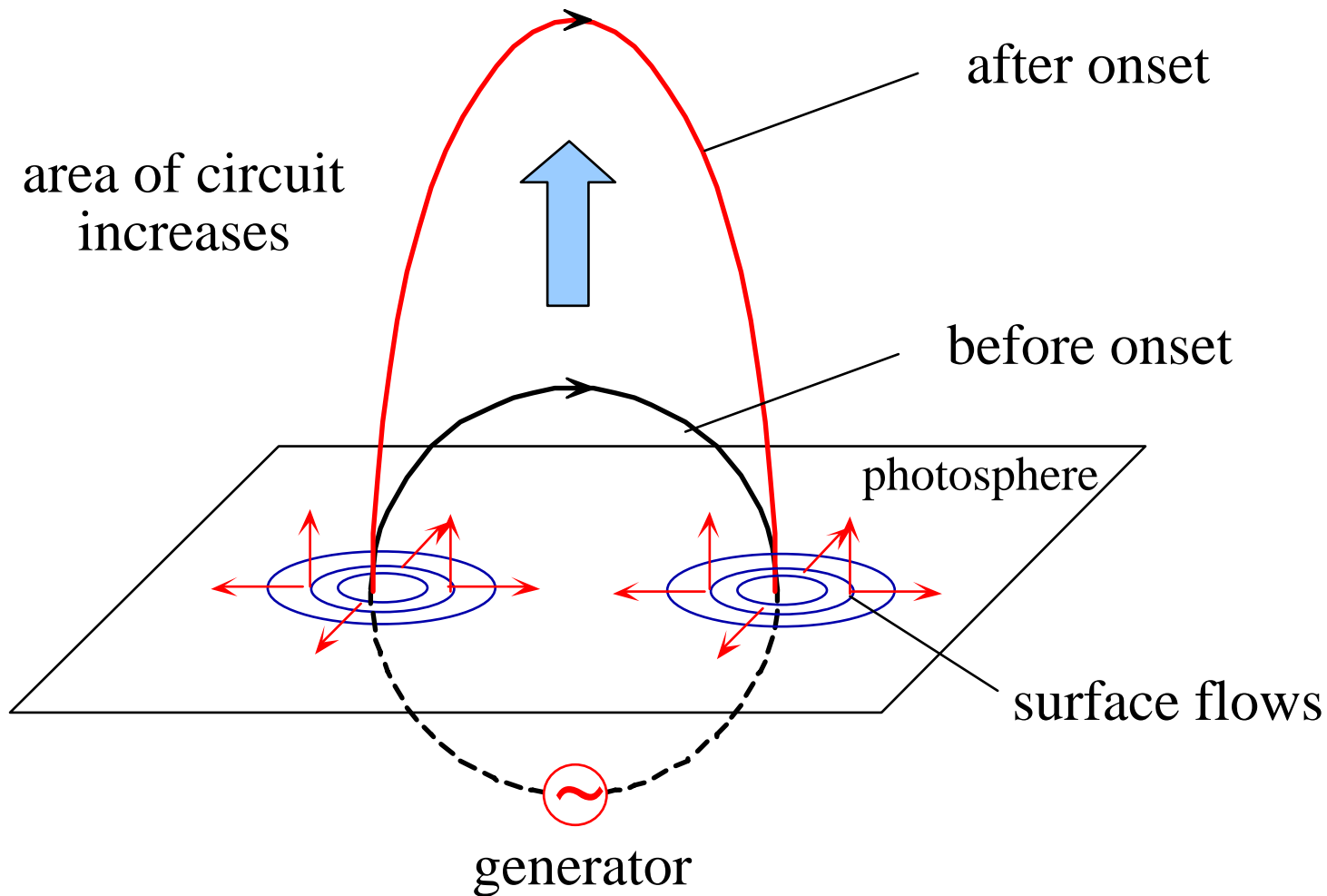
inertial line-tying at surface



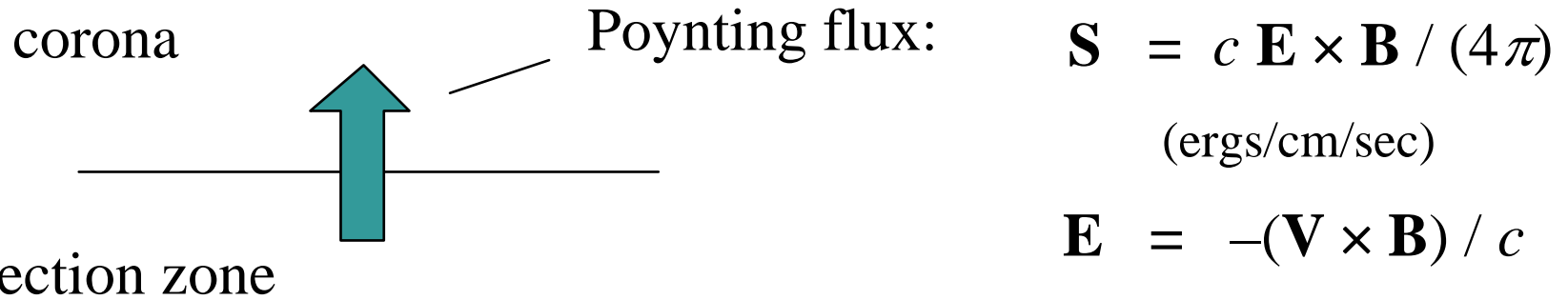
QuickTime™ and a YUV420 codec decompressor are needed to see this picture.

Flux Injection Models

(e.g. Chen 1989)

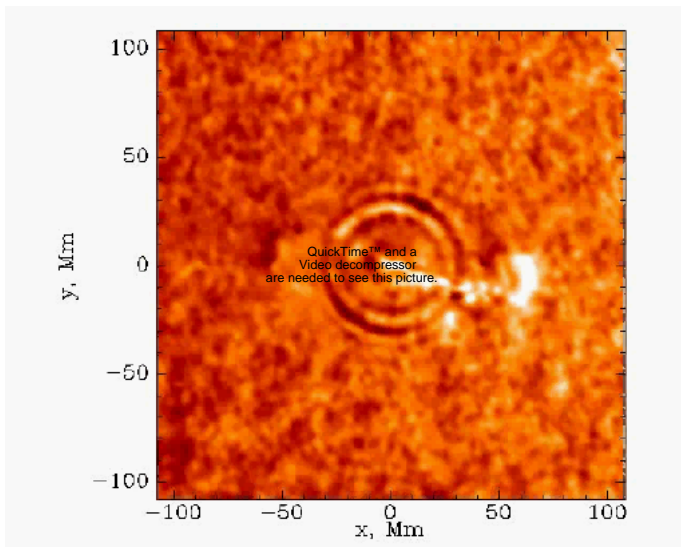


During injection energy flows through photosphere.

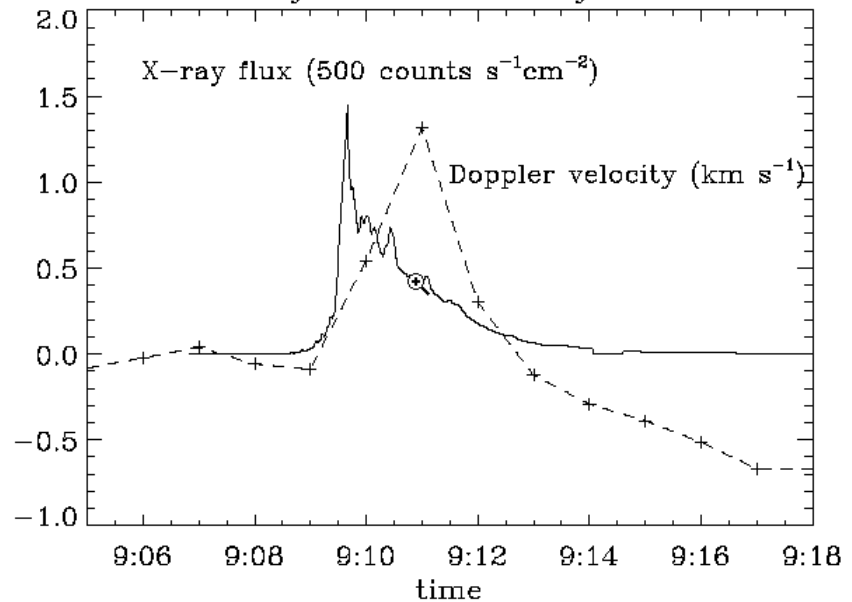


> 10 km/sec for > 10 minutes

Kosovichev et al. 1998

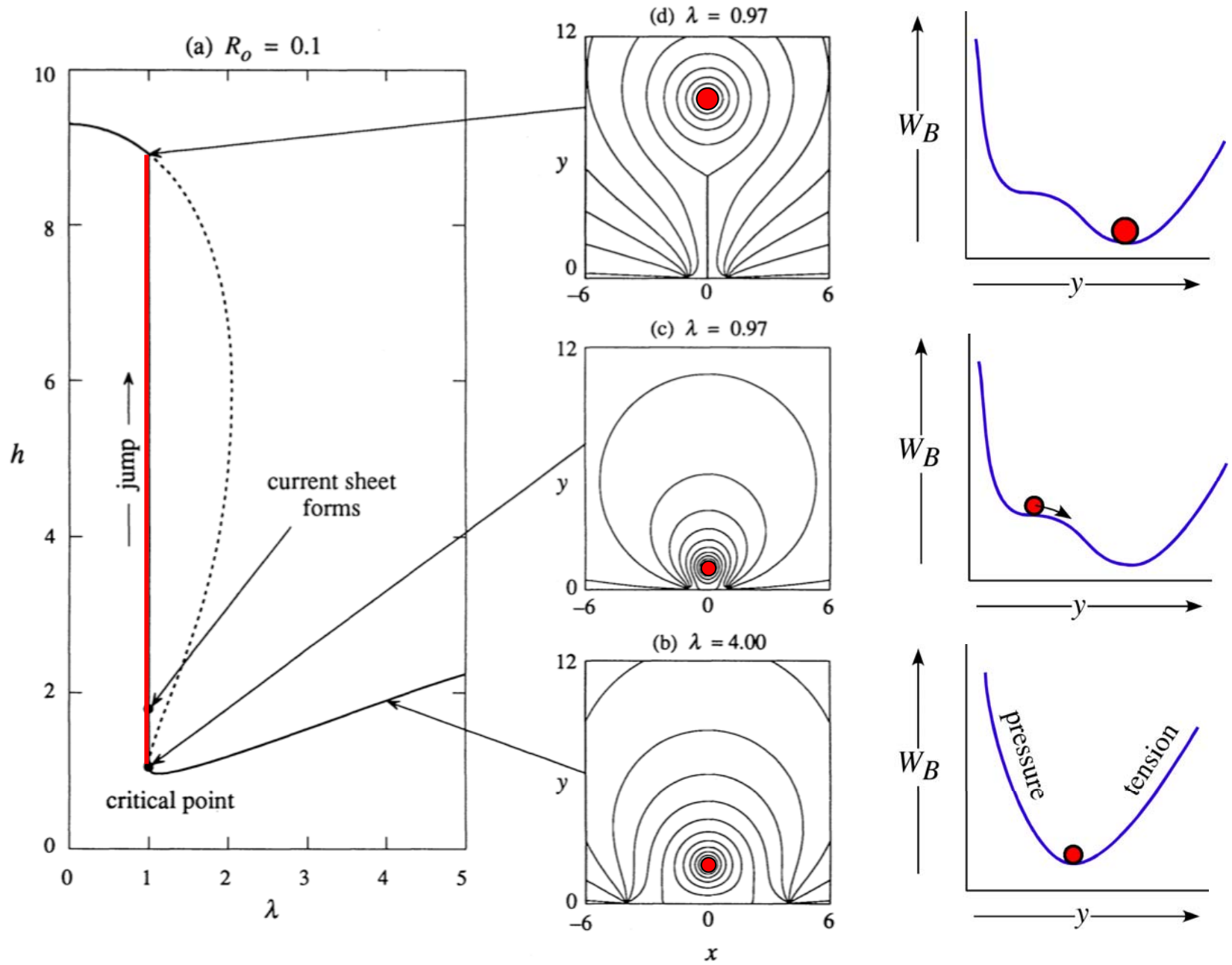


X-ray flare of 9 July 1996

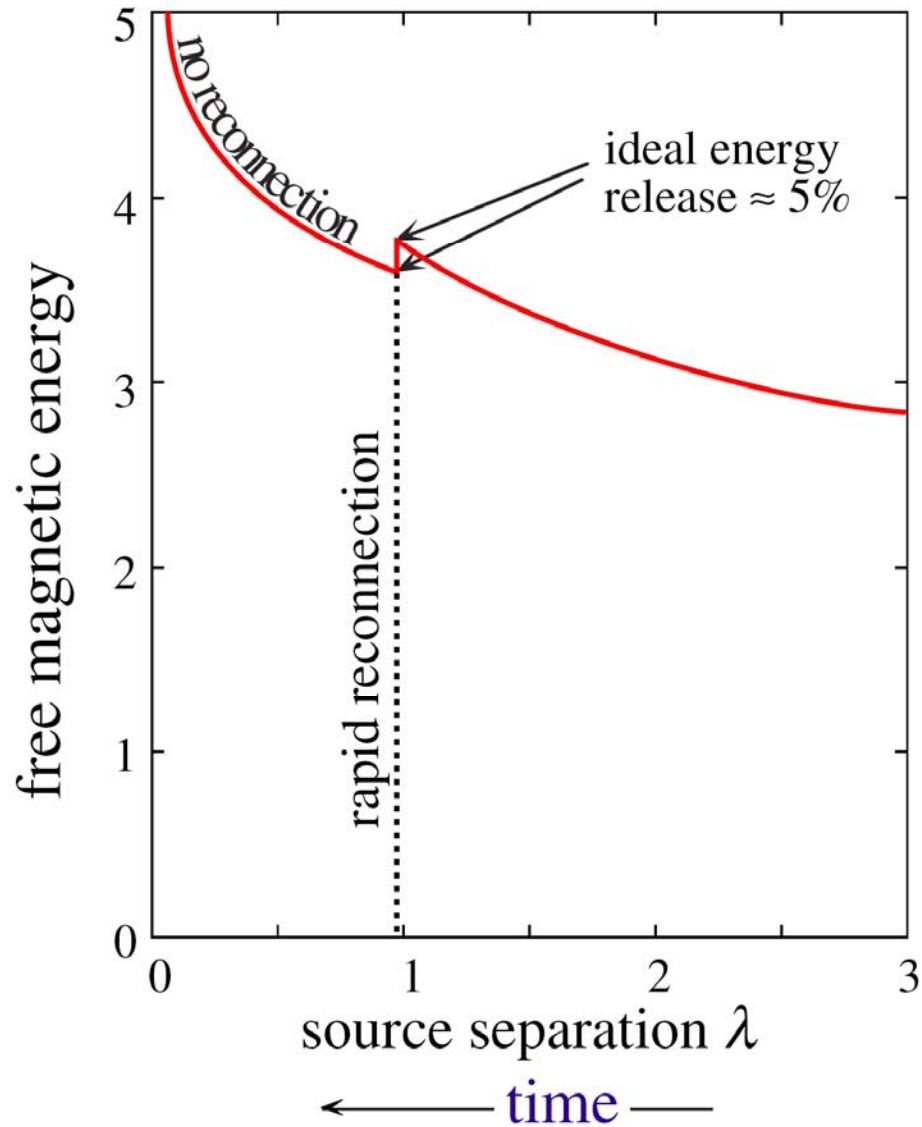


Injection models predict large surface flows which are never observed.

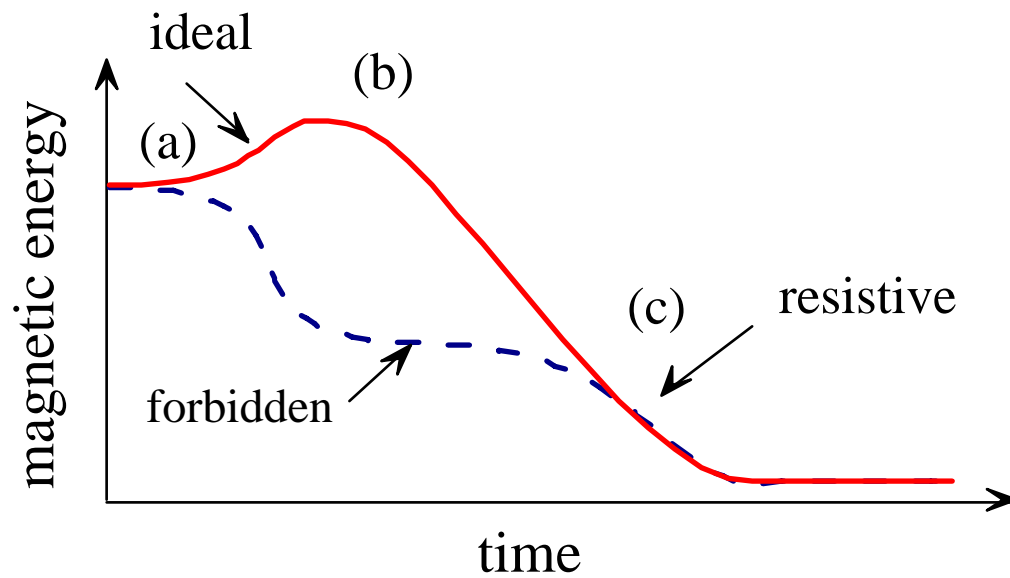
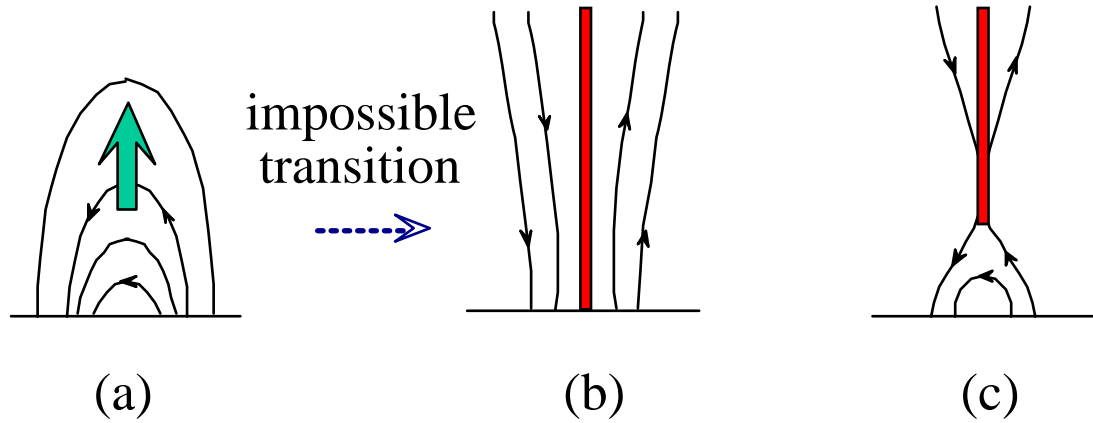
Loss of Equilibrium Model



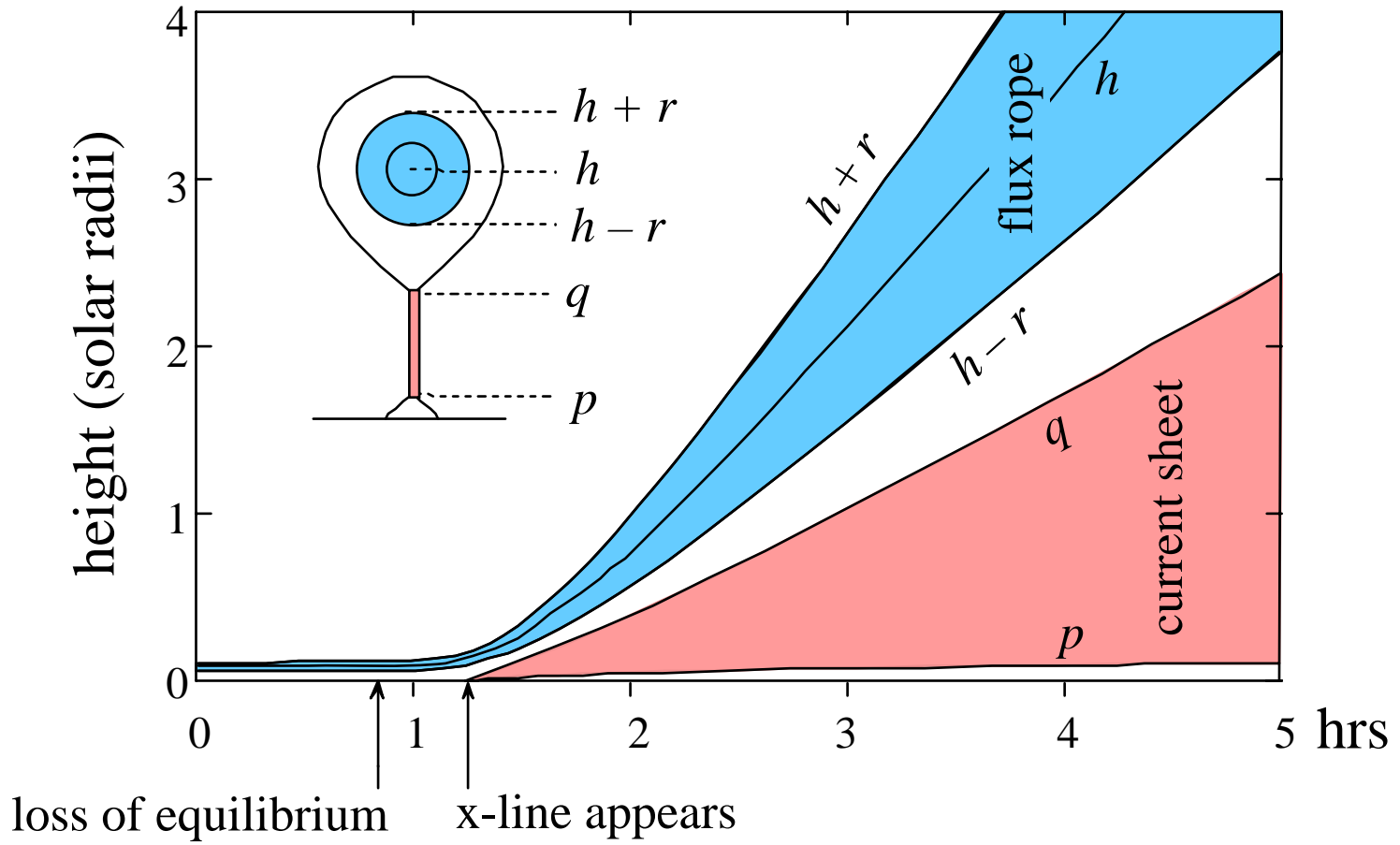
Energy Release in 2D Model



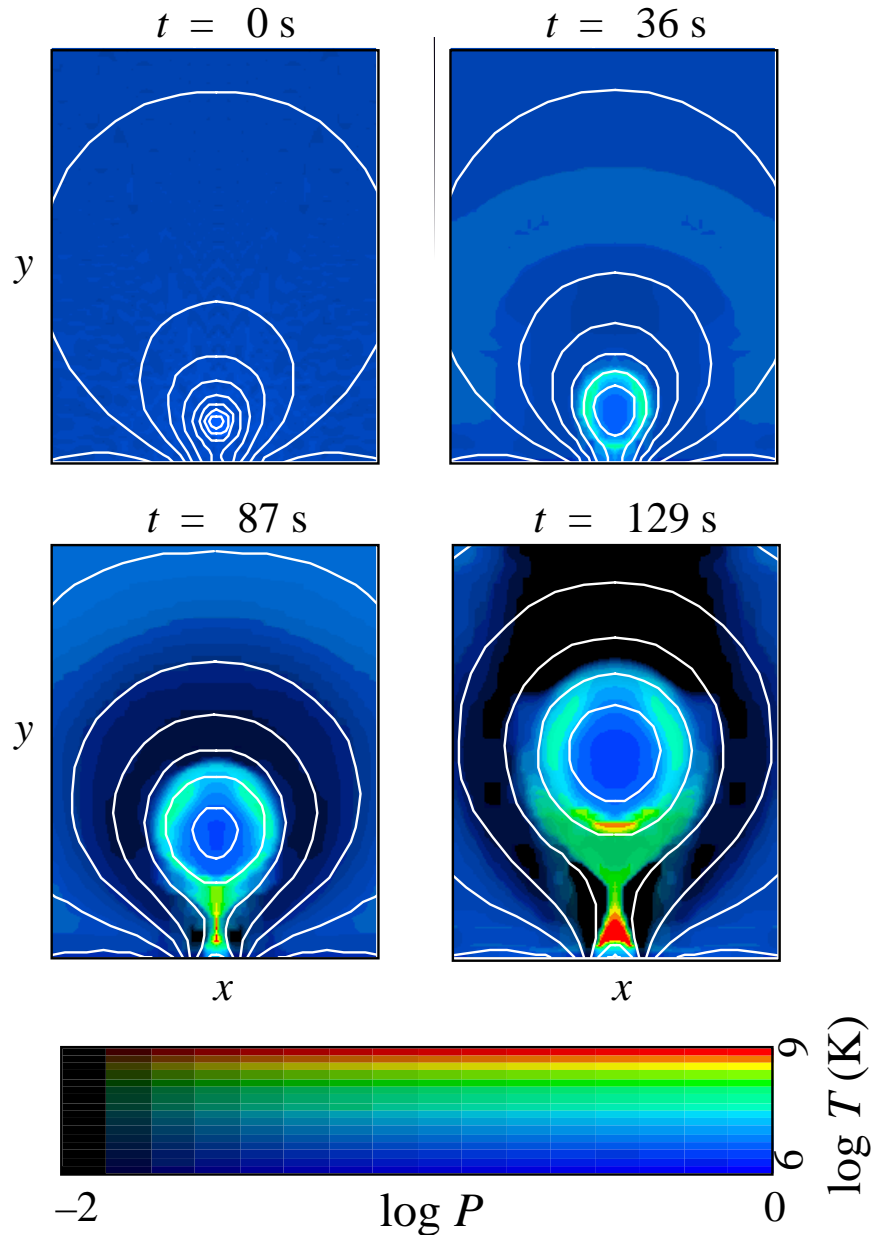
Aly - Sturrock Paradox



Trajectories



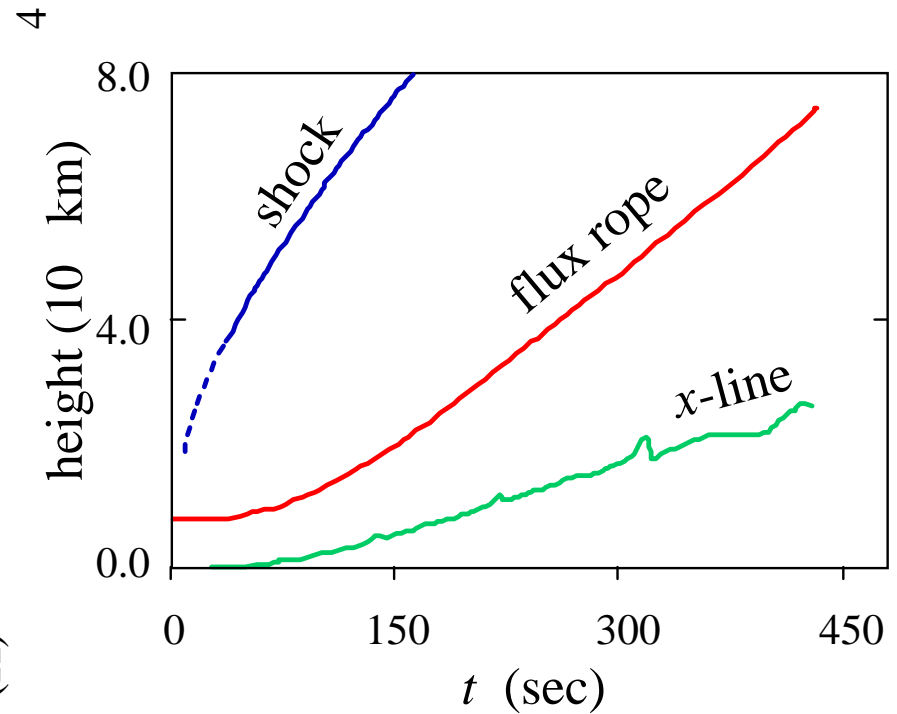
Numerical Simulation of Critical Point Configuration



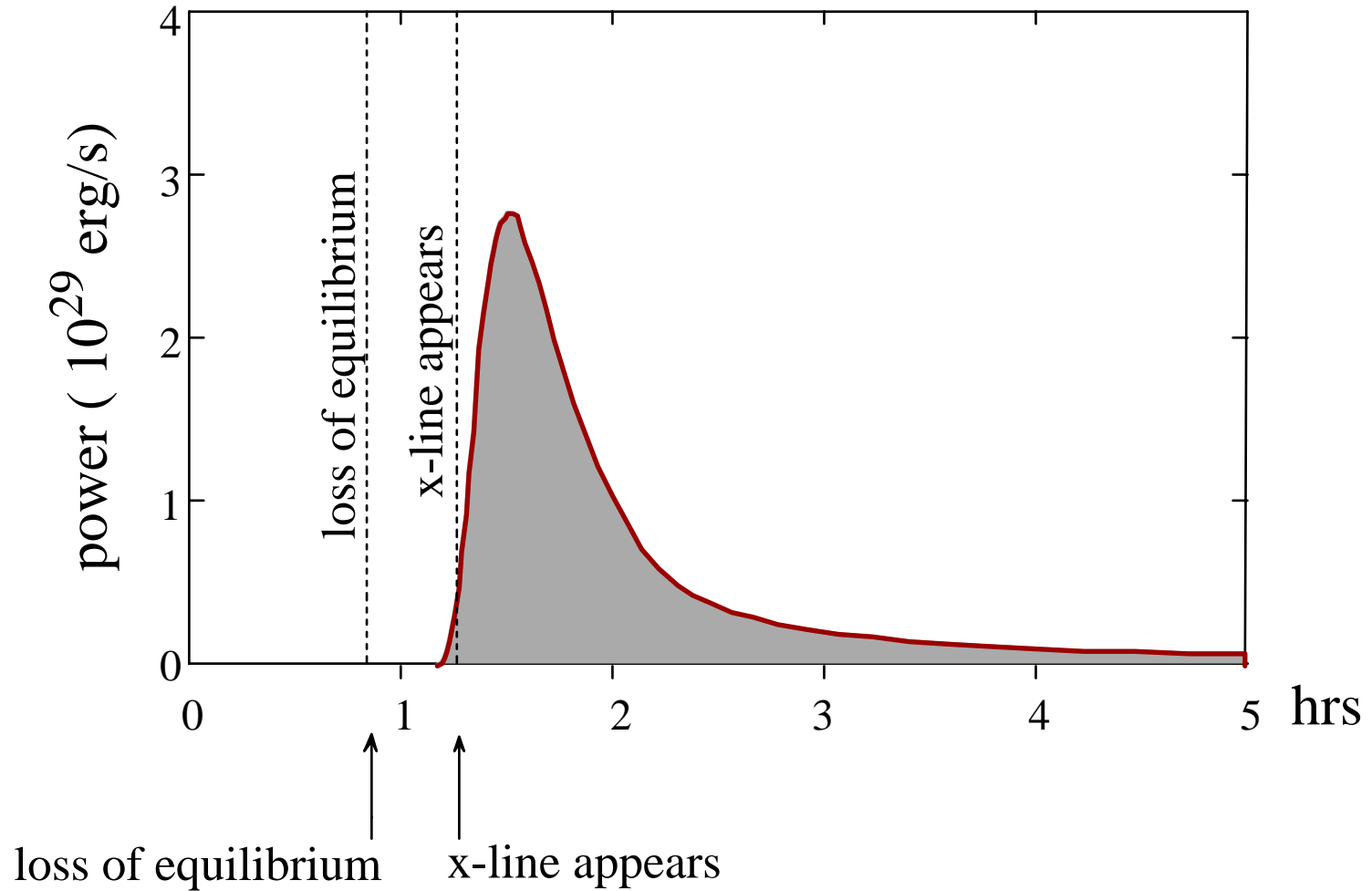
initial condition: $\mathbf{V} = 0$

energy equation: Ohmic heating
no cooling

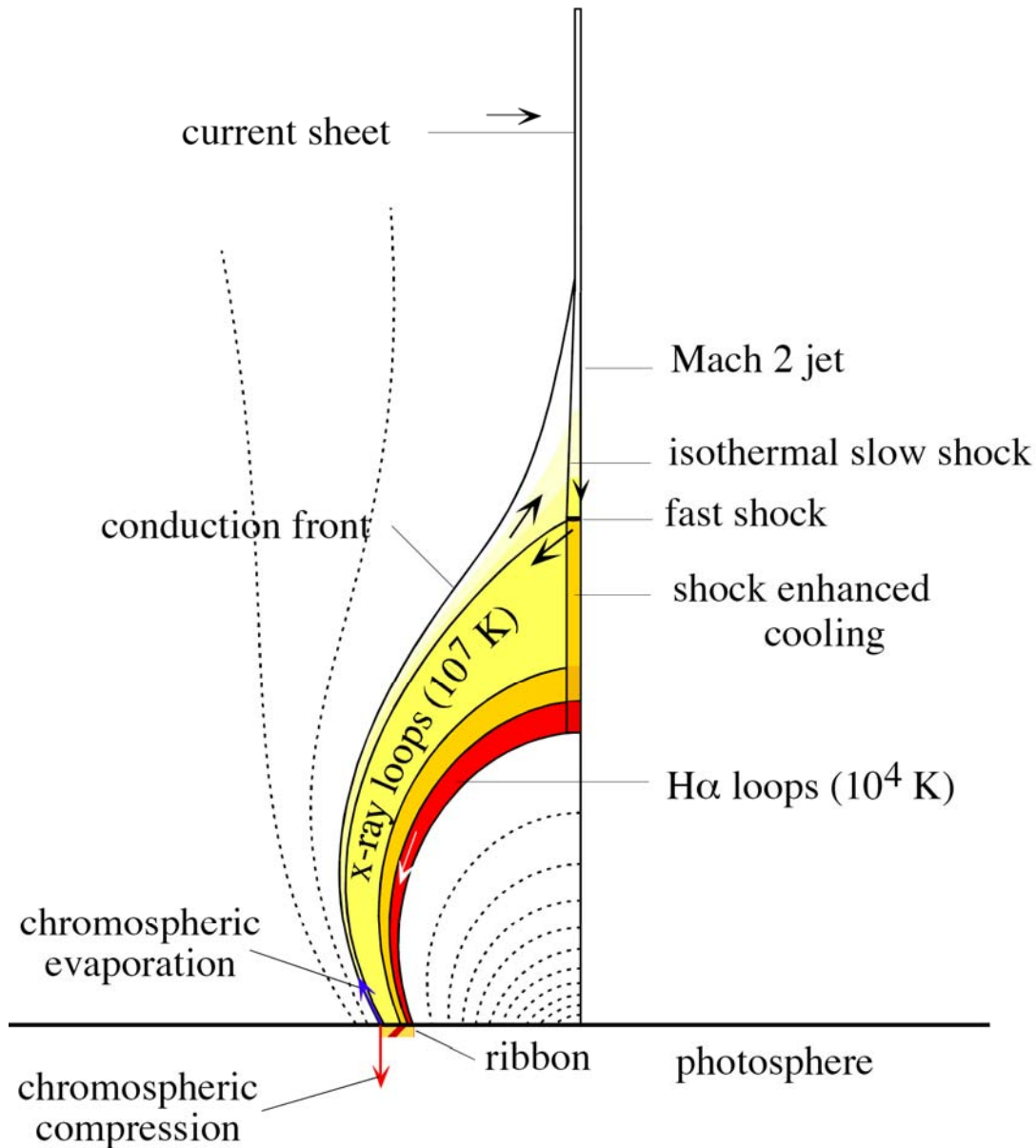
resistivity: uniform, $S = 500$



Power Output



Chromospheric Evaporation

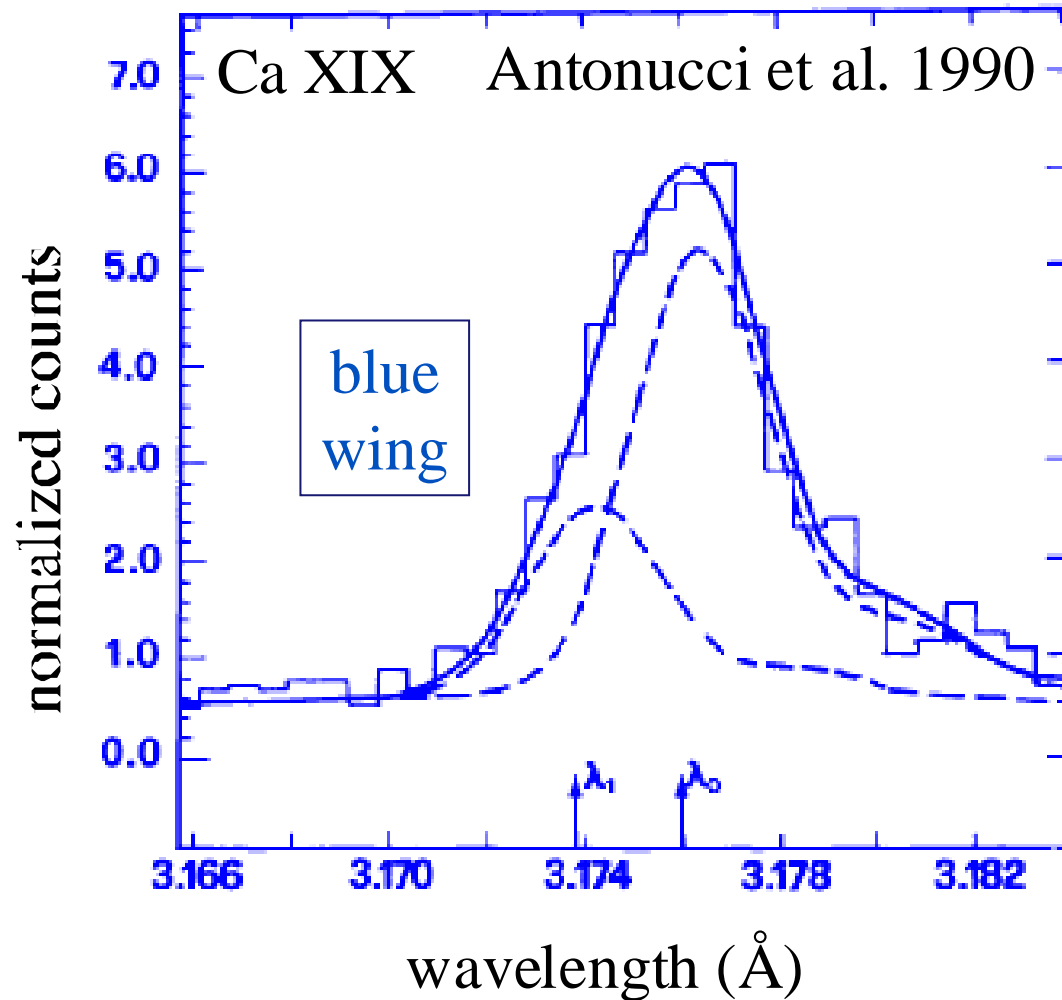


QuickTime™ and a
Animation decompressor
are needed to see this picture.

Evaporation Doppler Shift Puzzle

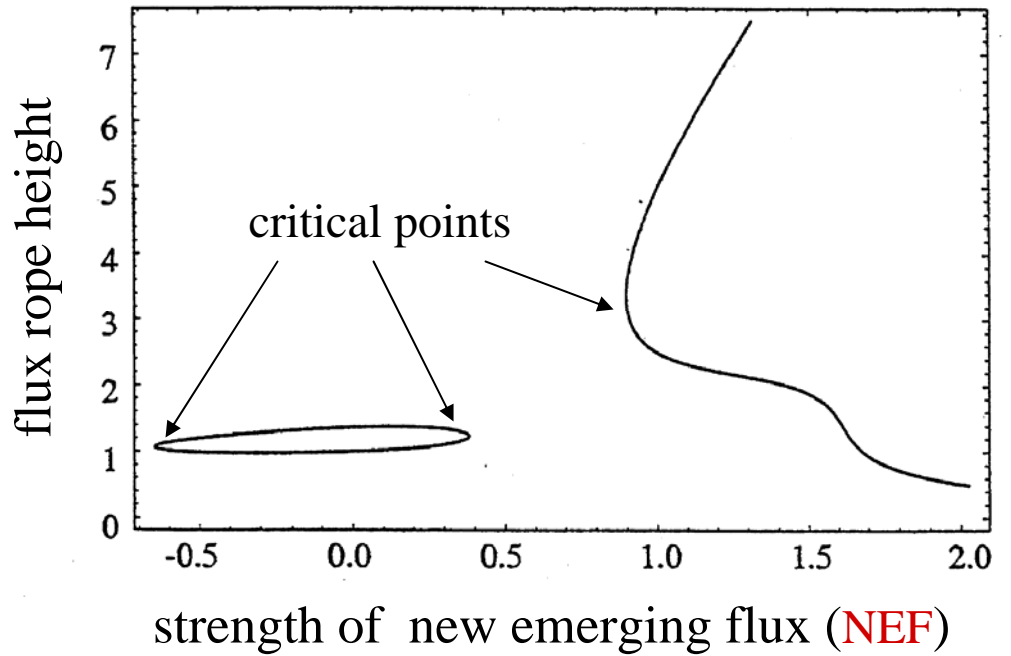
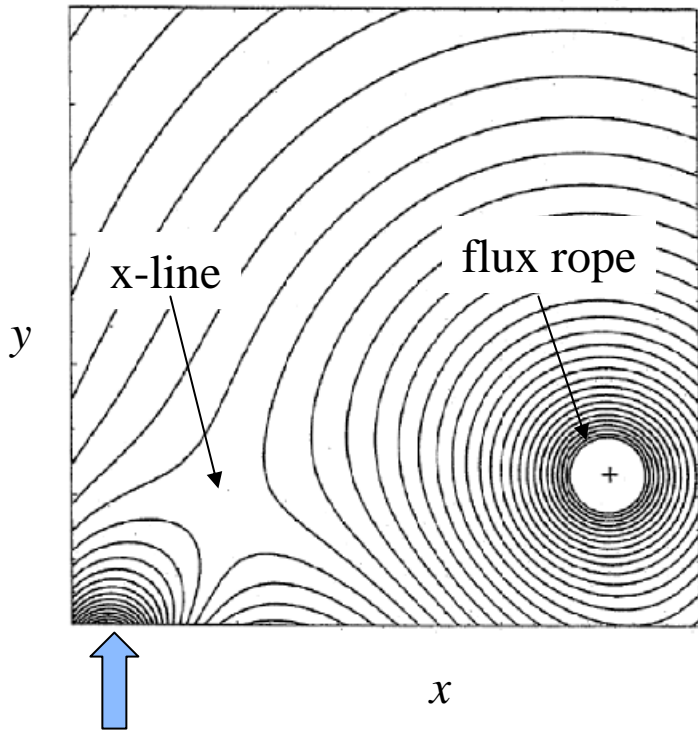
24 April 1984

BCS/SMM



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

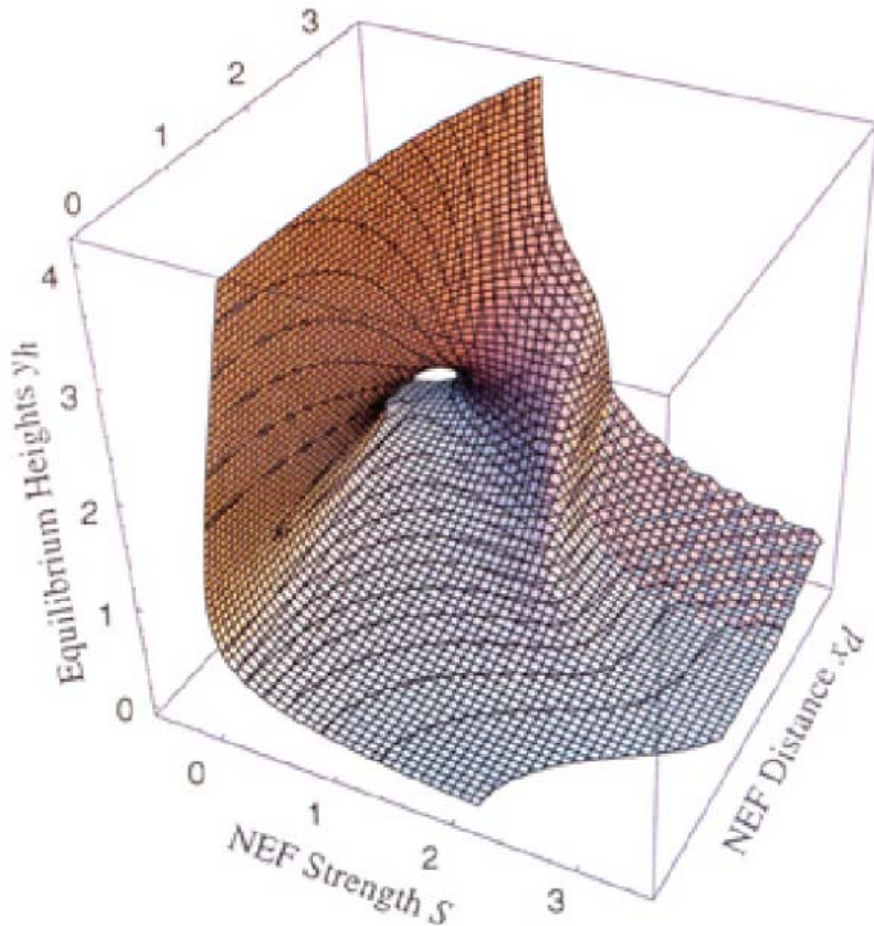
2D Asymmetric Quadrupole Model



NEF

test of “tether-cutting” concept

Equilibrium Manifold in 5D Parameter Space of Model



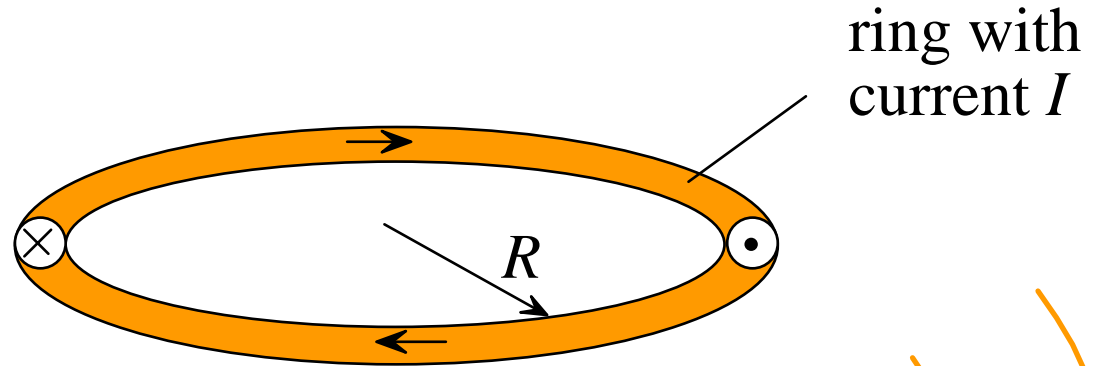
3D “cross section”

1. normalized radius of flux rope
2. normalized main arcade field
3. new emerging flux strength (NEF)
4. normalized depth of NEF
5. normalized distance of NEF

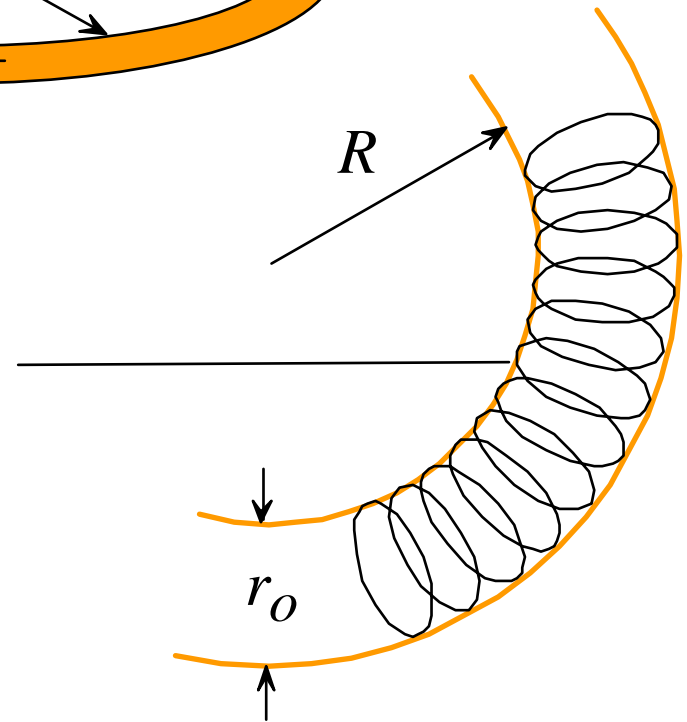
2nd order umbelic catastrophe

Basic Principles I

Driving Force:



inner edge is pinched
by curvature of rope

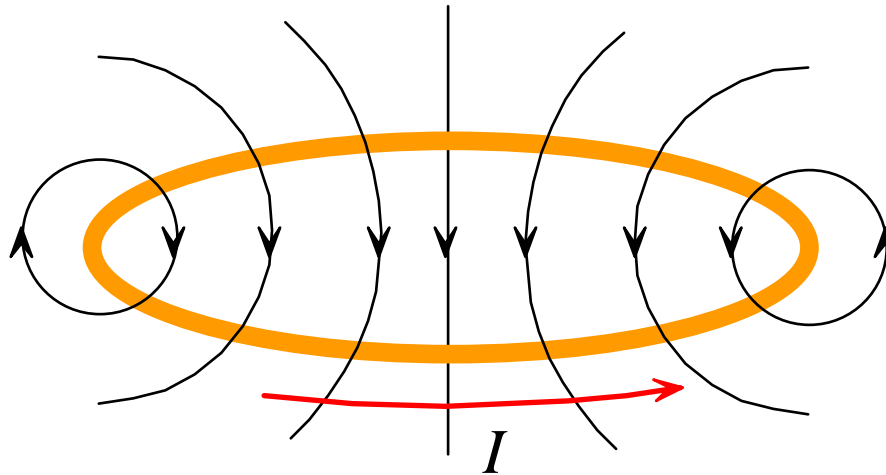


repulsive force:

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

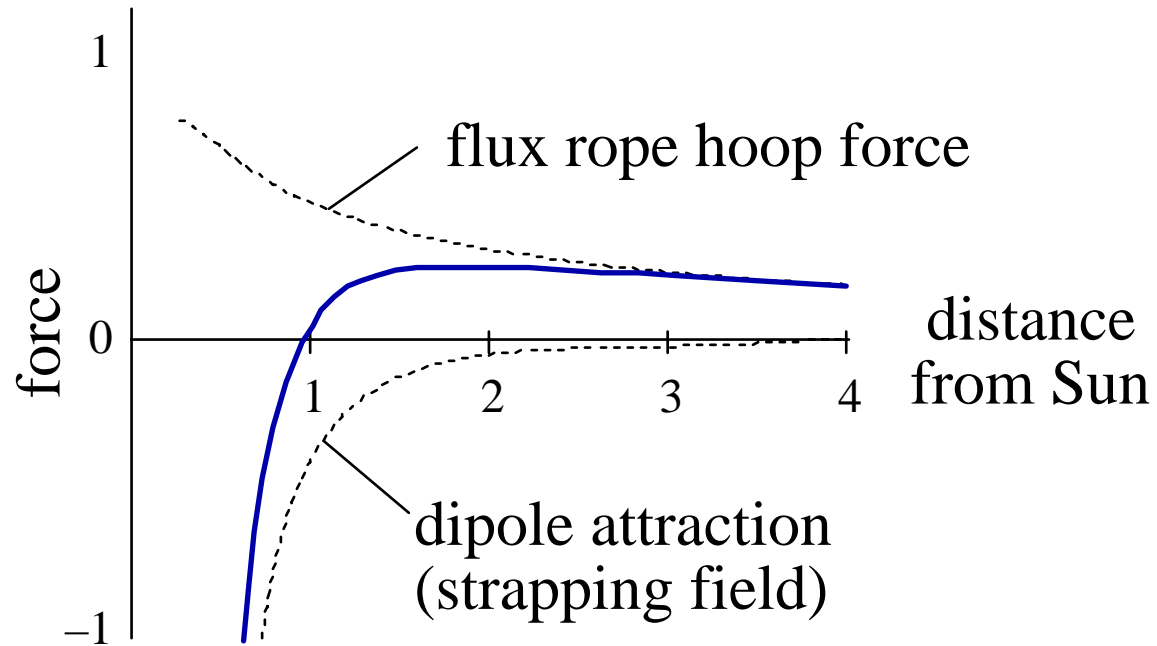
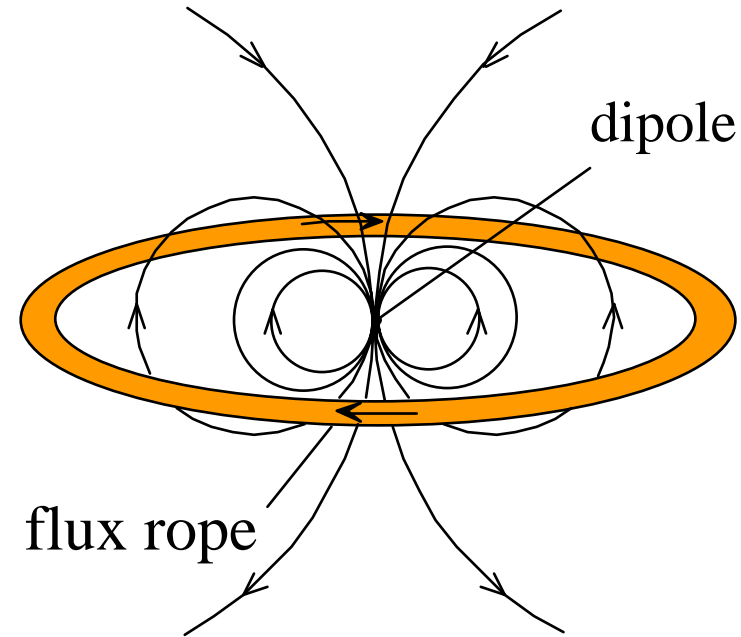
Basic Principles II

Flux Conservation:



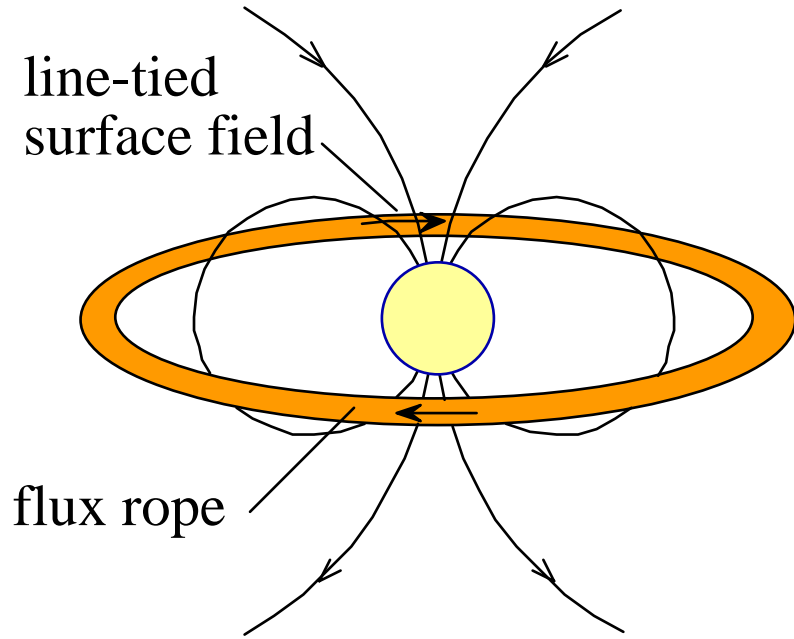
$$I \propto 1/[R \ln(R/r_0)]$$

How to Achieve Equilibrium

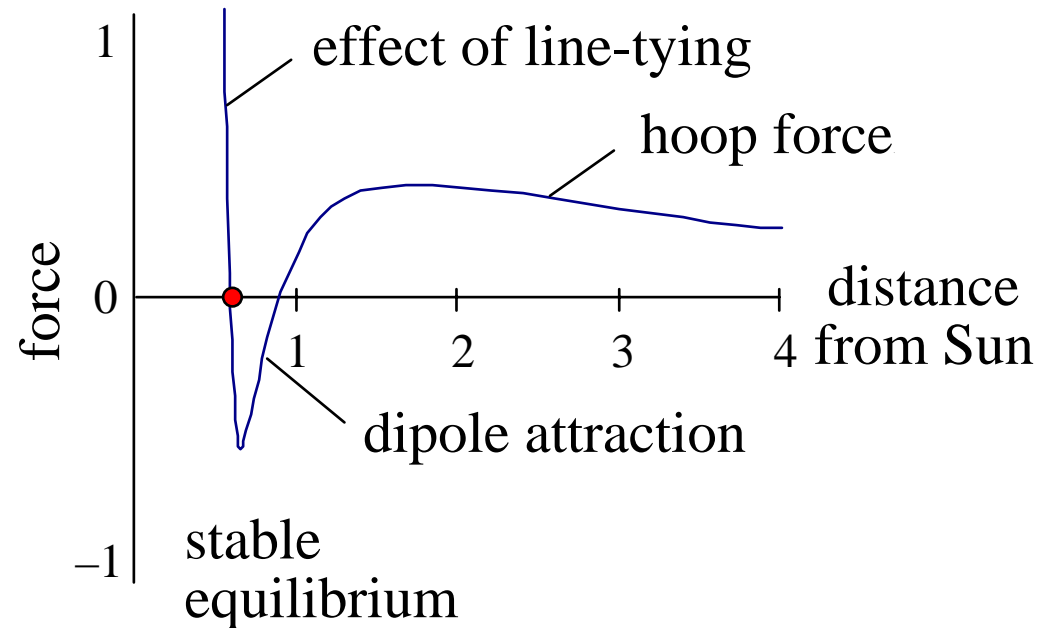


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium



Key factor: Line-tying



Line-tying creates a second, stable equilibrium

3D Loss-of-Equilibrium Model

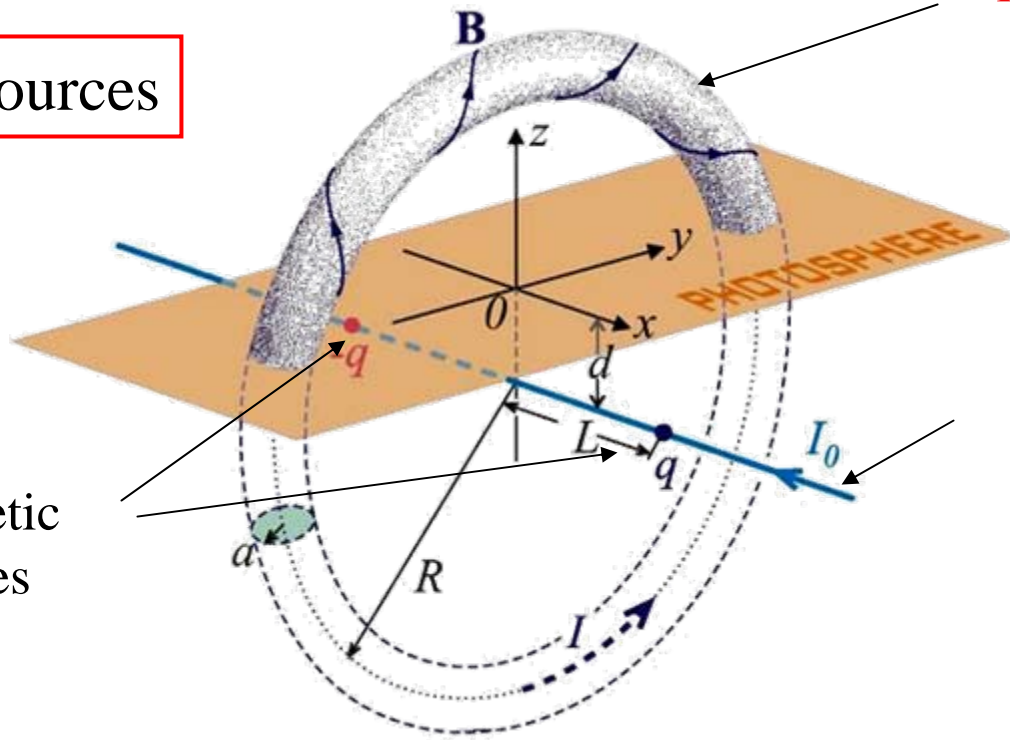
Titov & Démoulin (1999)

3 field sources

2. magnetic charges

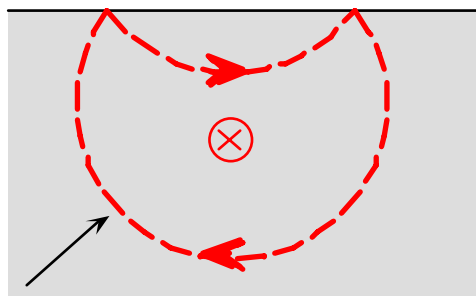
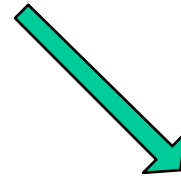
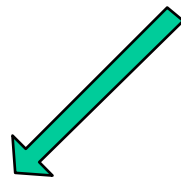
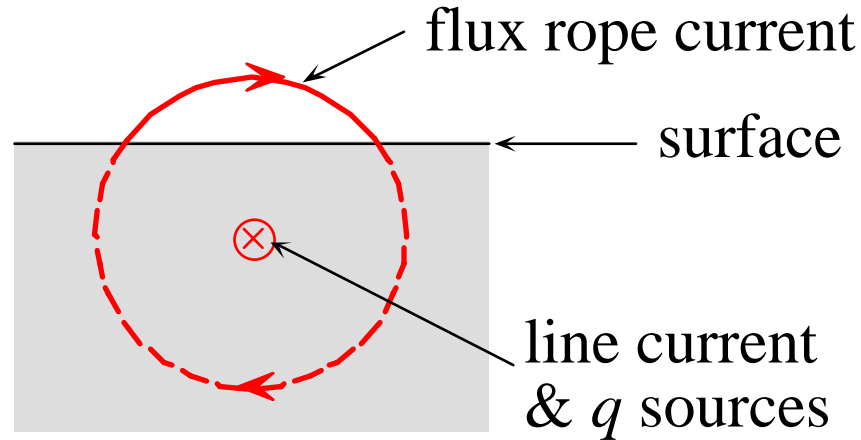
1. flux rope

3. line-current

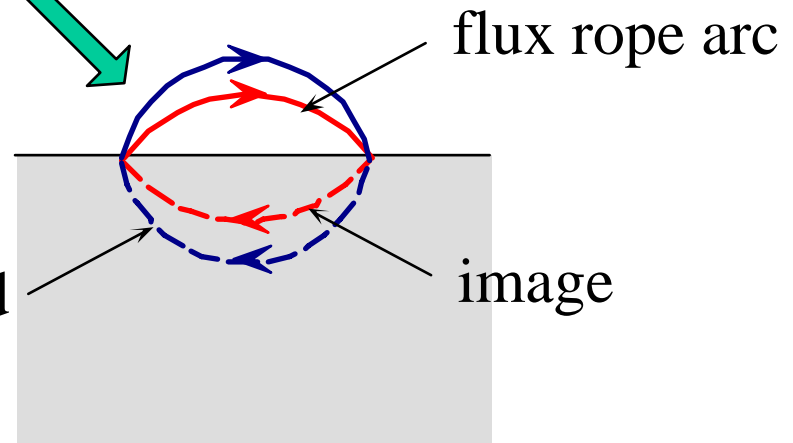


3D Line-Tied Solution by Method of Images

Solution for \mathbf{B} in terms of incomplete elliptical integrals



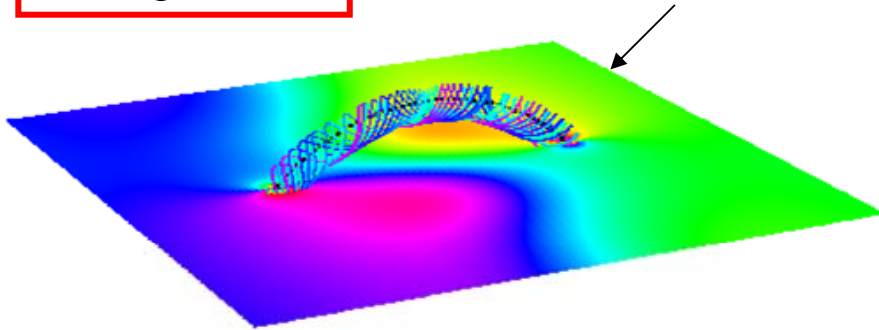
perturbed position



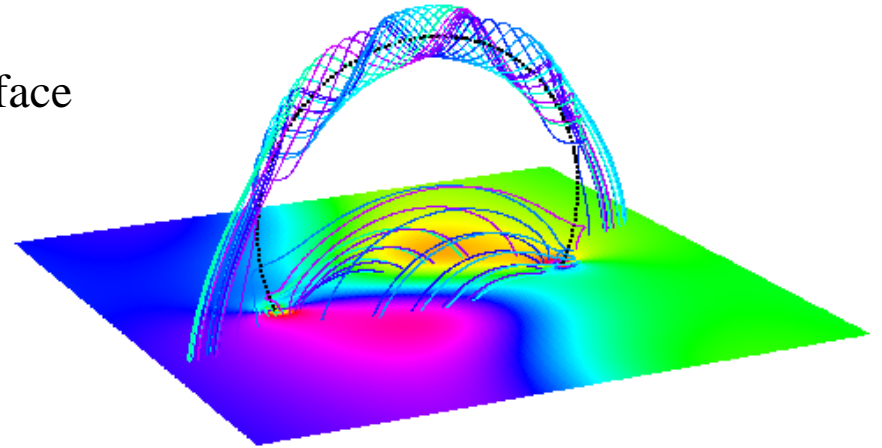
Line-Tied Evolution

initial
configuration

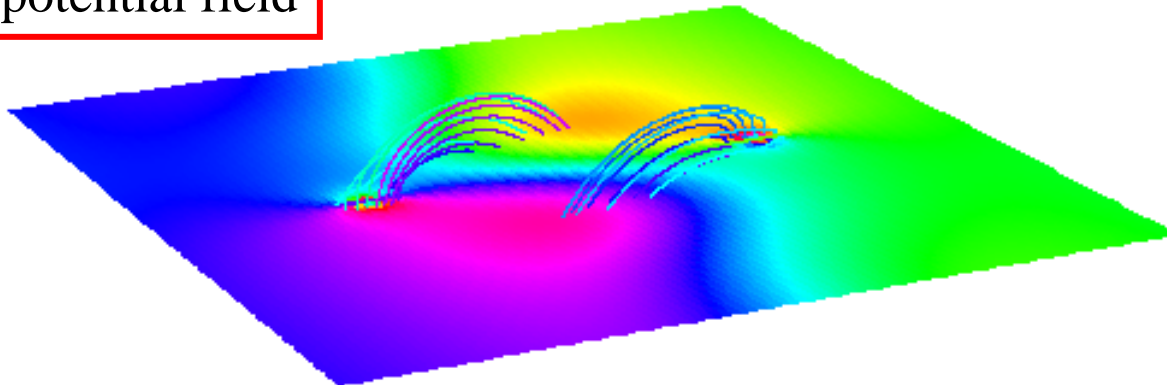
vertical field at surface



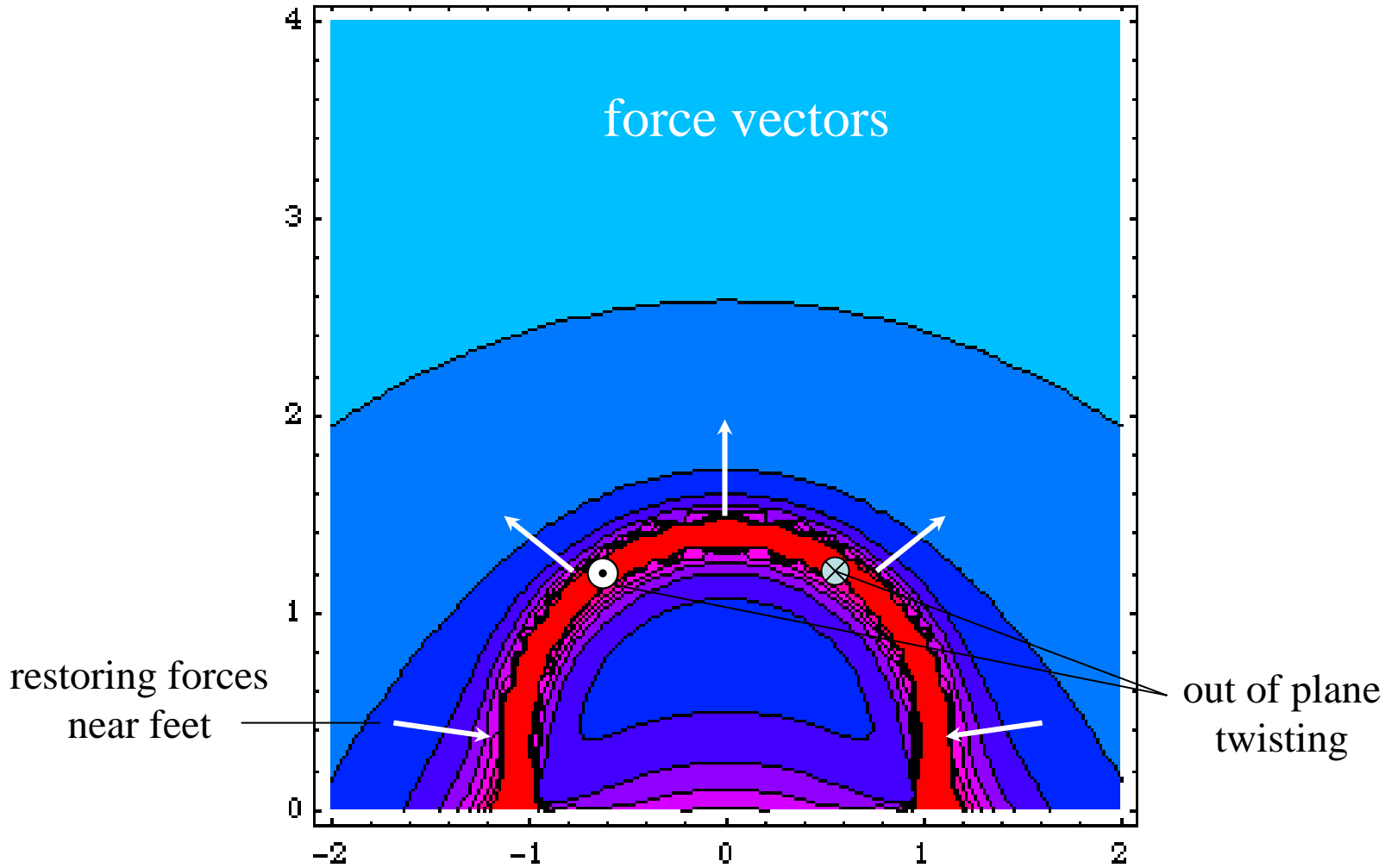
erupted configuration



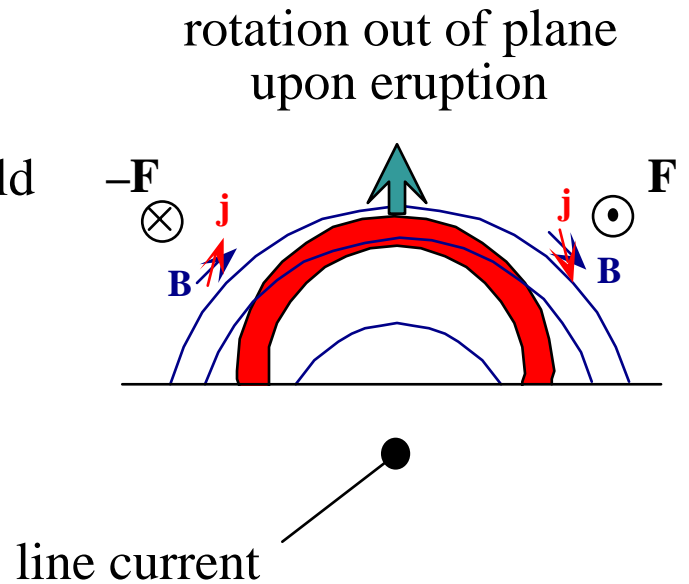
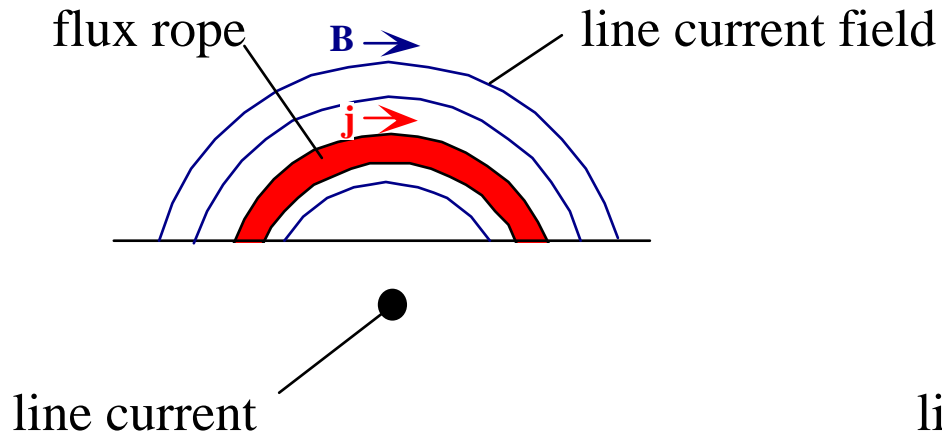
potential field



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

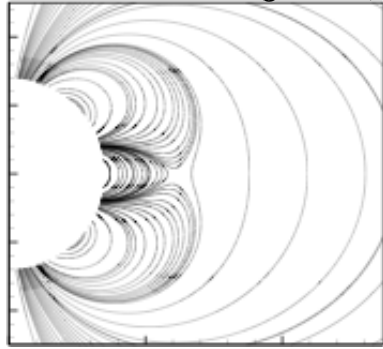
SAIC CME Simulation

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

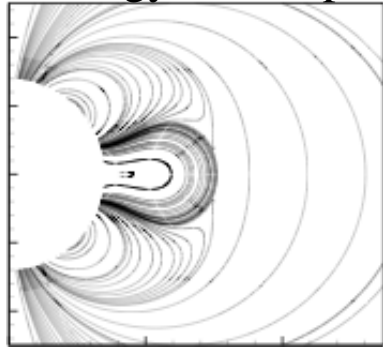
QuickTime™ and a
BMP decompressor
are needed to see this picture.

What is the Trigger Mechanism in the Breakout Model?

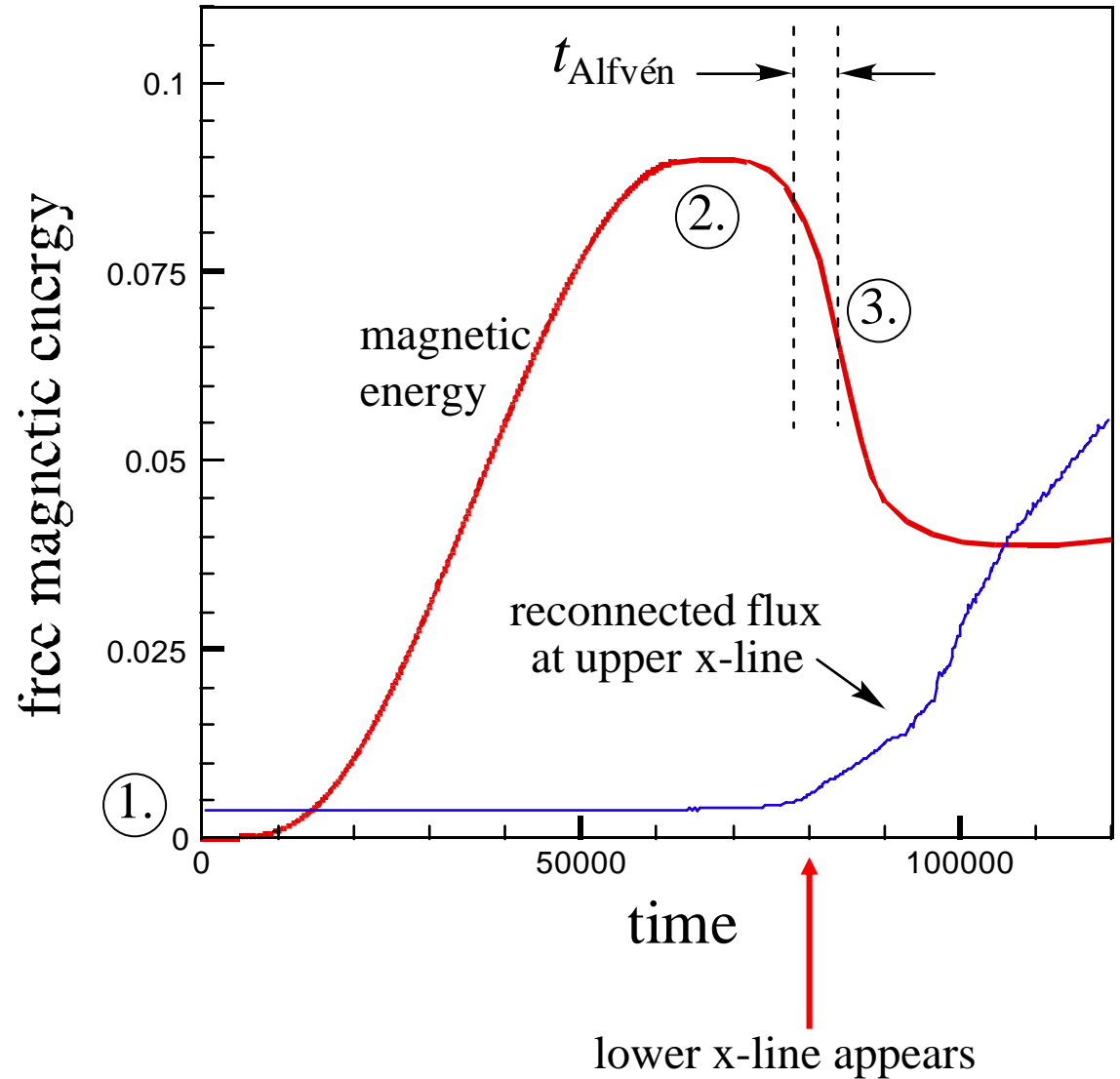
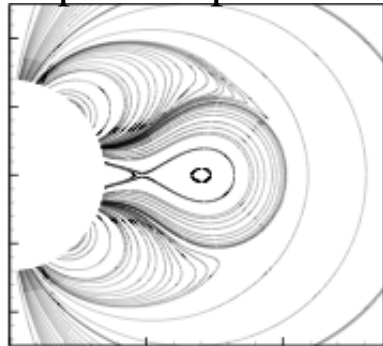
initial state ($j = 0$)



energy build-up



post eruption



Role of Reconnection in the Breakout Model

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

Flux Rope Emergence & Eruption

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

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

3D simulations of Fan & Gibson (2006)

Some Unanswered Questions

1. How are stressed magnetic fields formed?
 - magnetic energy storage —
2. What determines the rate of reconnection?
 - kinetic processes —
 - turbulence —
3. To what extent are flares & CMEs predictable?
 - loss of equilibria —
 - loss of stability —