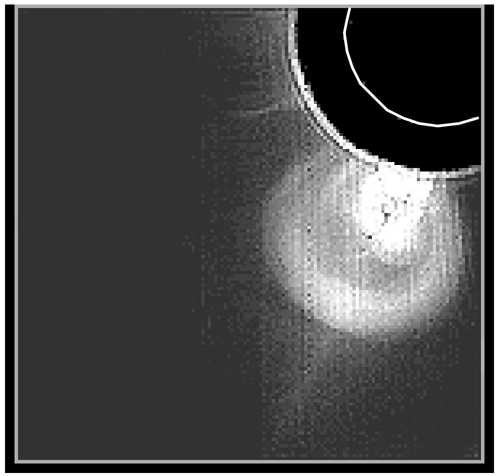
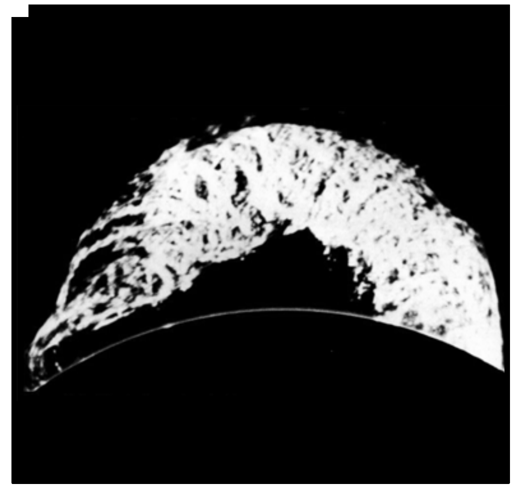
Theory & Modeling of Solar Eruptions

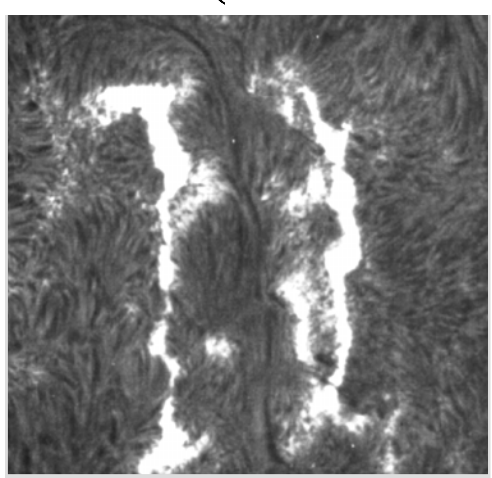
coronagraph (CME)



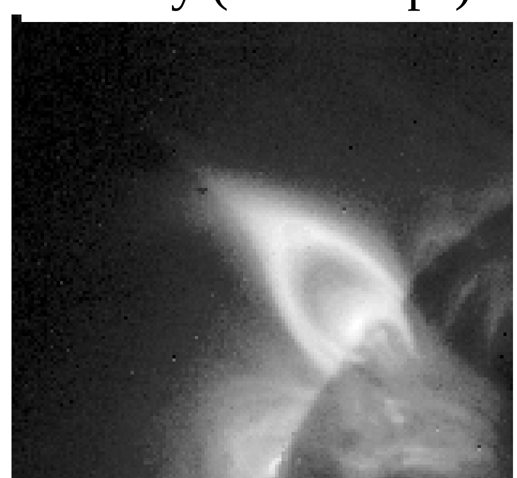
Hα limb (prominence)



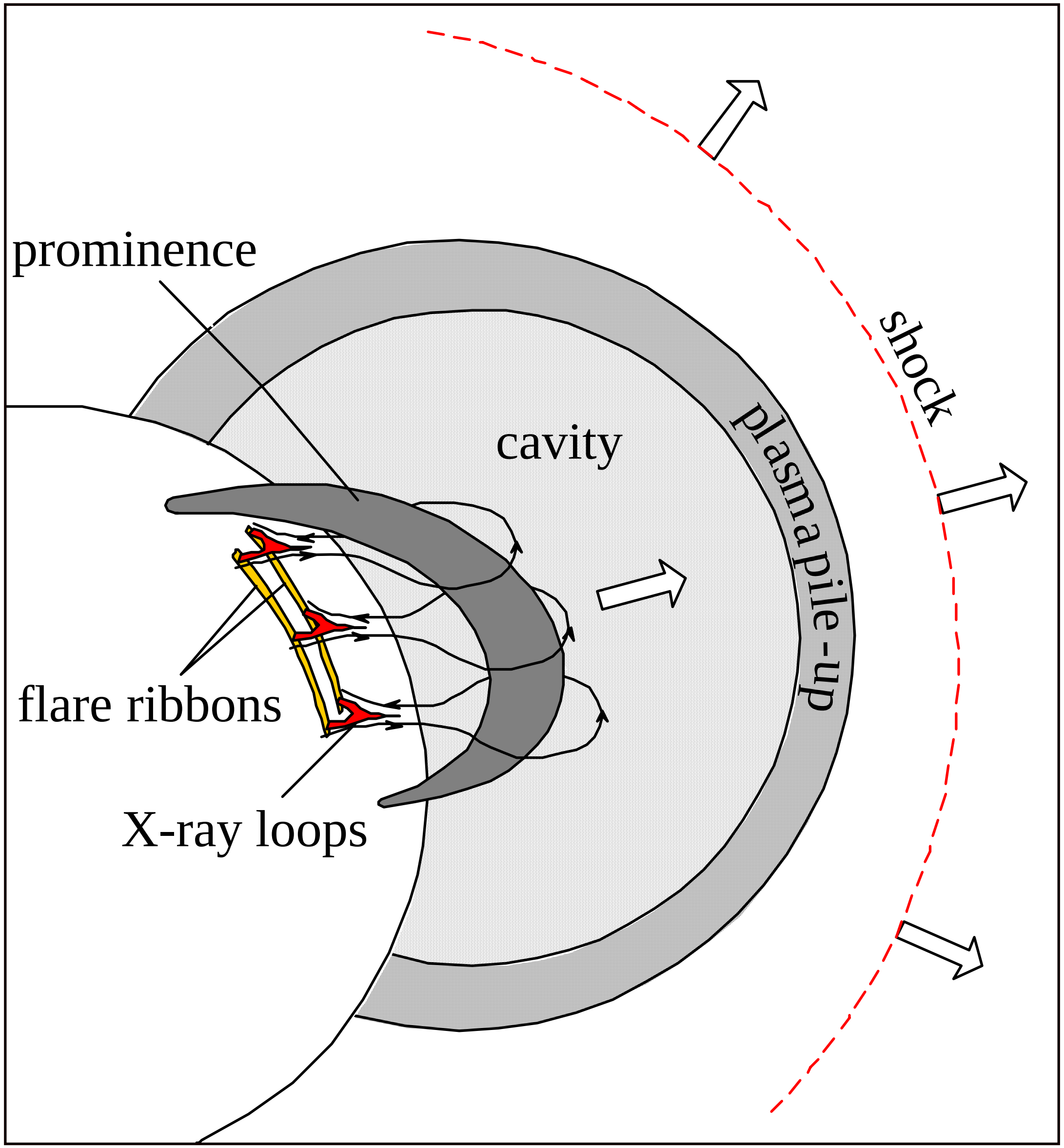
Hα disk (flare ribbons)



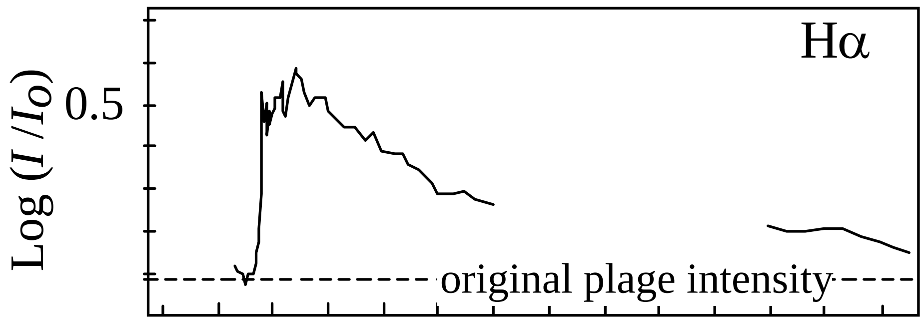
X-ray (flare loops)

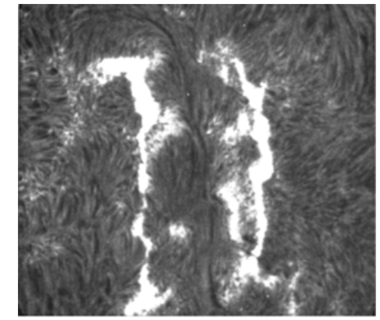


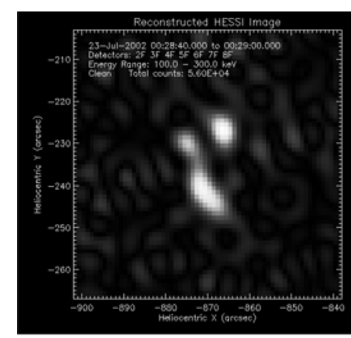
Large Solar Eruptions



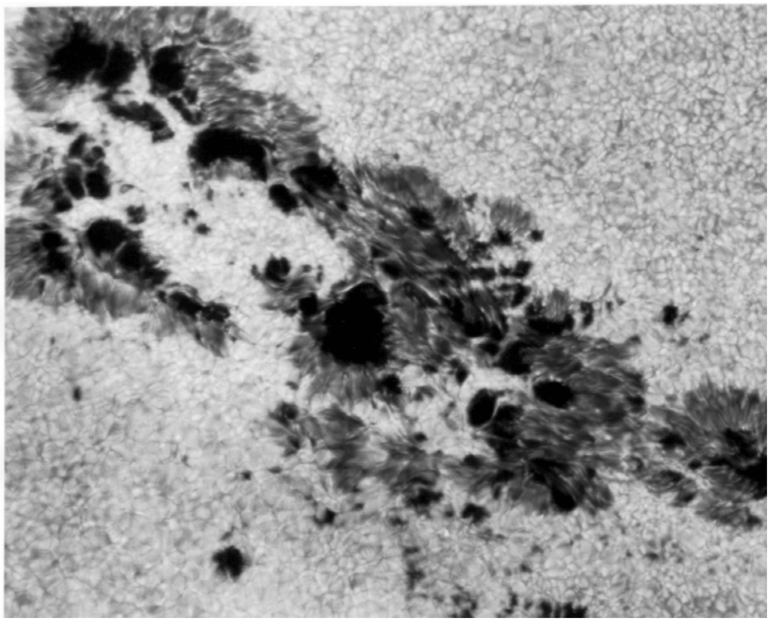
QuickTime™ and a
Video decompressor
are needed to see this picture.


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

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 erutions.

Photospheric boundary condition:

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

Photospheric convection is negligible

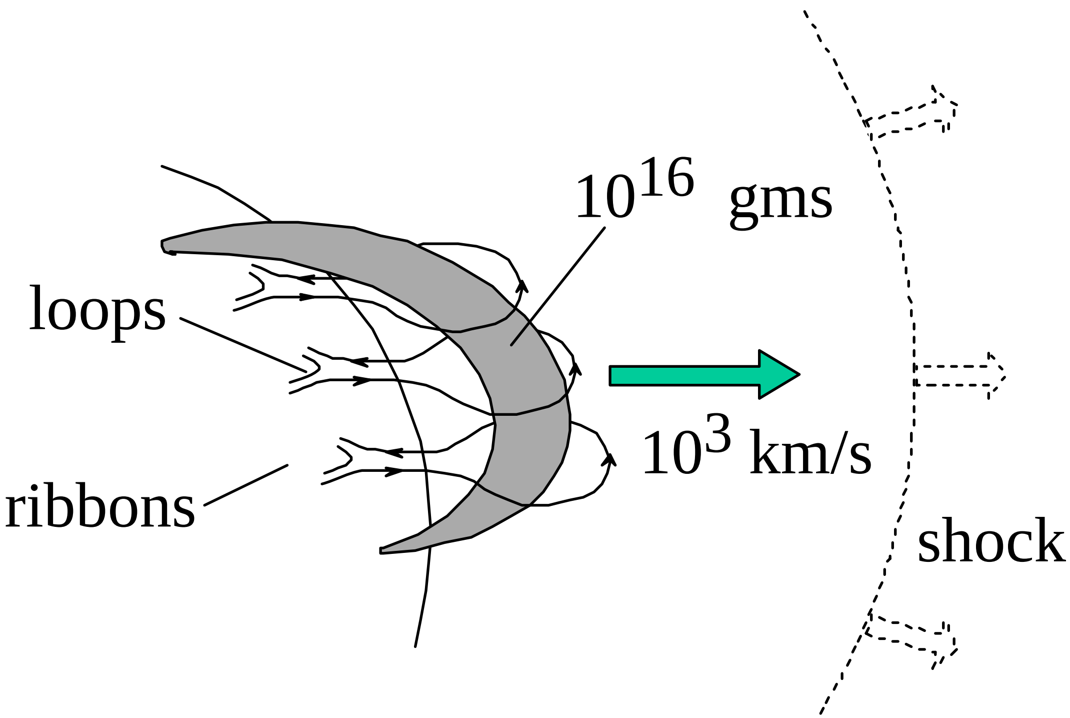
B normal to surface is fixed.

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:
$\lesssim 100$ ergs/cm^3

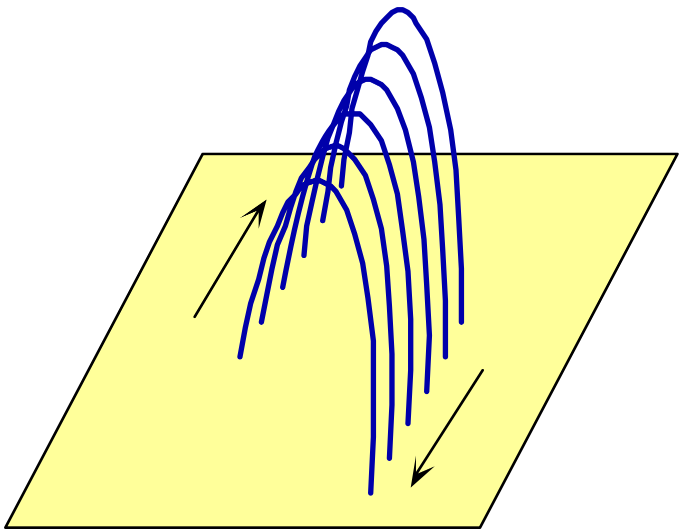
Nature of Energy Source: Required: ≈ 100 ergs/cm^3

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?

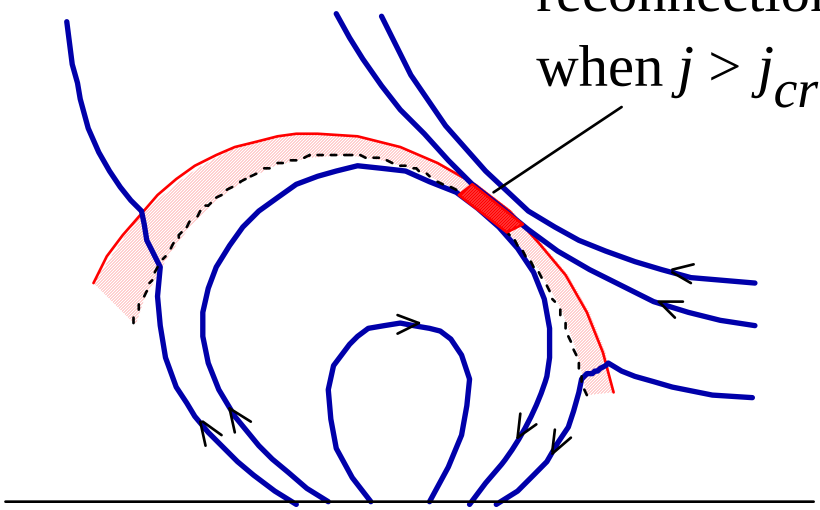
$\beta = 10^{-3}$ $\nabla p \approx 0$ $\mathbf{j} \times \mathbf{B} \approx 0$

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



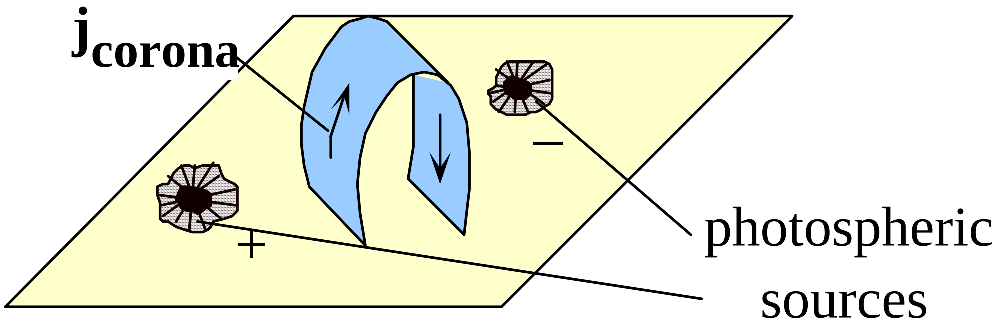
sheared magnetic fields

Current sheets:

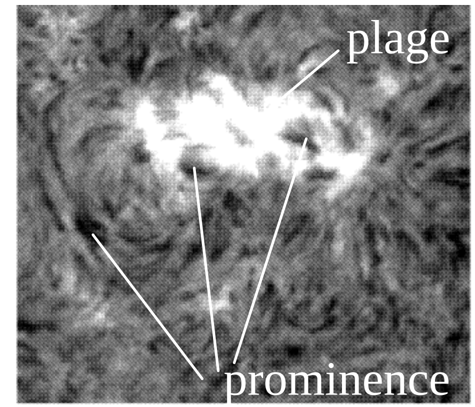


emerging flux model

How Much Energy is Stored?



Hα image



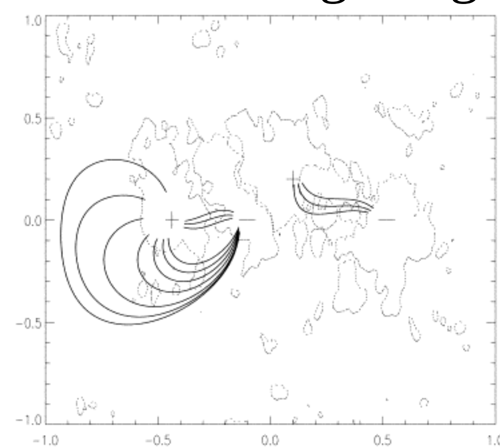
$$\mathbf{B} = \mathbf{B}_{\substack{\text{photospheric}\\ \text{currents}}} + \mathbf{B}_{\substack{\text{coronal}\\ \text{currents}}}$$

invariant during CME (→ photospheric currents)

source of CME energy (→ coronal currents)

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

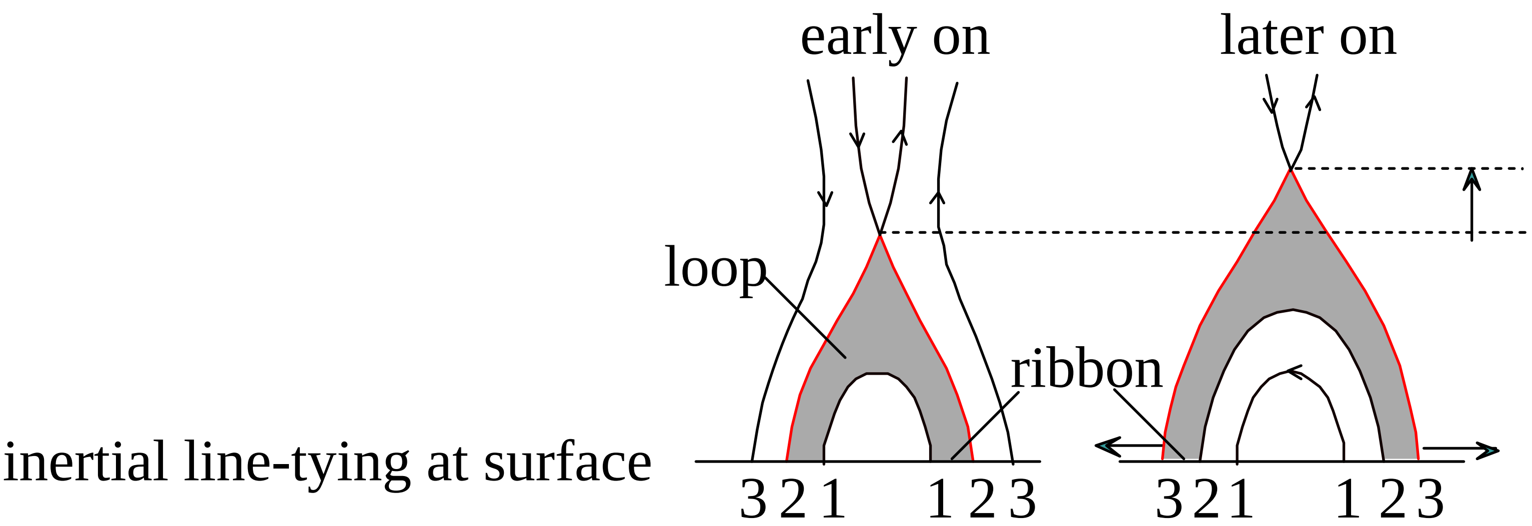
model with magnetogram



from Gaizauskas & Mackay (1997)

free magnetic energy ≈ 50% of total magnetic energy

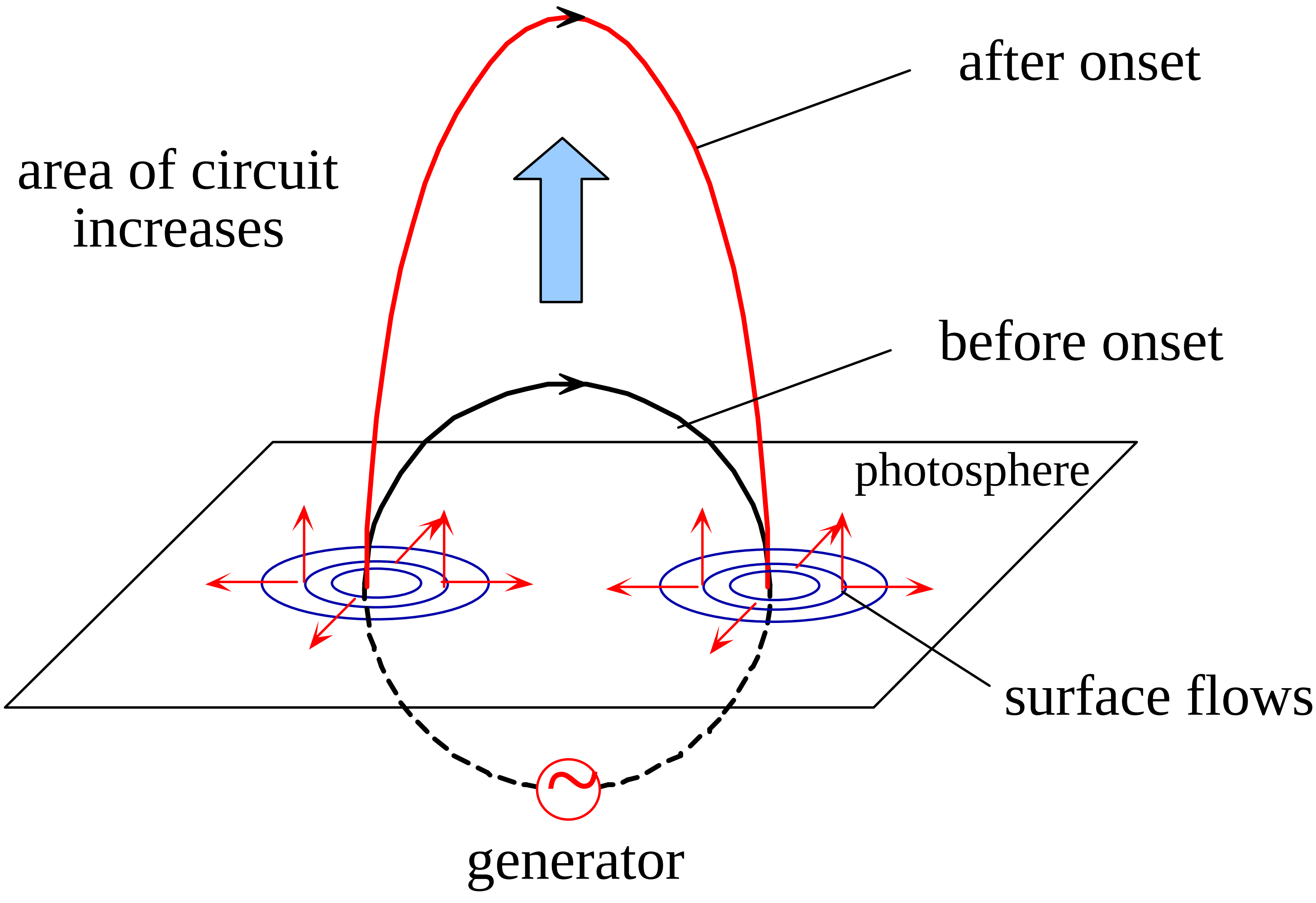
Apparent Motion of Loops & Ribbons



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

Flux Injection Models

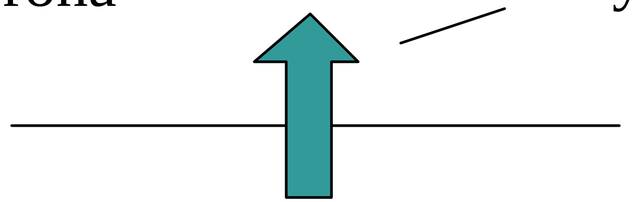
(e.g. Chen 1989)



During injection energy flows through photosphere.

corona

Poynting flux:



convection zone

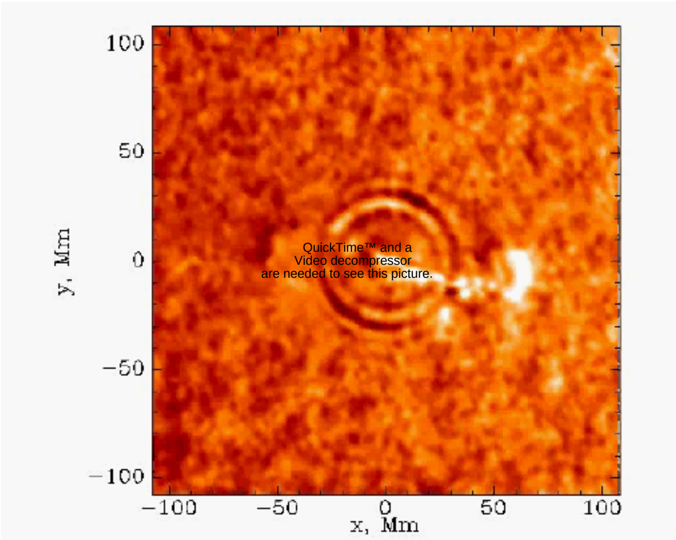
$$\mathbf{S} = c\,\mathbf{E} \times \mathbf{B} / (4\pi)$$

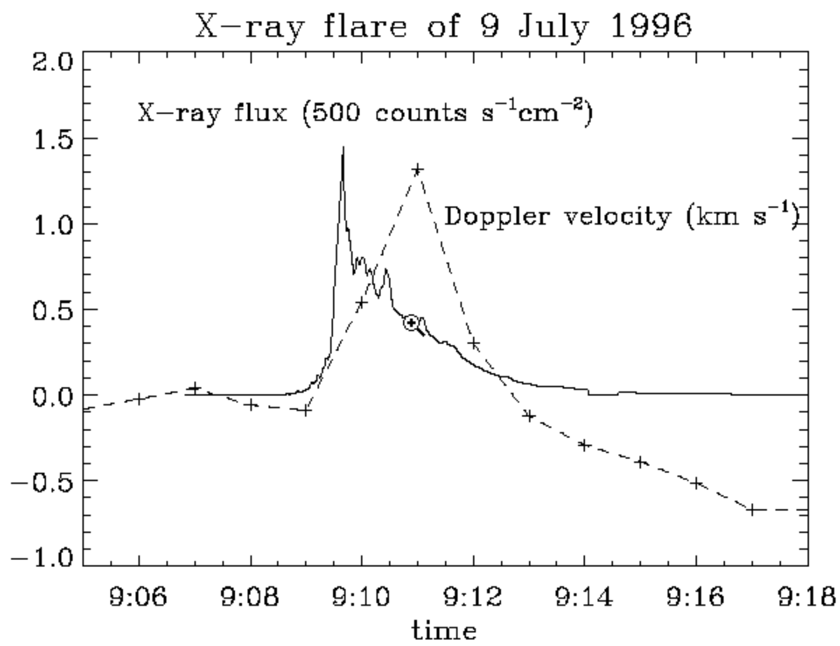
(ergs/cm/sec)

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

> 10 km/sec for > 10 minutes

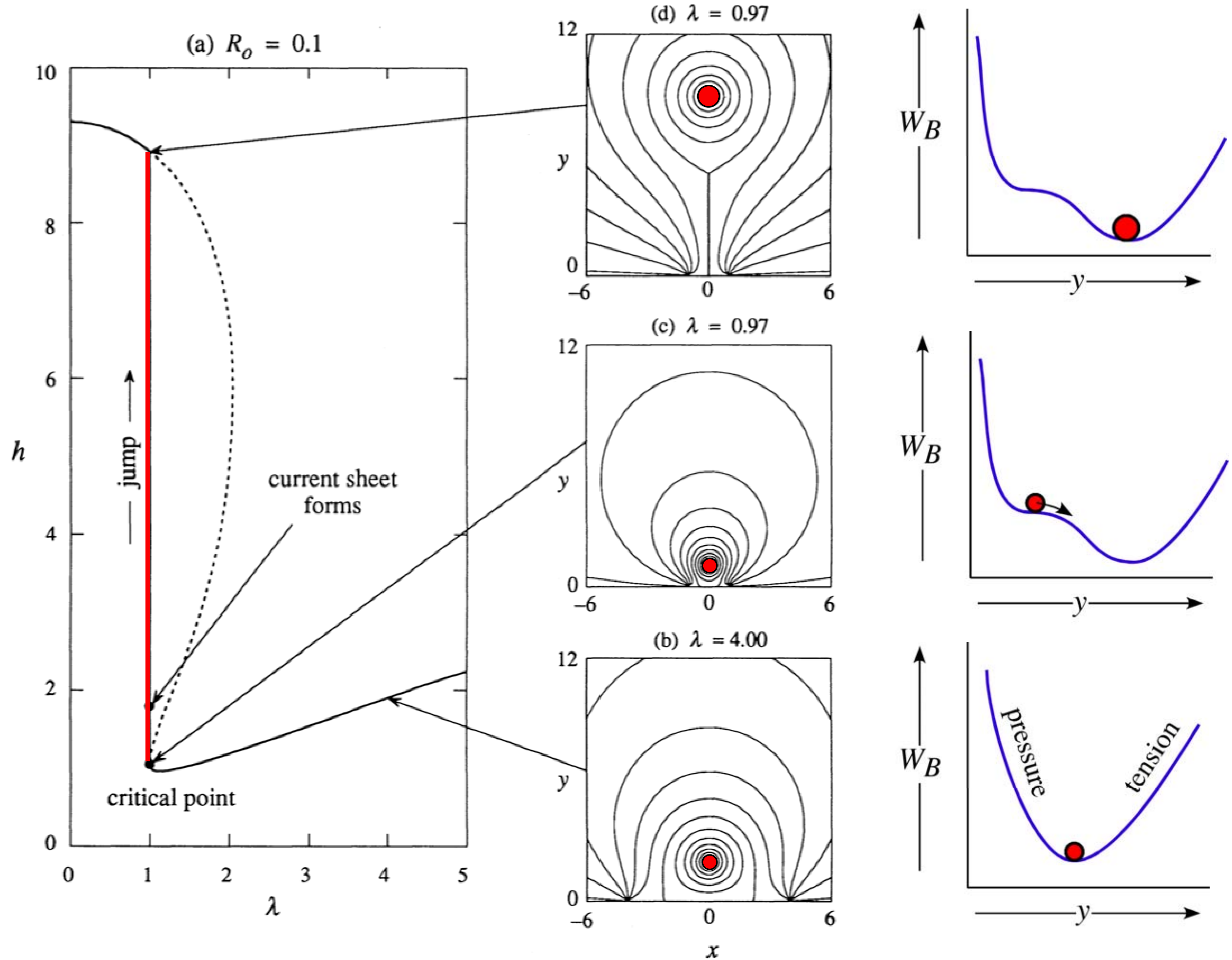
Kosovichev et al. 1998



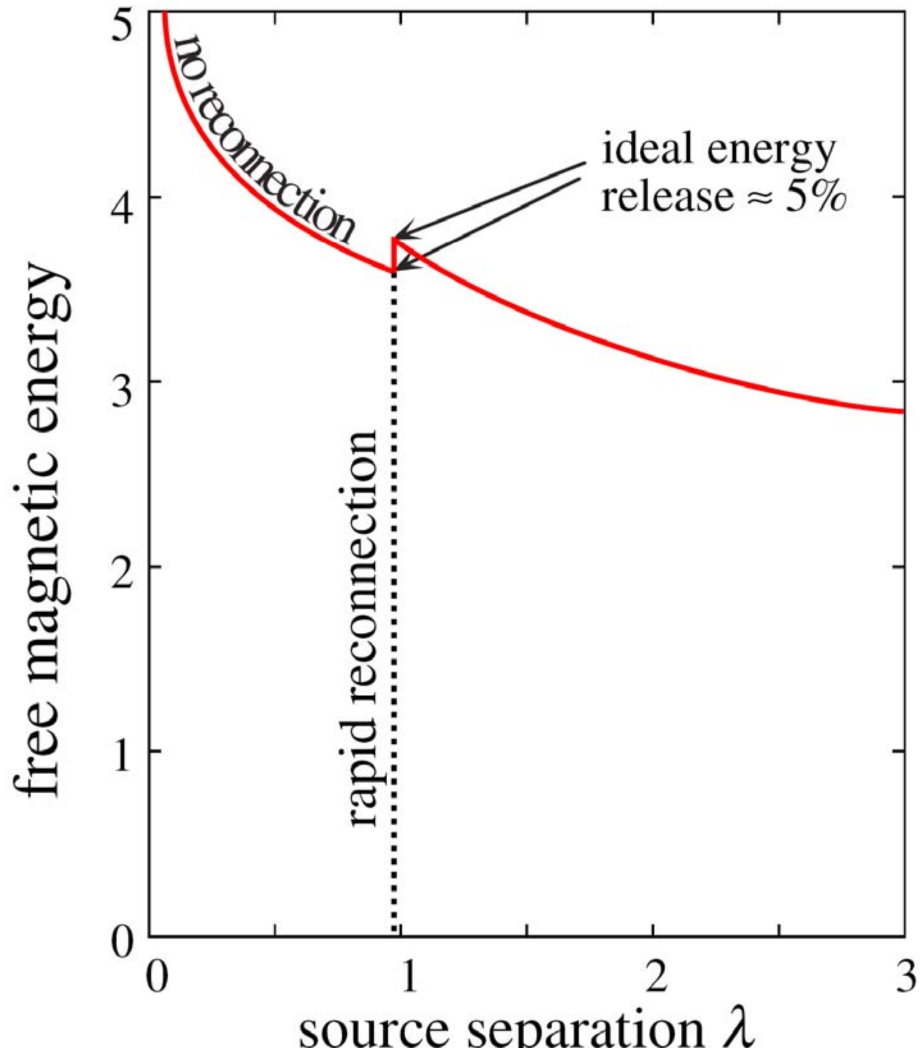


Injection models predict large surface flows which are never observed.

Loss of Equilibrium Model

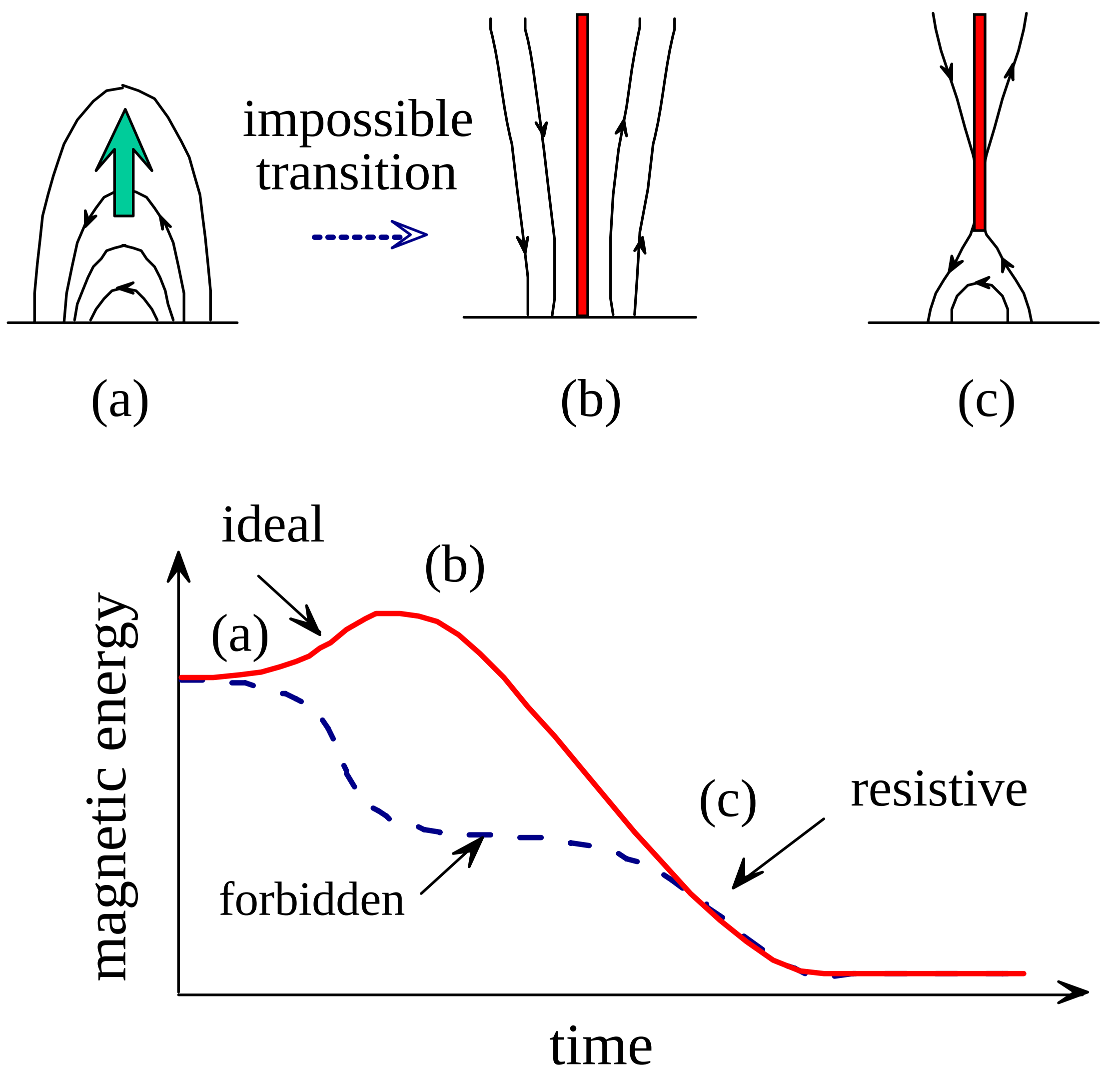


Energy Release in 2D Model

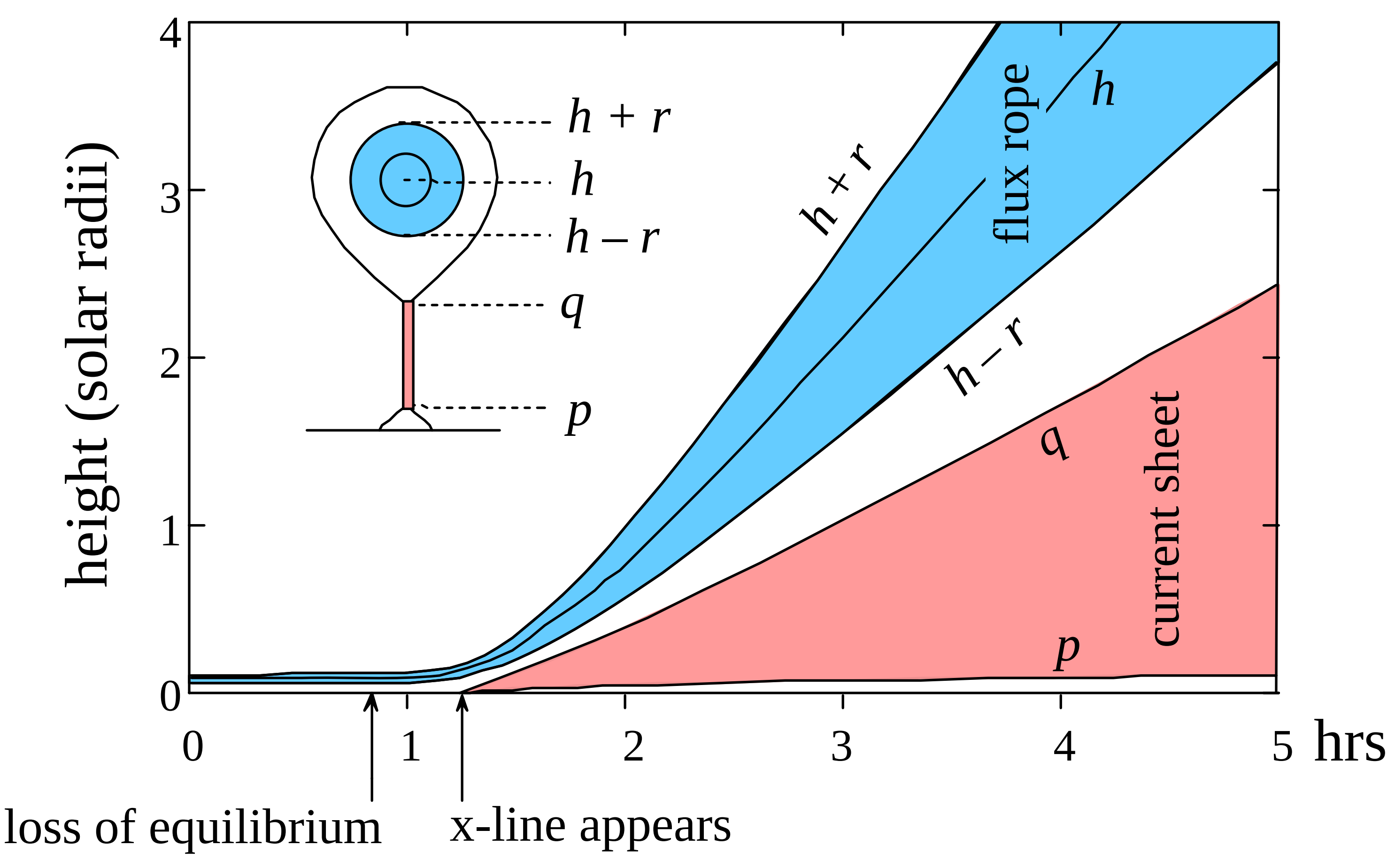


← time —

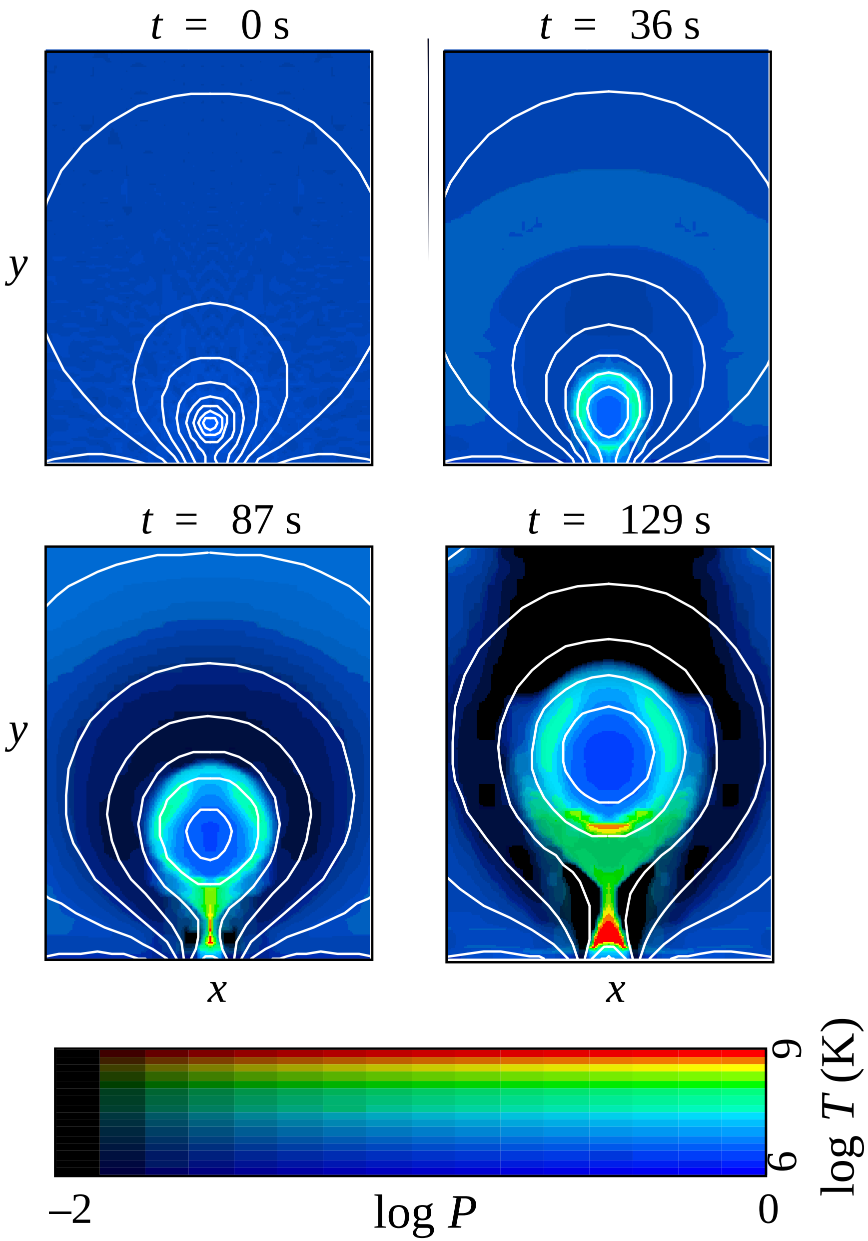
Aly - Sturrock Paradox



Trajectories



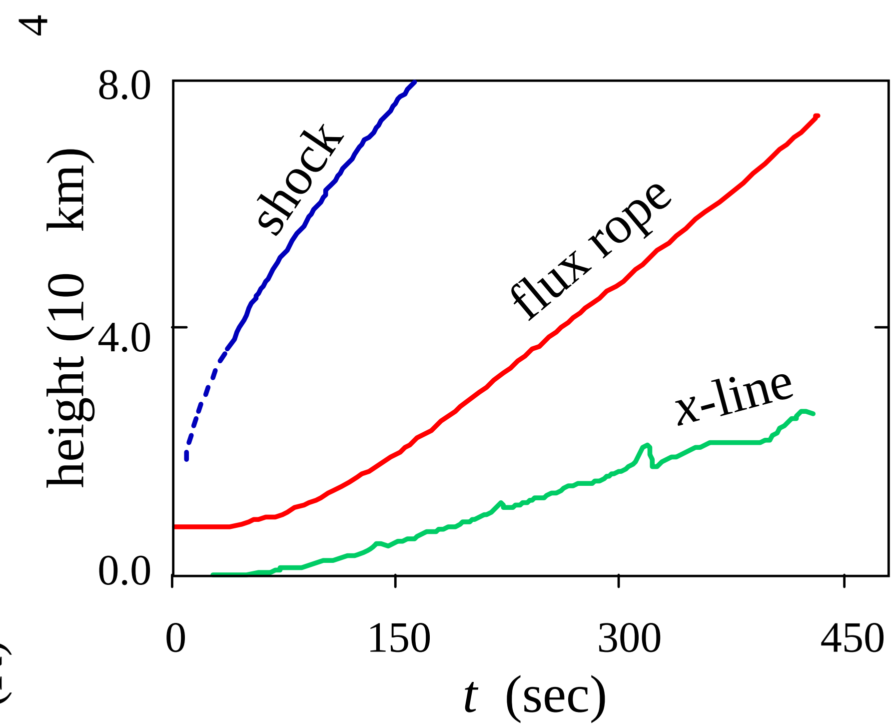
Numerical Simulation of Critical Point Configuration



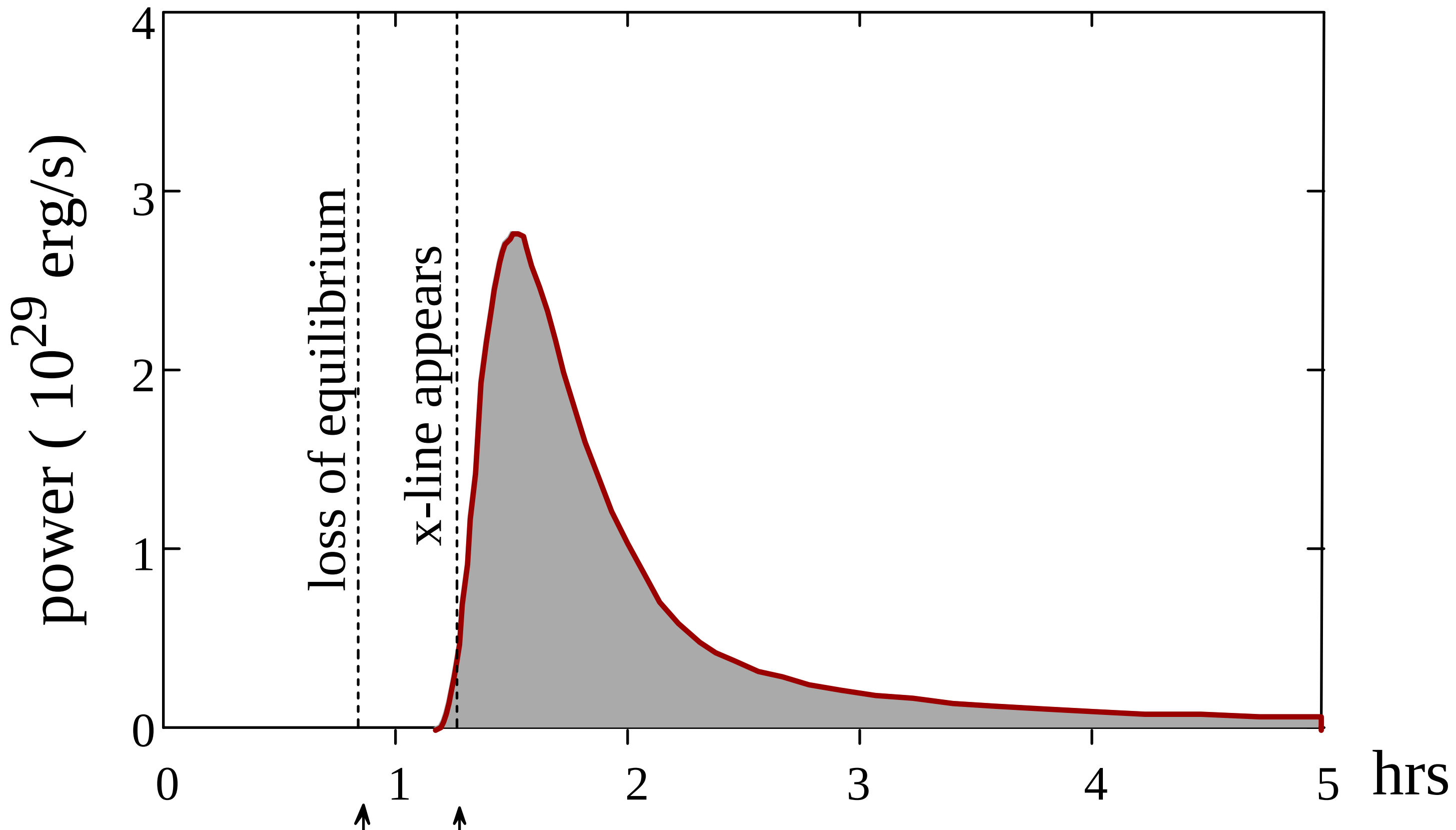
initial condition: **V** = 0

energy equation: Ohmic heating
no cooling

resistivity: uniform, *S* = 500



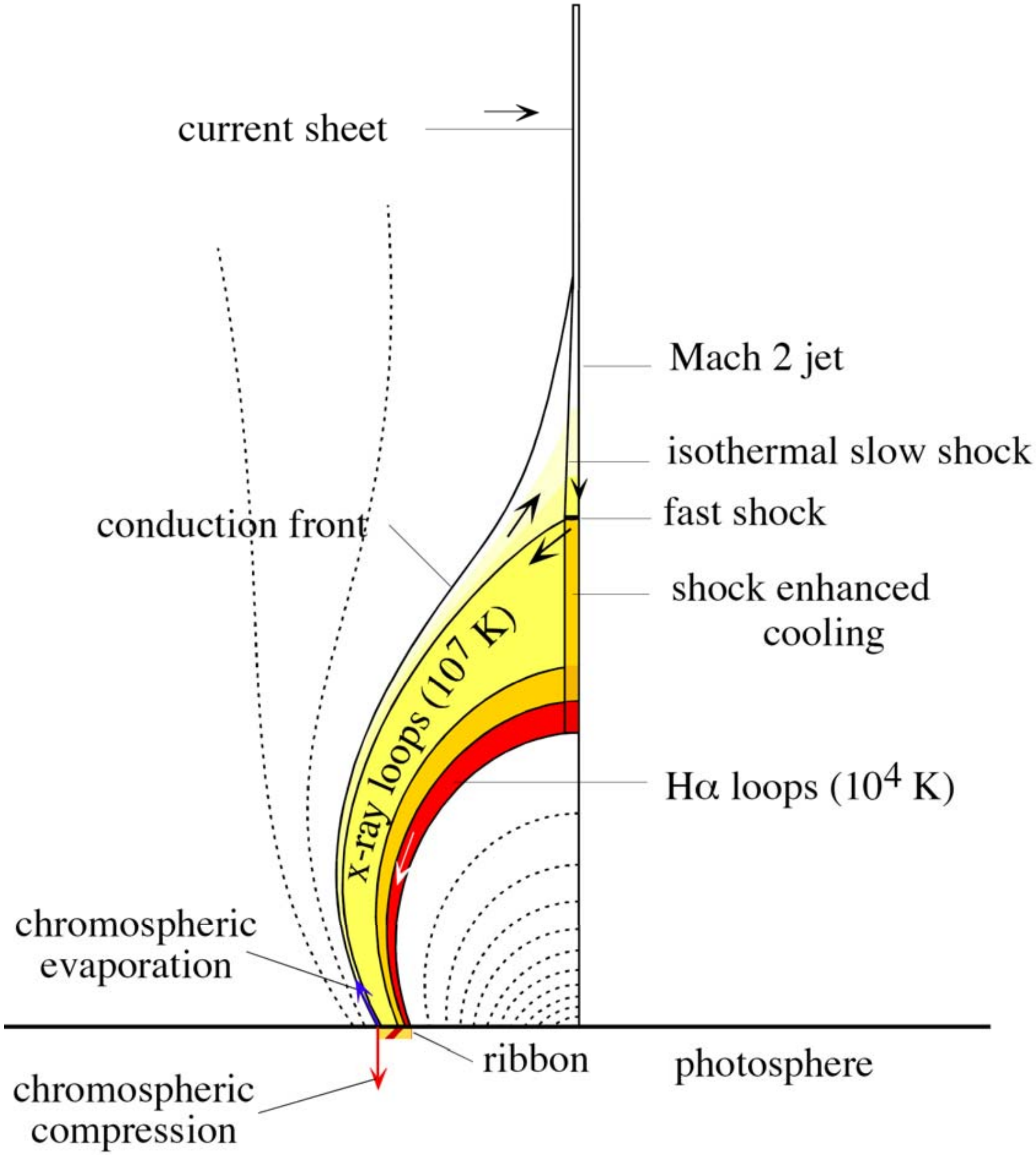
Power Output



loss of equilibrium

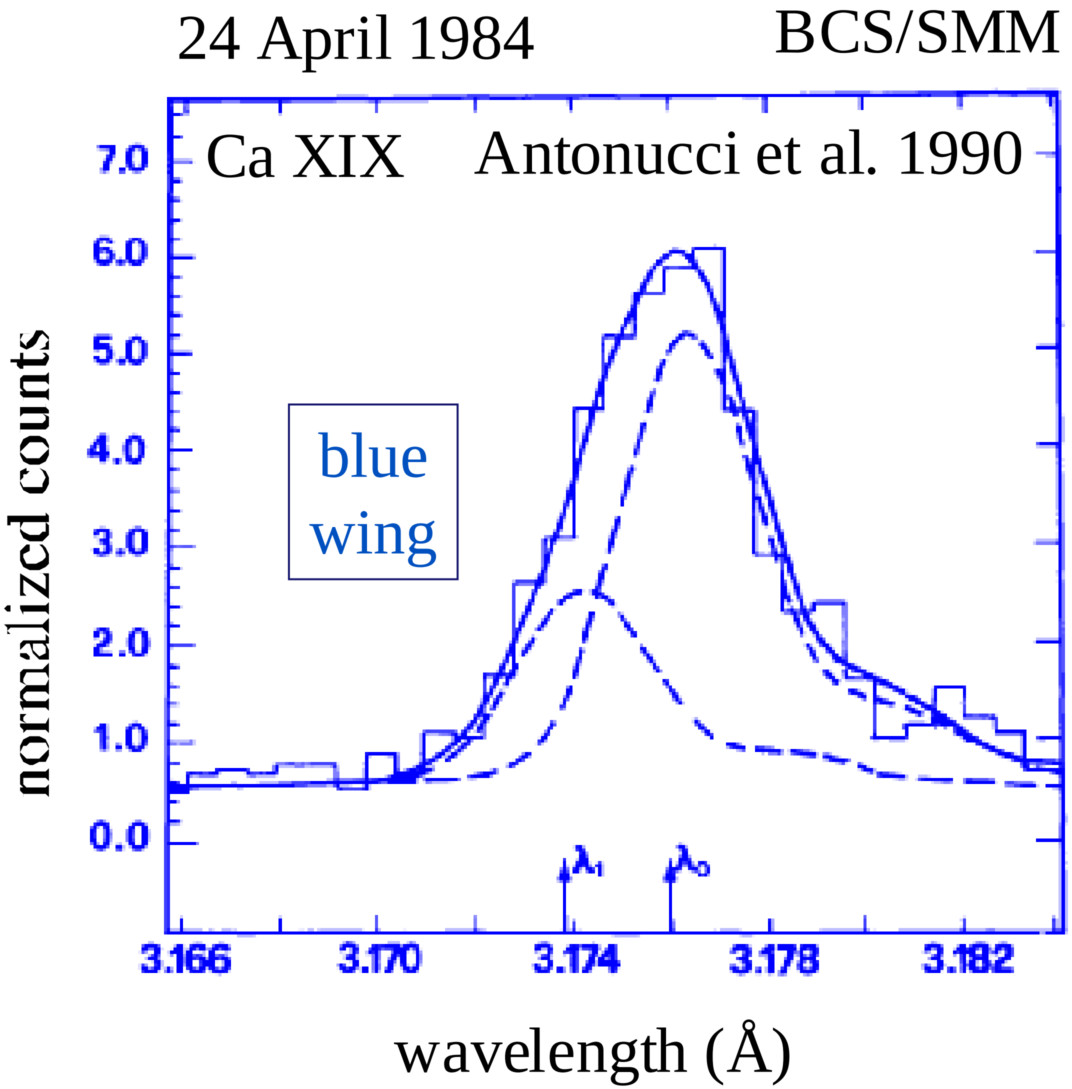
x-line appears

Chromospheric Evaporation



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

Evaporation Doppler Shift Puzzle



QuickTime™ and a
TIFF (Uncompressed) decompressor
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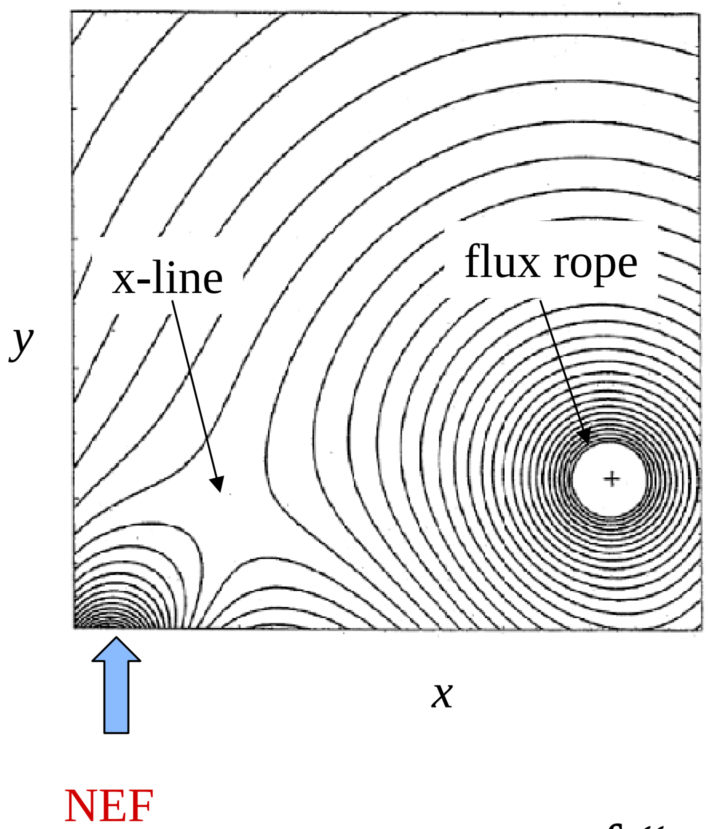
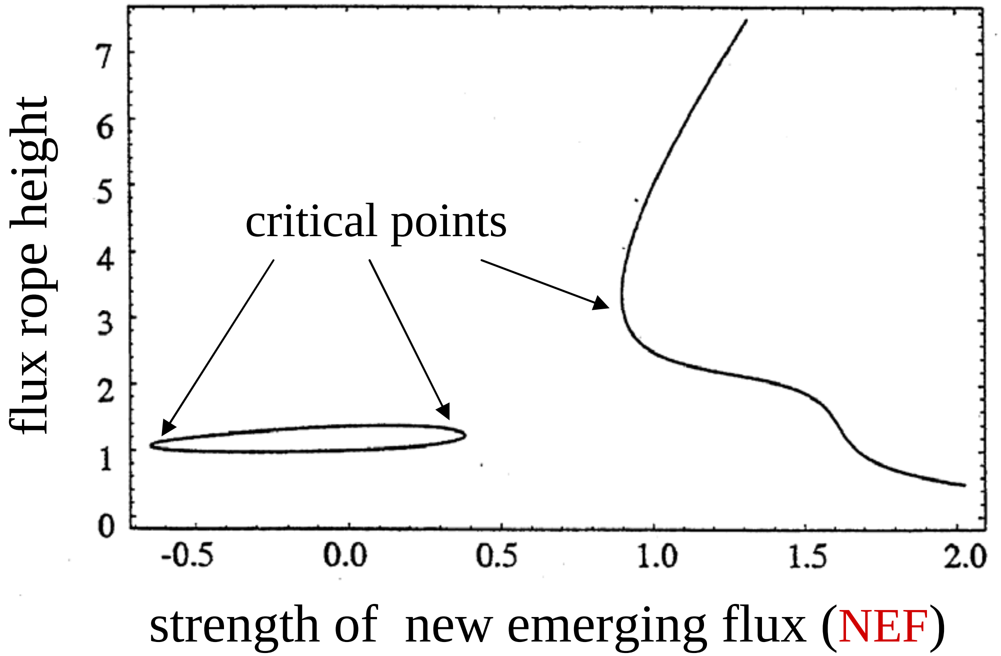
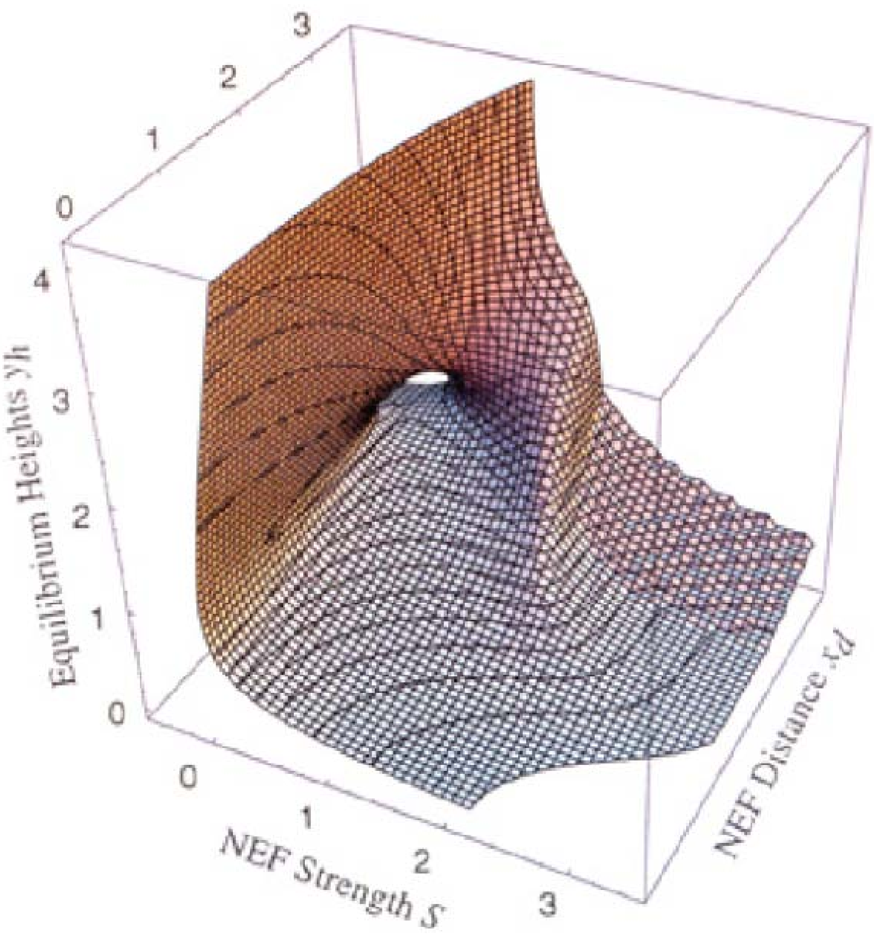
2D Asymmetric Quadrupole Model





test of "tether-cutting" concept

Equlibrium Manifold in 5D Parameter Space of Model



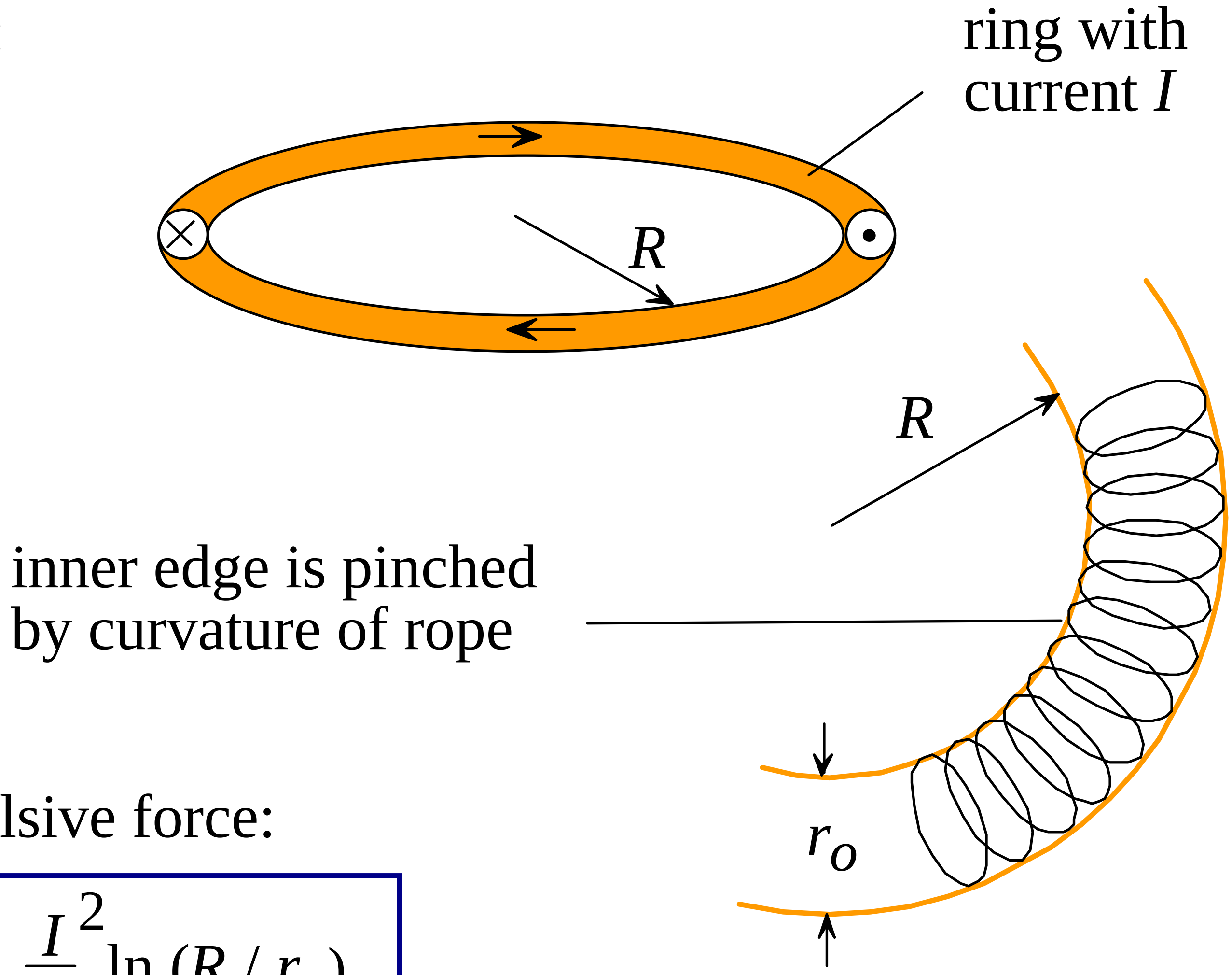
3D "cross section"

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:

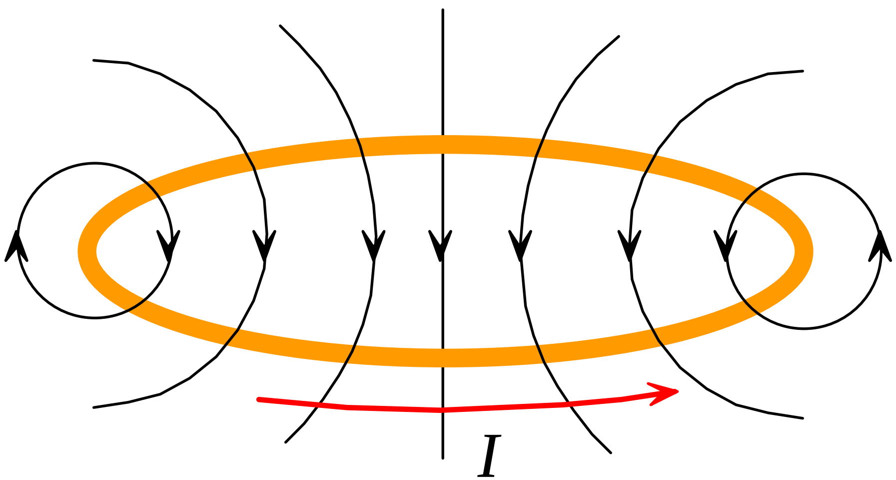


repulsive force:

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

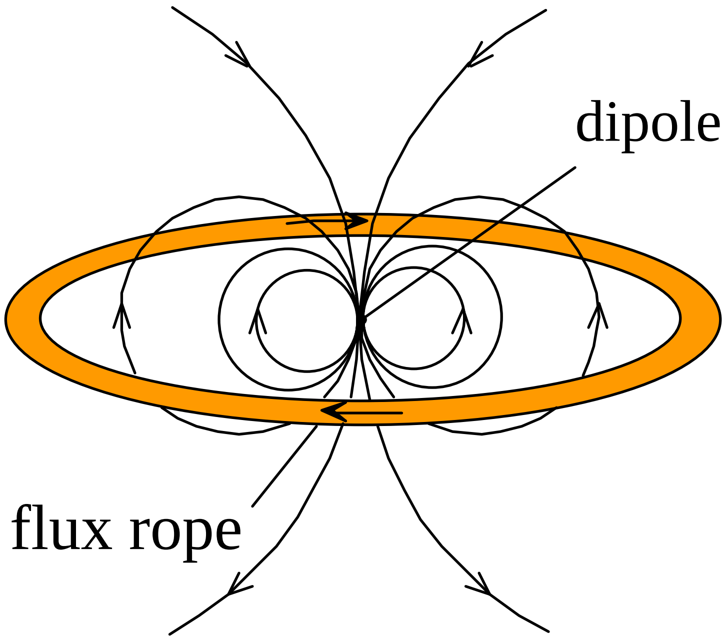
Basic Principles II

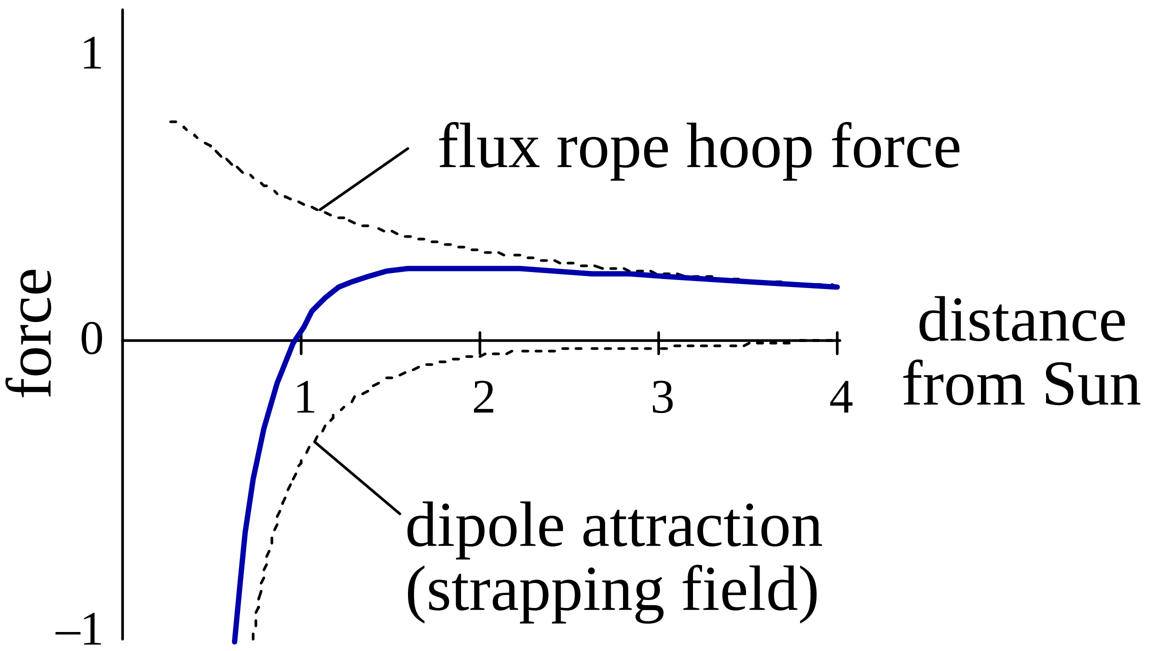
Flux Conservation:



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

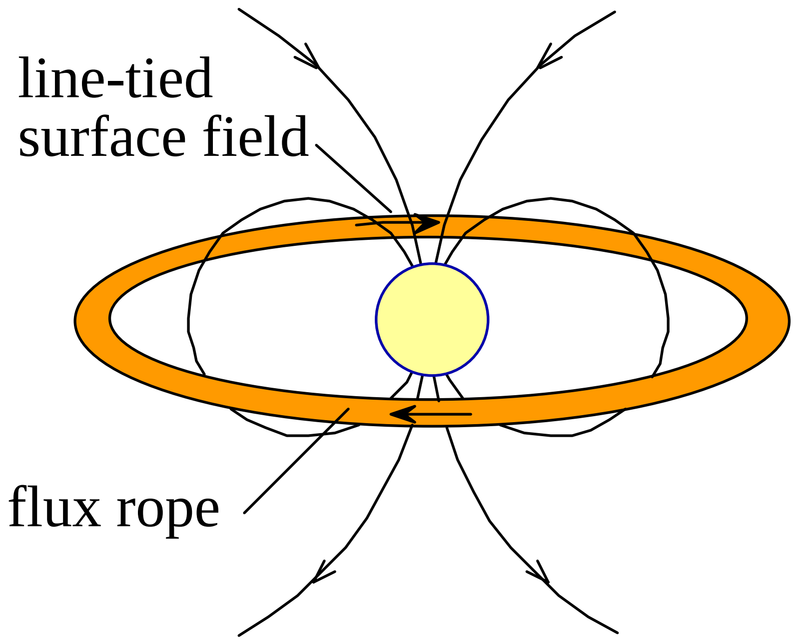
How to Achieve Equilibrium



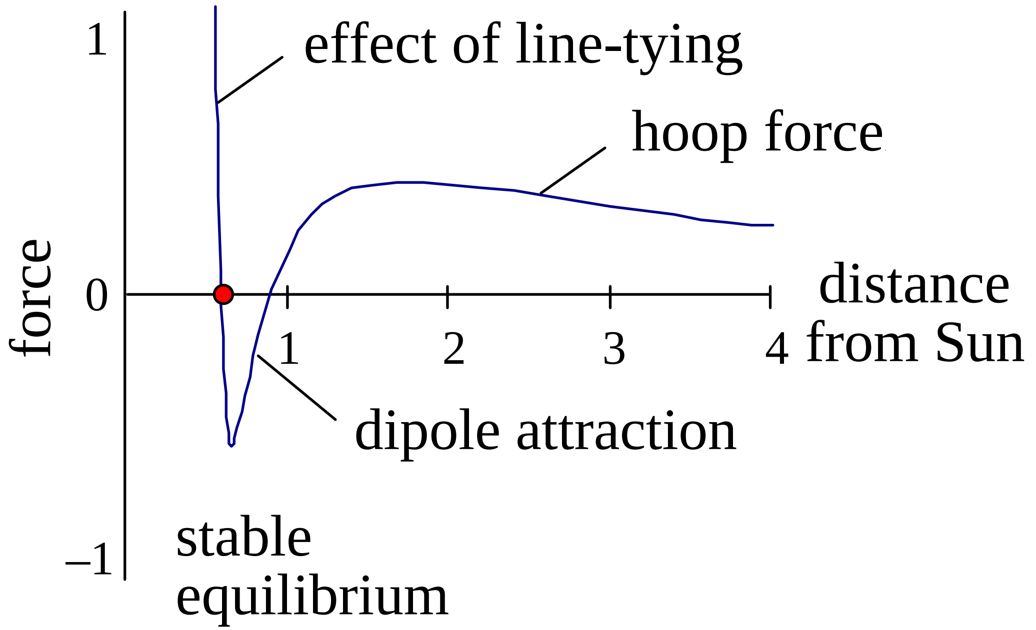


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium



Key factor: Line-tying



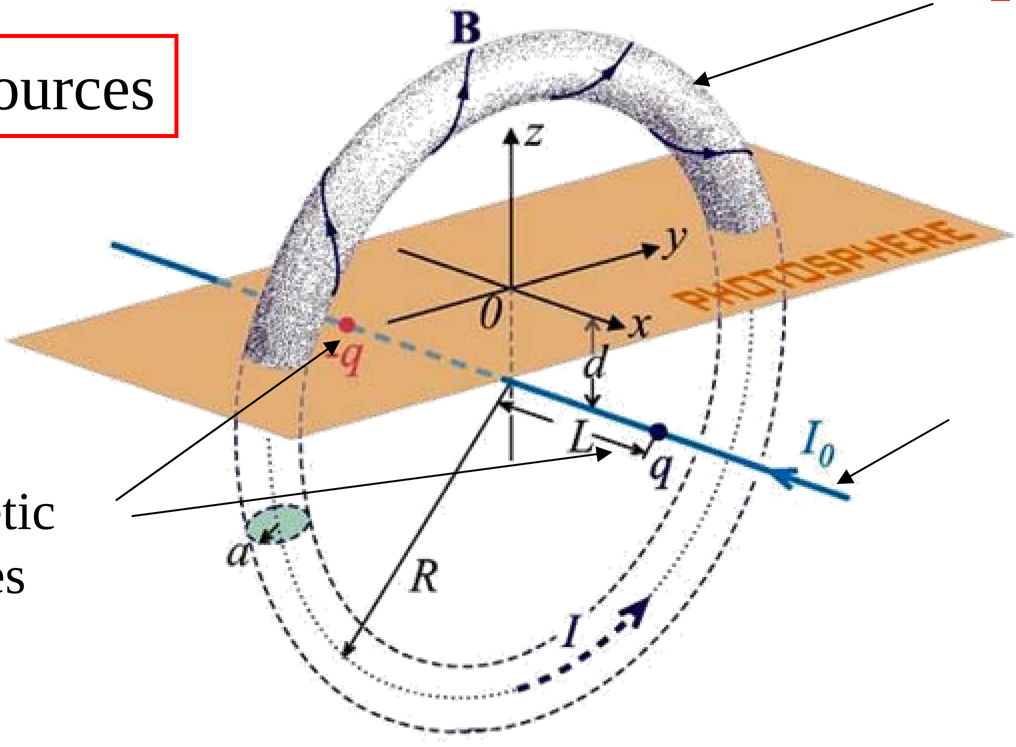
Line-tying creates a second, stable equilibrium

3D Loss-of-Equilibrium Model

Titov & Démoulin (1999)

3 field sources

1. flux rope

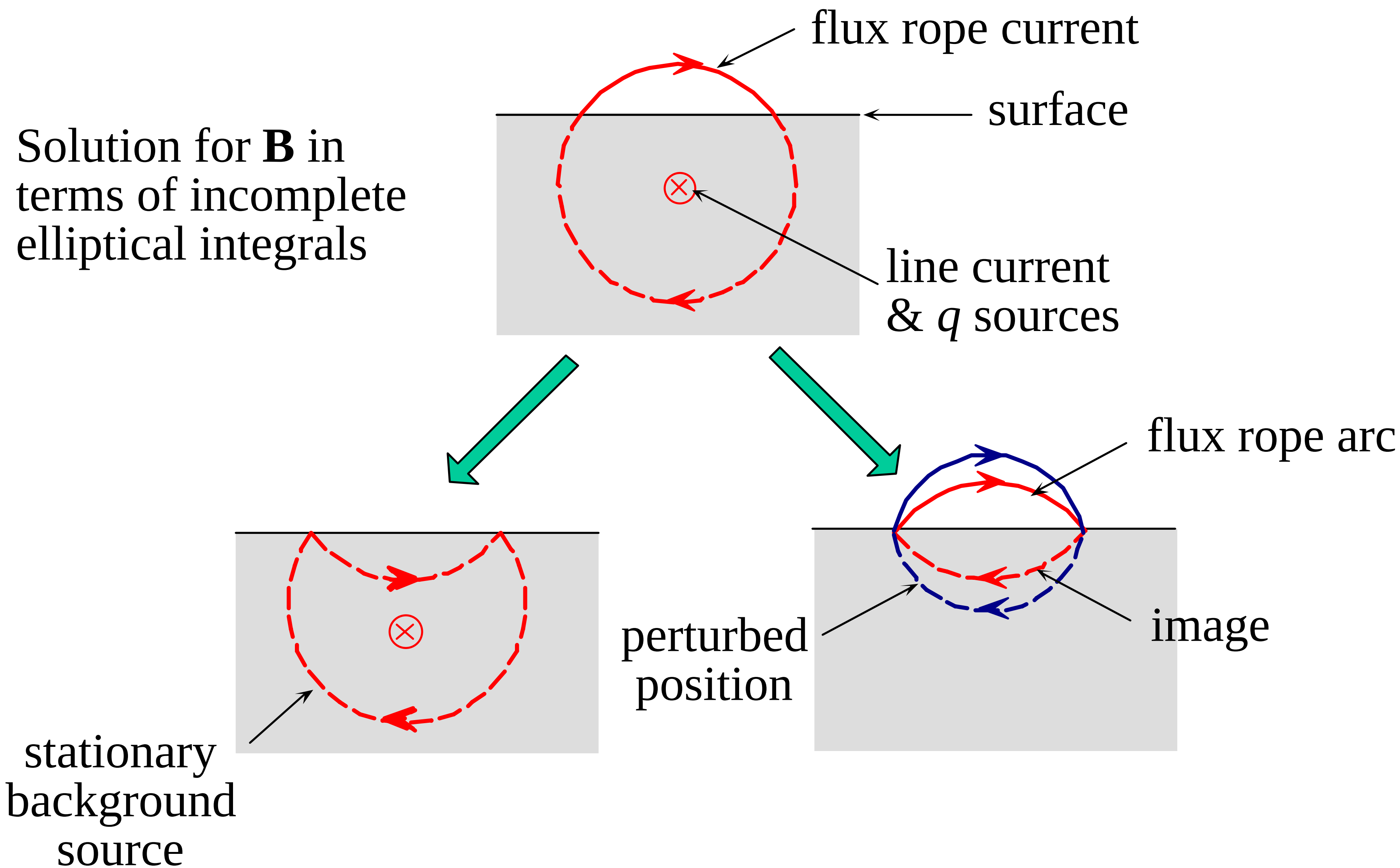


2. magnetic charges

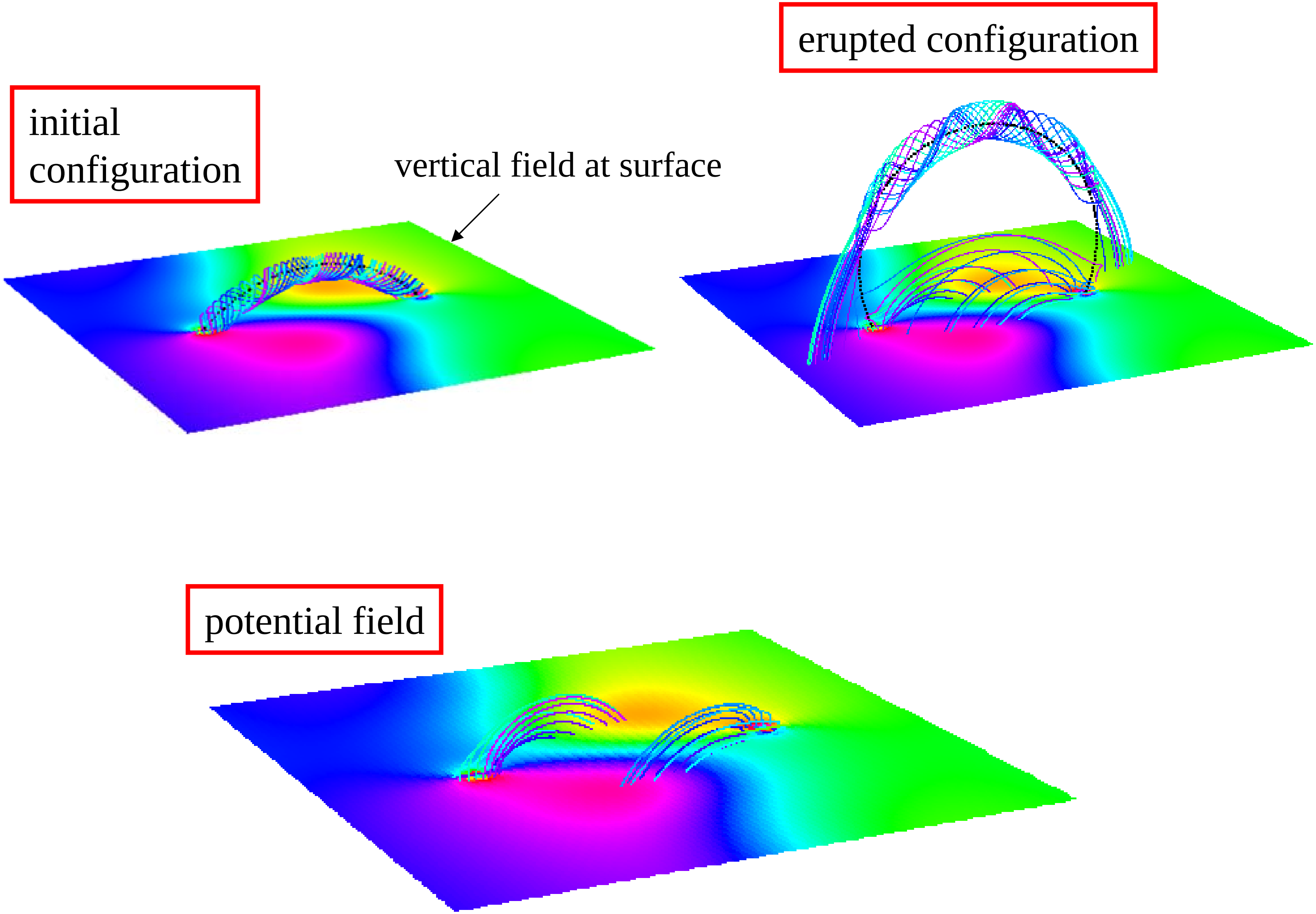
3. line-current

3D Line-Tied Solution by Method of Images

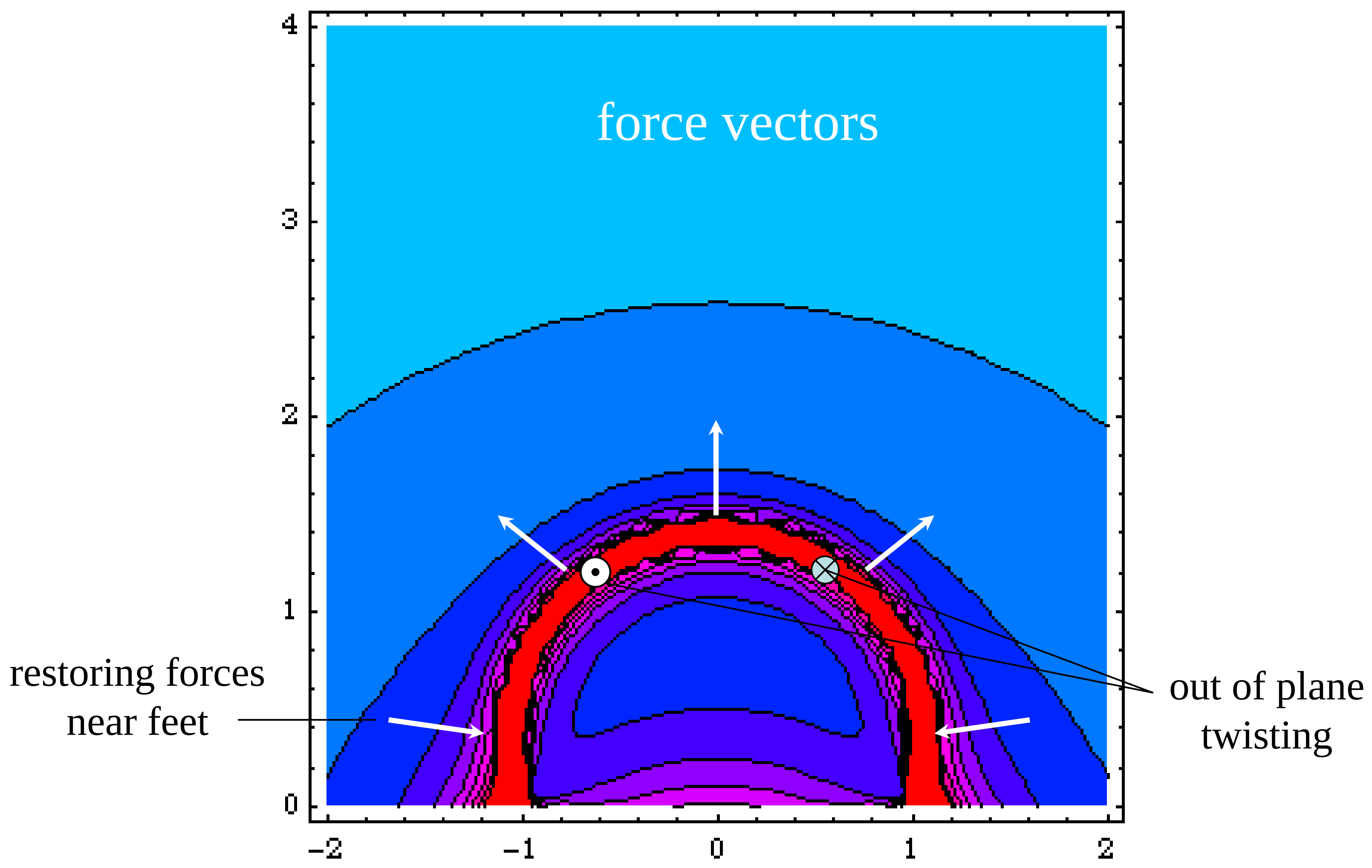
Solution for **B** in terms of incomplete elliptical integrals



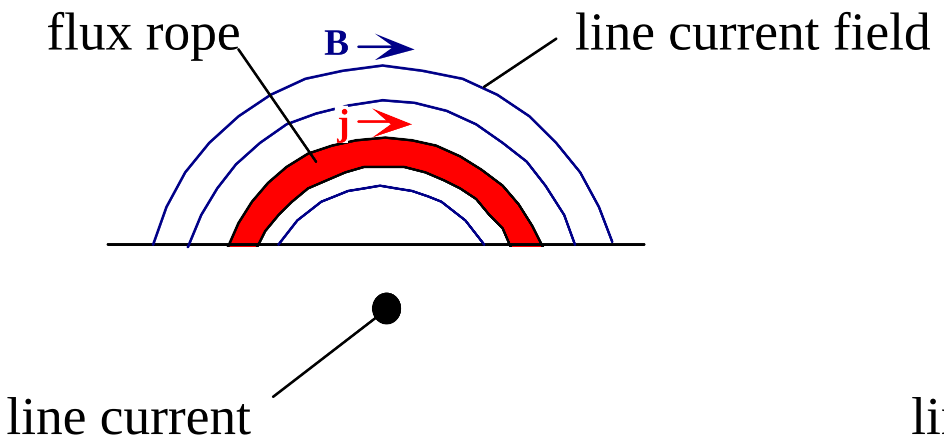
Line-Tied Evolution

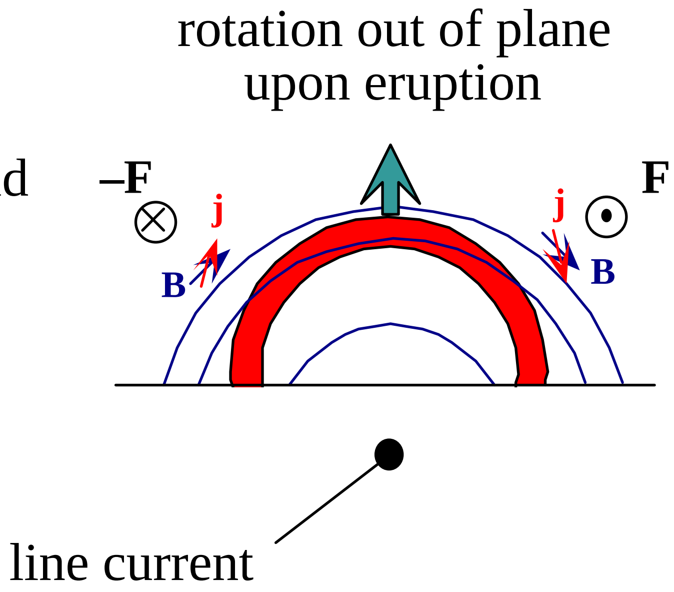


Forces Acting on Flux Rope



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
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Linker et al. (2001)

QuickTime™ and a
BMP decompressor
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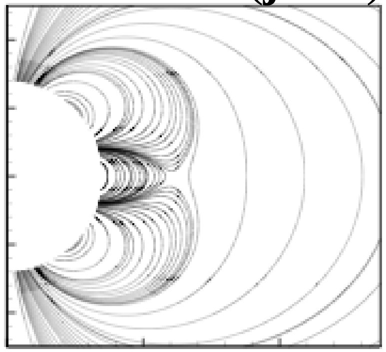
What is the Trigger Mechanism in the Breakout Model?

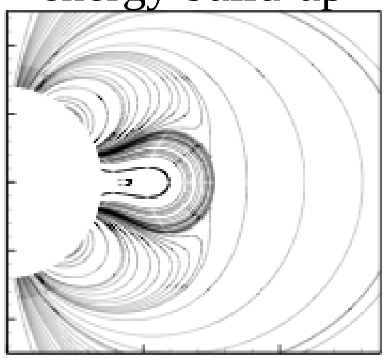
1.

initial state (**j** = 0)



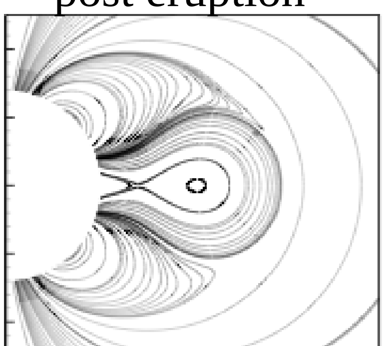
2.

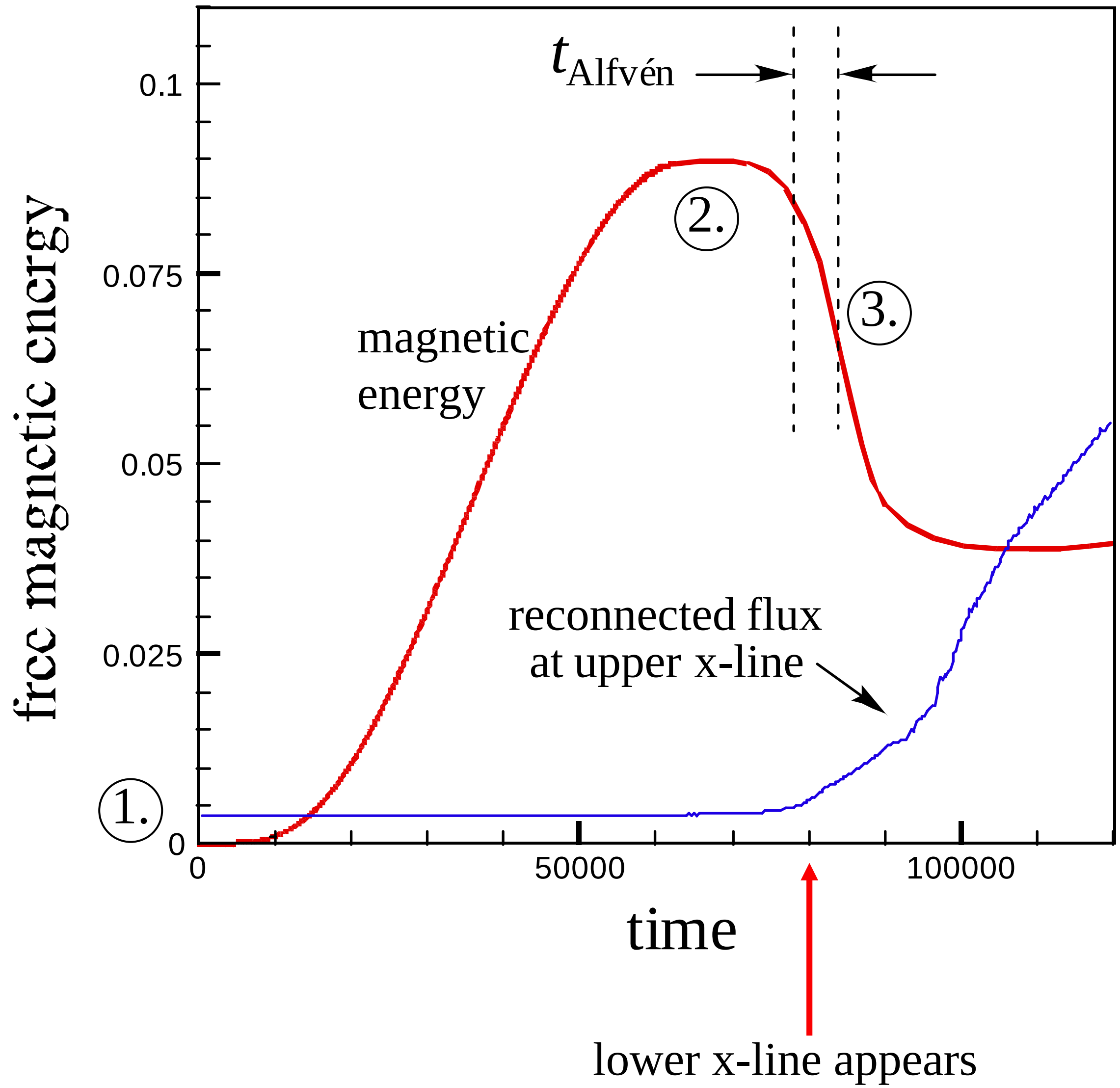
energy build-up



3.

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 —