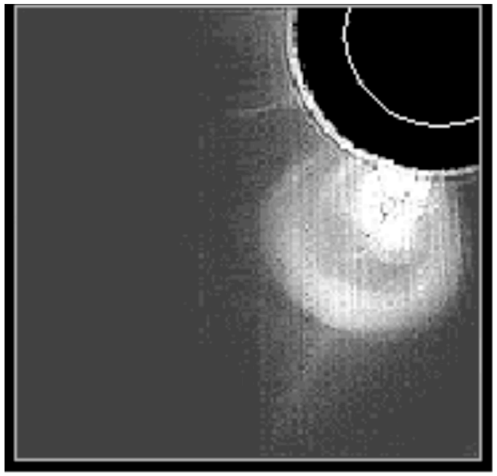
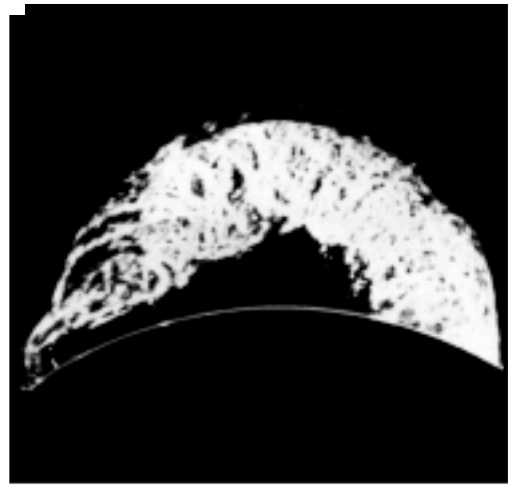
Theory & Modeling of Solar Eruptions

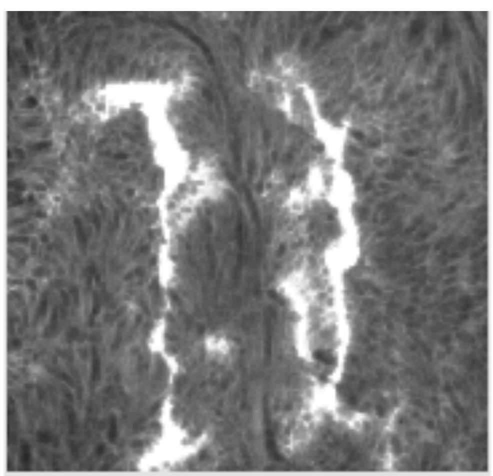
coronagraph (CME)



Hα limb (prominence)

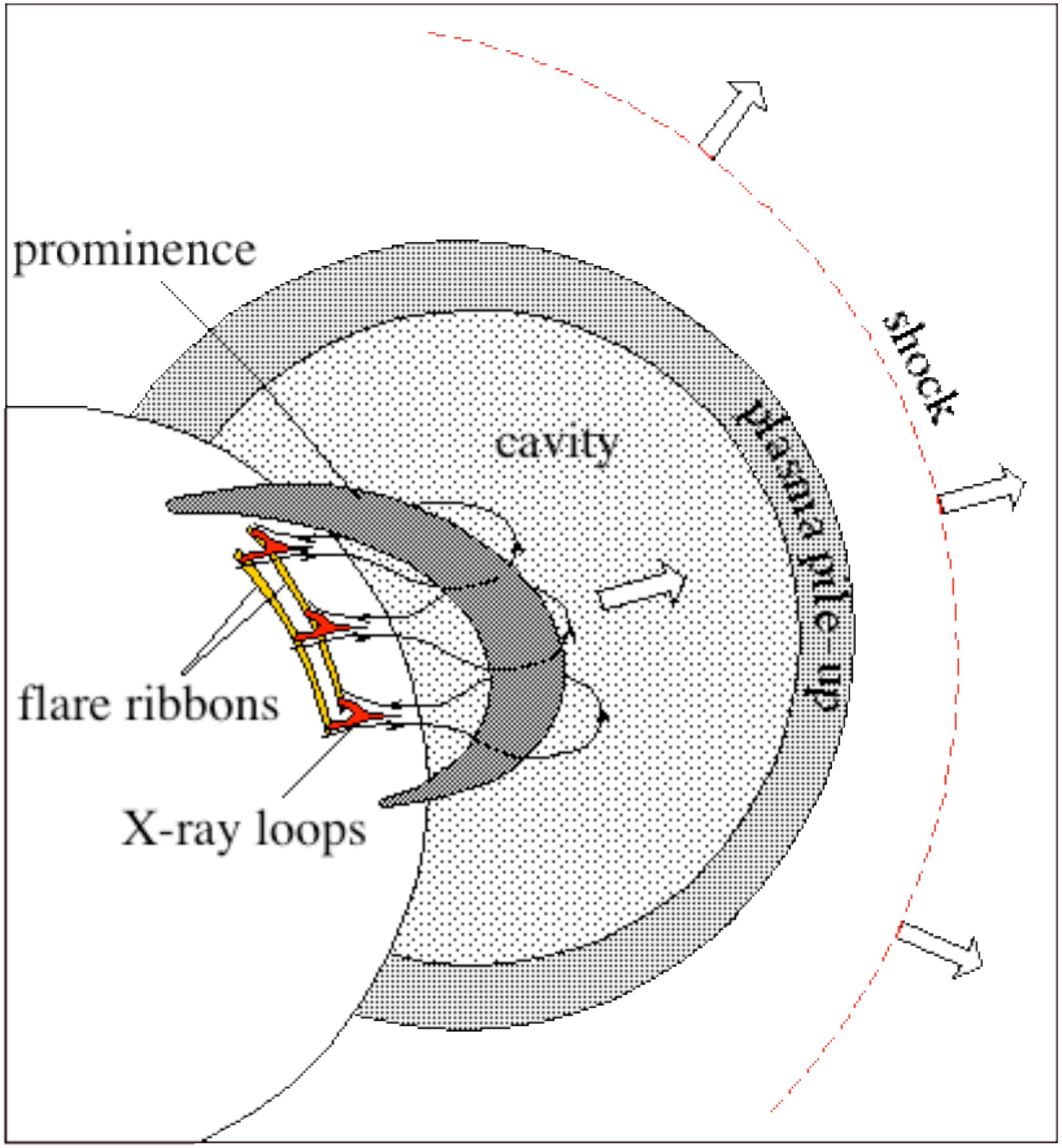


Hα disk (flare ribbons)

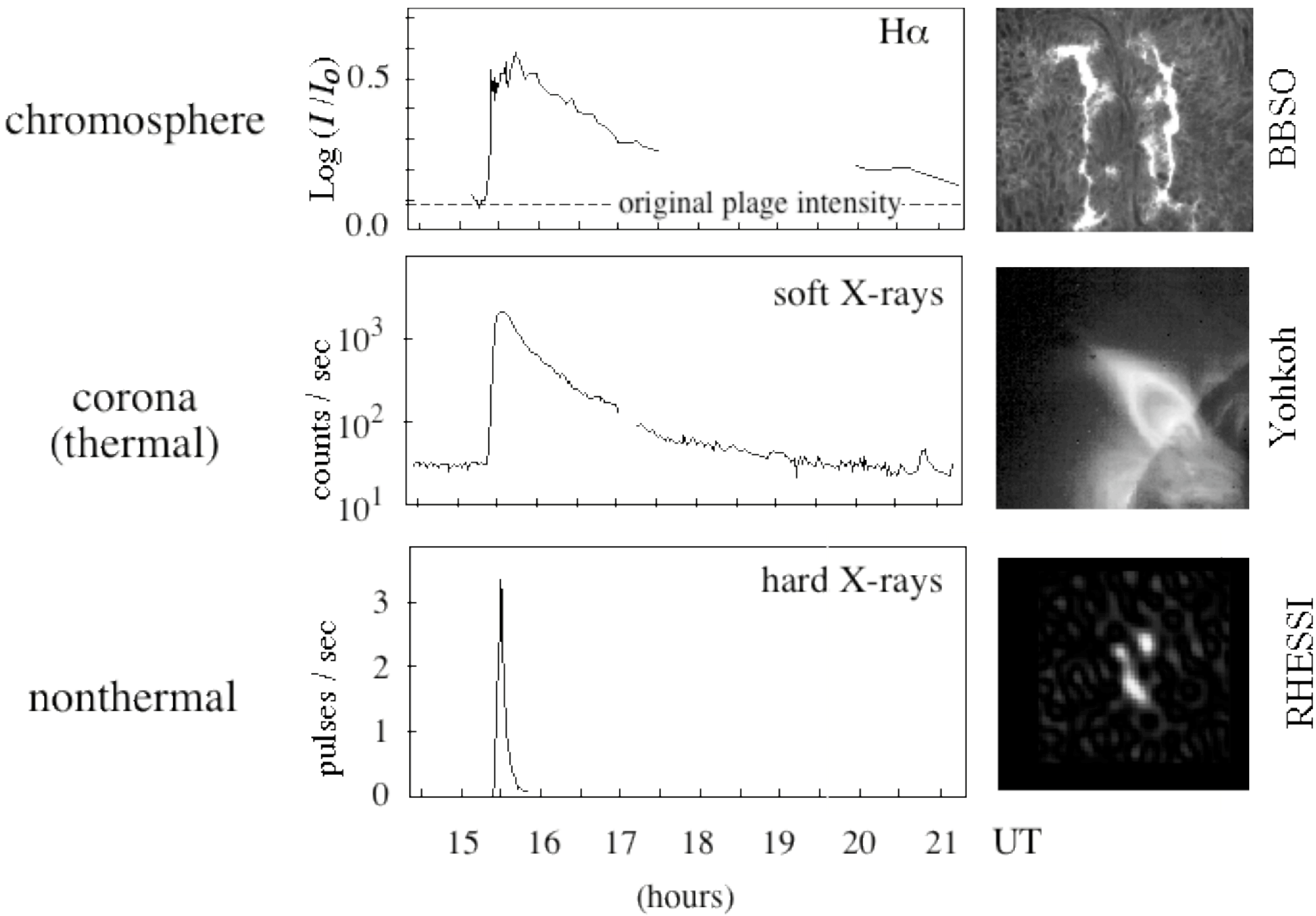


X-ray (flare loops)

Large Solar Eruptions



Light Curves

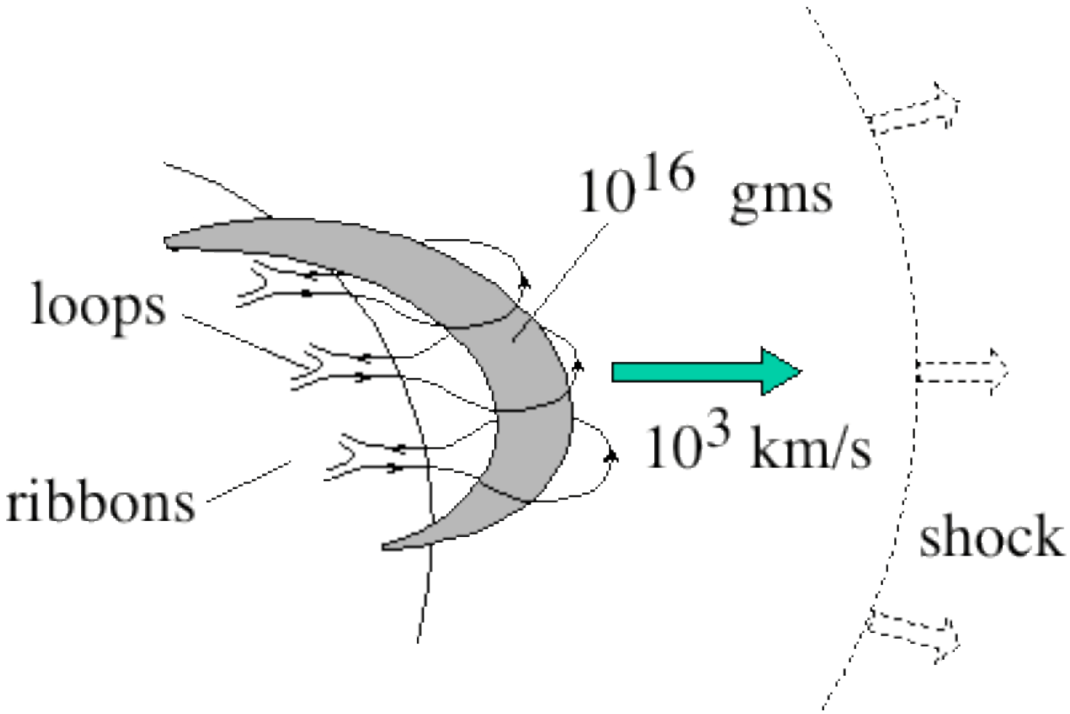


CME/Flare Energetics

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

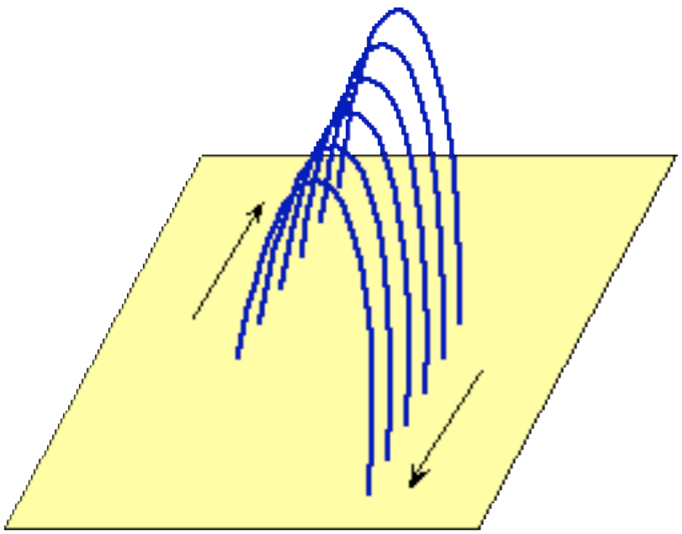
Nature of Energy Source: Required: ≈ 100 ergs/cm^3

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?

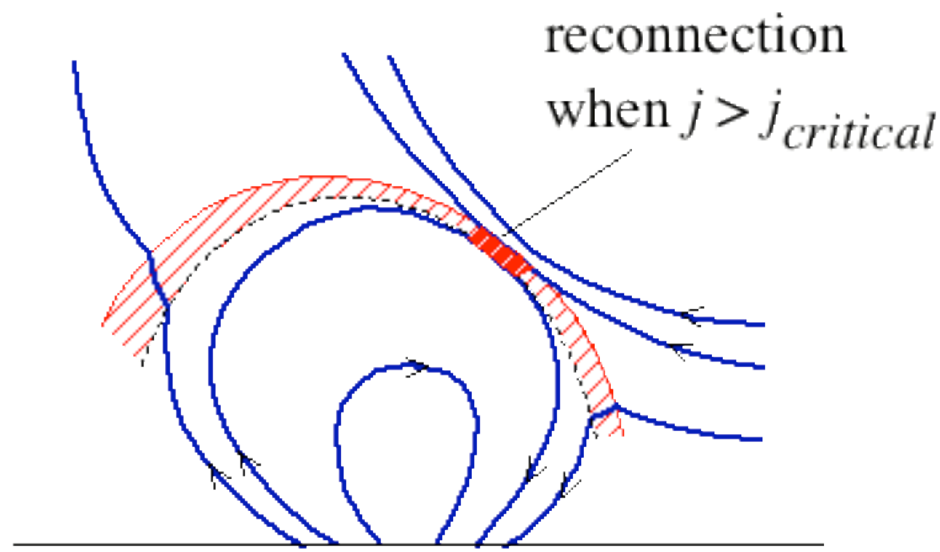
$$\beta = 10^{-3} \qquad \nabla p \approx 0 \qquad \mathbf{j} \times \mathbf{B} \approx 0$$

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



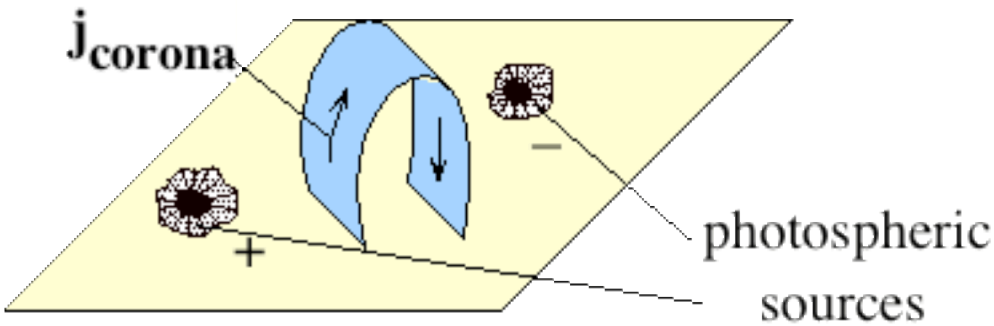
sheared magnetic fields

Current sheets:

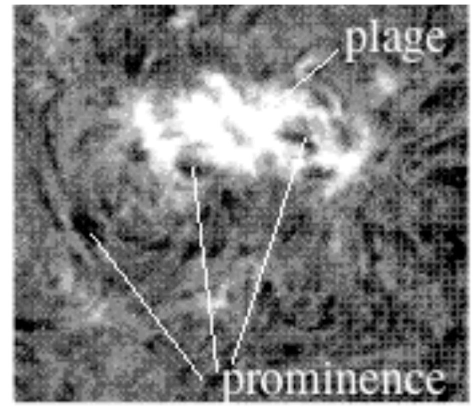


emerging flux model

How Much Energy is Stored?



Hα image



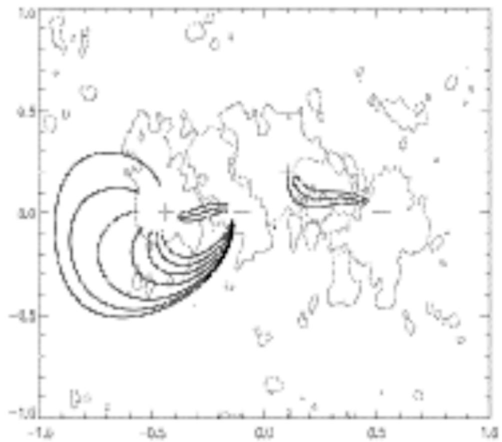
$$\mathbf{B} = \mathbf{B}_{\substack{\text{photospheric}\\ \text{currents}}} + \mathbf{B}_{\substack{\text{coronal}\\ \text{currents}}}$$

invariant during CME (photospheric currents)

source of CME energy (coronal currents)

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

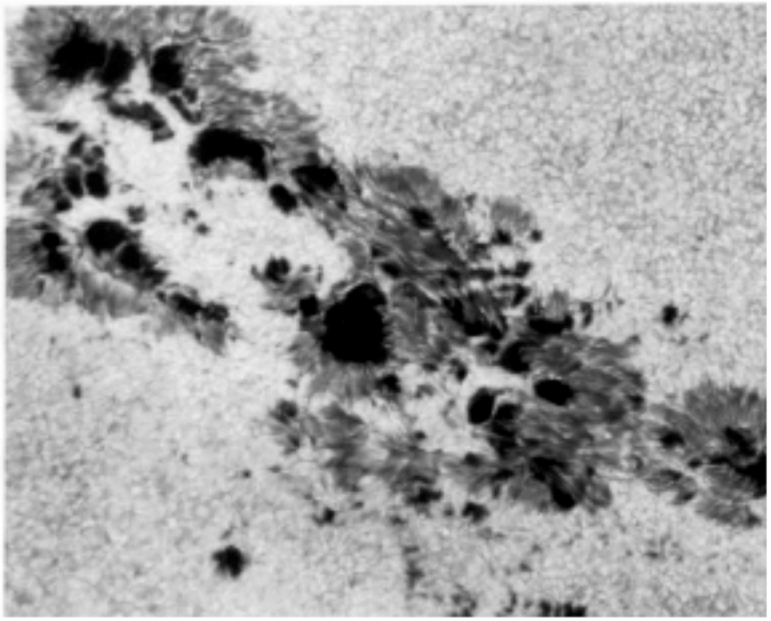
model with magnetogram



from Gaizauskas & Mackay (1997)

free magnetic energy ≈ 50% of total magnetic energy

Inertial Line-Tying



Photospheric boundary condition:

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

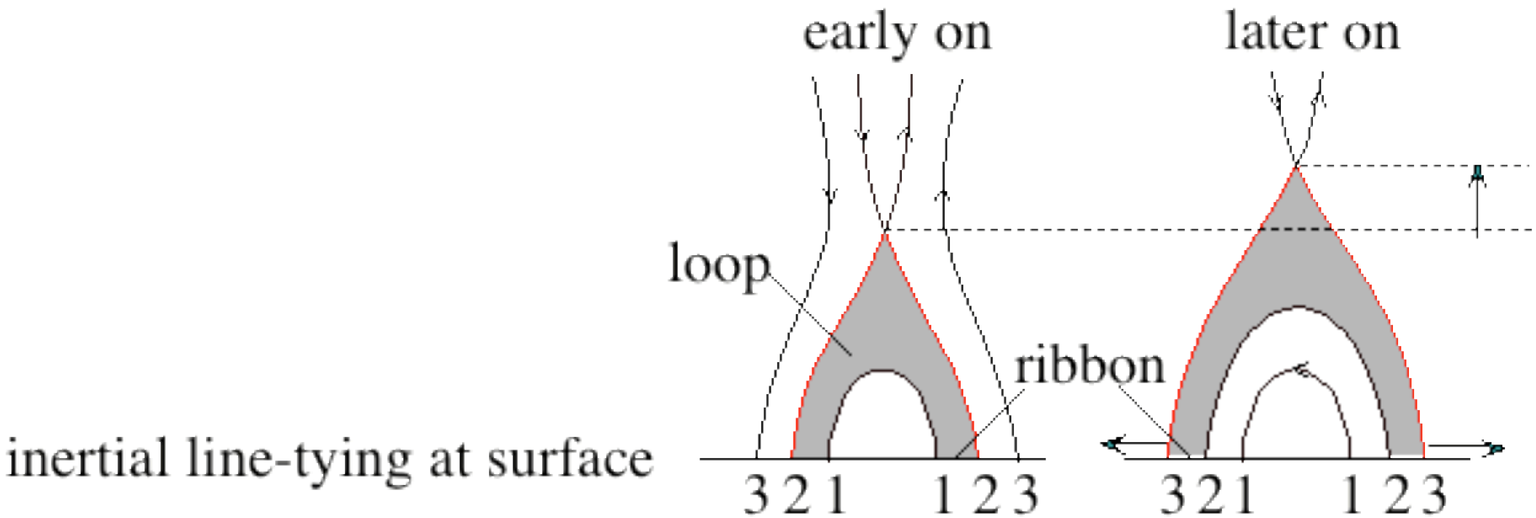
Photospheric convection is negligible

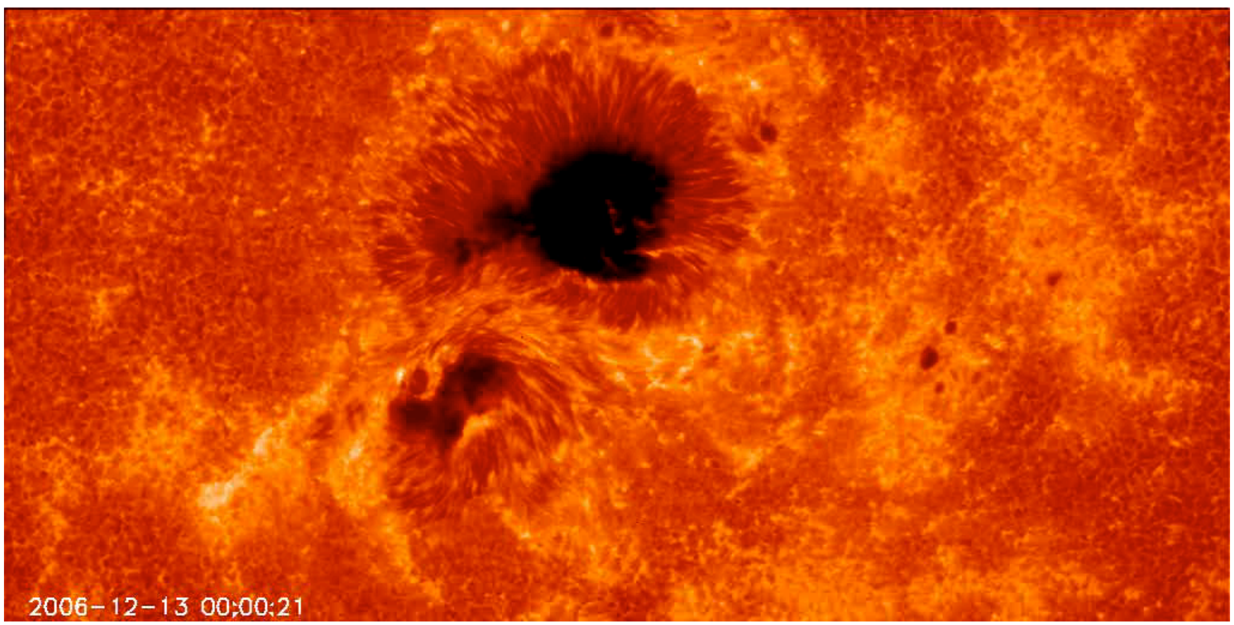
Plasma below the photosphere is both massive and a good conductor.

B normal to surface is fixed.

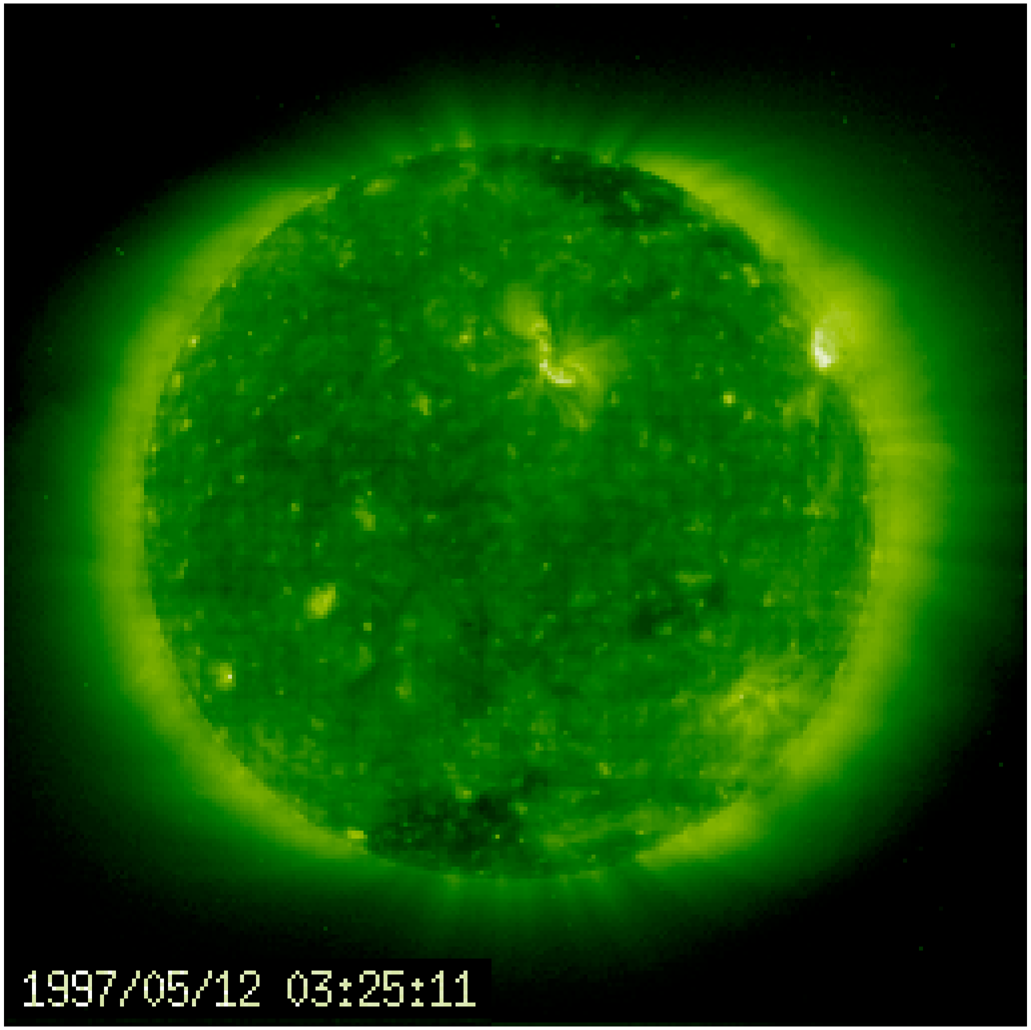
Evolution of the photosphere is slow compared to time scale of eruptions.

Apparent Motion of Loops & Ribbons

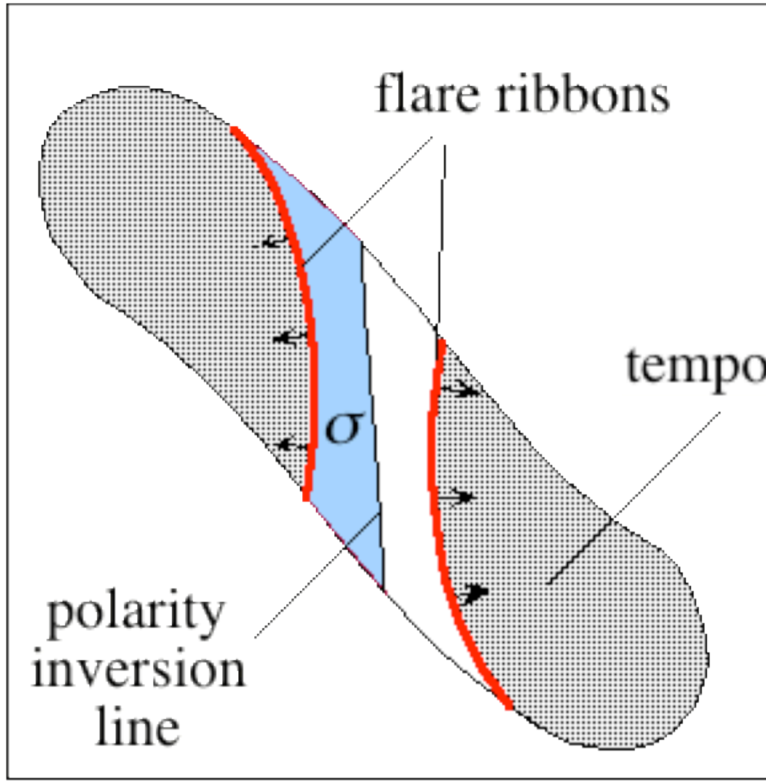




Transient Coronal Holes as Seen by EIT



Reconnection Electric Fields



newly reclosed flux:

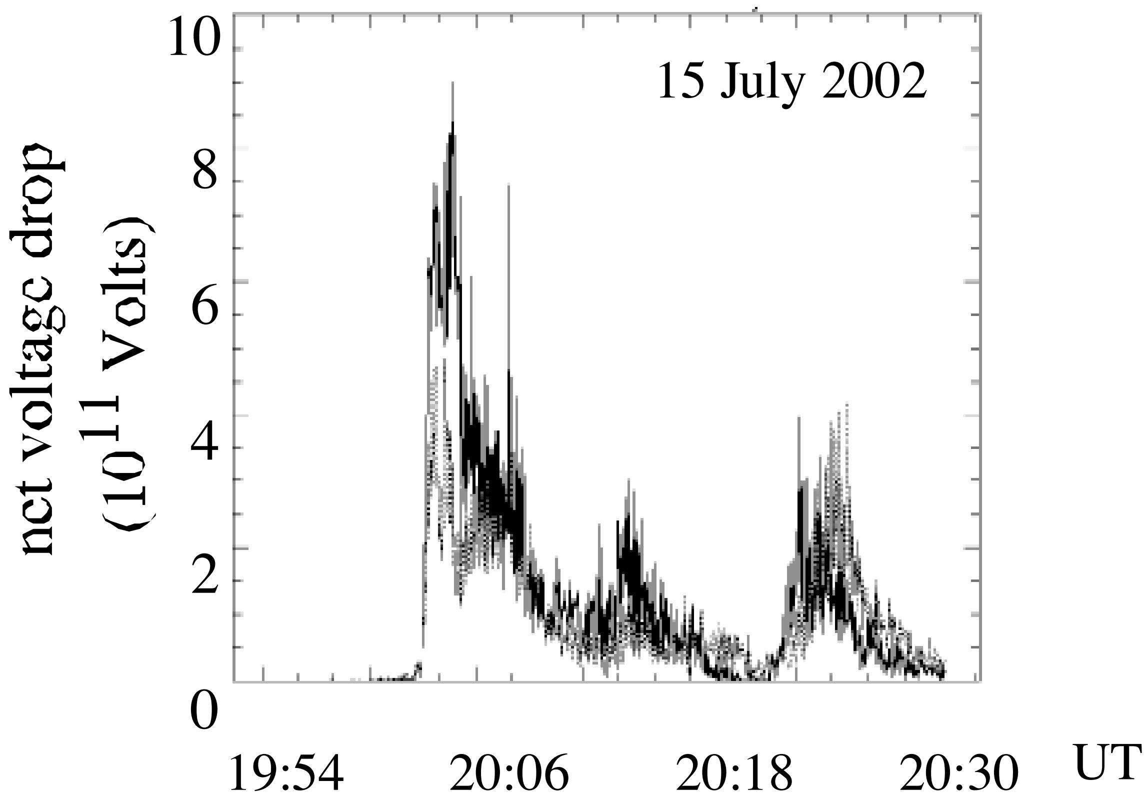
$$\Phi_B = \iint_\sigma B_z \, dx dy$$

global reconnection rate:

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

CME/Flare Reconnection Rate

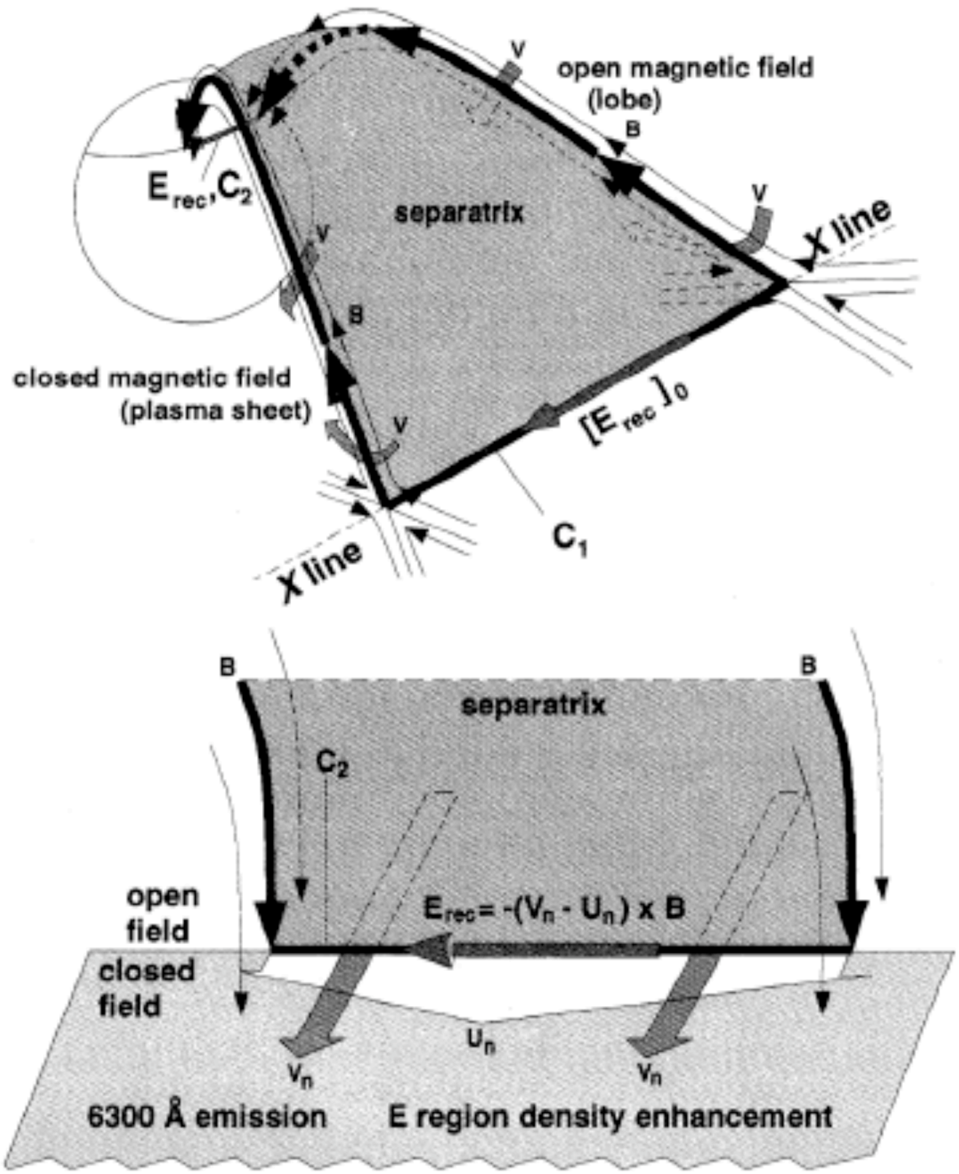
Observed Reconnection Rate for X3 Flare



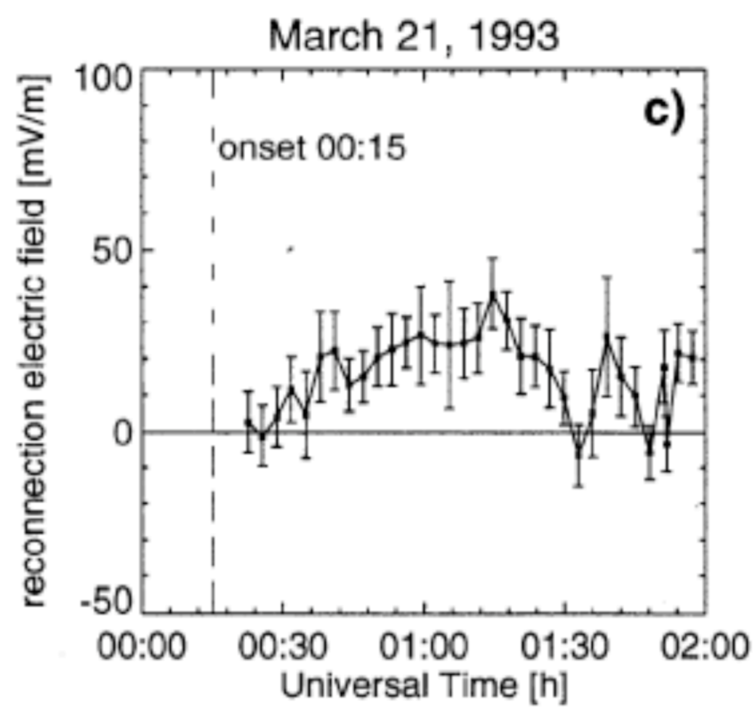
$$E_{reconnect} / E_{Dreicer} = 10^6 >> 1$$

collisionless processes involved

Substorm Reconnection Rate



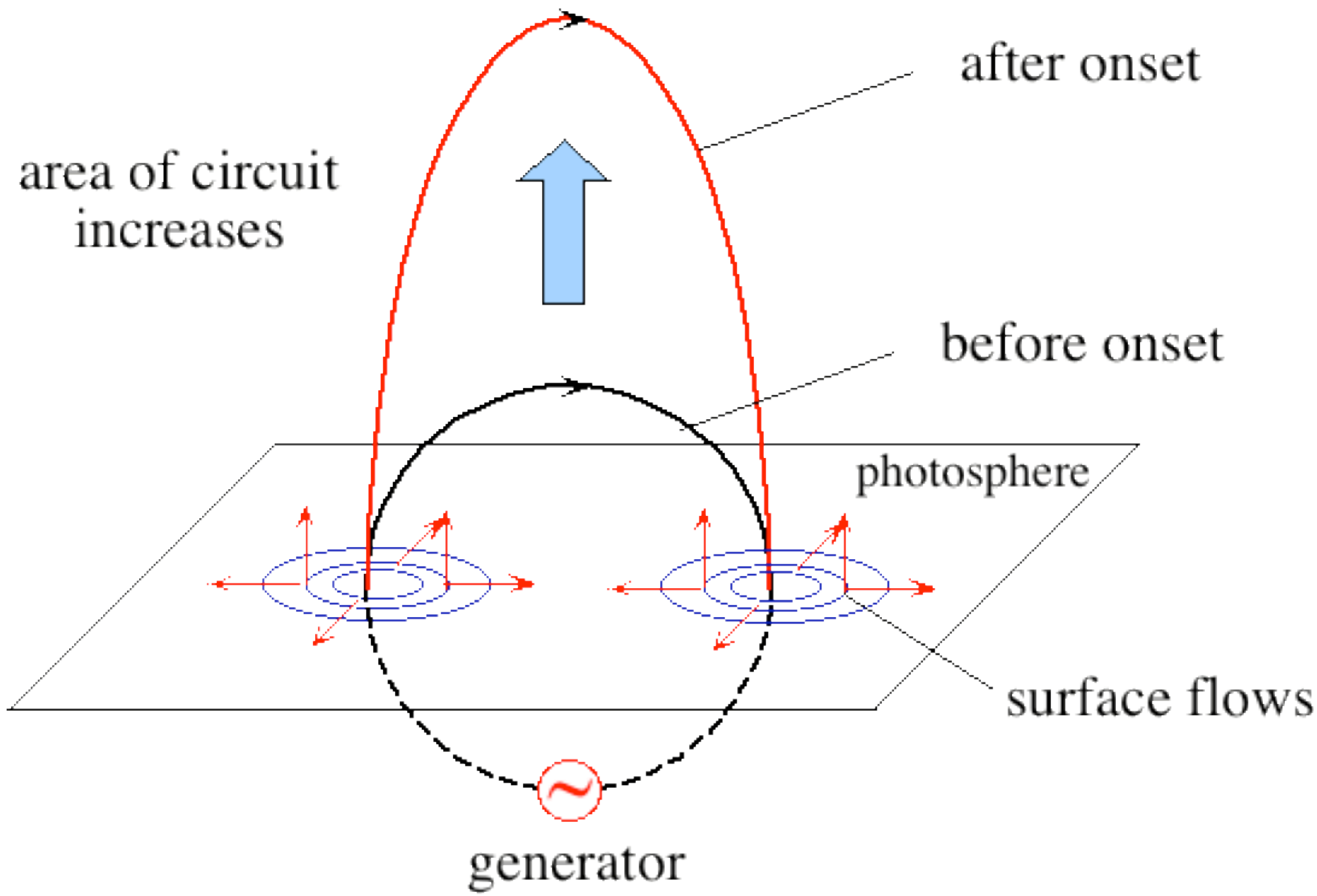
$$\int_{C_1} [\mathbf{E_{rec}}]_0 \cdot \mathbf{dl} = \int_{C_2} B(V_n - U_n)dl$$



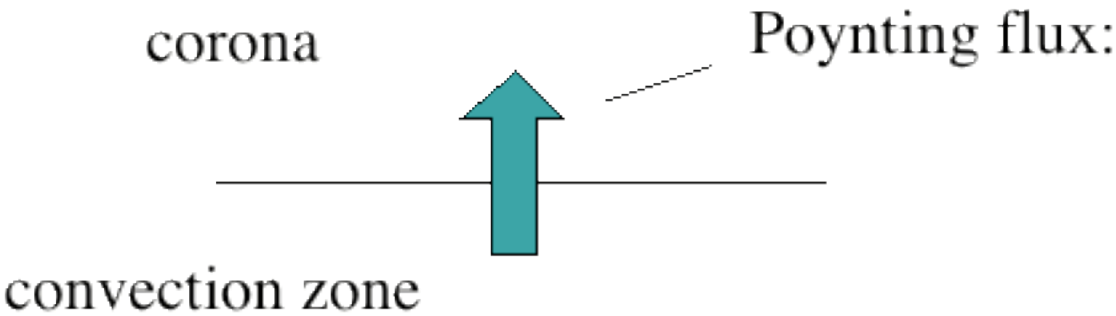
Blanchard et al. (1996)

Flux Injection Models

(e.g. Chen 1989)



During injection energy flows through photosphere.



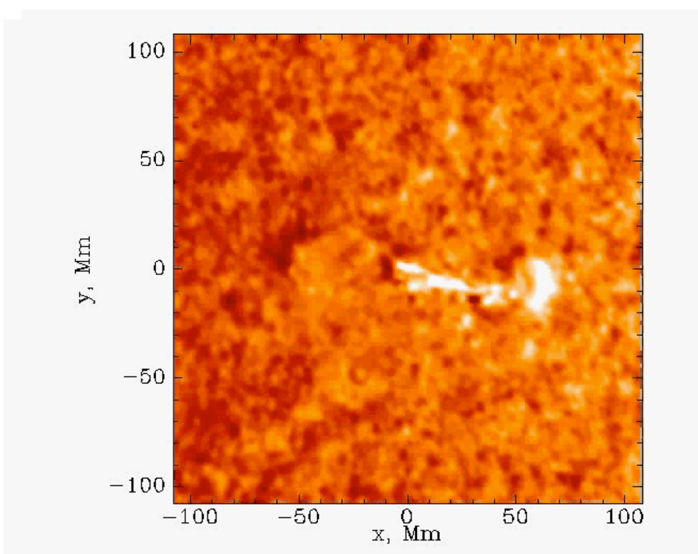
$$\mathbf{S} = c\,\mathbf{E} \times \mathbf{B} \,/\, (4\pi)$$

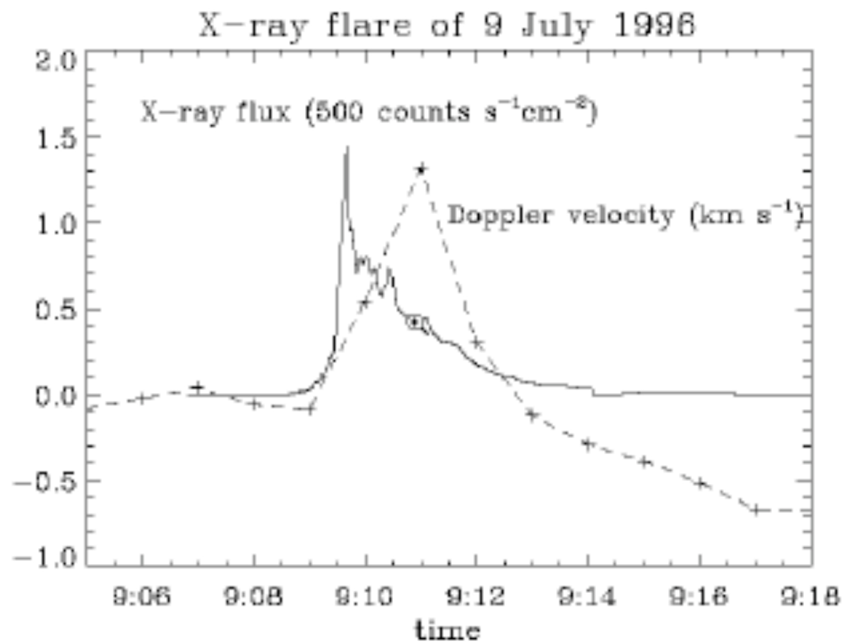
(ergs/cm/sec)

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

> 10 km/sec for > 10 minutes

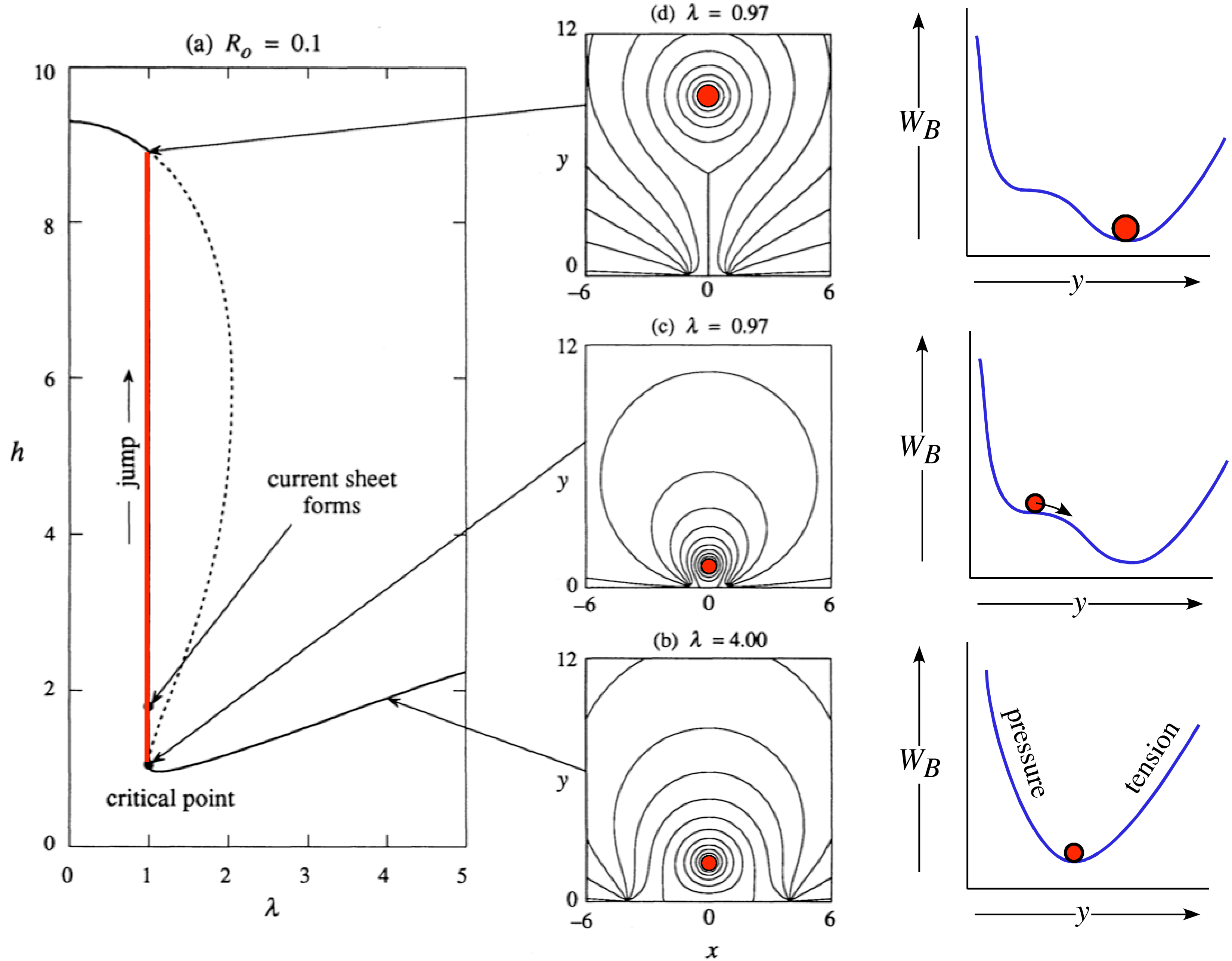
Kosovichev et al. 1998



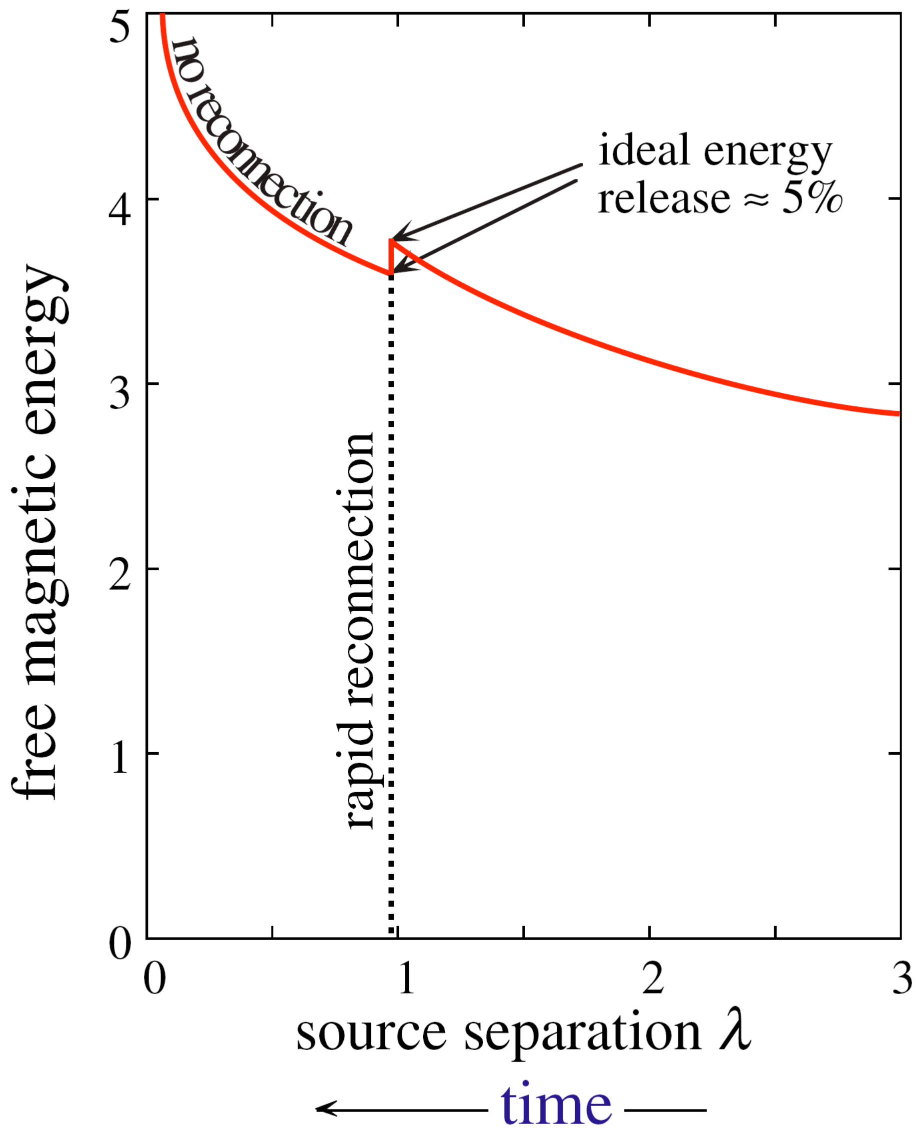


Injection models predict large surface flows which are never observed.

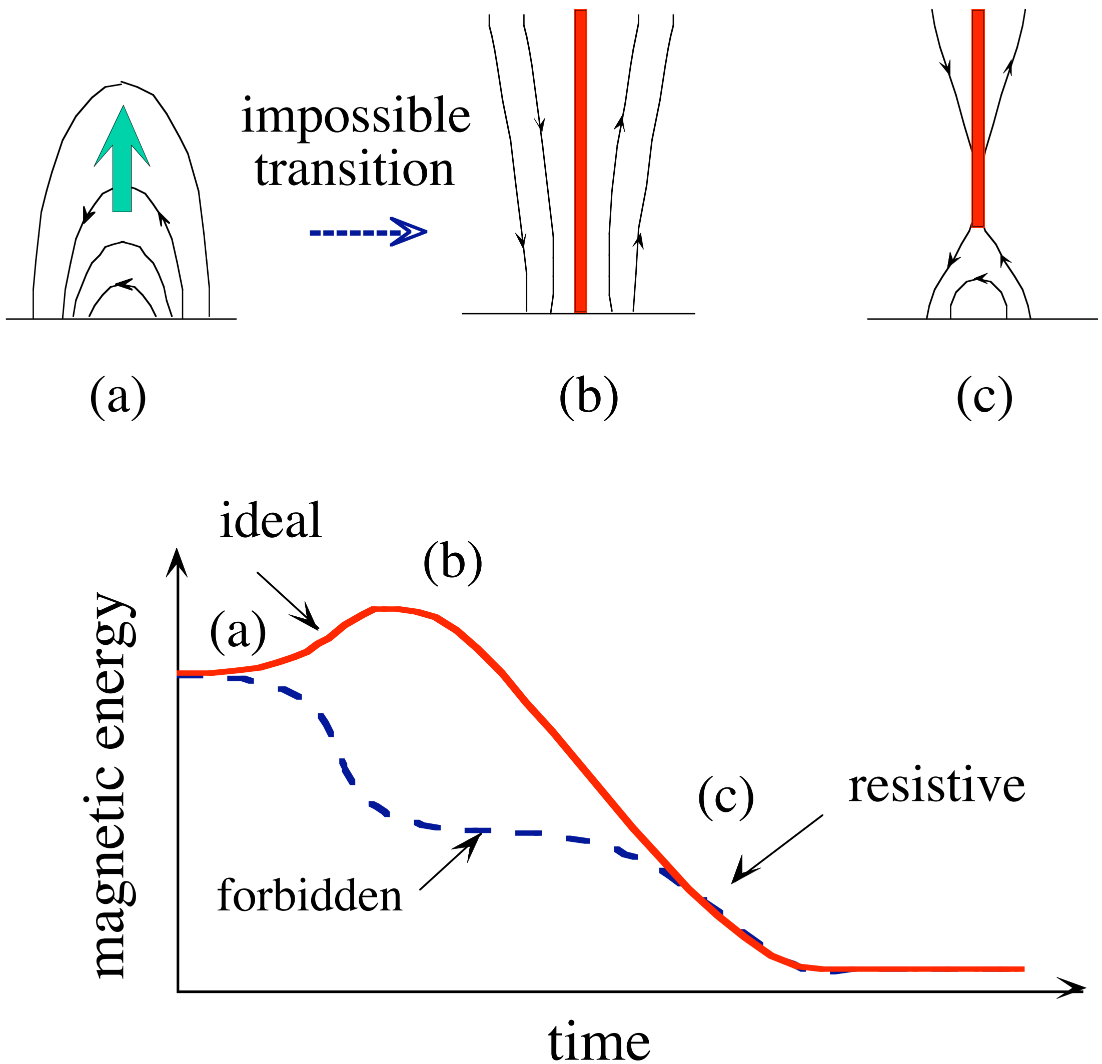
Loss of Equilibrium Model



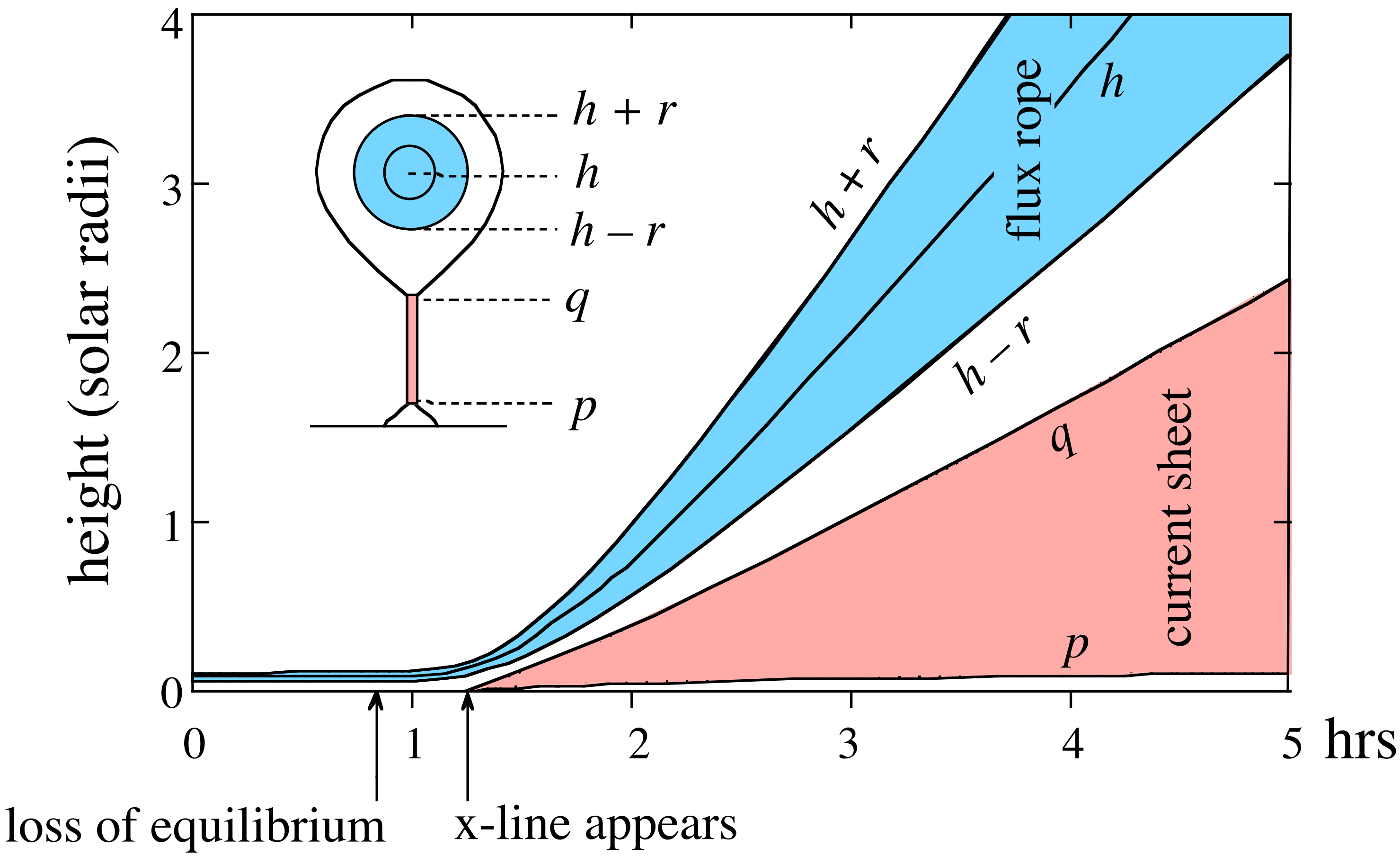
Energy Release in 2D Model



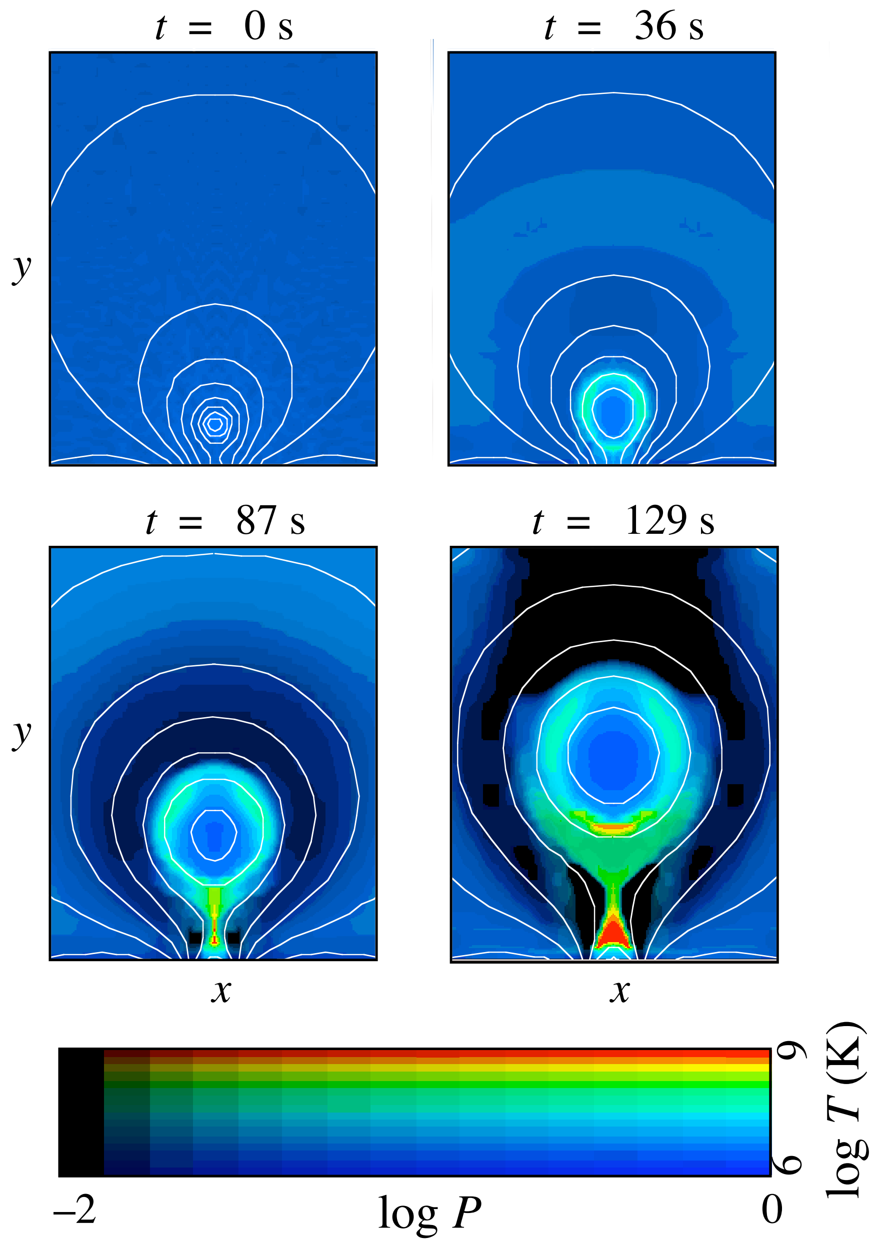
Aly - Sturrock Paradox



Trajectories



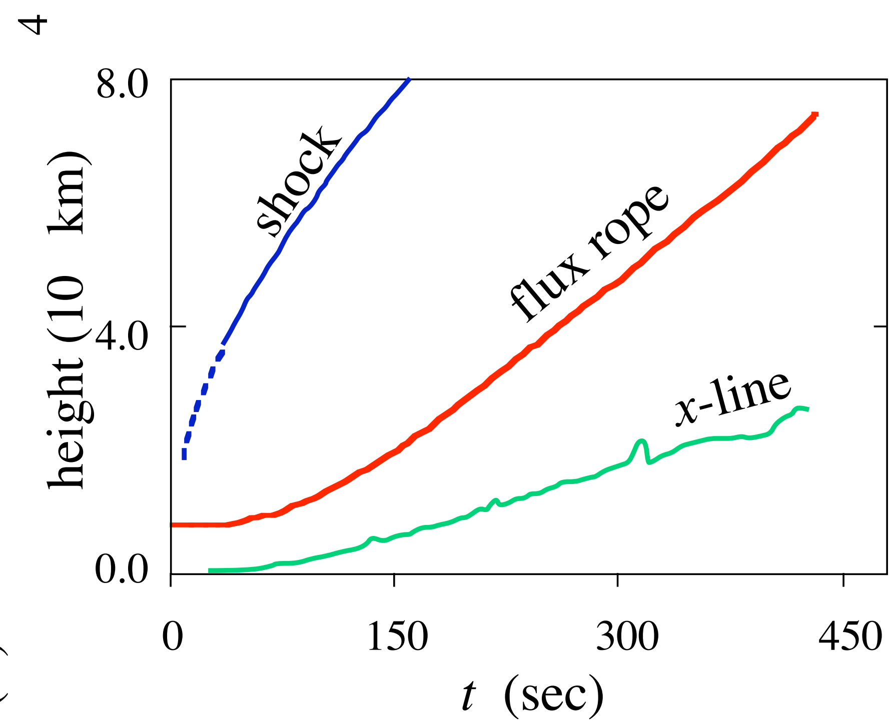
Numerical Simulation of Critical Point Configuration



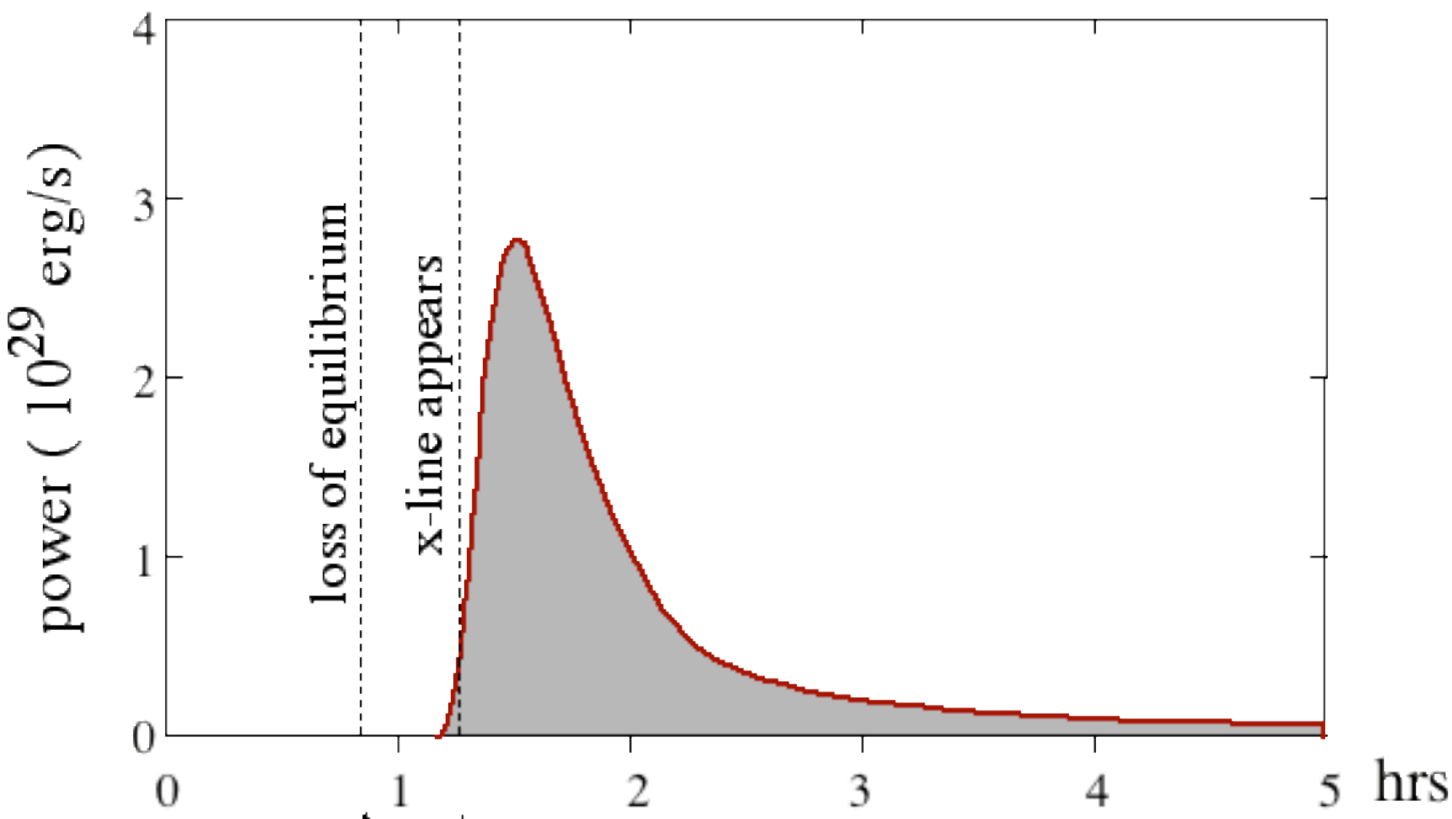
initial condition: **V** = 0

energy equation: Ohmic heating
no cooling

resistivity: uniform, S = 500

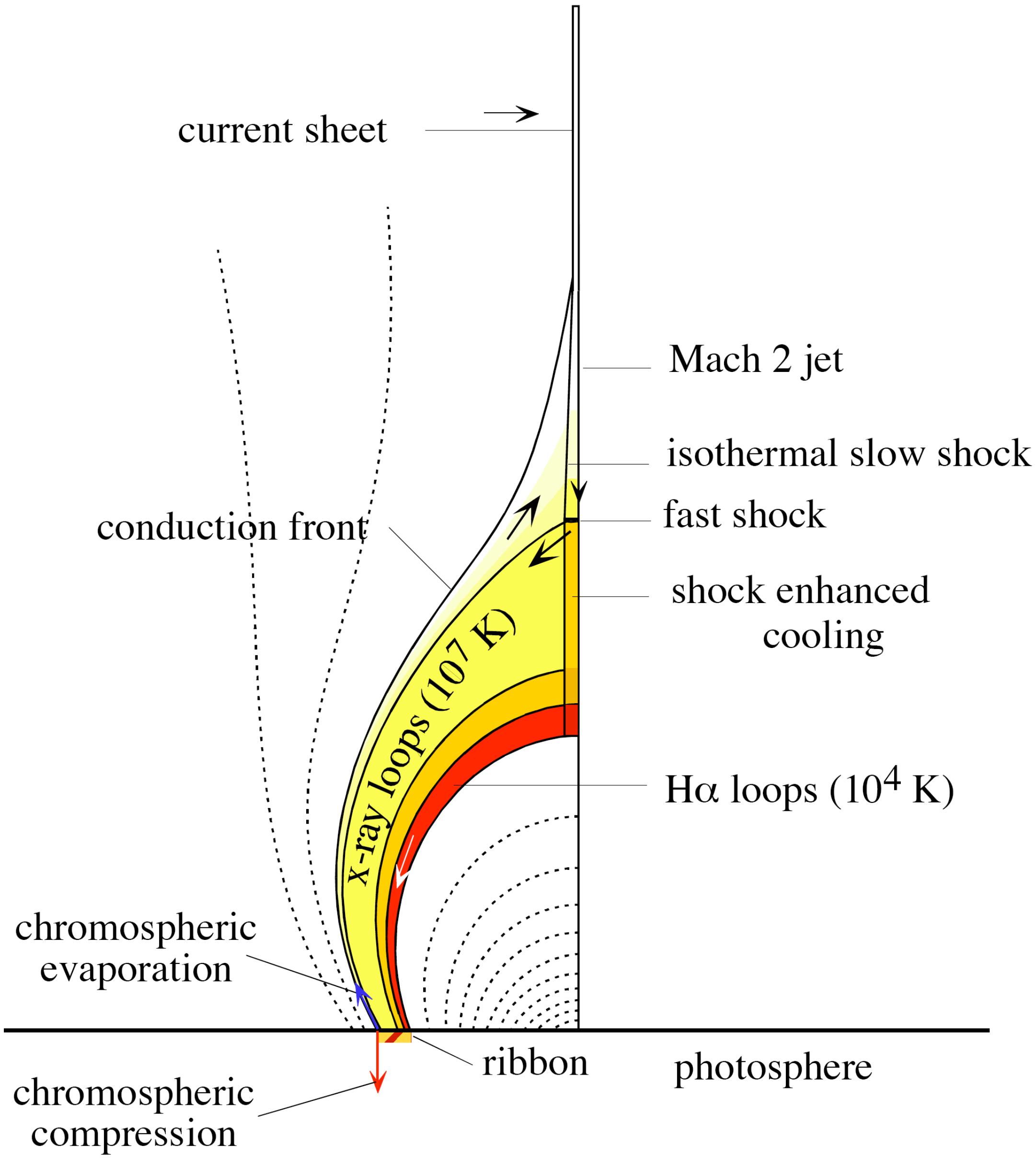


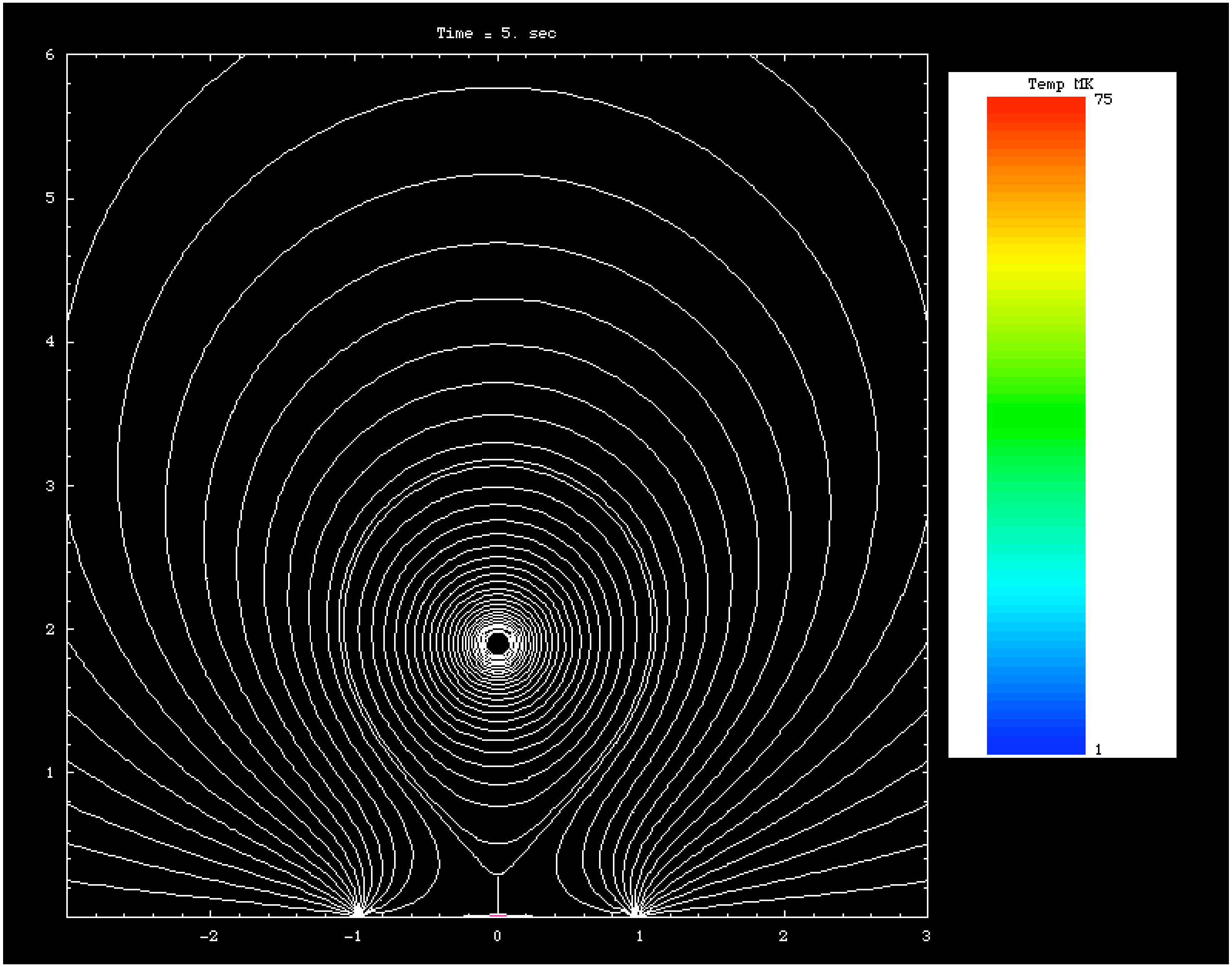
Power Output



loss of equilibrium x-line appears

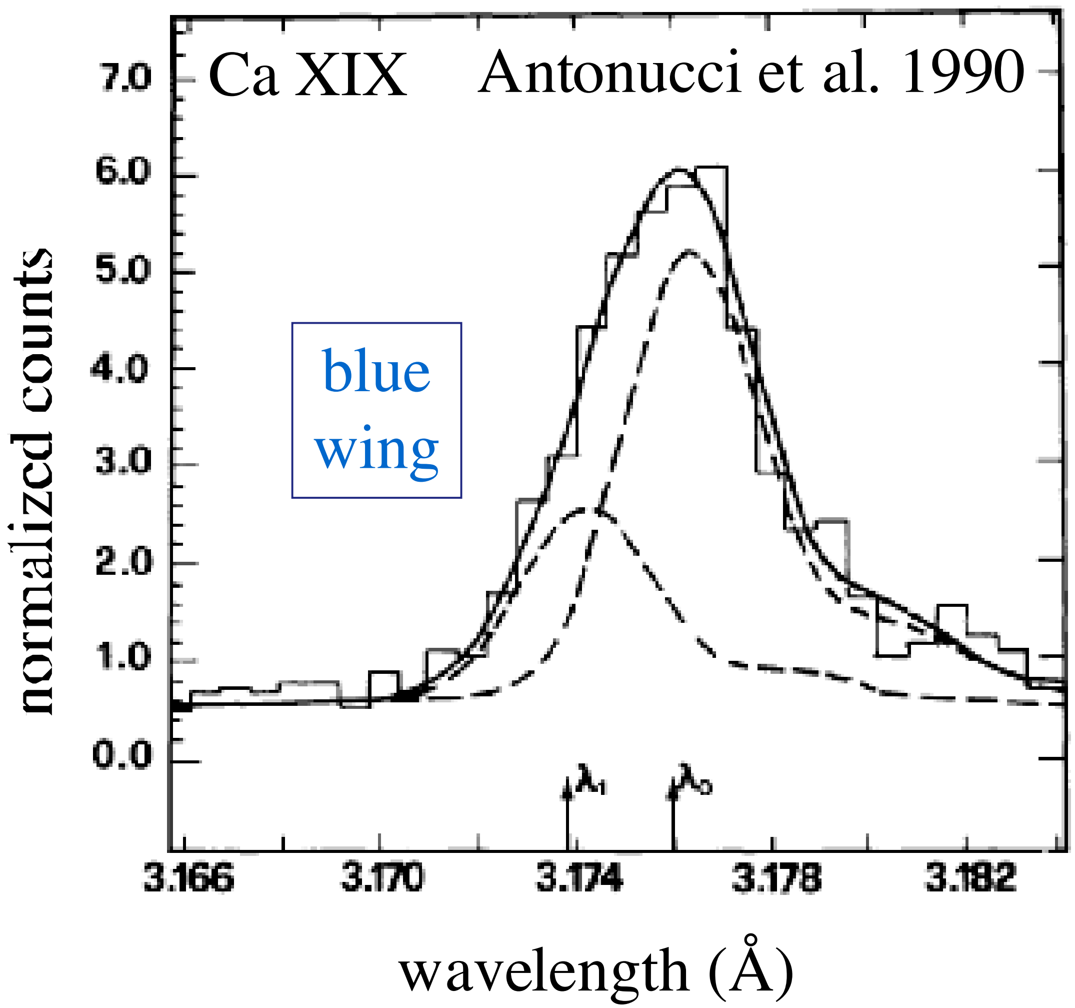
Chromospheric Evaporation

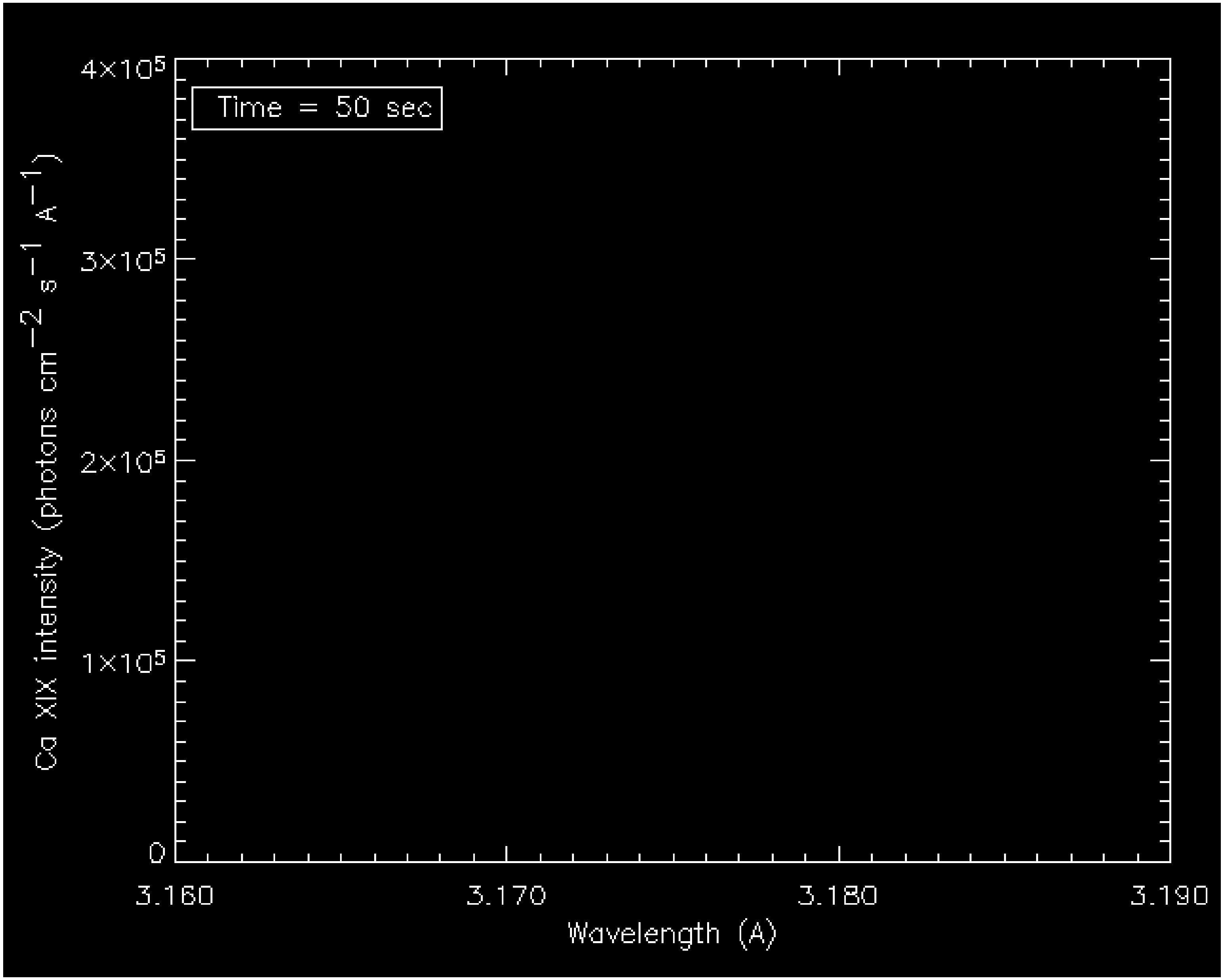



Time = 5. sec
6
5
4
3
2
1
-2
-1
0
1
2
3
Temp MK
75
1

Evaporation Doppler Shift Puzzle

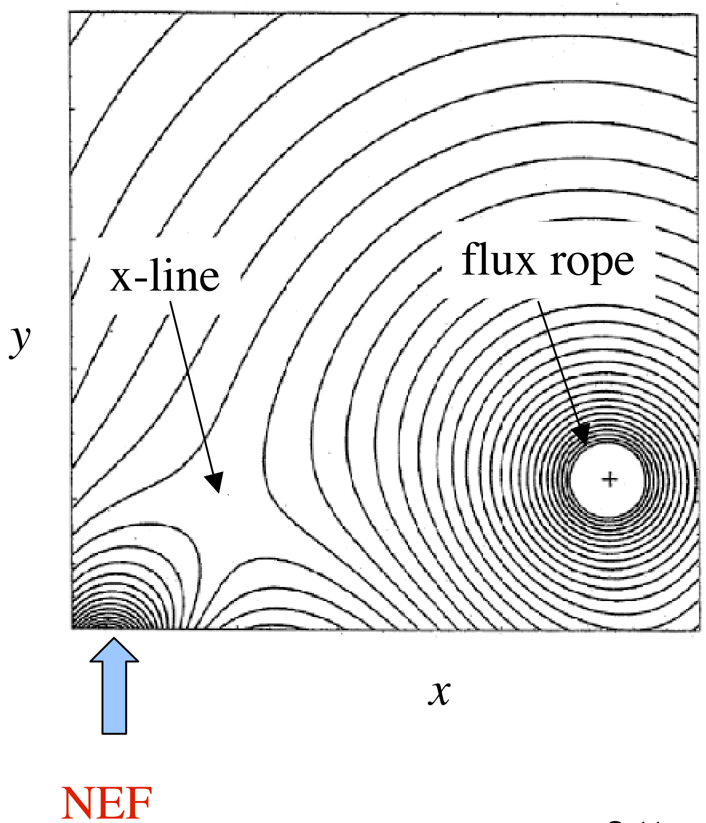
24 April 1984 BCS/SMM

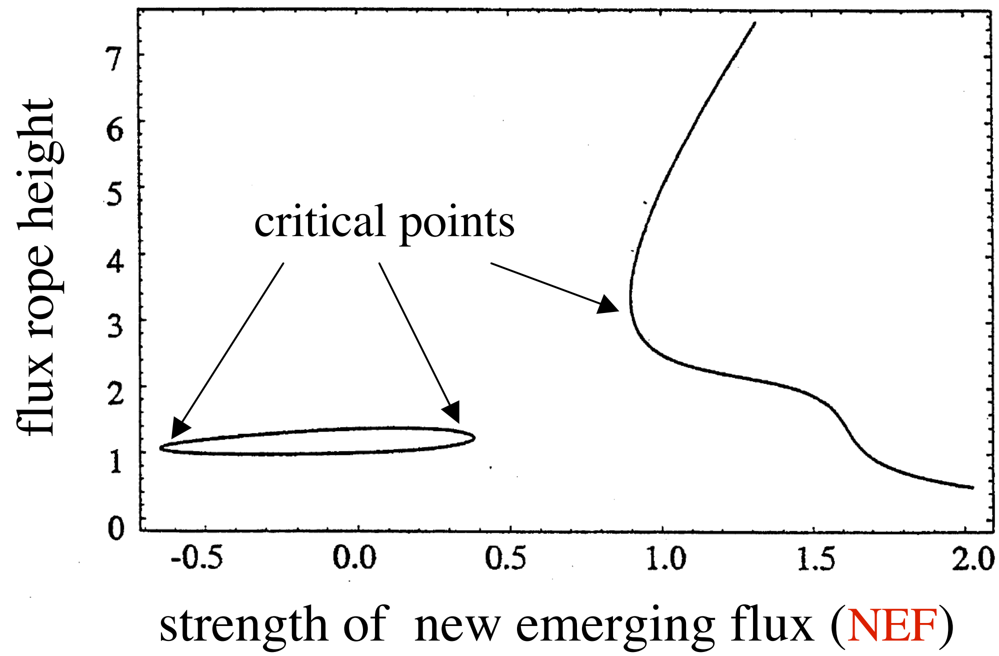




Time = 50 sec
Ca XIX intensity (photons cm^{-2} s^{-1} A^{-1})
4×10^5
3×10^5
2×10^5
1×10^5
0
3.160
3.170
3.180
3.190
Wavelength (A)

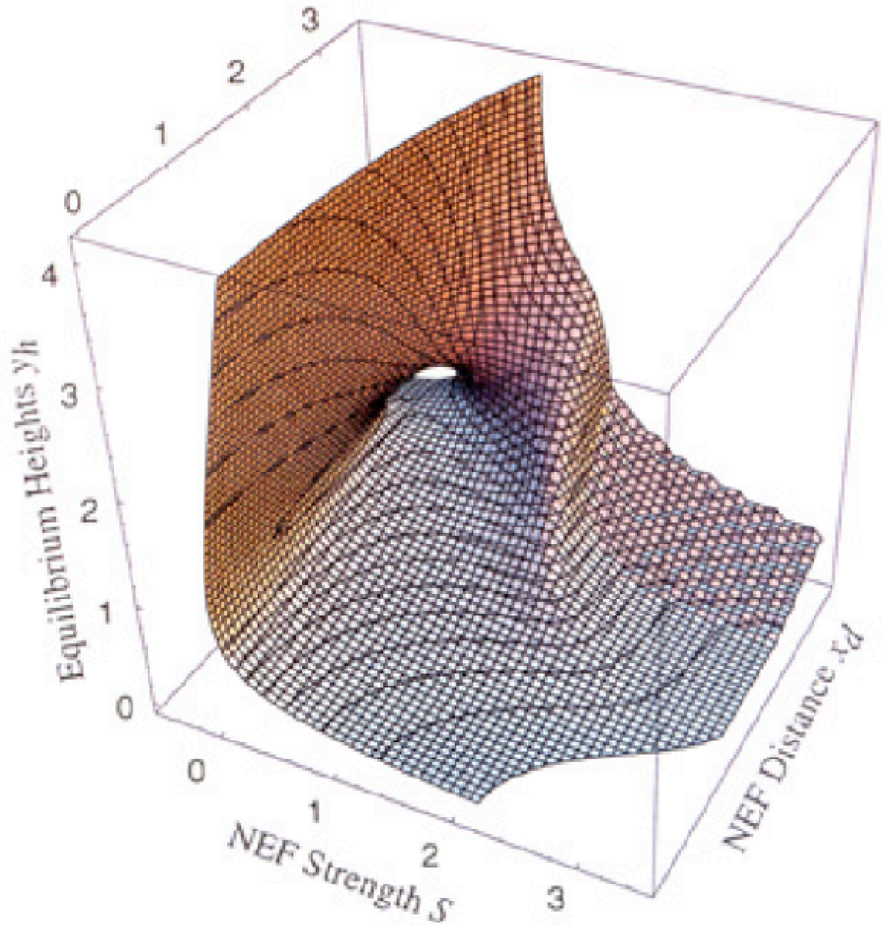
2D Asymmetric Quadrupole Model





test of “tether-cutting” concept

Equlibrium Manifold in 5D Parameter Space of Model



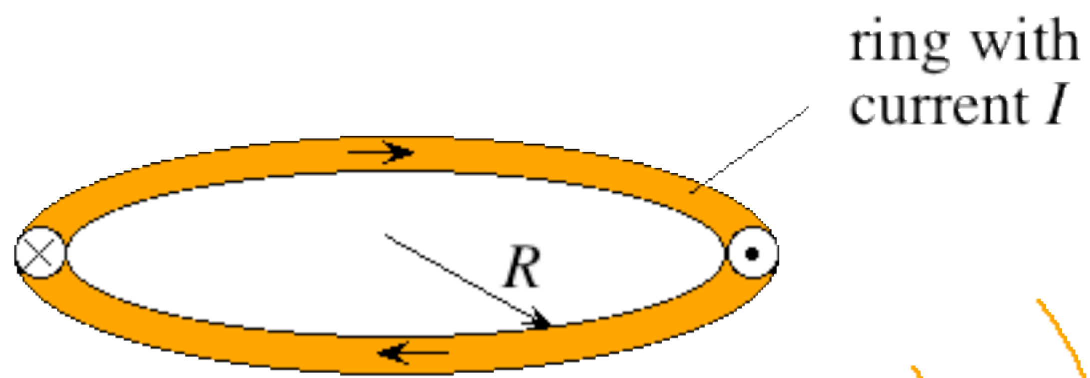
3D "cross section"

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

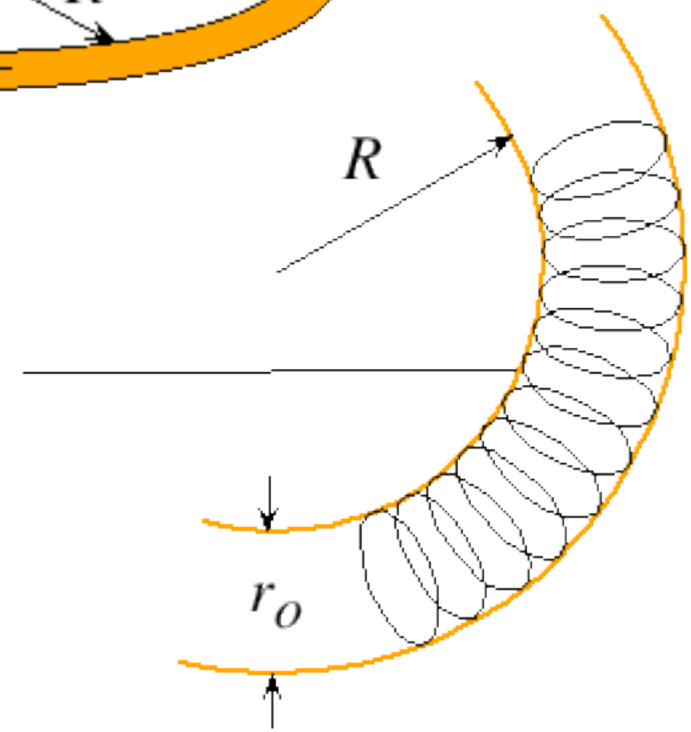
2nd order umbelic catastrophe

Basic Principles I

Driving Force:



inner edge is pinched
by curvature of rope

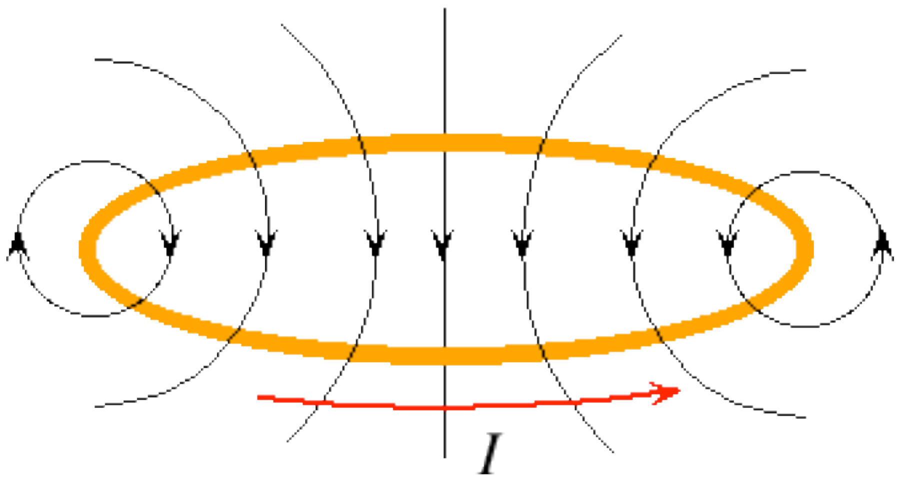


repulsive force:

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

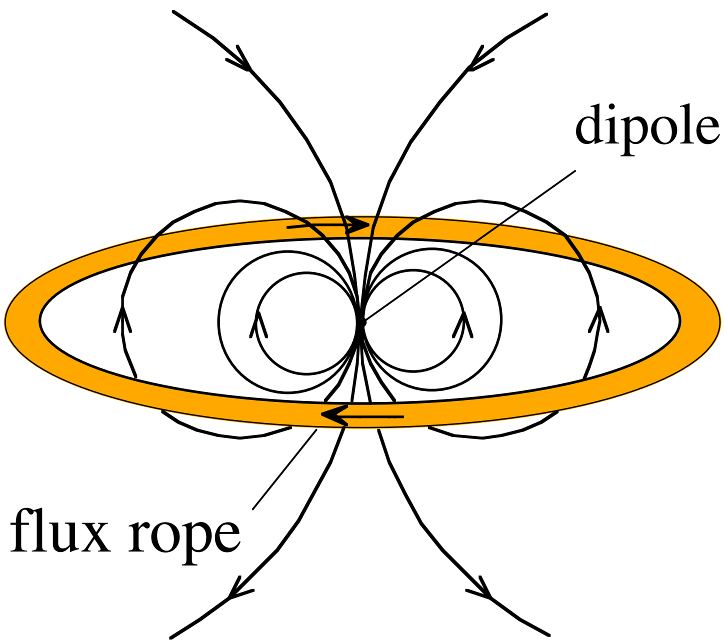
Basic Principles II

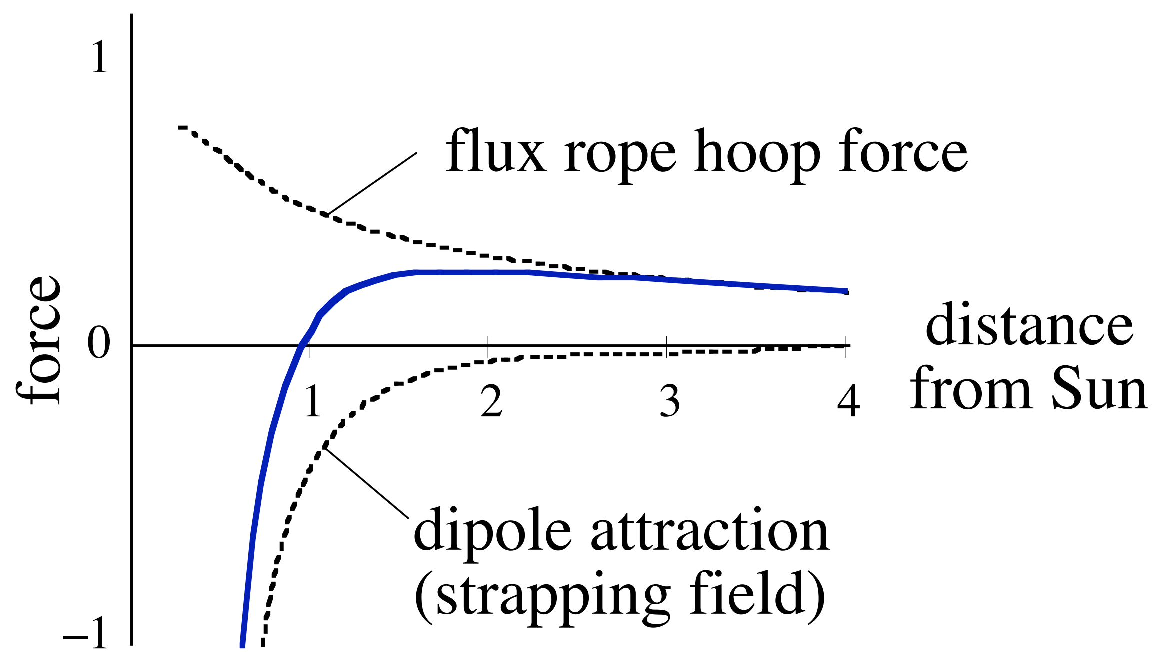
Flux Conservation:



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

How to Achieve Equilibrium

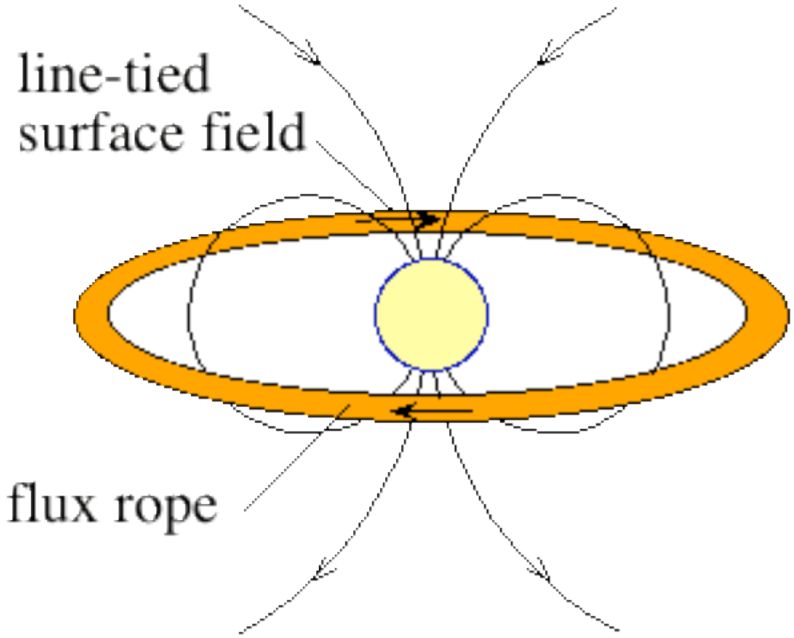


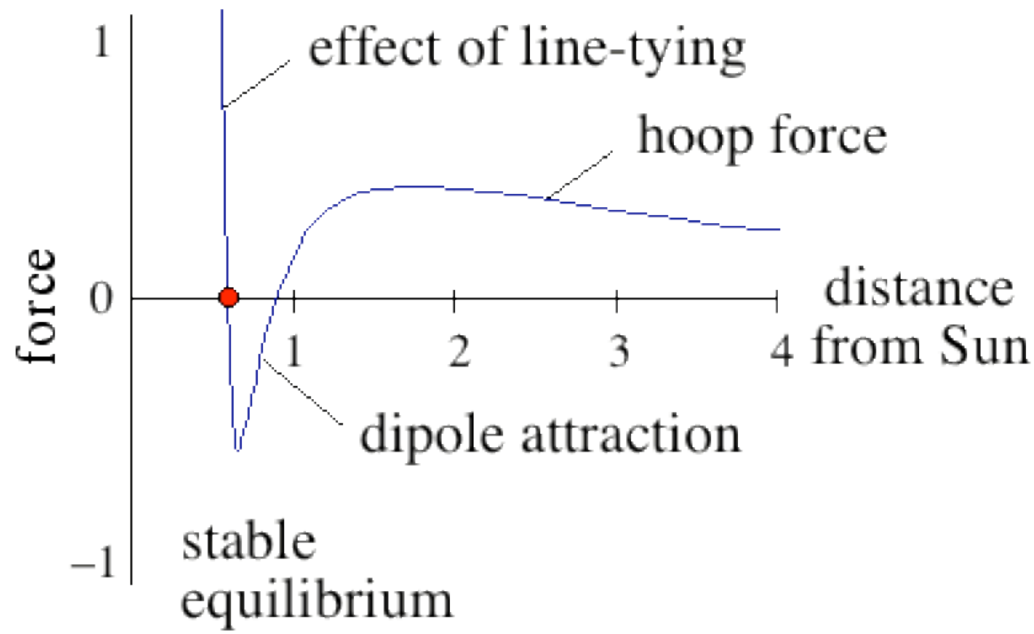


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium

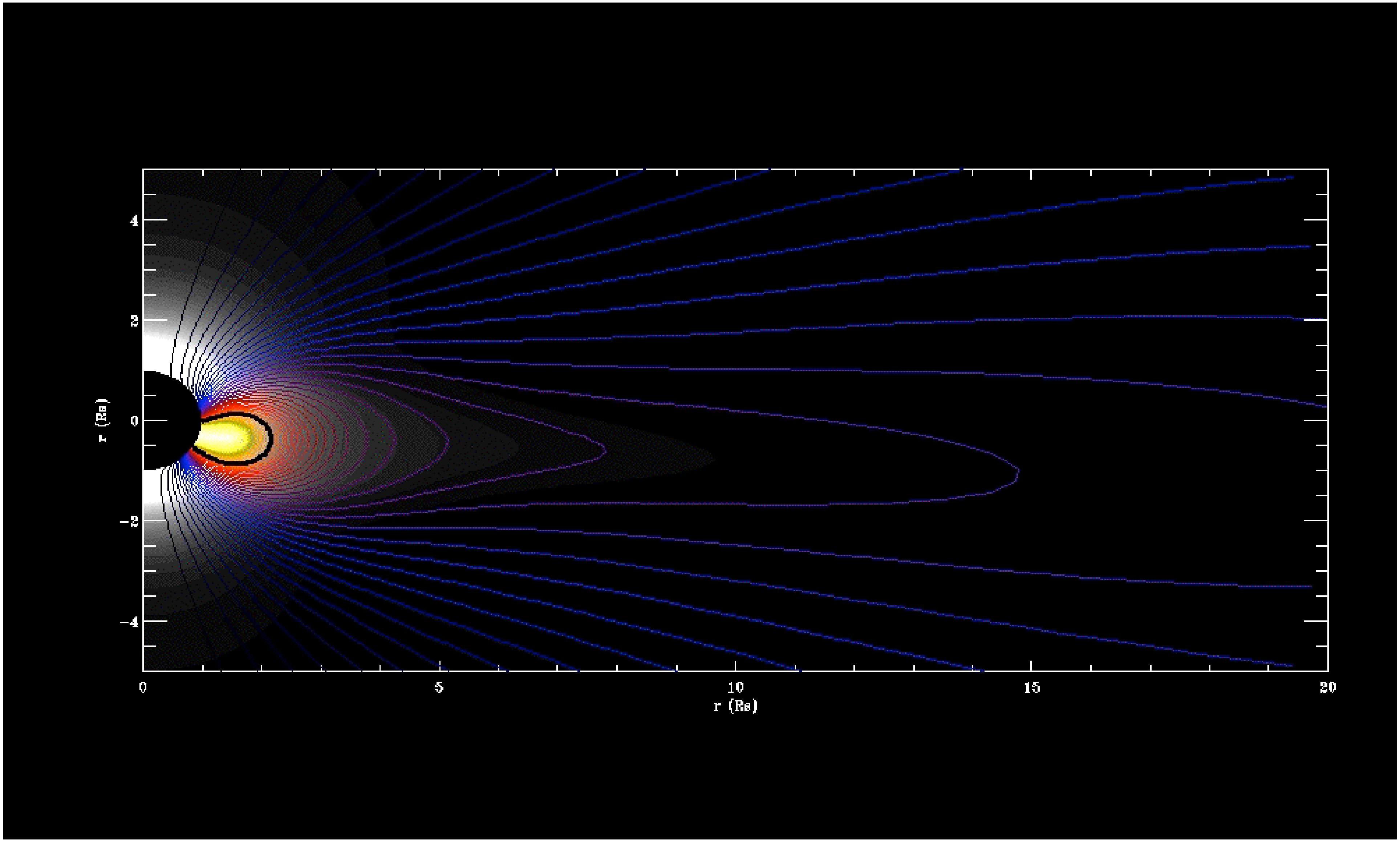
Key factor: Line-tying





Line-tying creates a second, stable equilibrium

SAIC CME Simulation



Linker et al. (2001)

3D Loss-of-Equilibrium Model

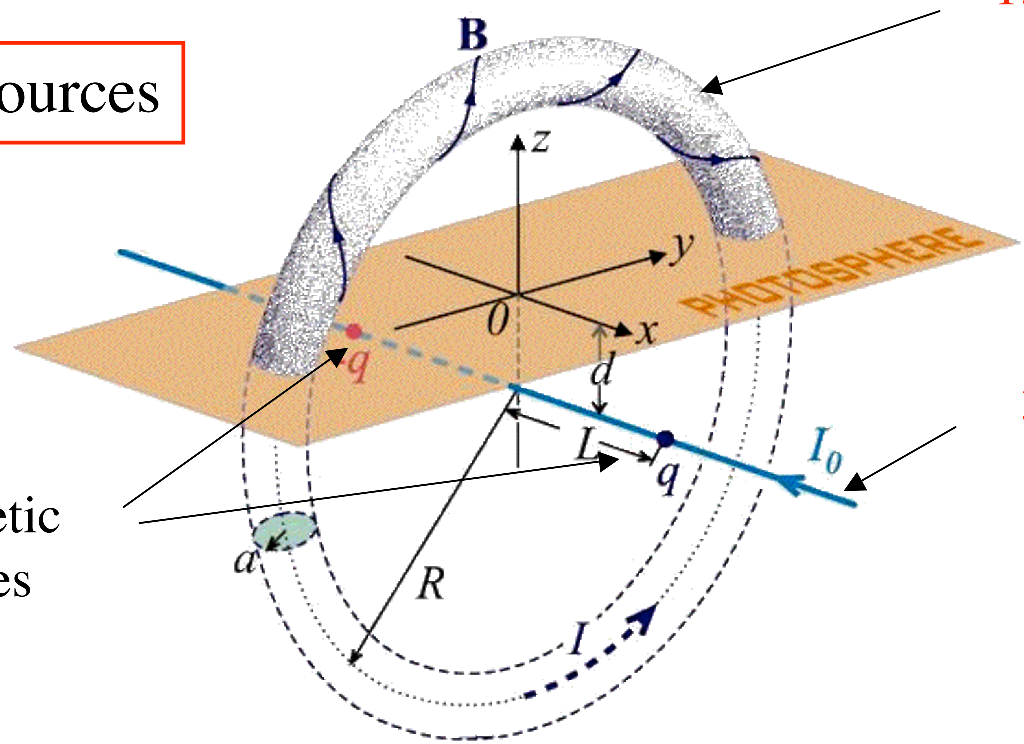
Titov & Démoulin (1999)

3 field sources

1. flux rope

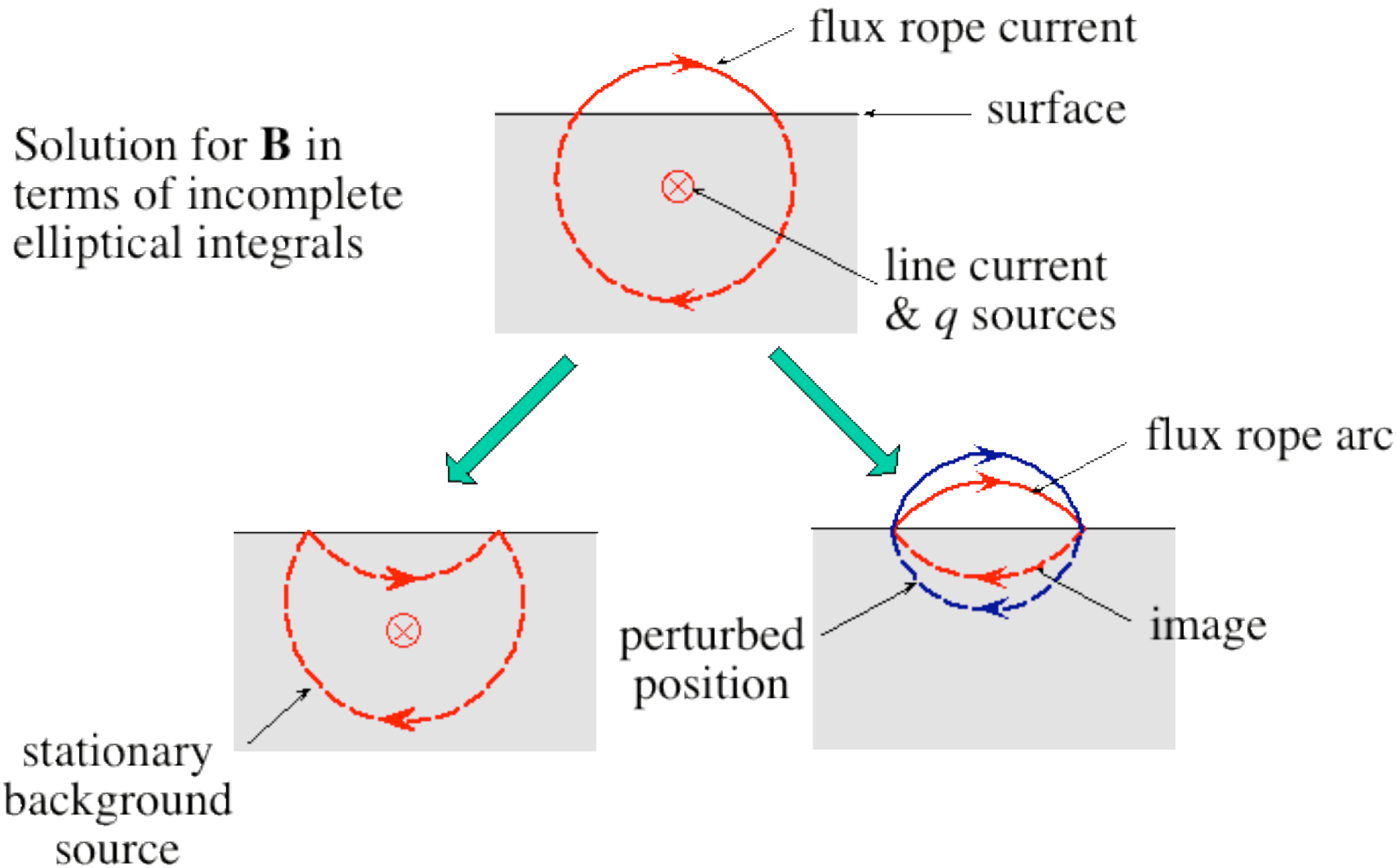
2. magnetic charges

3. line-current



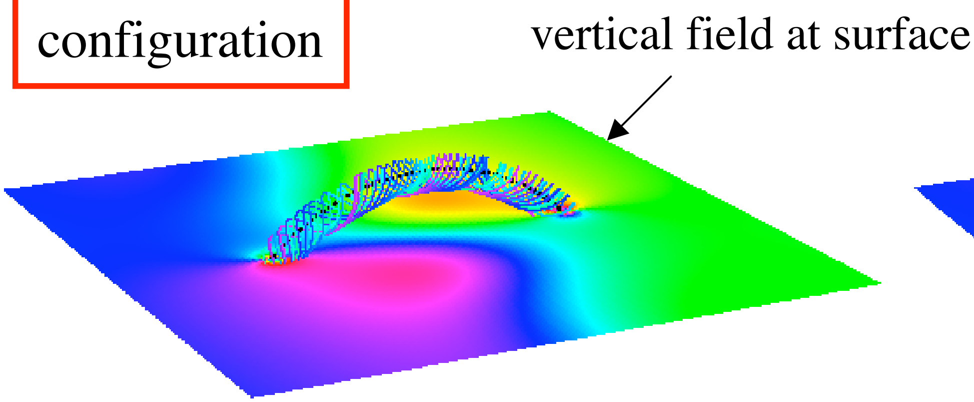
3D Line-Tied Solution by Method of Images

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

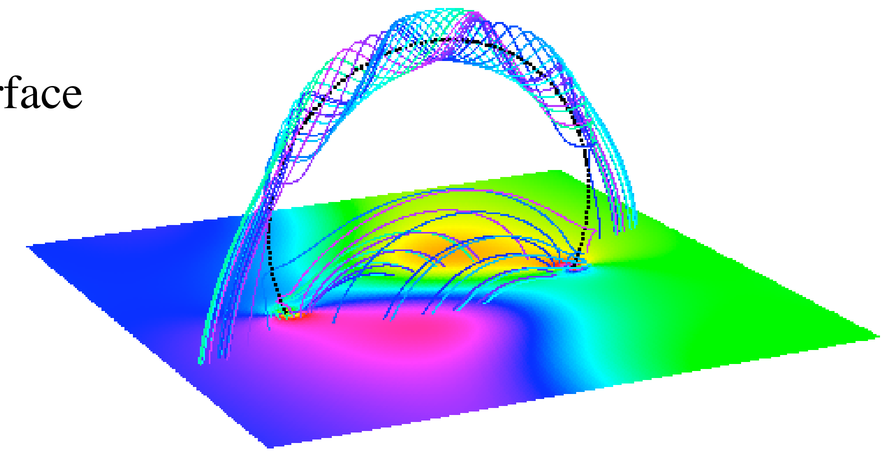


Line-Tied Evolution

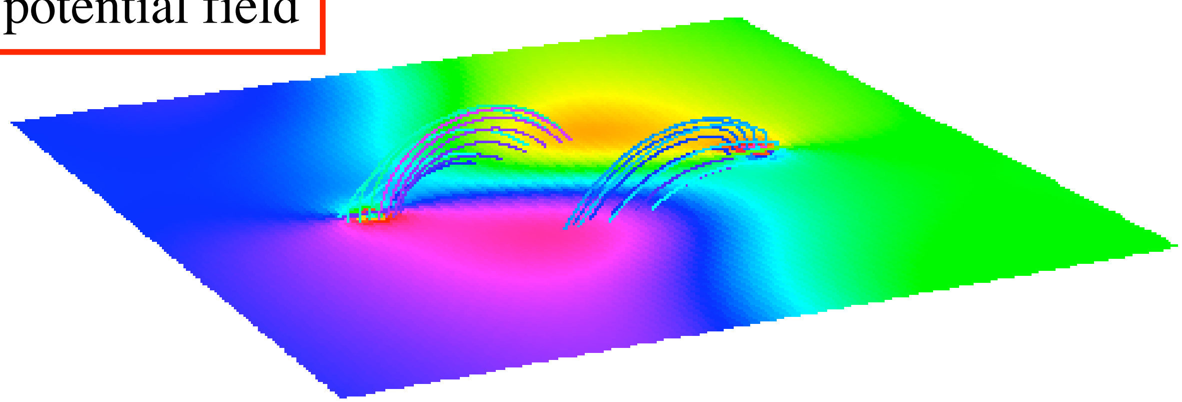
initial configuration



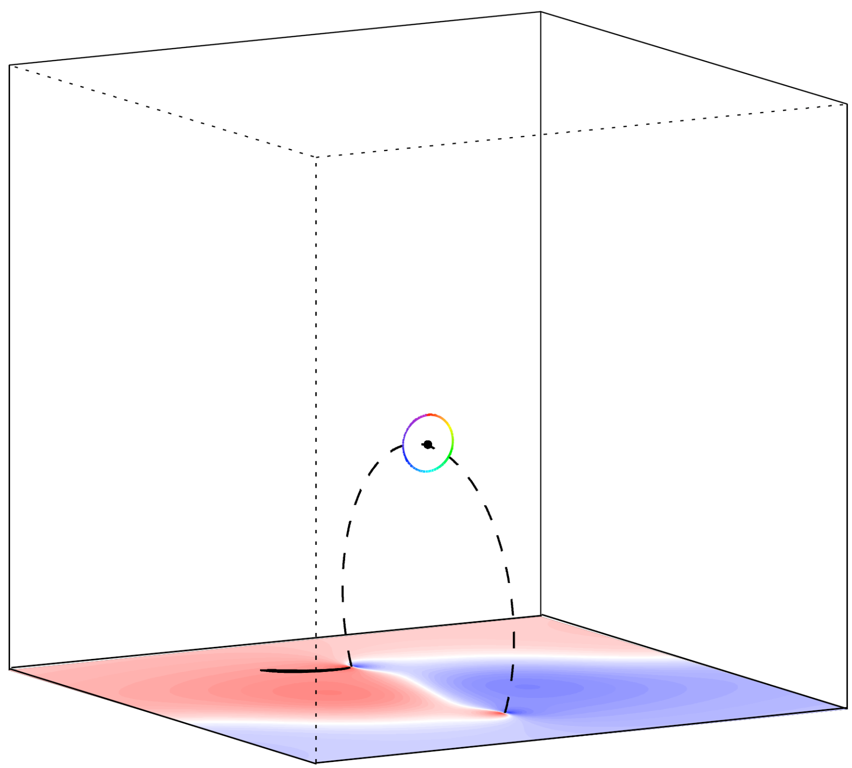
erupted configuration

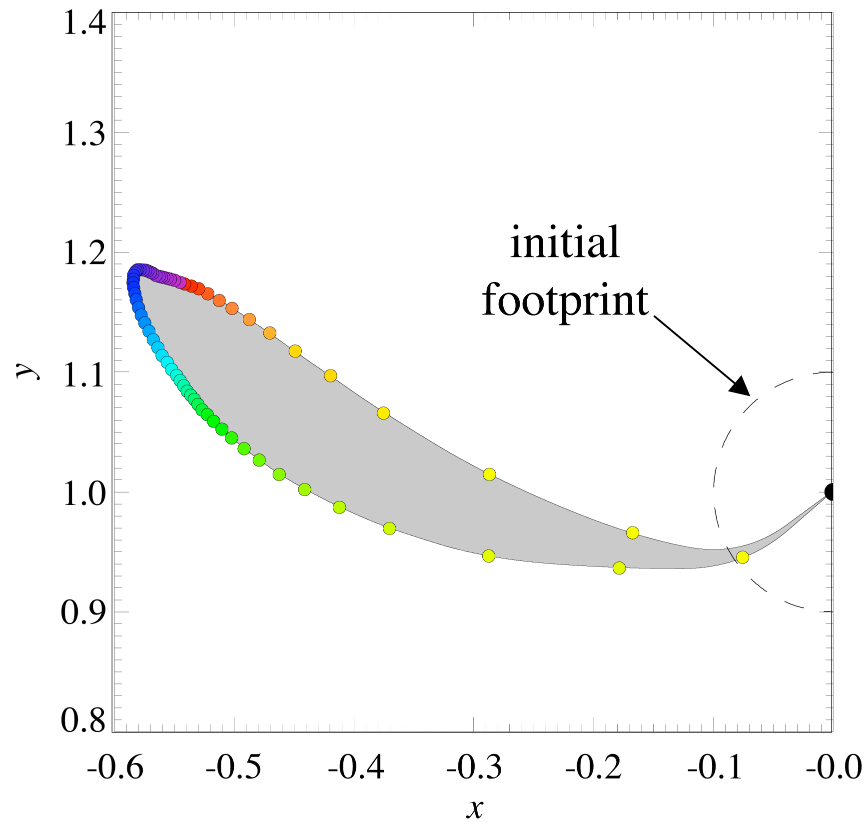


potential field



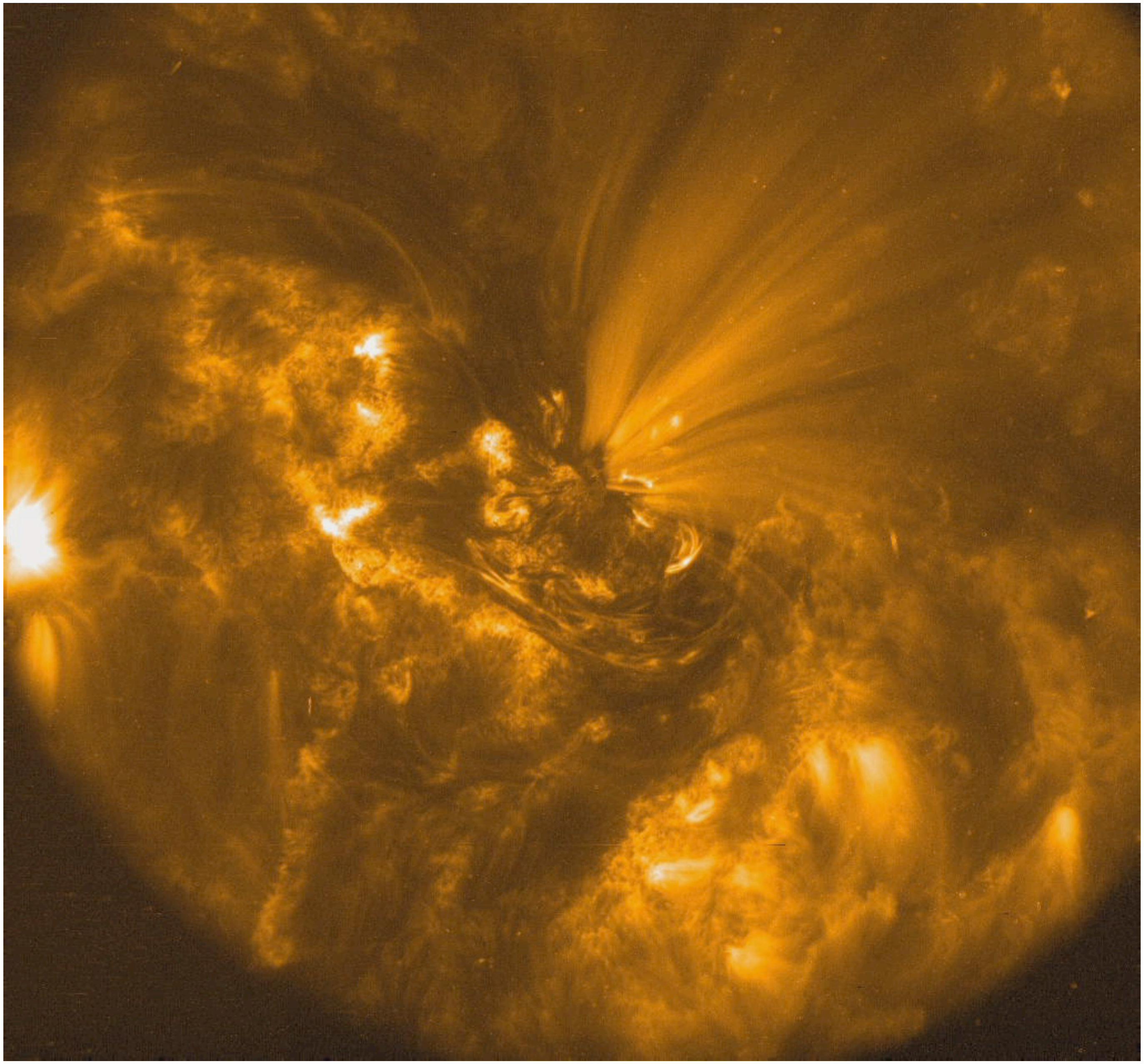
Flux-Rope Footprint



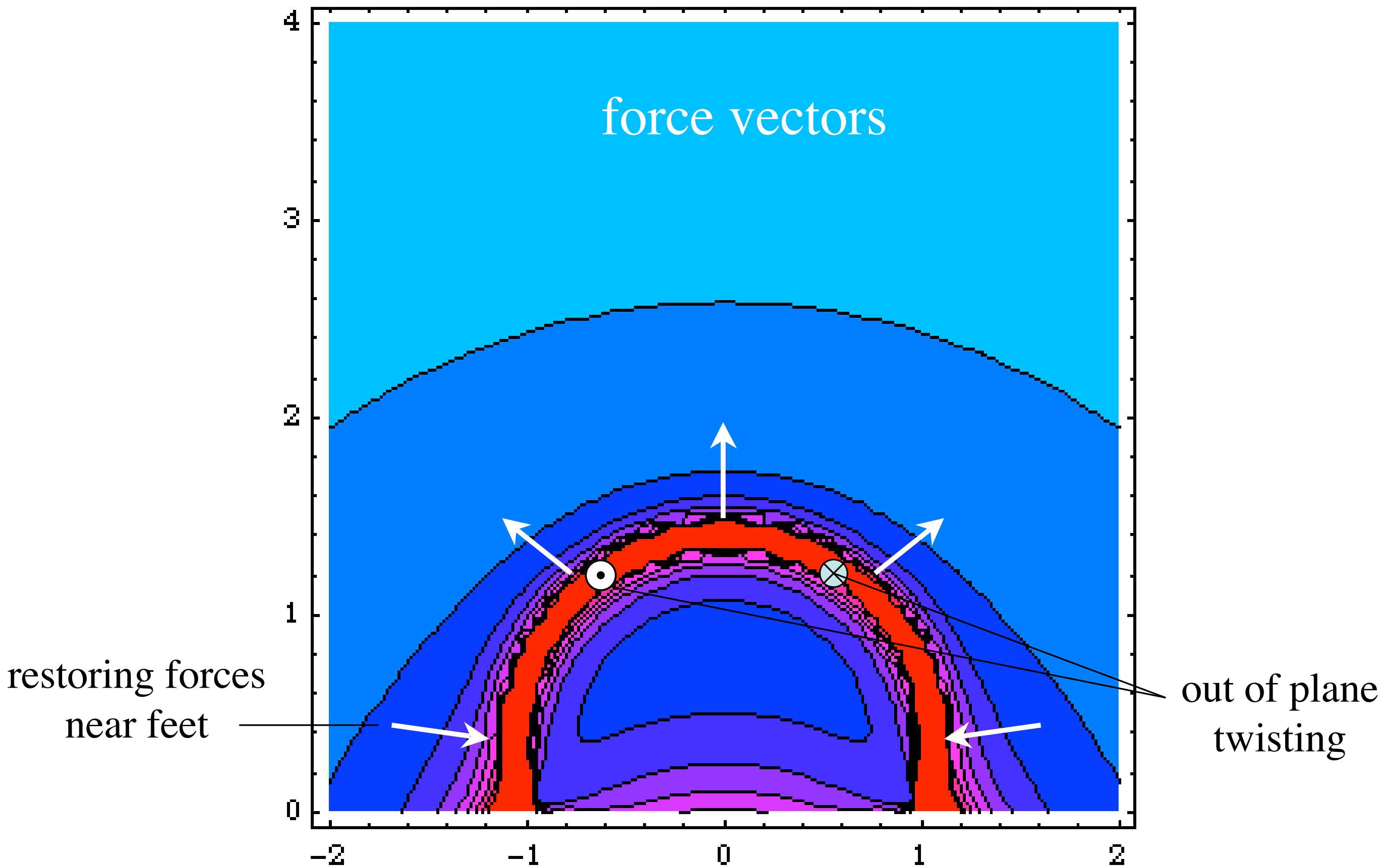


images courtesy of B. Kliem

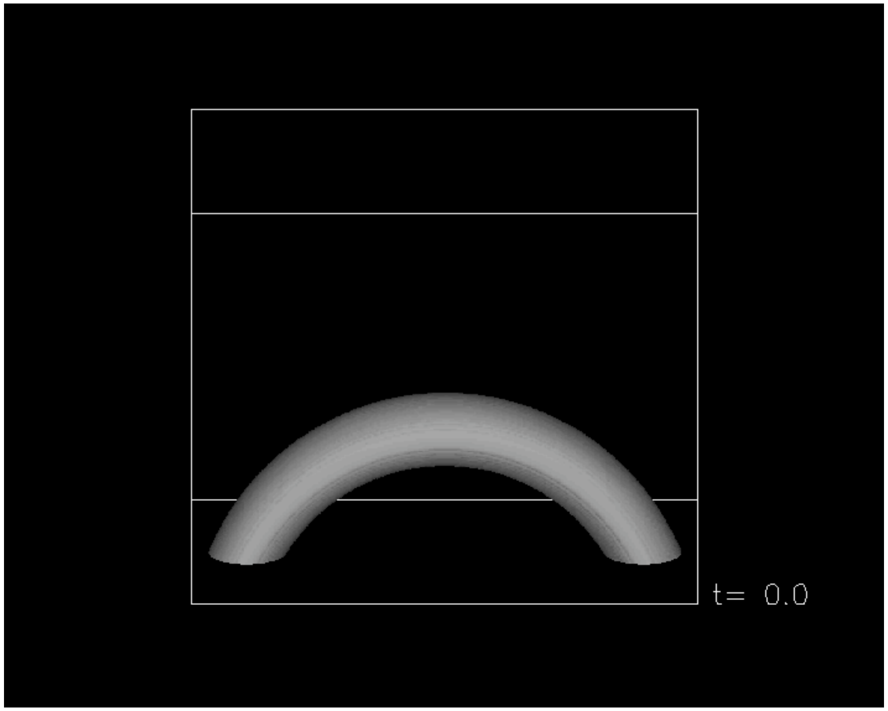
Transient Coronal Holes as Seen by TRACE

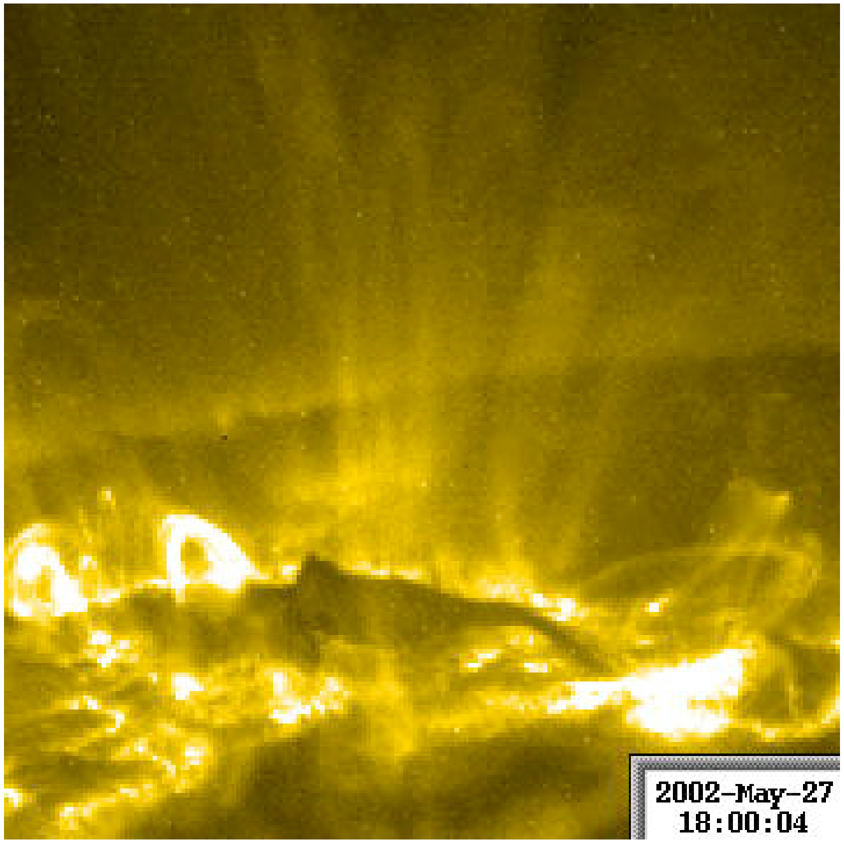


Forces Acting on Flux Rope



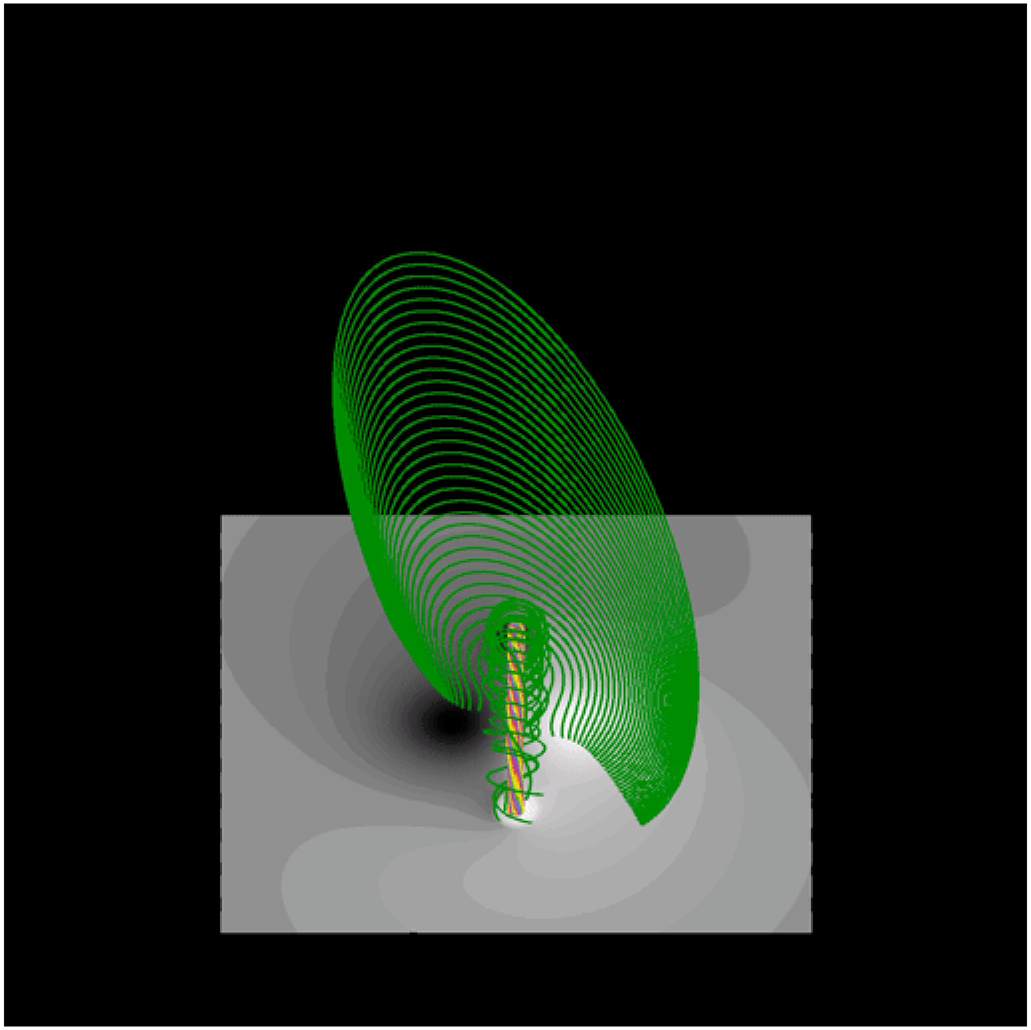
current density





Kliem & Török (2004)

Simulation of Kliem & Török

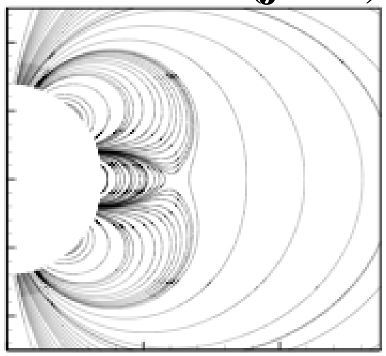


1. line current replaced by quadrupole
2. subcritical twist for helical kink
3. torus center near surface

What is the Trigger Mechanism in the Breakout Model?

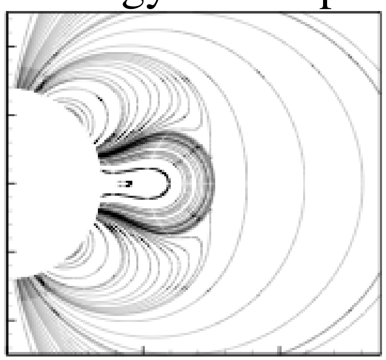
1.

initial state ($\mathbf{j} = 0$)



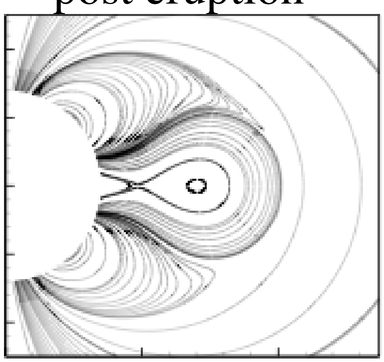
2.

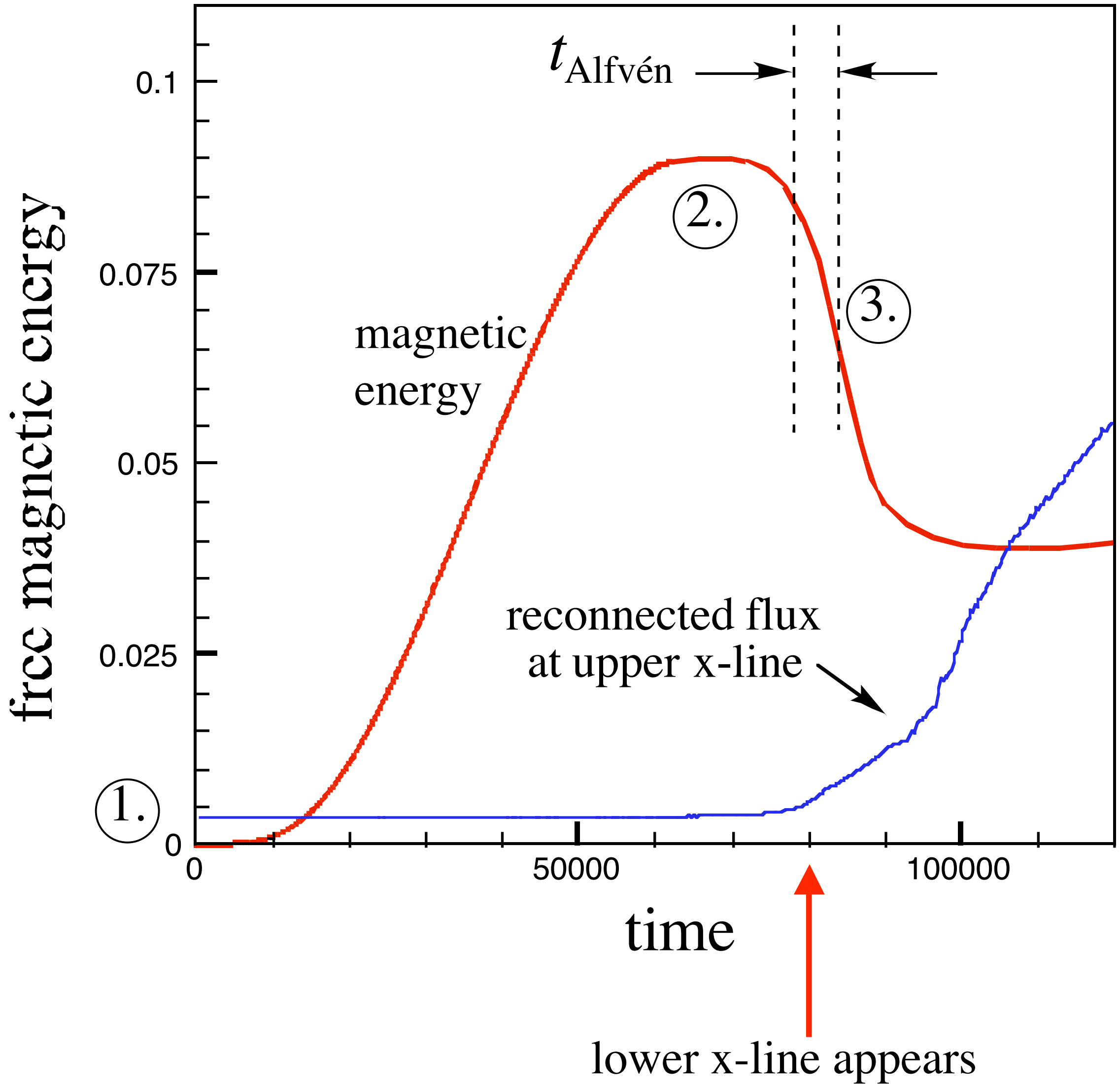
energy build-up



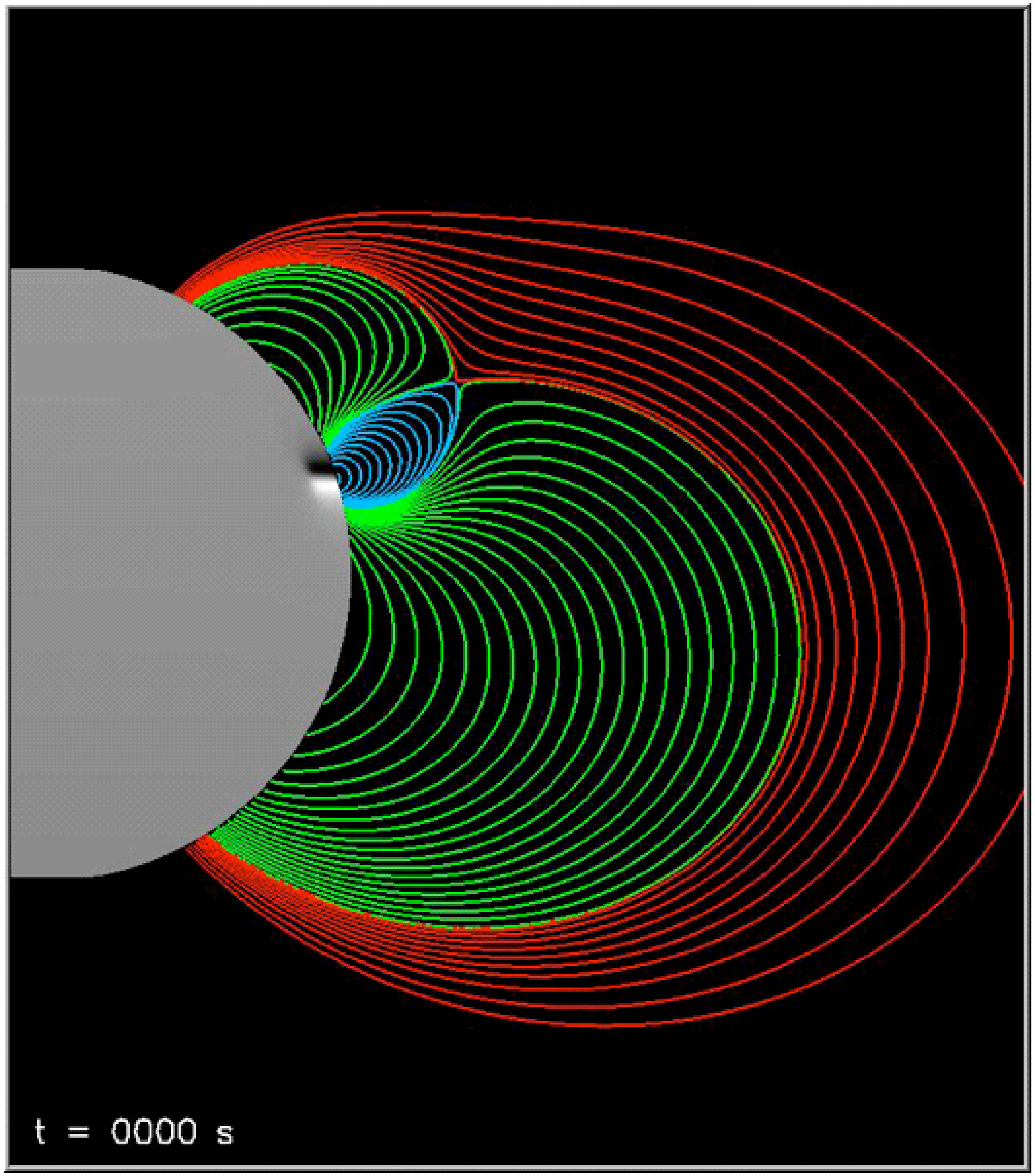
3.

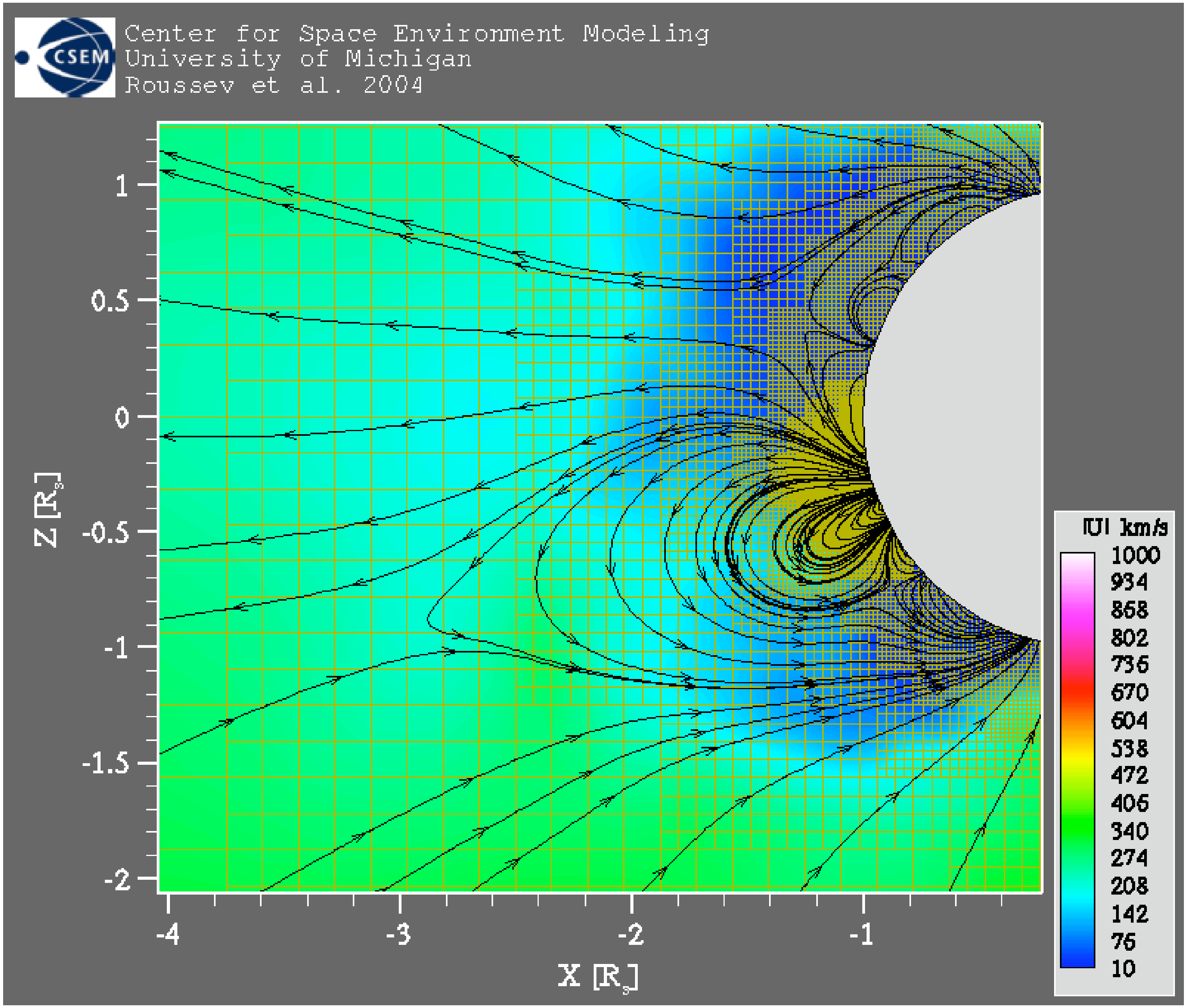
post eruption





Role of Reconnection in the Breakout Model

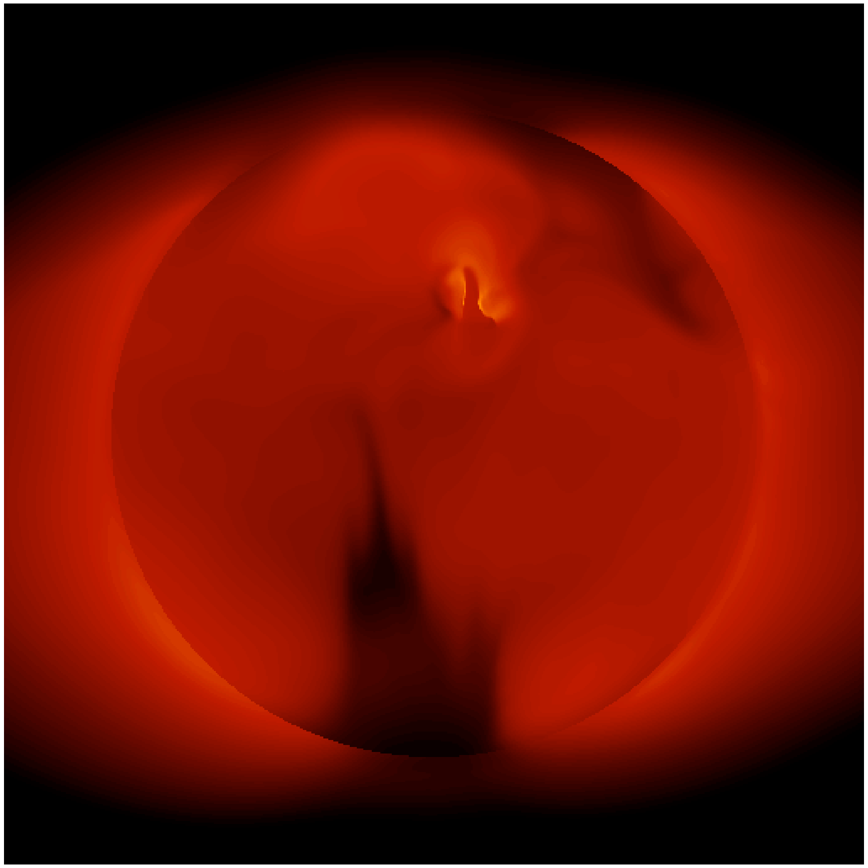




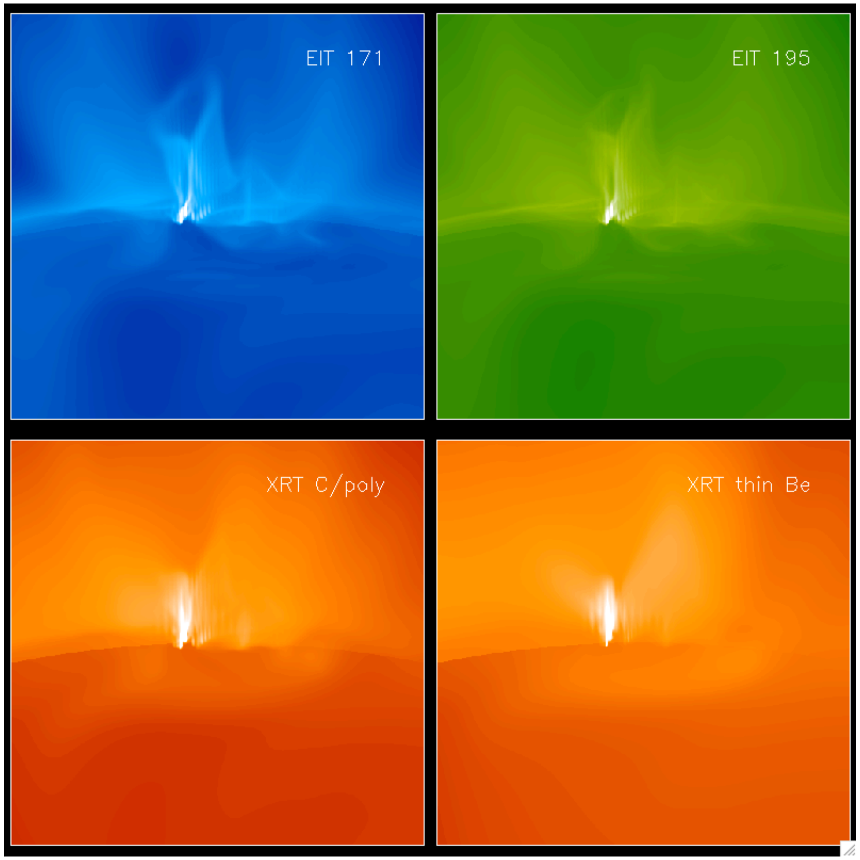
Center for Space Environment Modeling
University of Michigan
Roussev et al. 2004
CSEM
Z [R$_s$]
X [R$_s$]
1
0.5
0
-0.5
-1
-1.5
-2
-4
-3
-2
-1
|U| km/s
1000
934
868
802
736
670
604
538
472
406
340
274
208
142
76
10

Simulation of Flux-Rope Eruption in 3D MHD

top view (XRT)

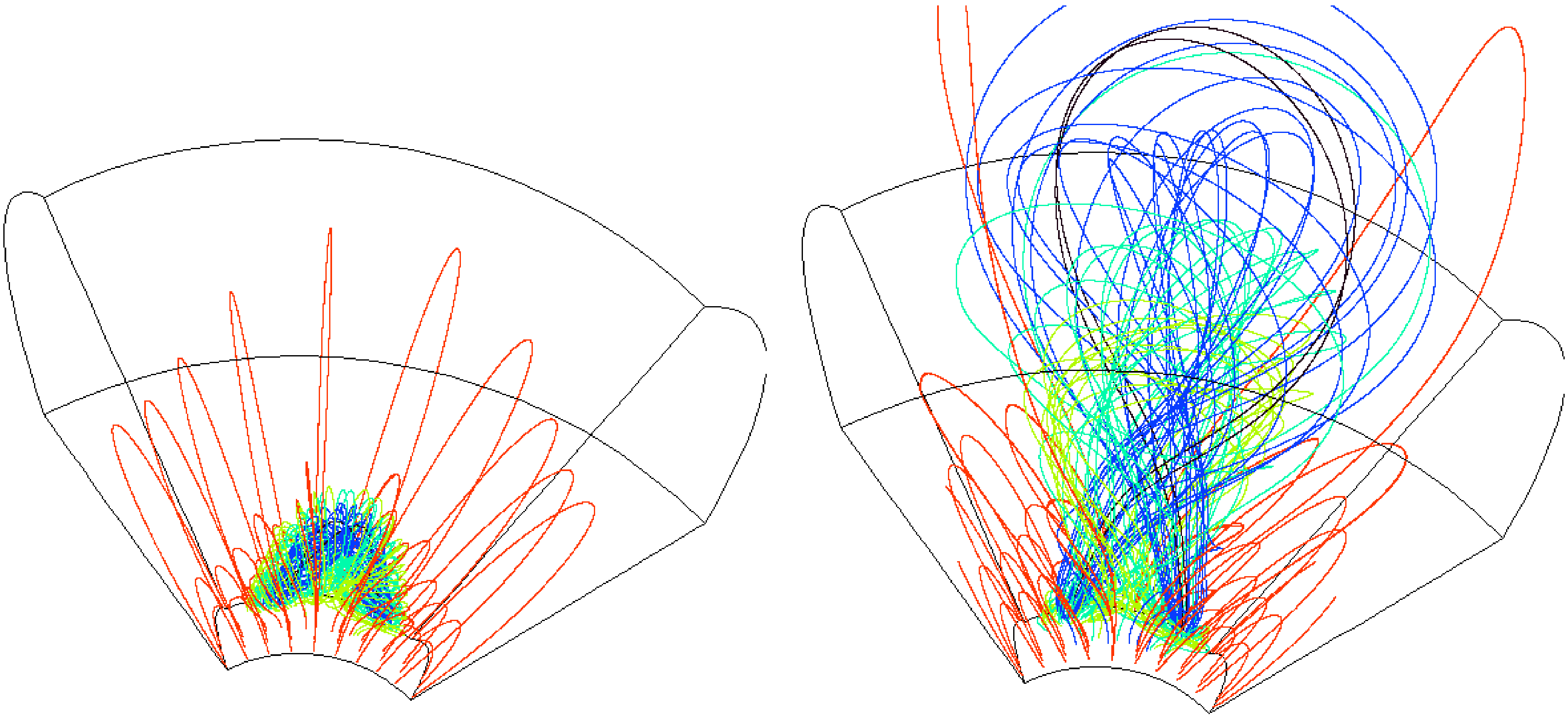


side views



courtesy of John Linker at Predictive Science

Flux Rope Emergence & Eruption



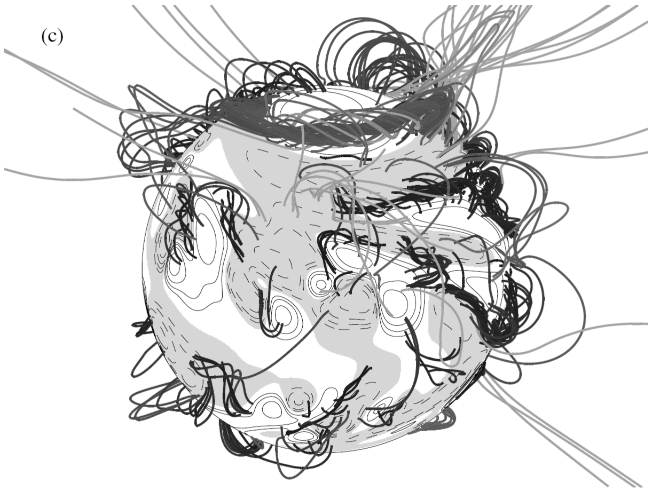
t=143.

$t = 94 \ (R_S/V_{A0})$

3D simulations of Fan & Gibson (2006)

Flux Ropes Are Characteristic of Low β Plasmas

van Ballegooijen & Mackay 2007



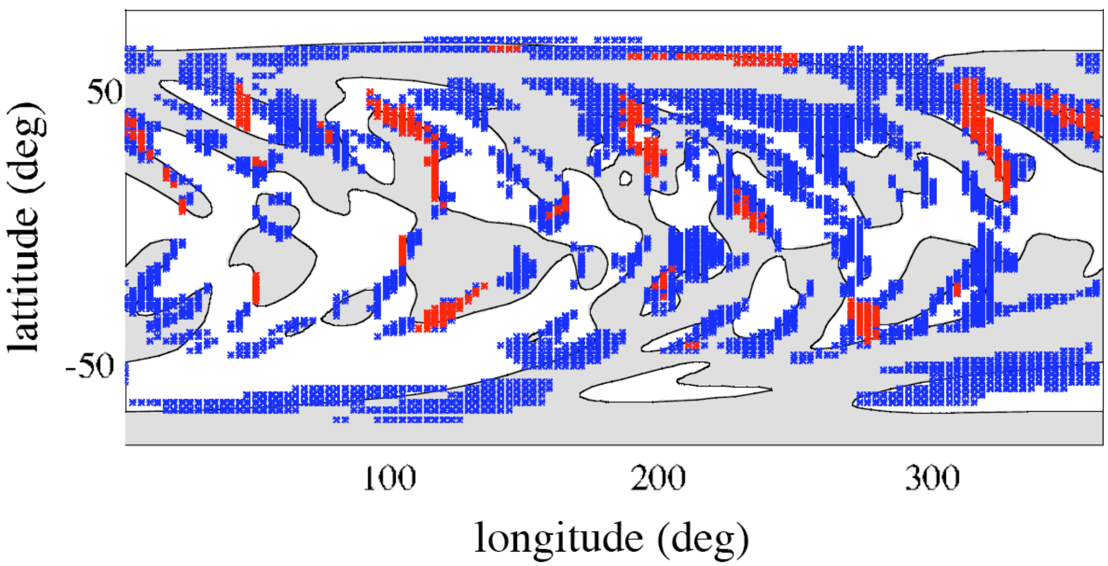
prominence plasma $\beta << 1$

$$\nabla P \approx 0 : \mathbf{j} \times \mathbf{B} \approx 0 \qquad \mathbf{j} \parallel \mathbf{B}$$

j along **B** produces twist

flux rope defined as enough twist to produce inverse polarity

(about 1 turn)



blue: flux ropes

red: flux ropes that erupted

Yeates & Mackay 2009

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 —