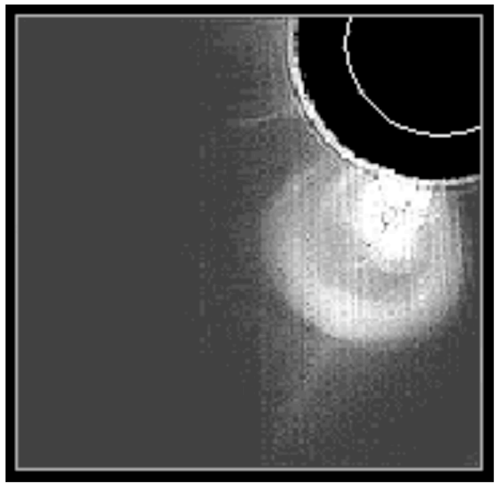
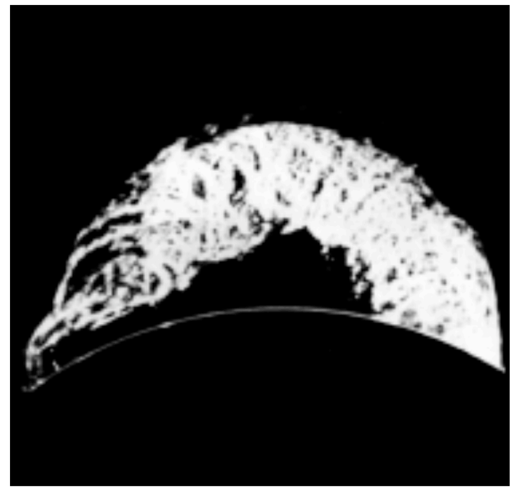
Different Aspects of Solar Eruptions

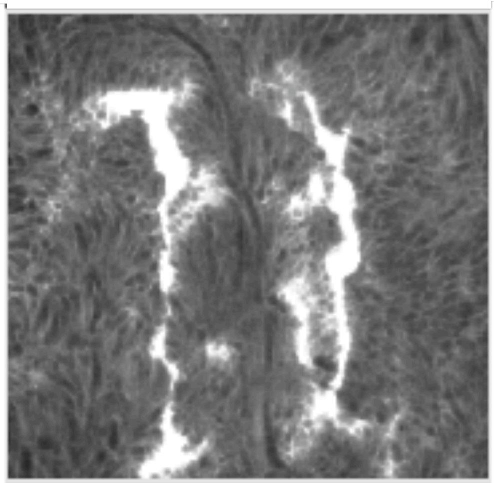
CME



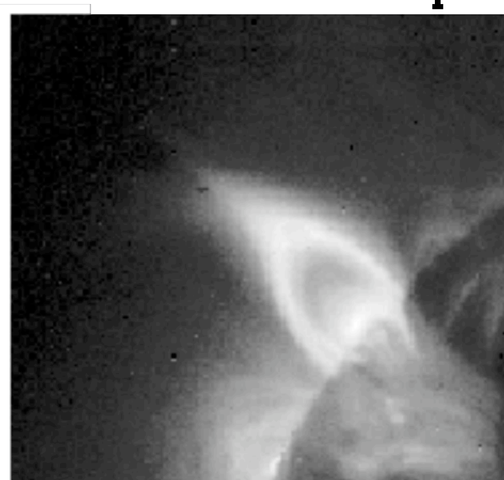
Erupting Prominence

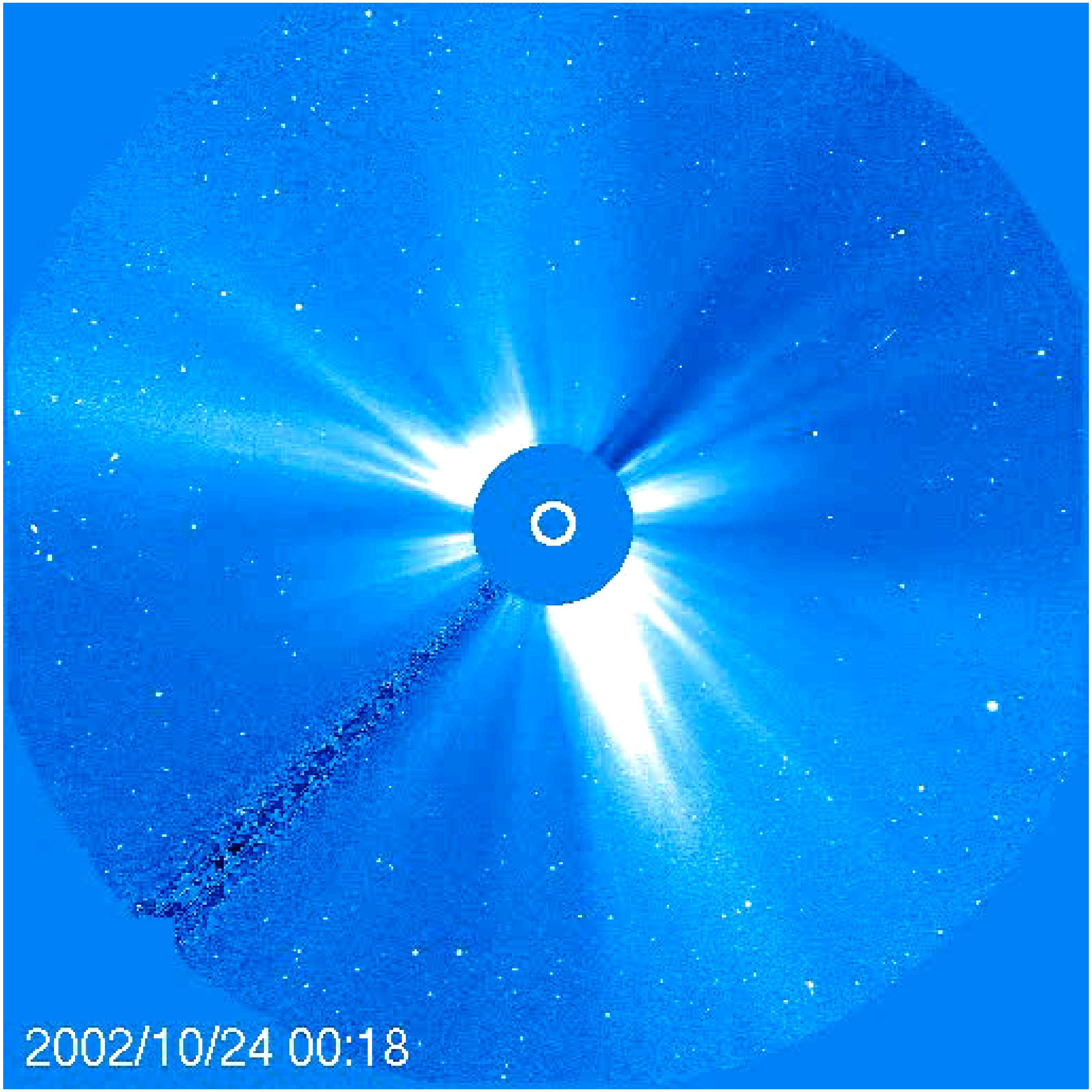


CME/Flare Ribbons



CME/Flare Loops

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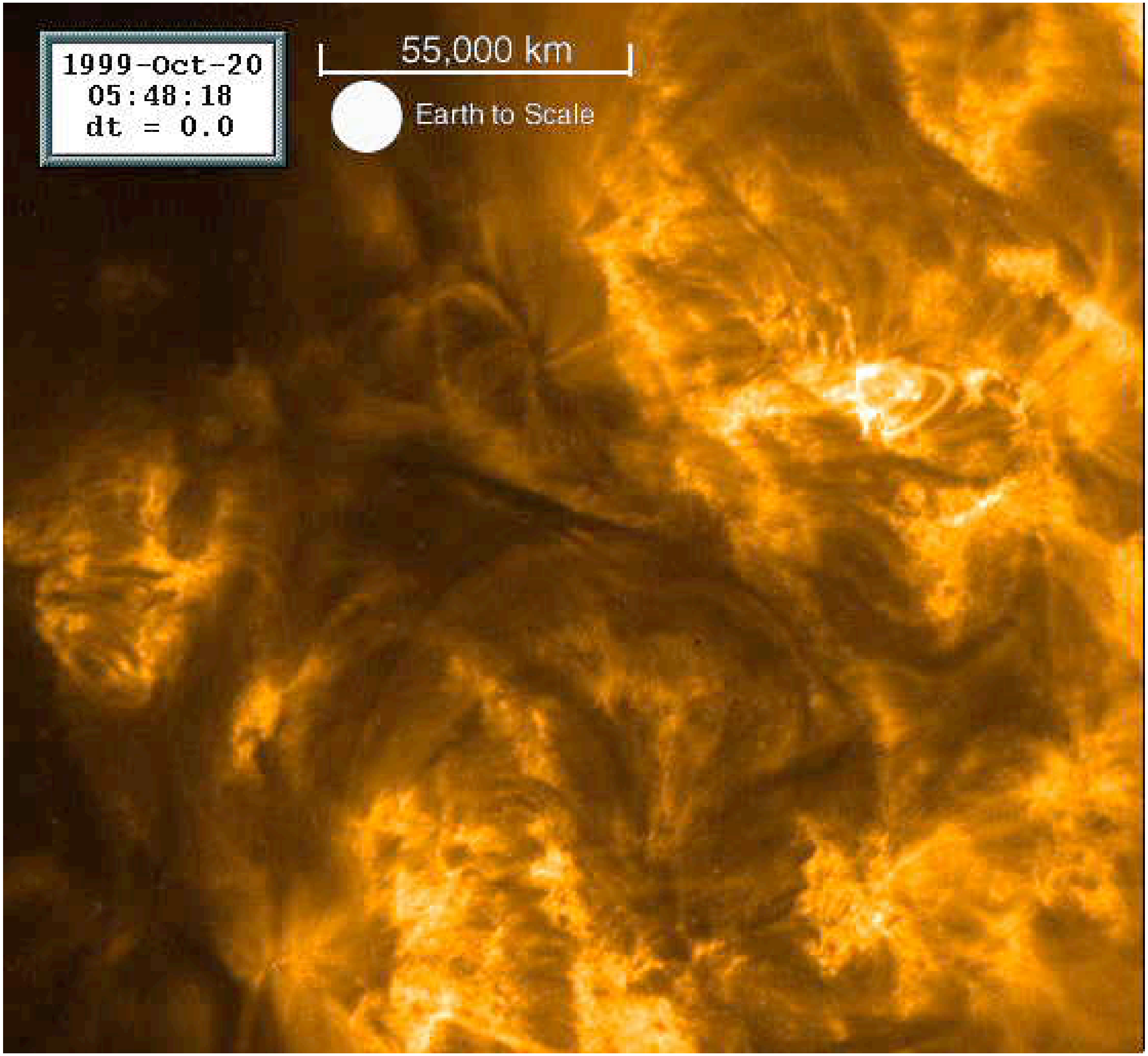
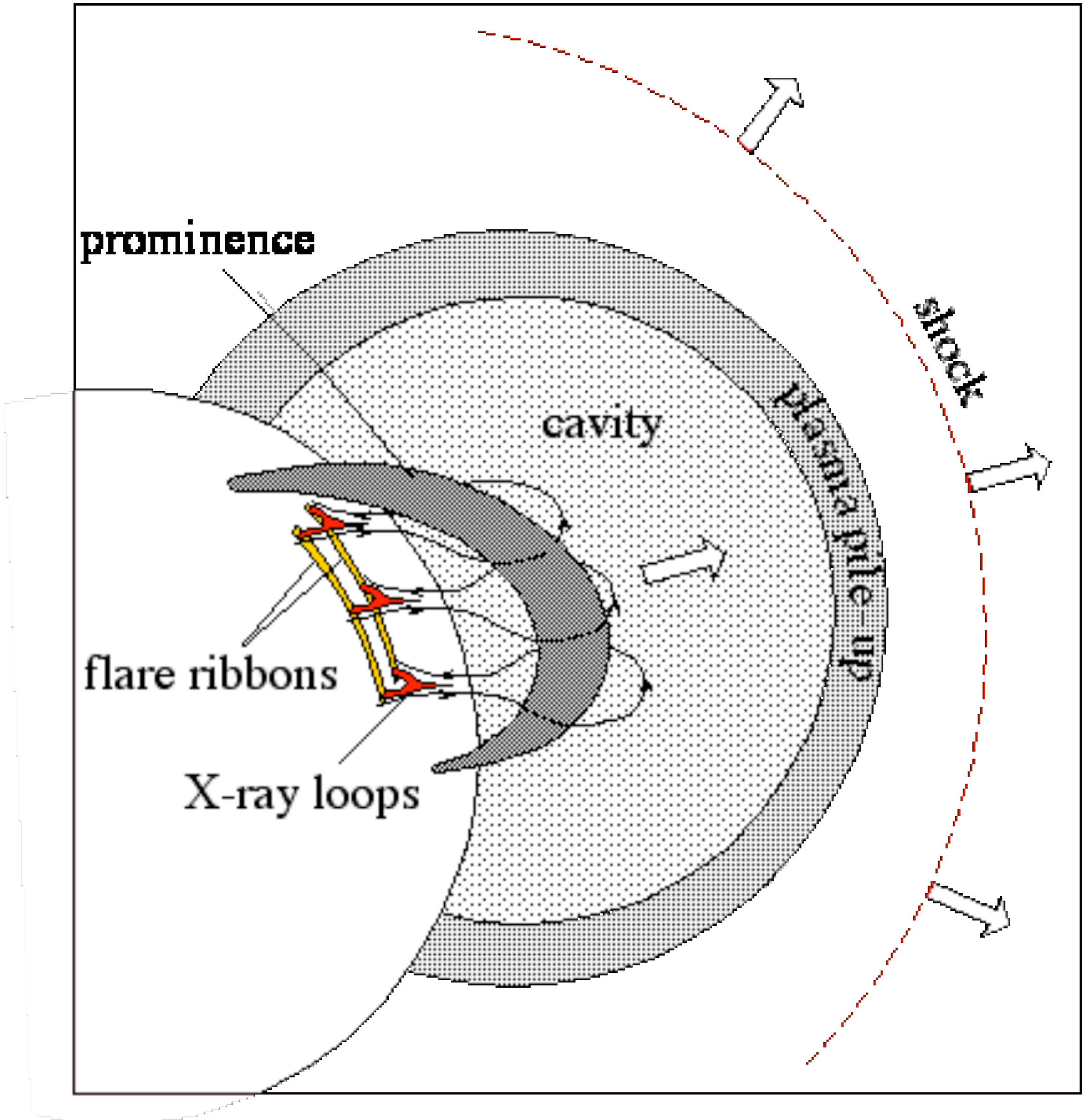
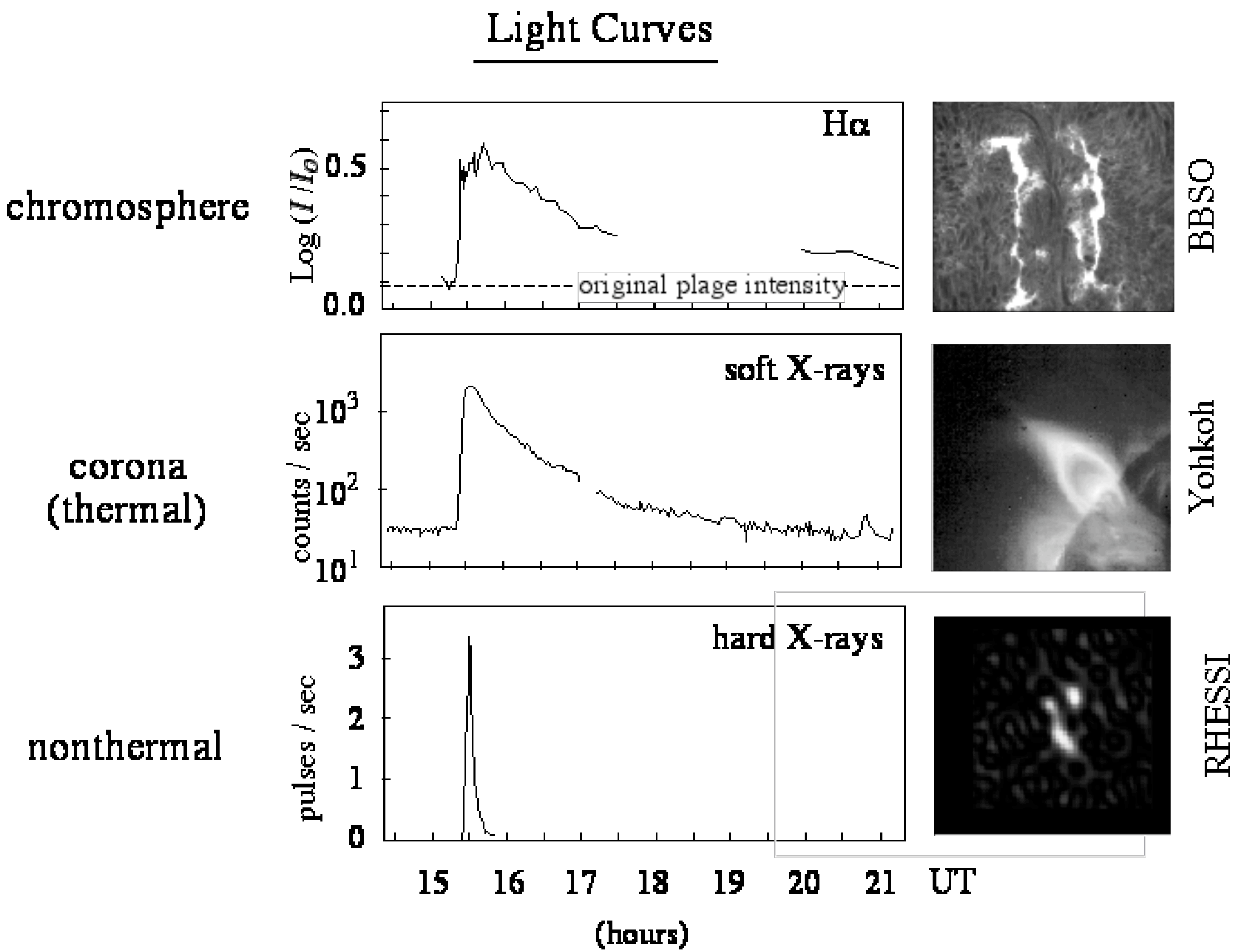
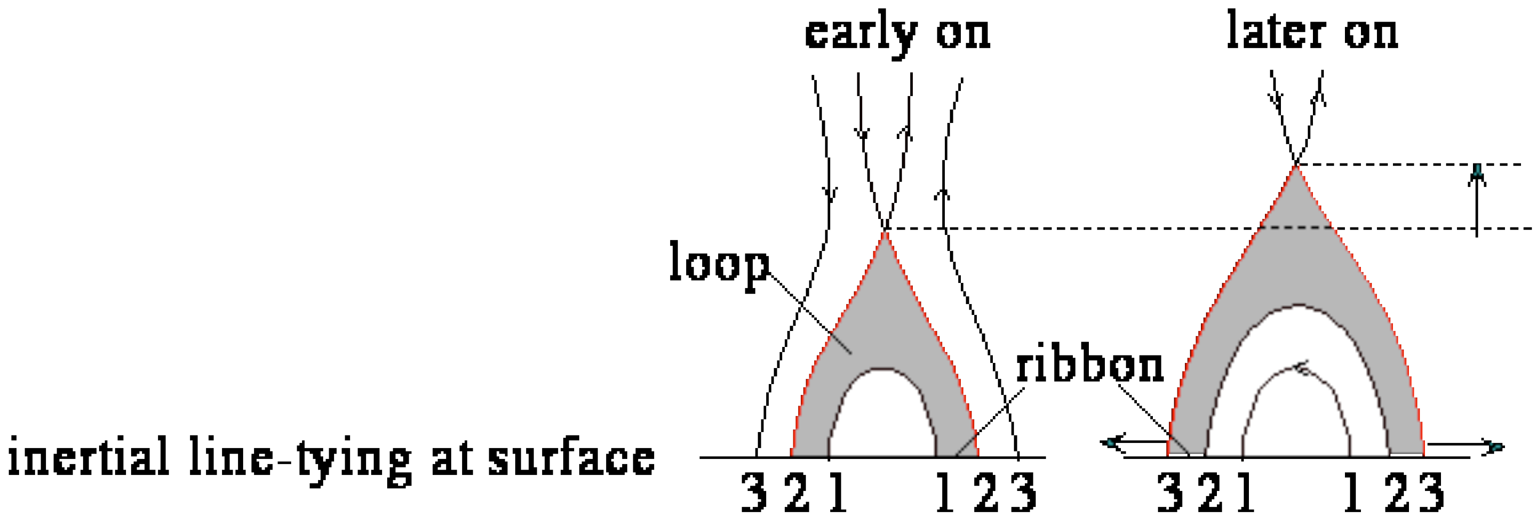

1999-Oct-20
05:48:18
dt = 0.0
55,000 km
Earth to Scale

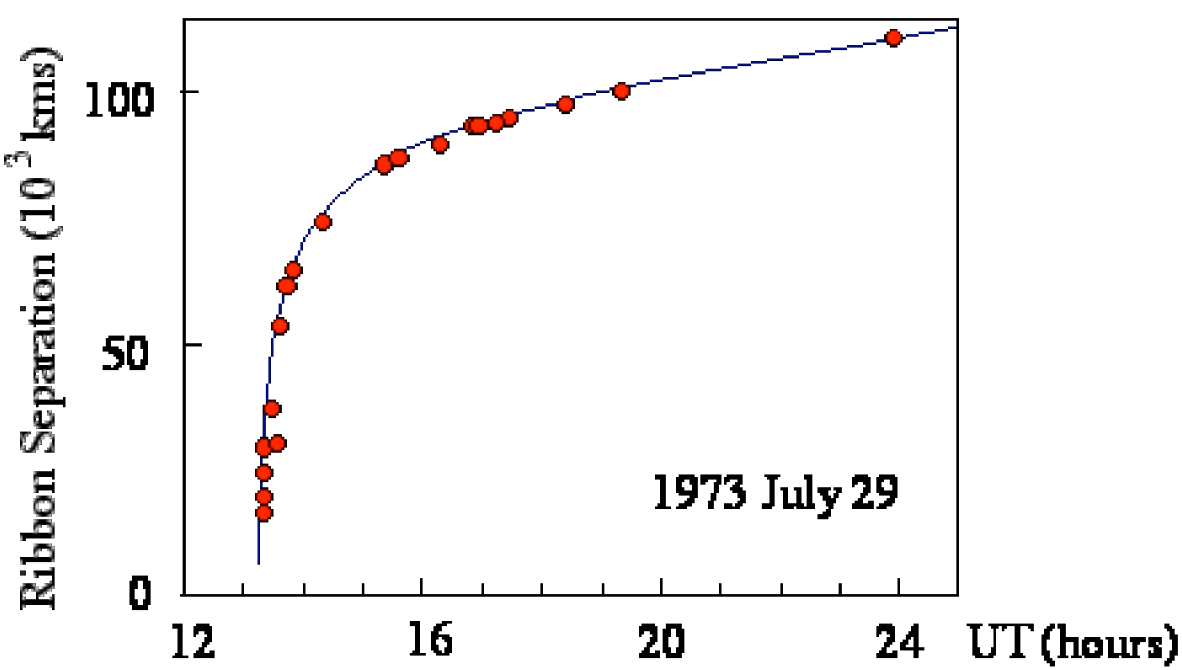
Large Solar Eruptions



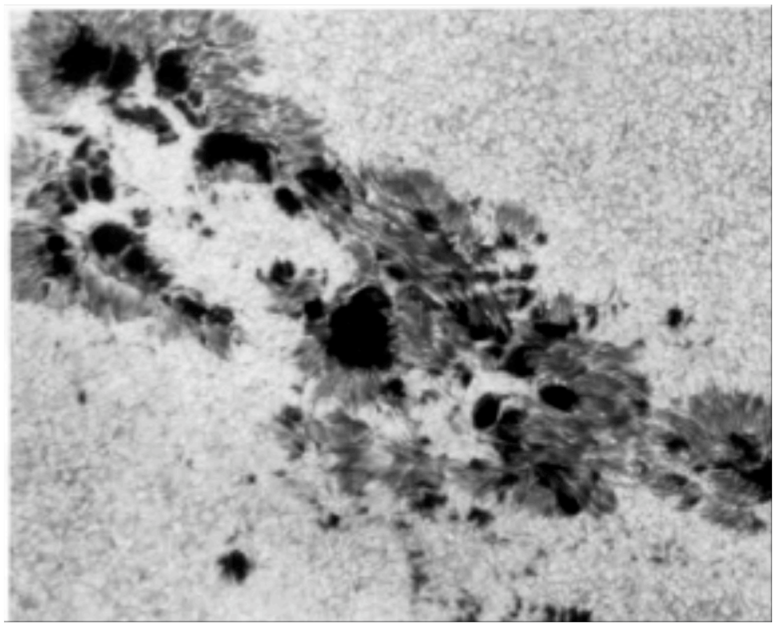

Light Curves
chromosphere
corona
(thermal)
nonthermal
Hα
original plage intensity
Log (I / I₀)
0.0
0.5
soft X-rays
counts / sec
10¹
10²
10³
hard X-rays
pulses / sec
0
1
2
3
15
16
17
18
19
20
21
UT
(hours)
BBSO
Yohkoh
RHESSI

Apparent Motion of Loops & Ribbons





Inertial Line-Tying



Photospheric boundary condition:

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

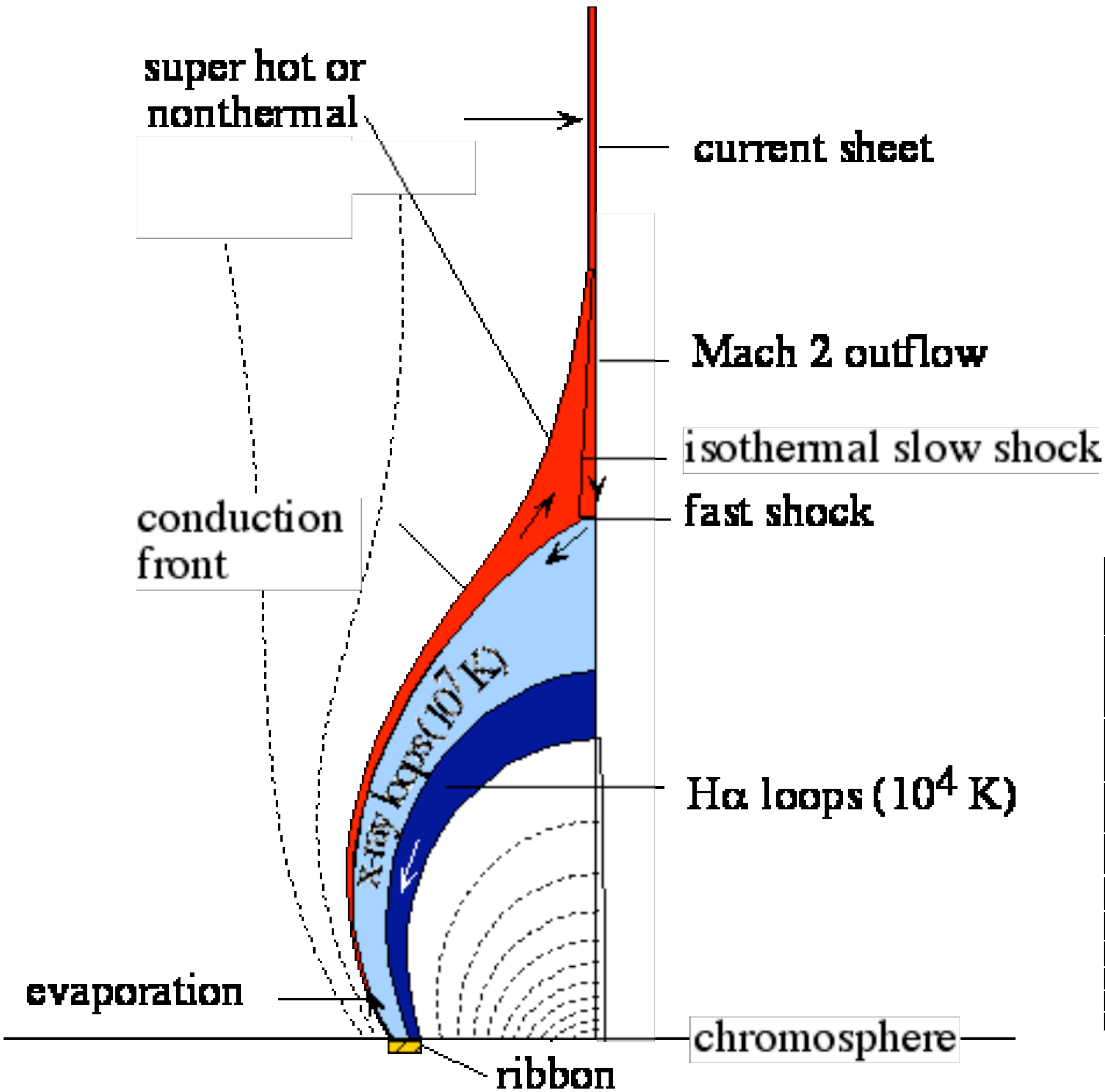
Photospheric convection is negligible

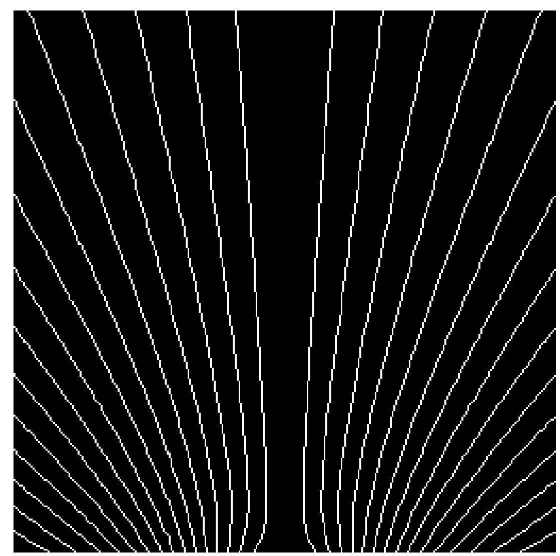
Plasma below the photosphere is both massive and a good conductor.

B normal to surface is fixed.

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

CME/Flare Loop Structures



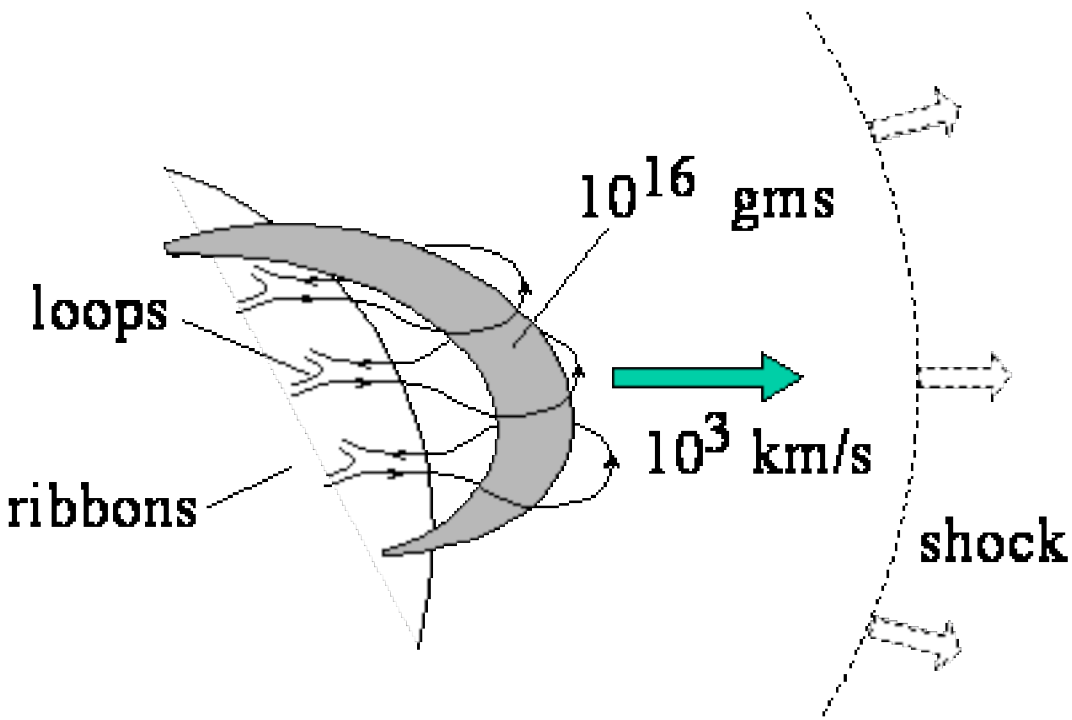


CME/Flare Energetics

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

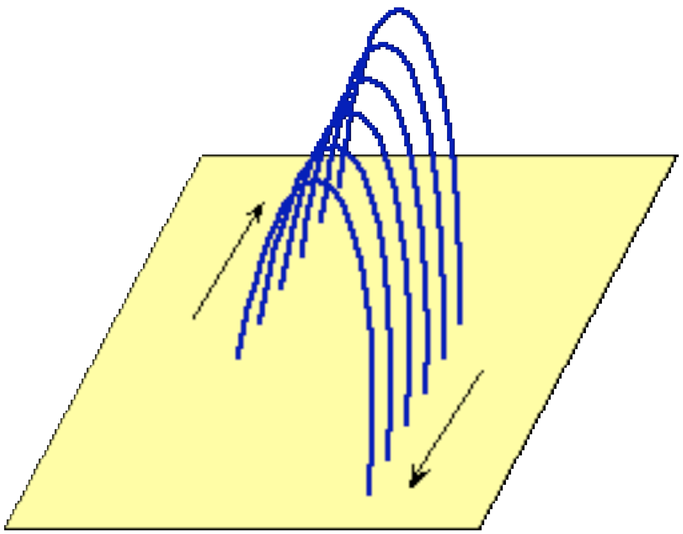
Nature of Energy Source: Required: ≈ 100 ergs/cm^3

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?

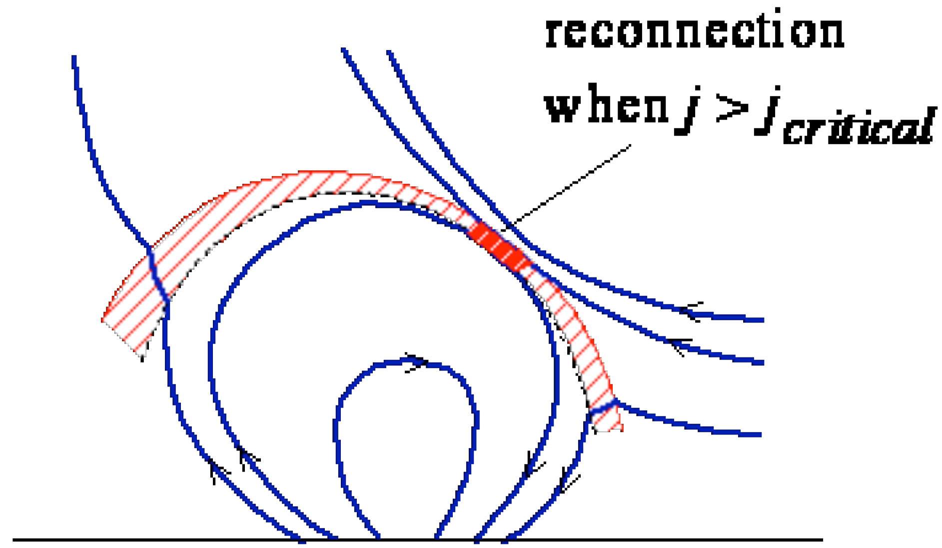
$\beta = 10^{-3}$ $\nabla p \approx 0$ $\mathbf{j} \times \mathbf{B} \approx 0$

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



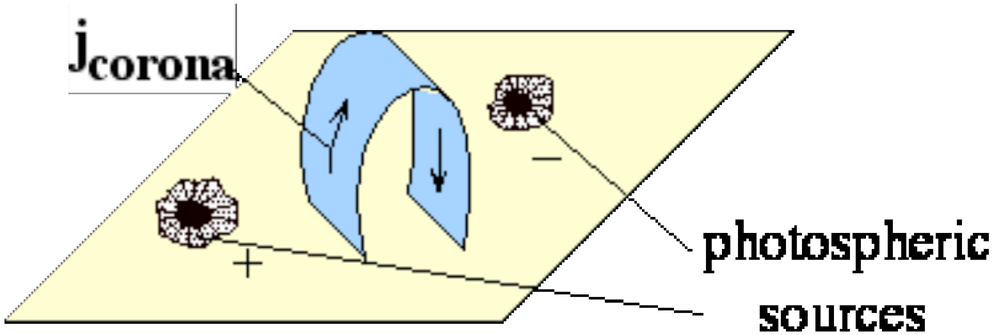
sheared magnetic fields

Current sheets:

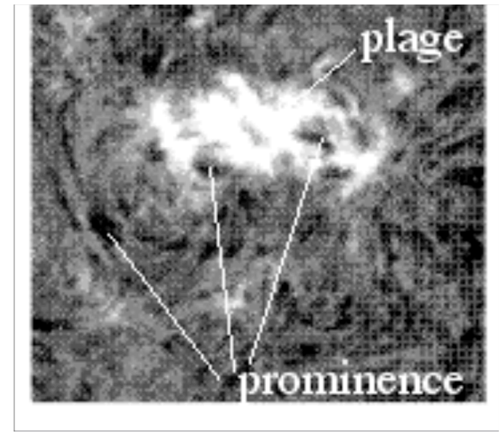


emerging flux model

How Much Energy is Stored?



Hα image



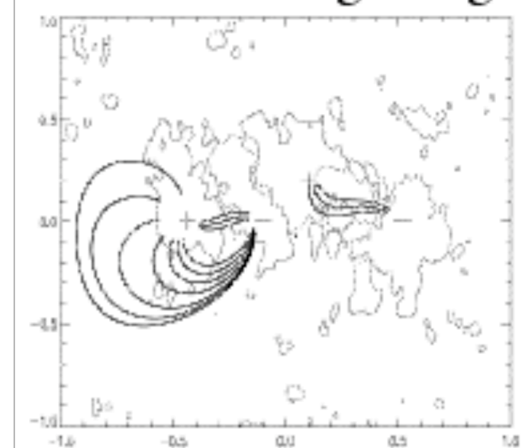
$$B = B_{\substack{\text{photospheric}\\\text{currents}}} + B_{\substack{\text{coronal}\\\text{currents}}}$$

invariant during CME

source of CME energy

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

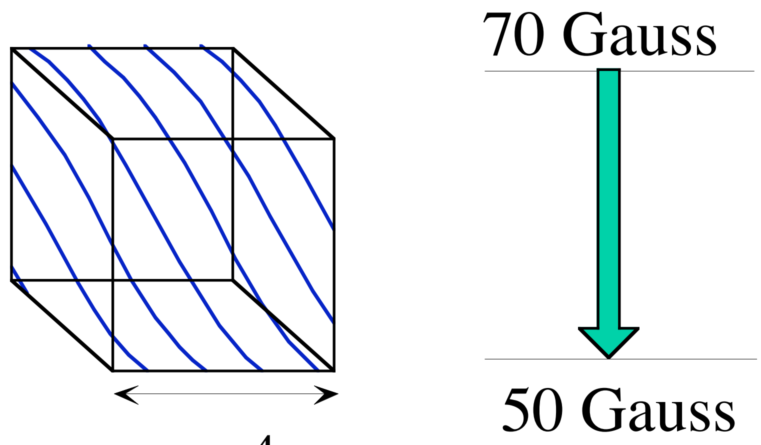
model with magnetogram



from Gaizauskas & Mackay (1997)

free magnetic energy ≈ 50% of total magnetic energy

Magnetic Energy Conversion:

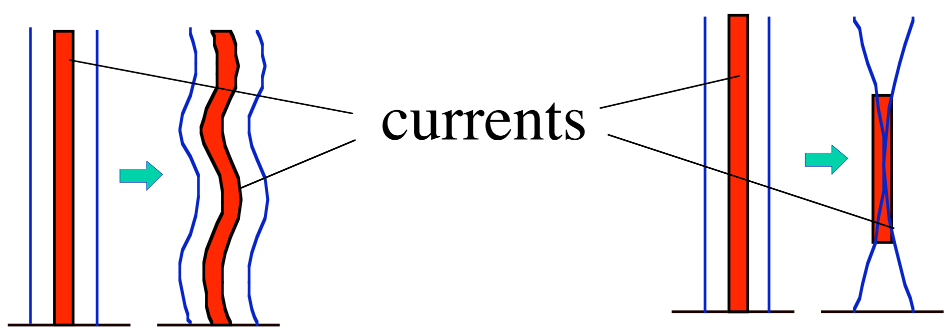


$L = 6 \times 10^4$ km

$W_B = 10^{32}$ ergs

ideal MHD

reconnection



inefficient (< 10%)

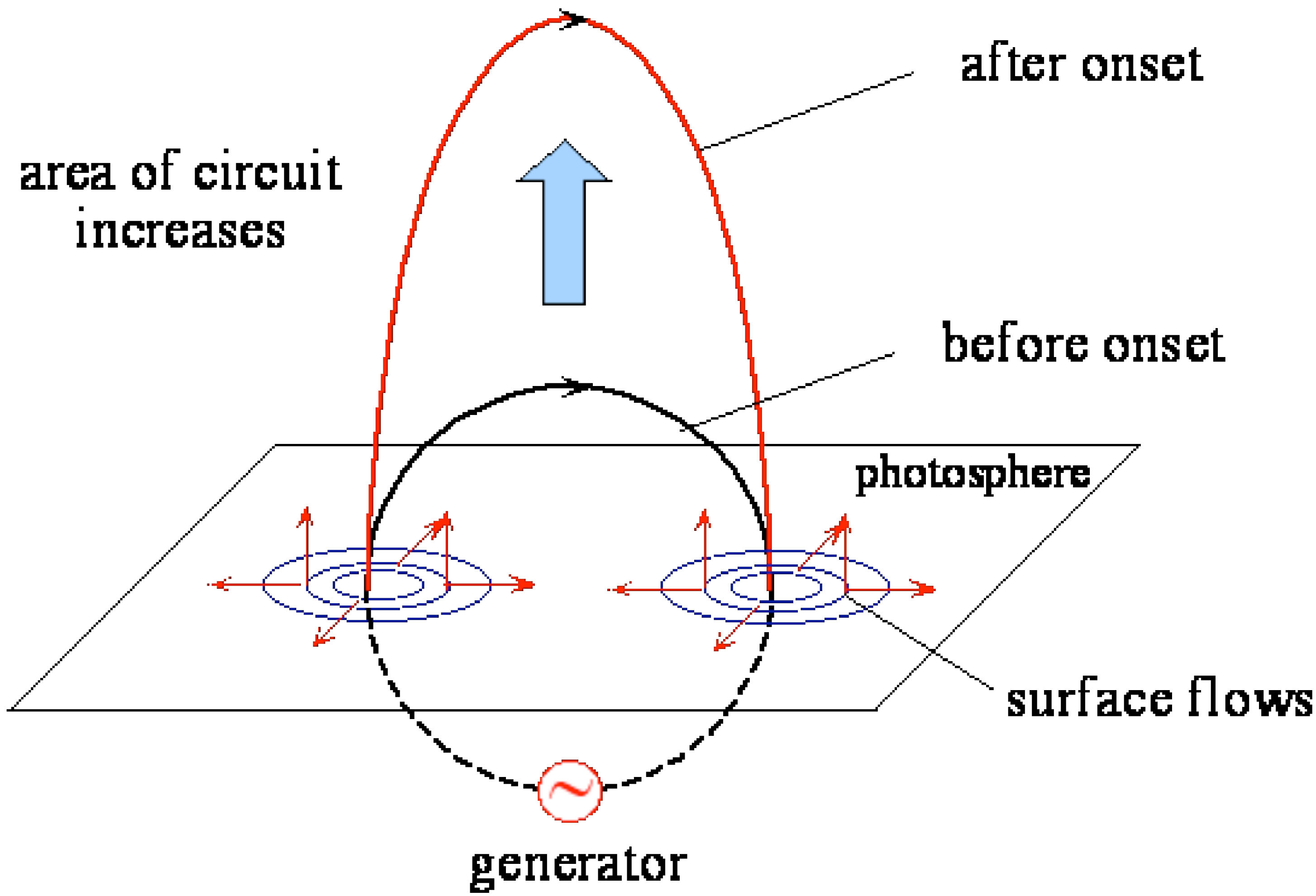
fast

efficient (100%)

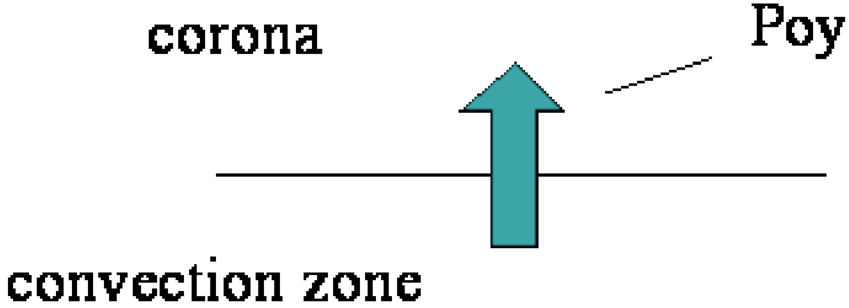
slow

Flux Injection Models

(e.g. Chen 1989)



During injection energy flows through photosphere.



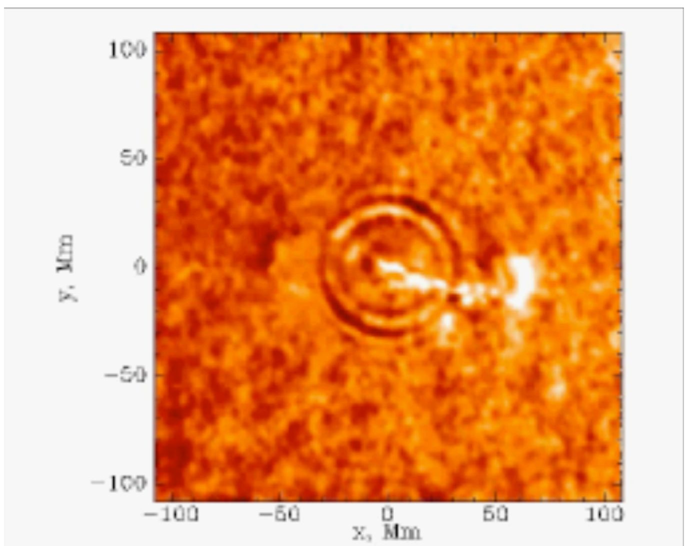
Poynting flux: $\mathbf{S} = c\,\mathbf{E} \times \mathbf{B} \,/\, (4\pi)$

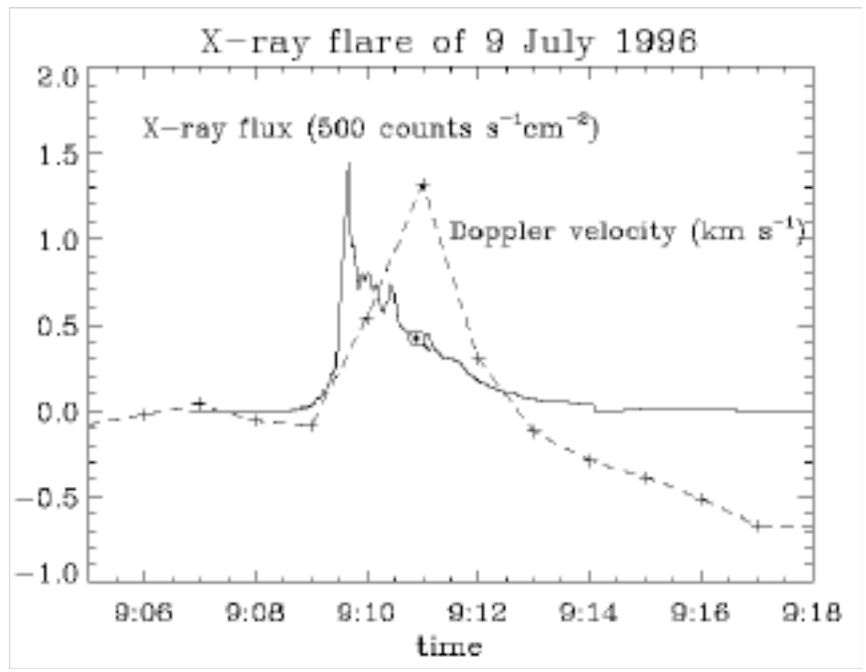
(ergs/cm/sec)

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

> 10 km/sec for > 10 minutes

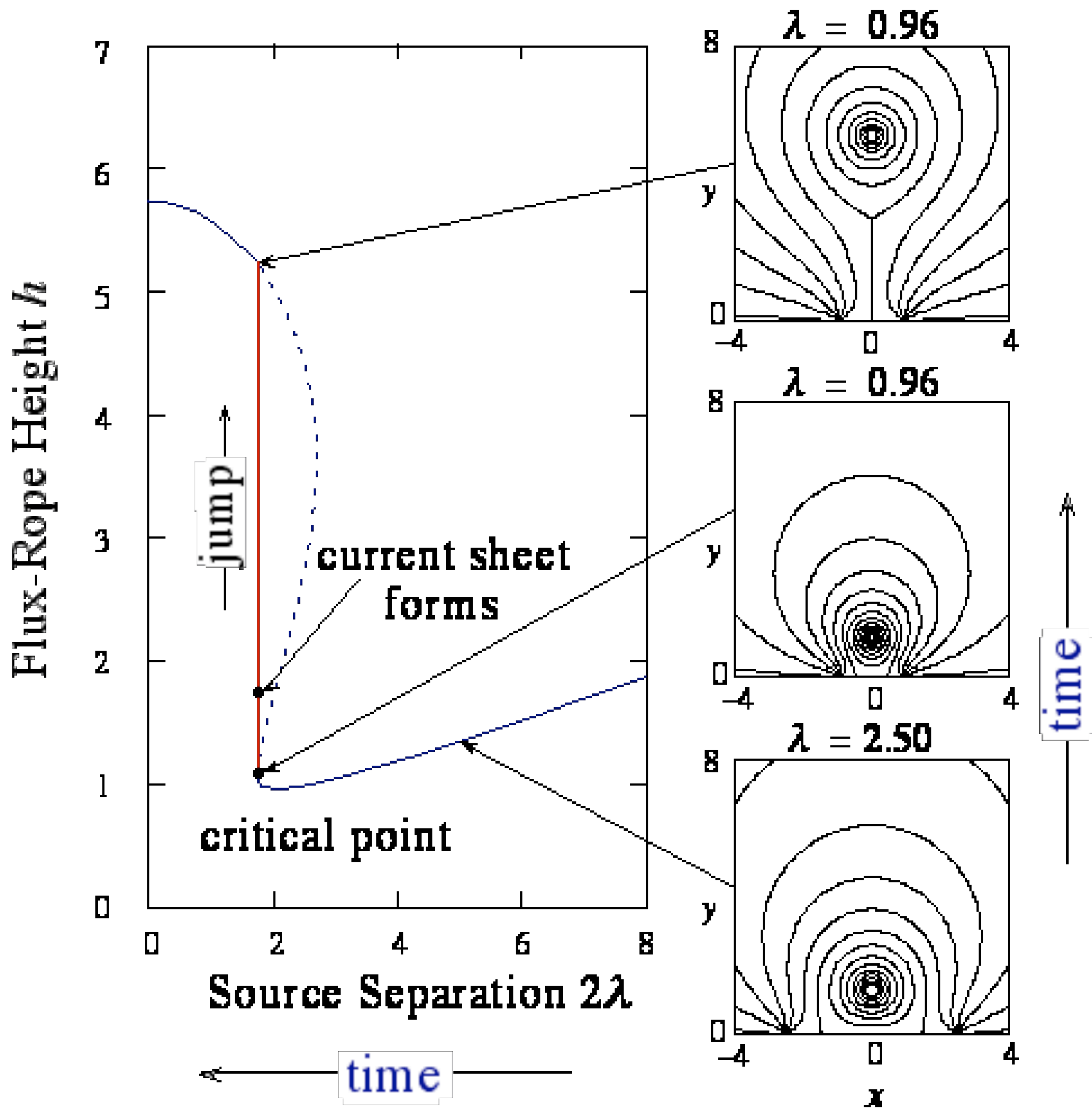
Kosovichev et al. 1998



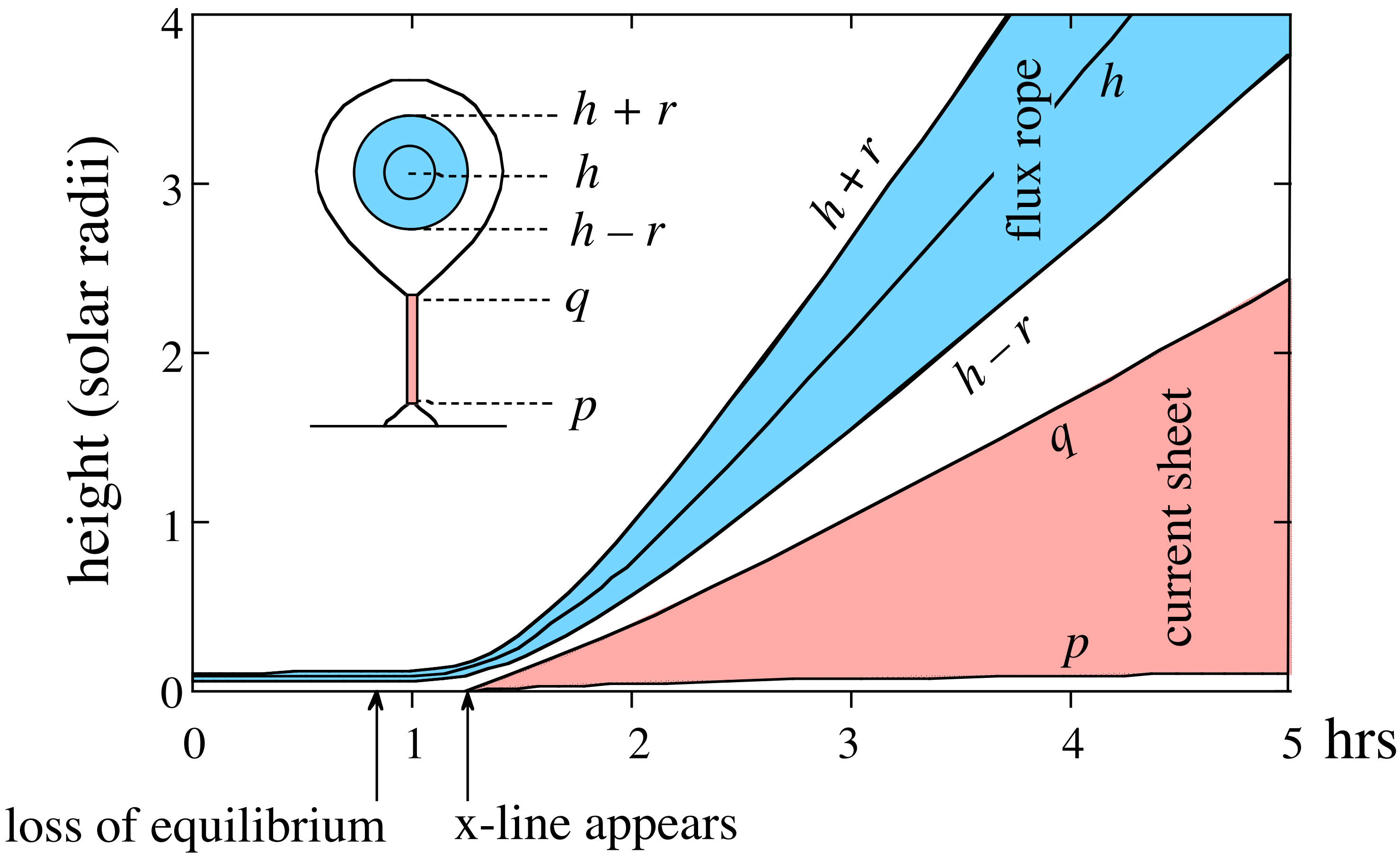


Injection models predict large surface flows which are never observed.

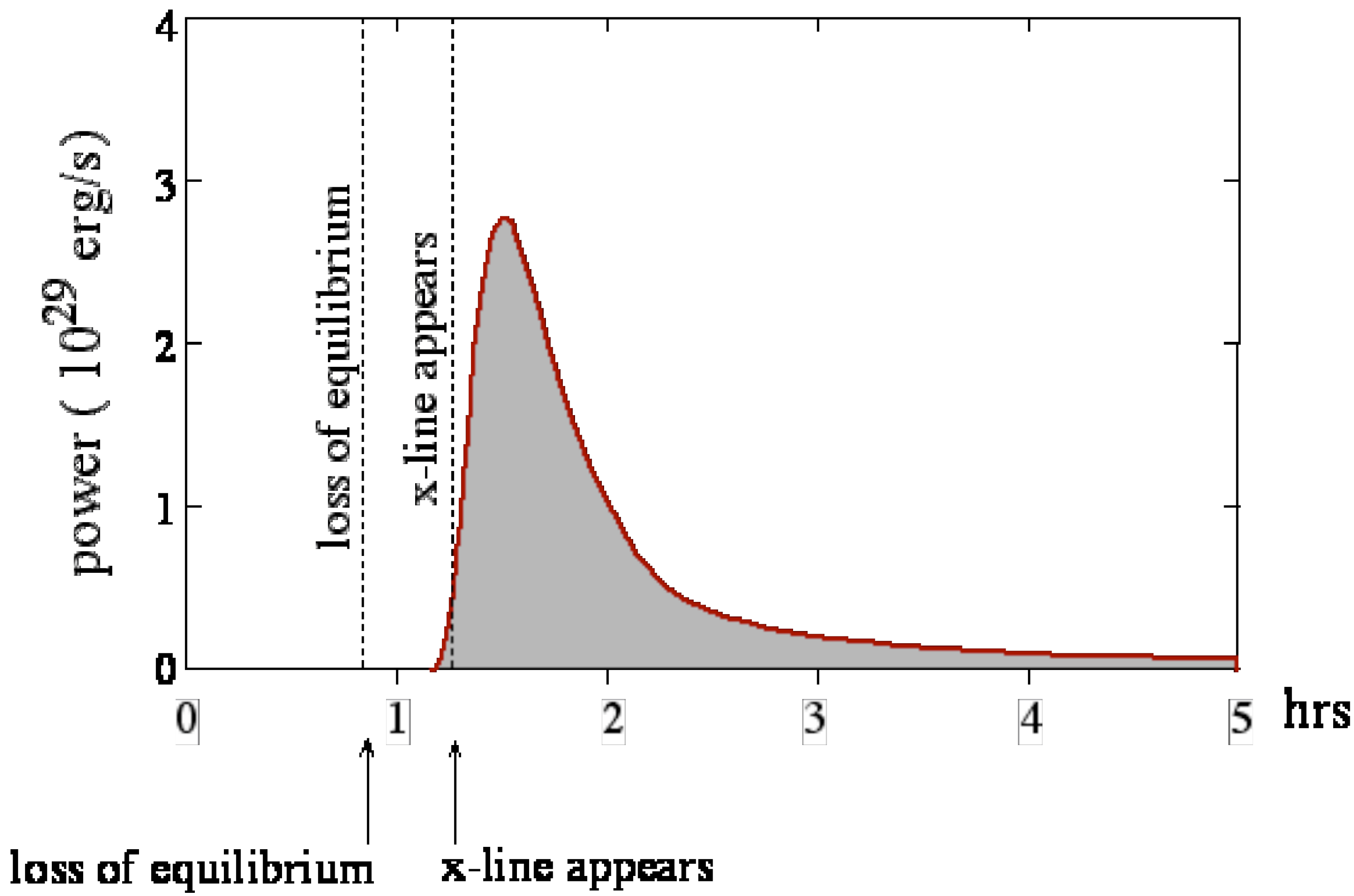
A Storage Model



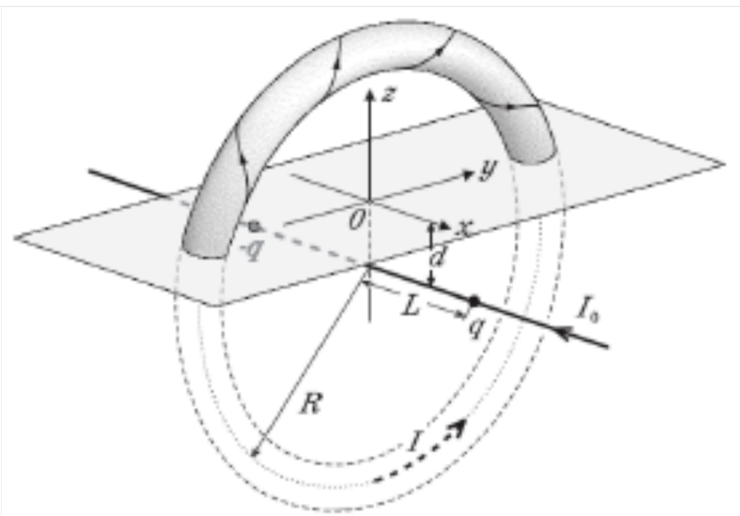
Trajectories



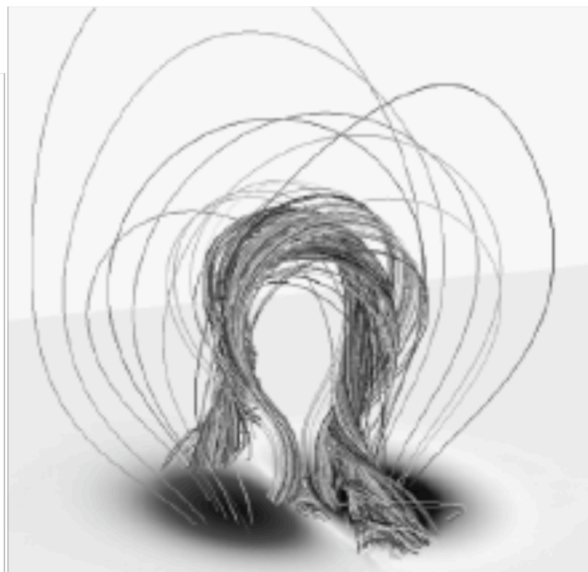
Power Output



Three-Dimensional Storage Models



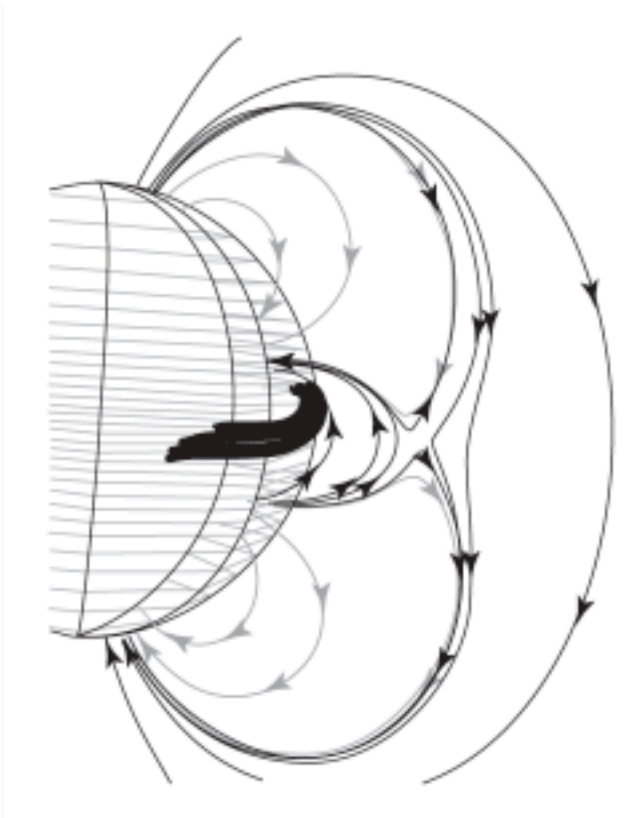
Titov & Démoulin 1999



Amari et al. 2000

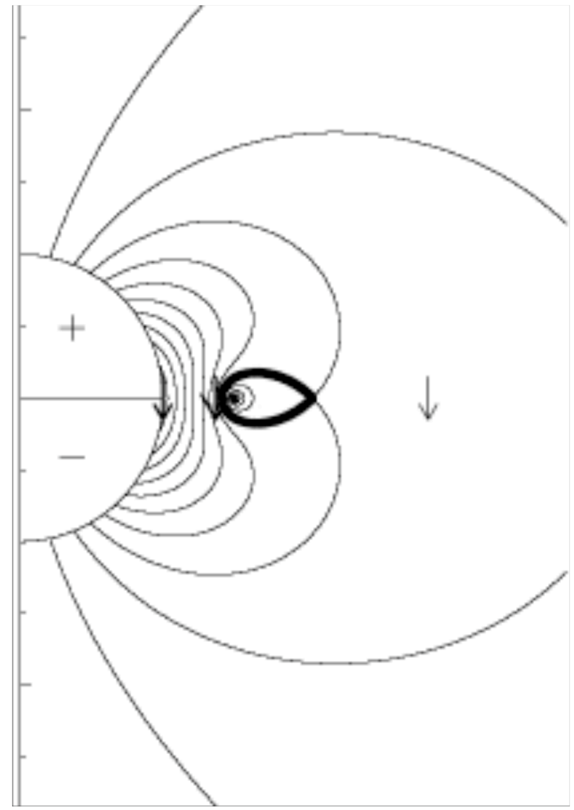
Sturrock et al 2001

Other Storage Models



breakout model

(Antiochos et al. 1999)



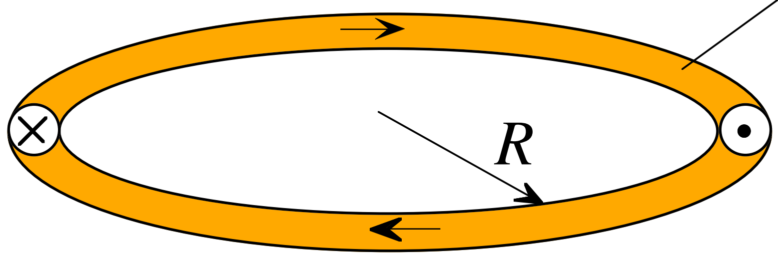
flux rope with normal polarity

(Low & Zhang 2002)

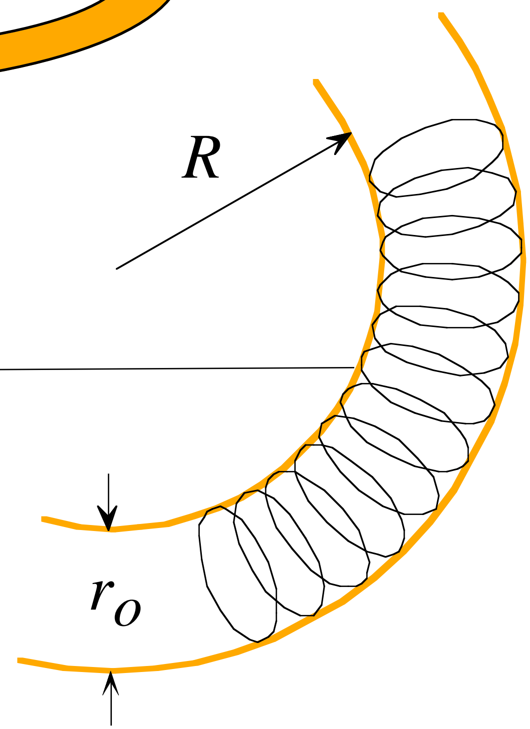
Basic Principles I

Driving Force:

ring with
current I



inner edge is pinched
by curvature of rope

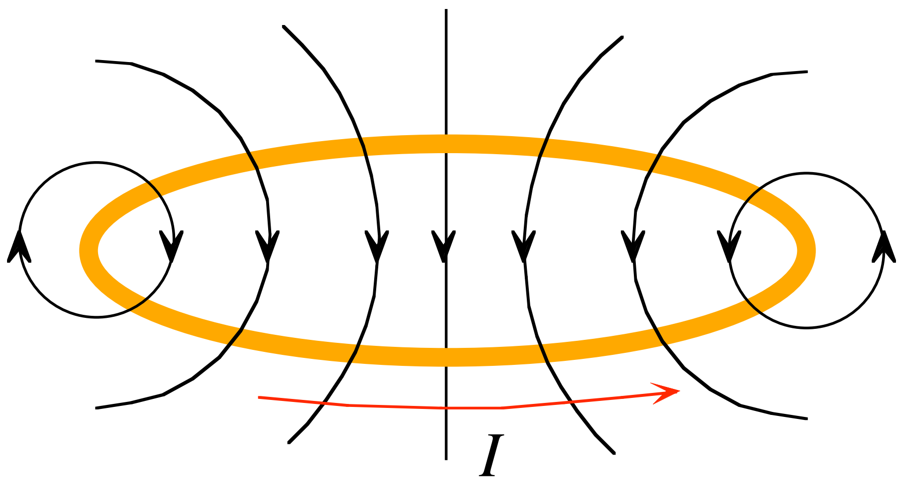


repulsive force:

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

Basic Principles II

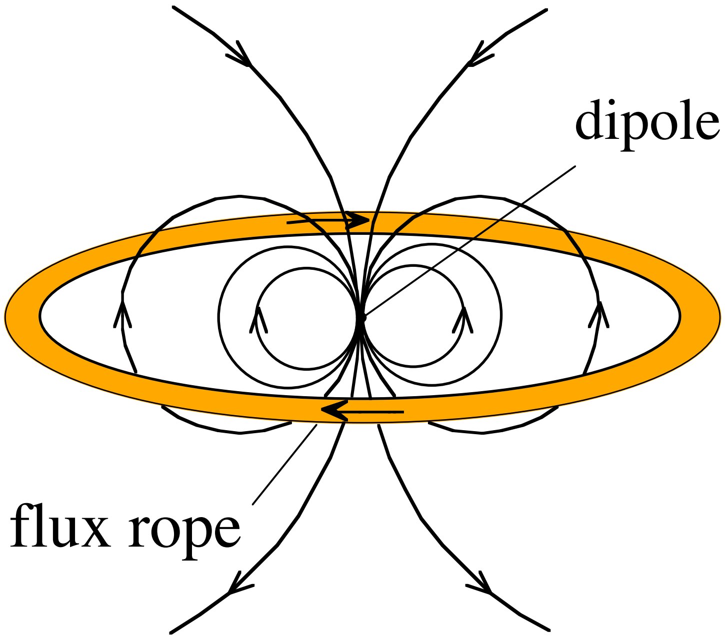
Flux Conservation:

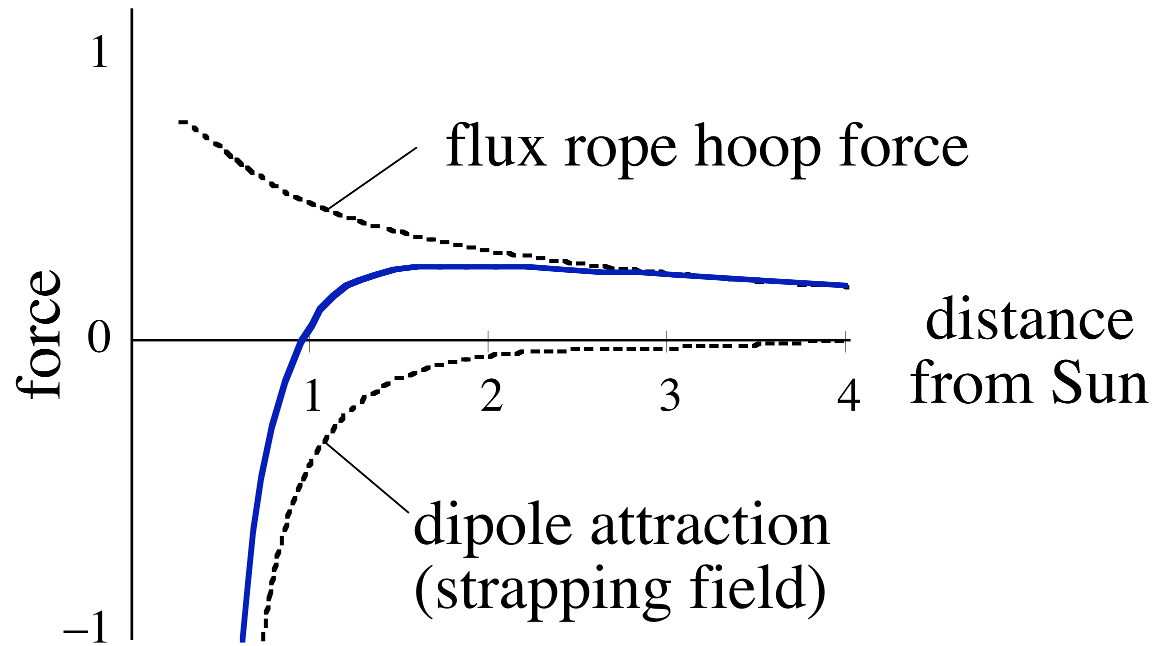


$$I \approx \frac{I_o}{\ln\,(R\,/\,r_o)}$$

(I_o is initial I)

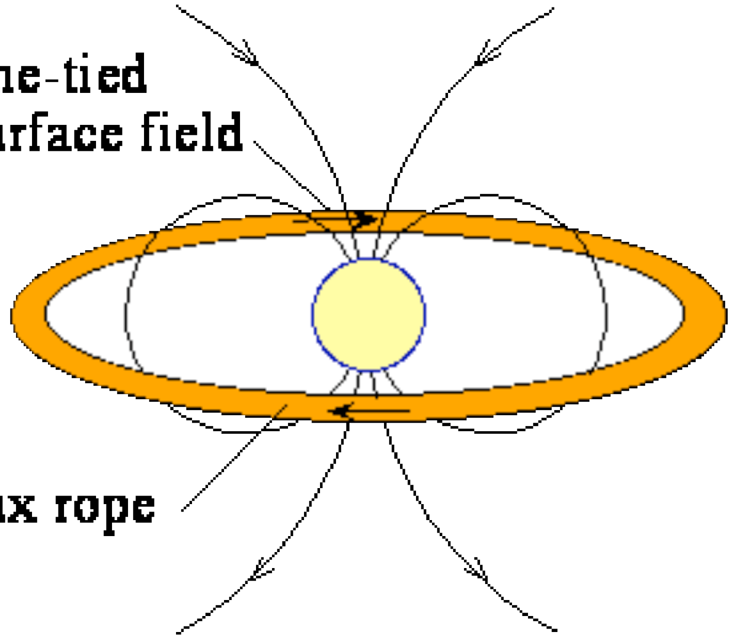
How to Achieve Equilibrium



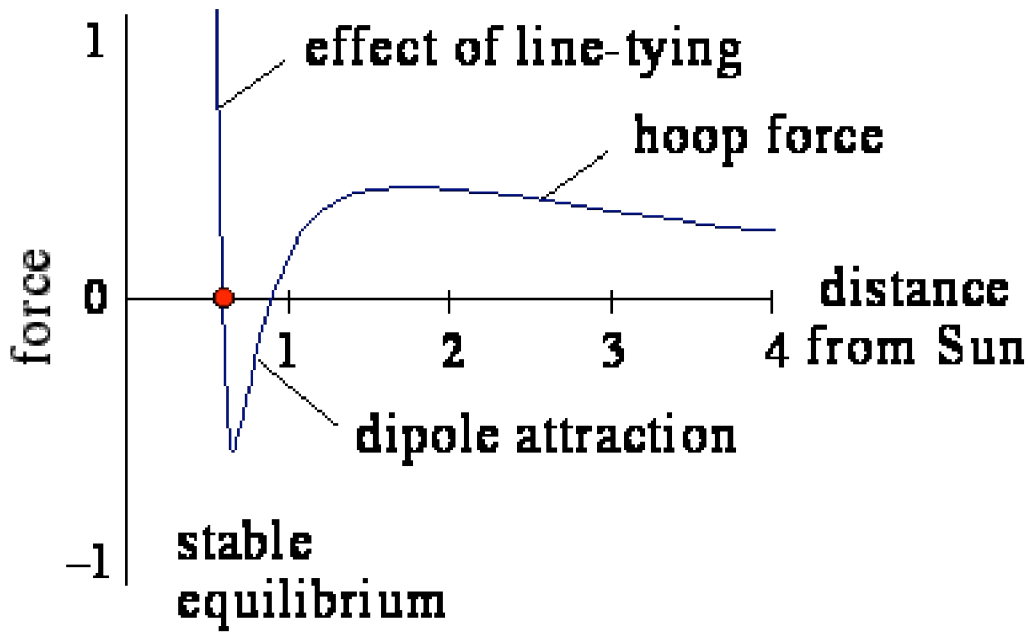


However, such an equilibrium is unstable!

How to Achieve a Stable Equilibrium

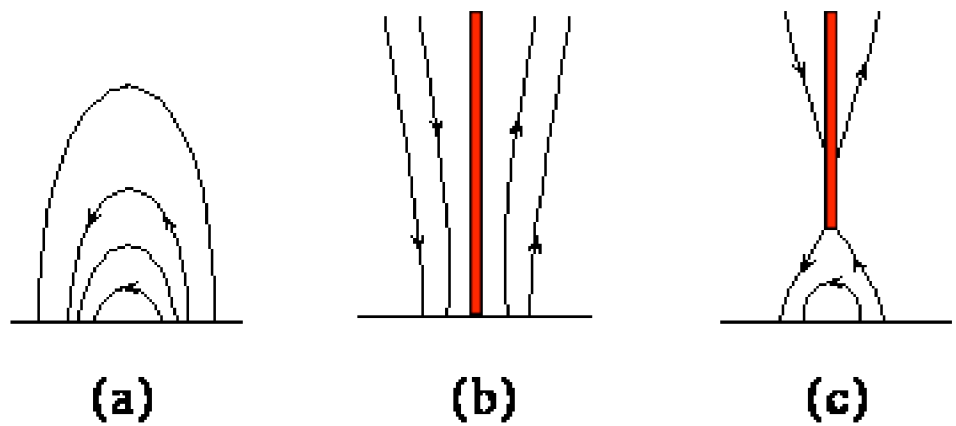


Key factor: Line-tying

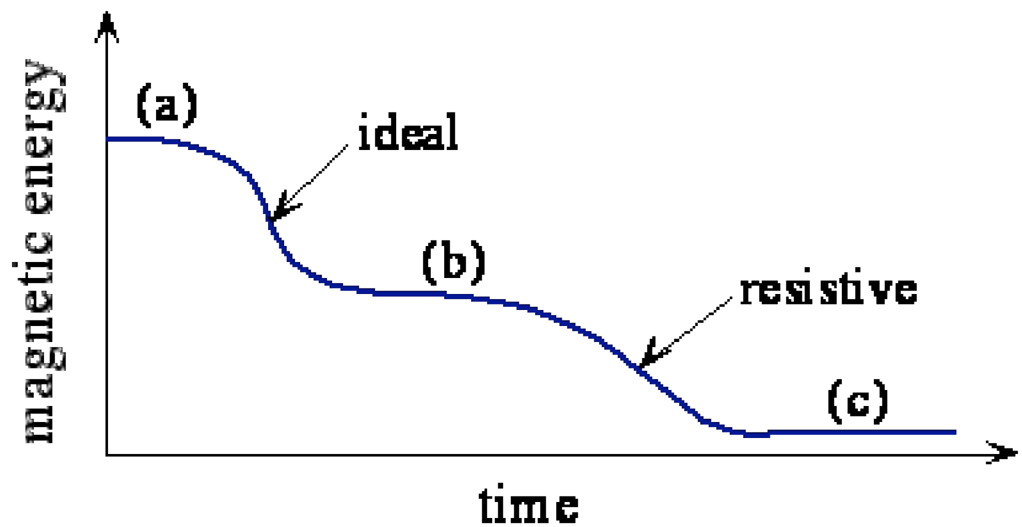


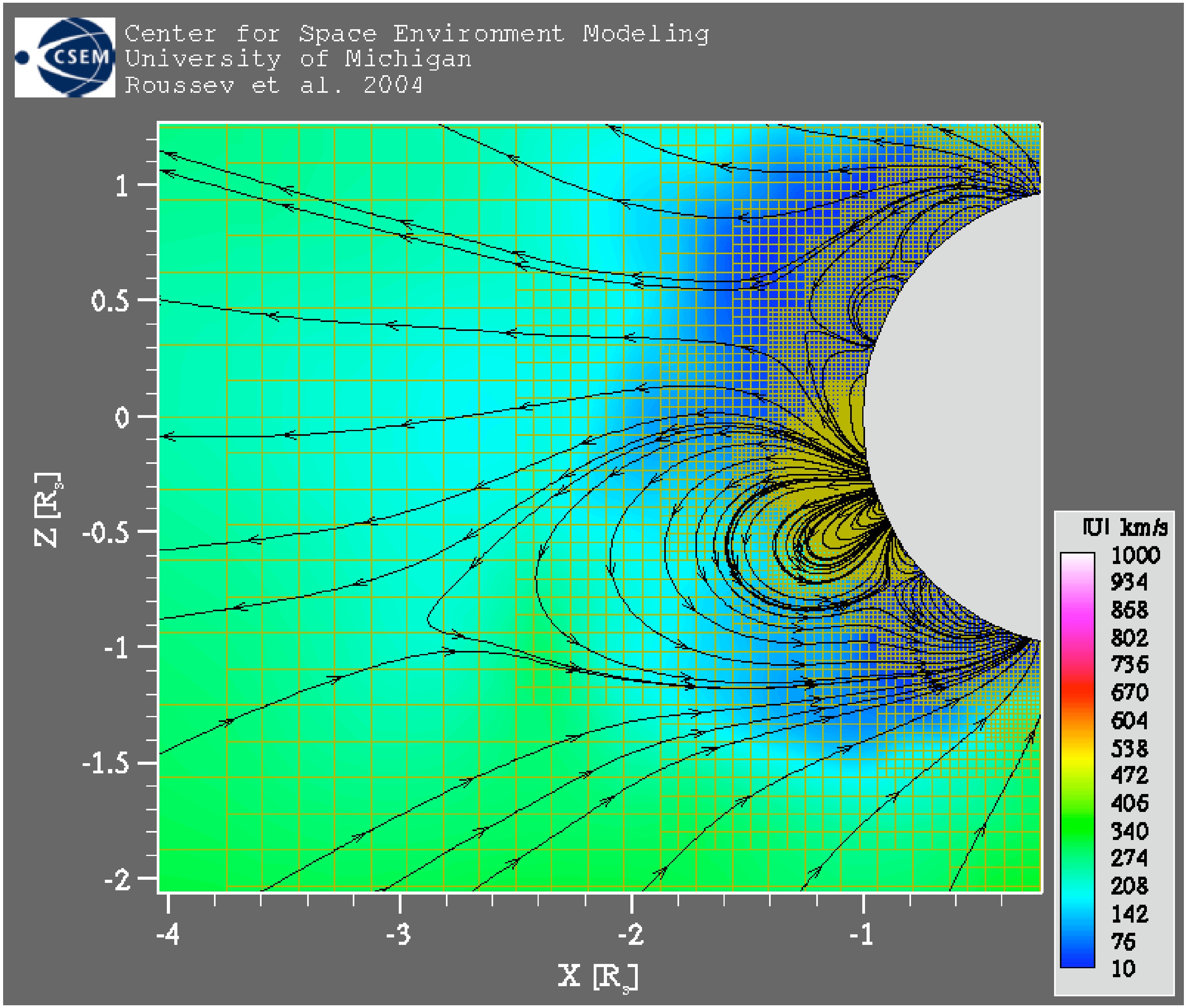
Line-tying creates a second, stable equilibrium

Aly - Sturrock Conjecture



impossible transition




Center for Space Environment Modeling
University of Michigan
Roussev et al. 2004
CSEM
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0.5
0
-0.5
-1
-1.5
-2
Z [Rs]
-4
-3
-2
-1
X [Rs]
|U| km/s
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802
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670
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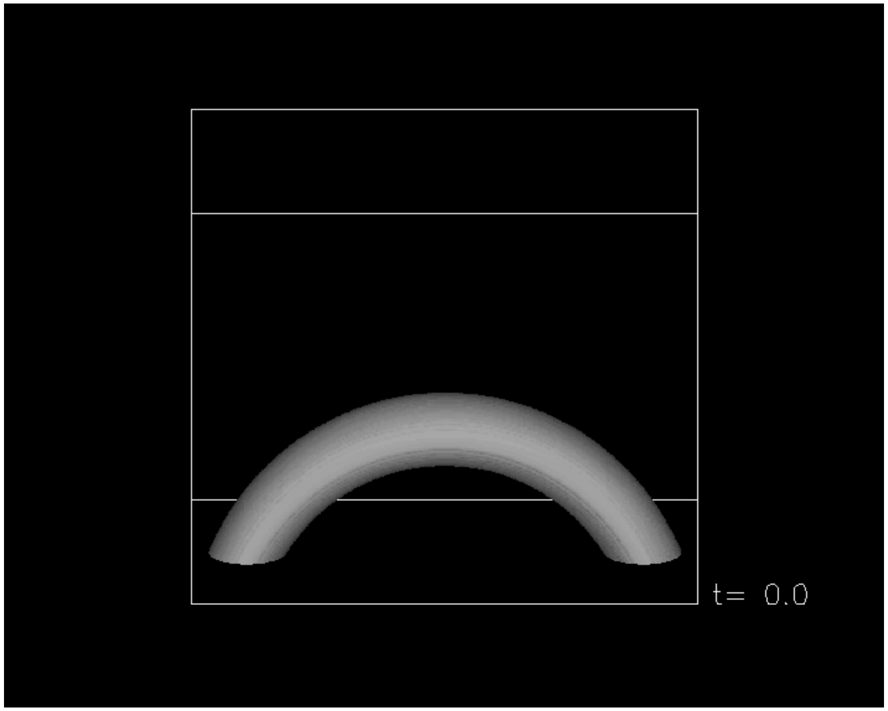
472
406
340
274
208
142
76
10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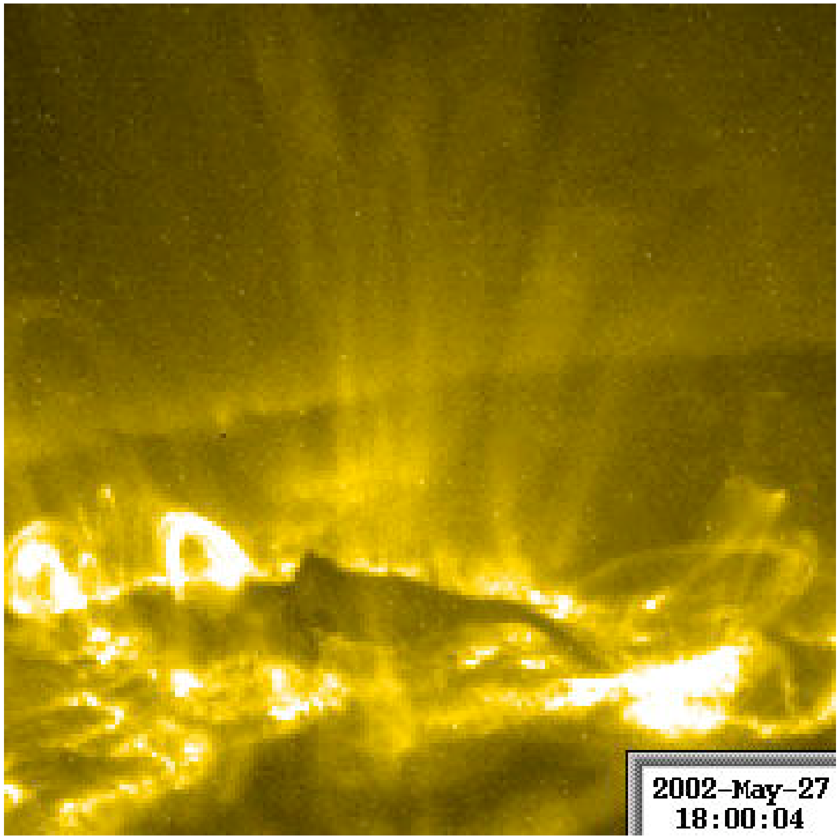
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Summary

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.