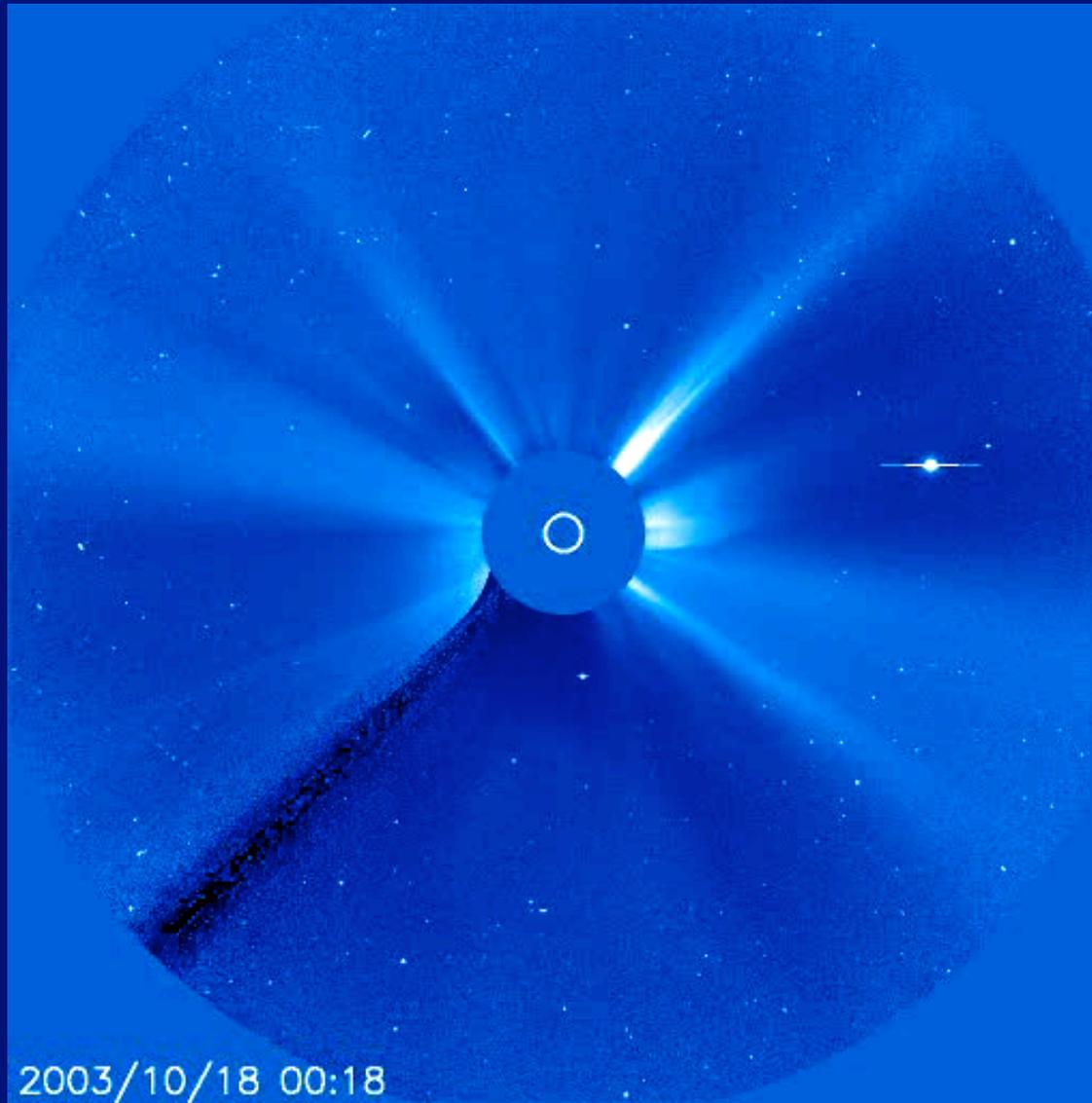


Origins of Solar Eruptions

Spiro K. Antiochos
Naval Research Laboratory

- Observations of CME/Filament Ejection/Eruptive Flare event
- Formation of Pre-Eruption State
 - Subsurface/surface evolution
- Mechanisms for initiation

CME Observations



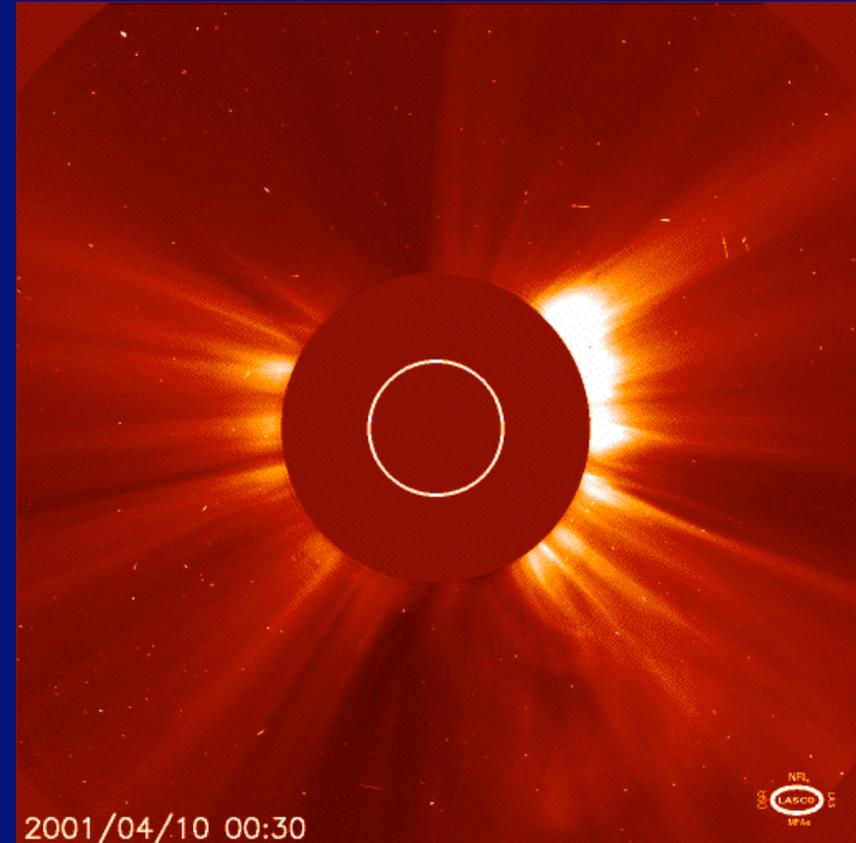
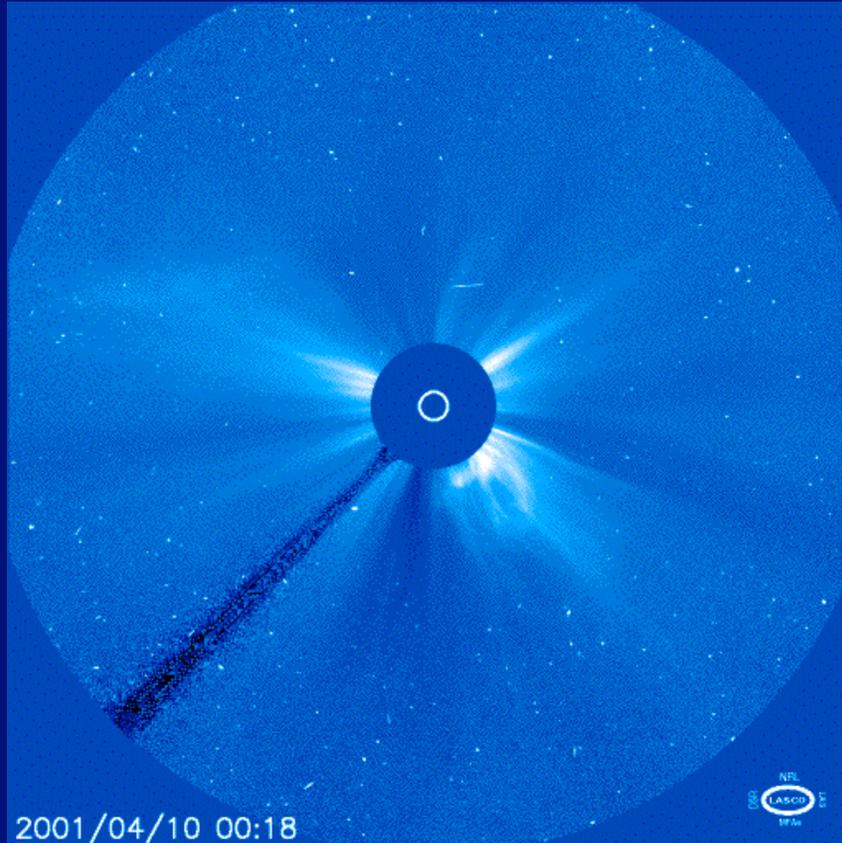
(NRL/NASA/ESA LASCO C3 Coronagraph on SOHO)

CME Observations

C2 1998/06/02 00:28:11

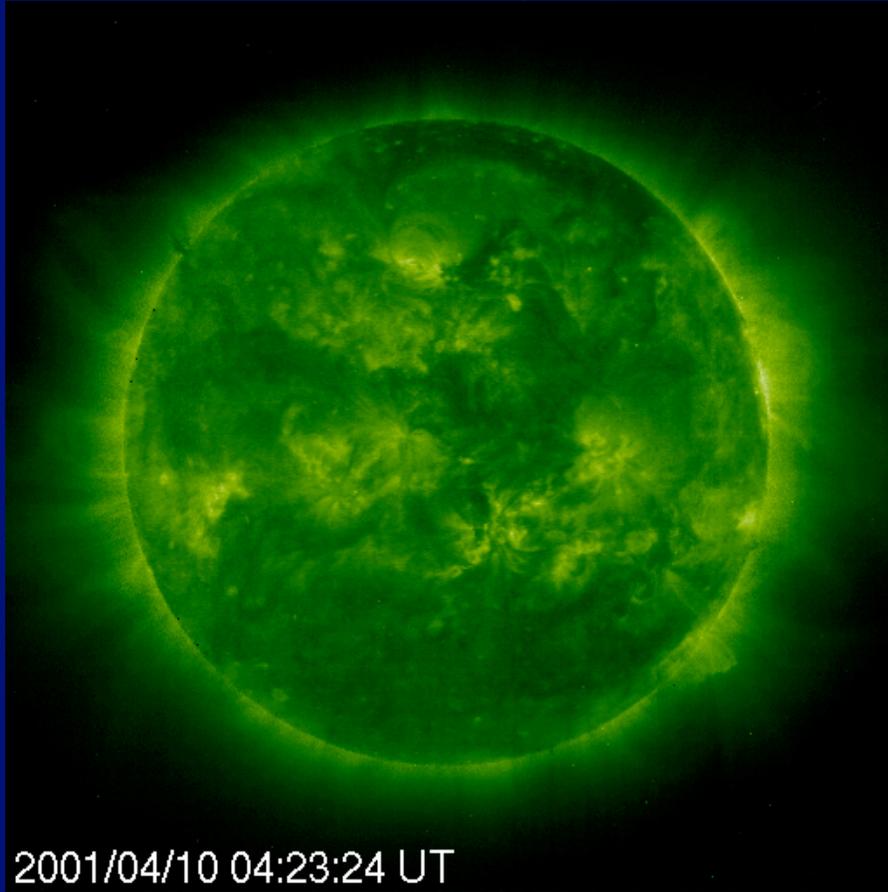
- Structure must be due to magnetic field

CME Observations



- $V \sim 1,000$ km/s, angular extent $\sim 90^\circ$
- $M \sim 10^{16}$ gm ~ 10 billion tons
- Coronal plus dense filament plasma

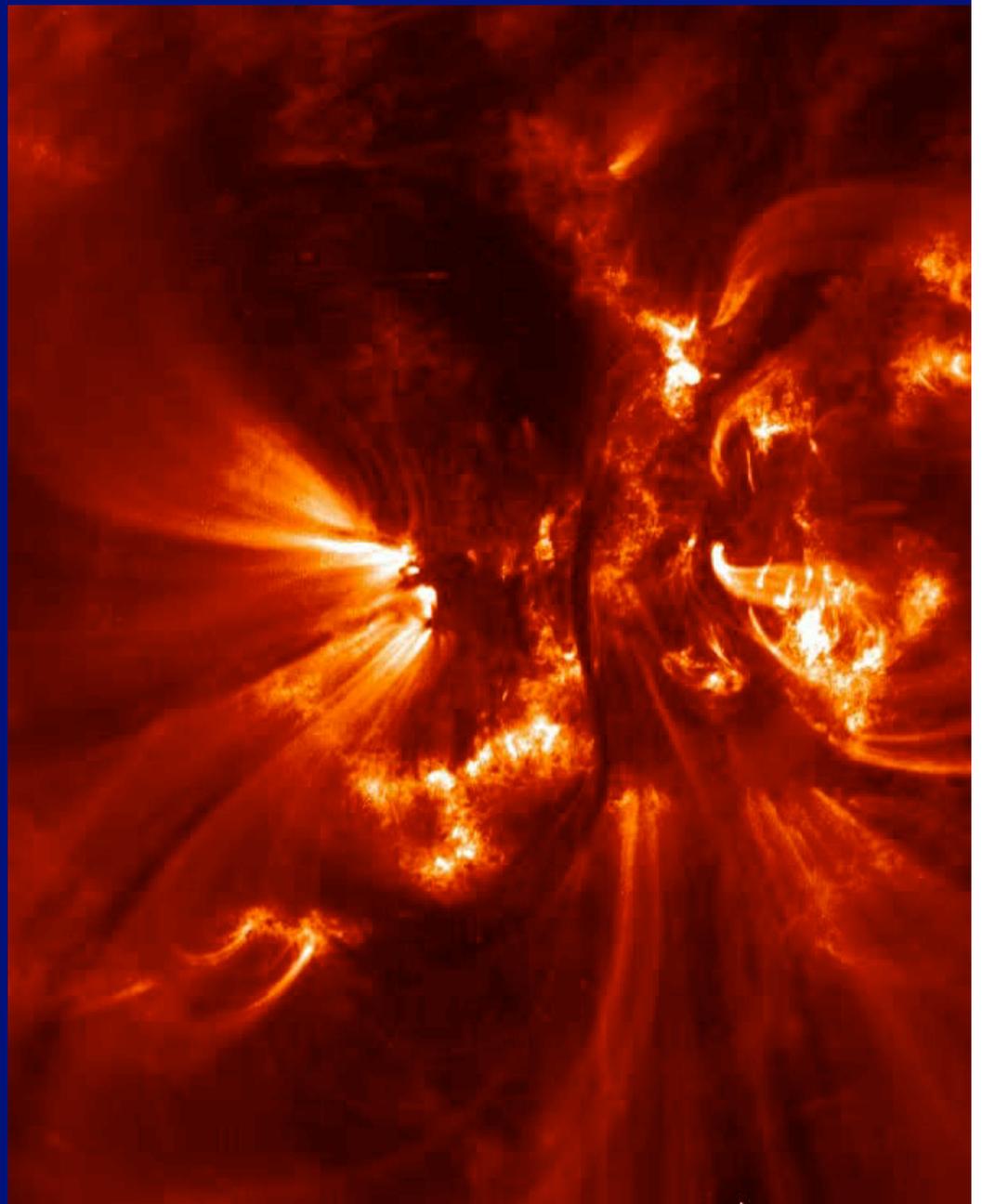
CME Observations



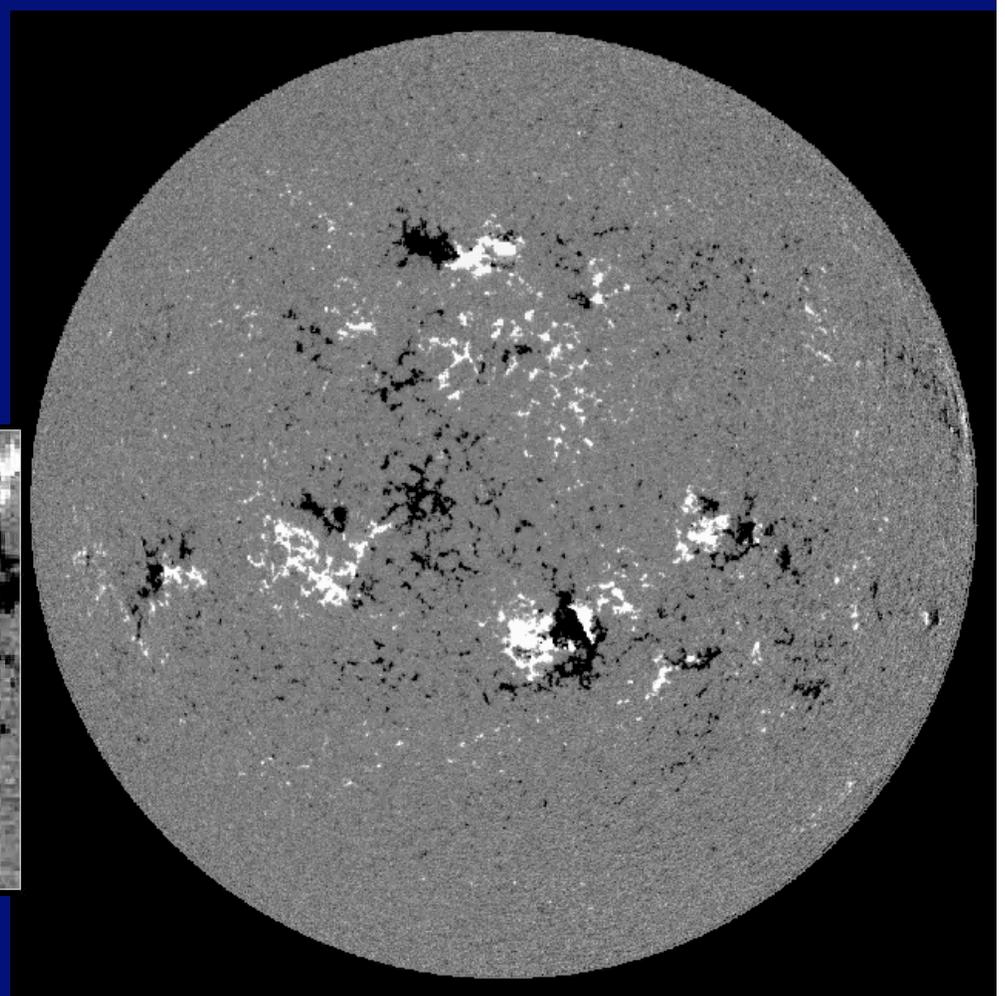
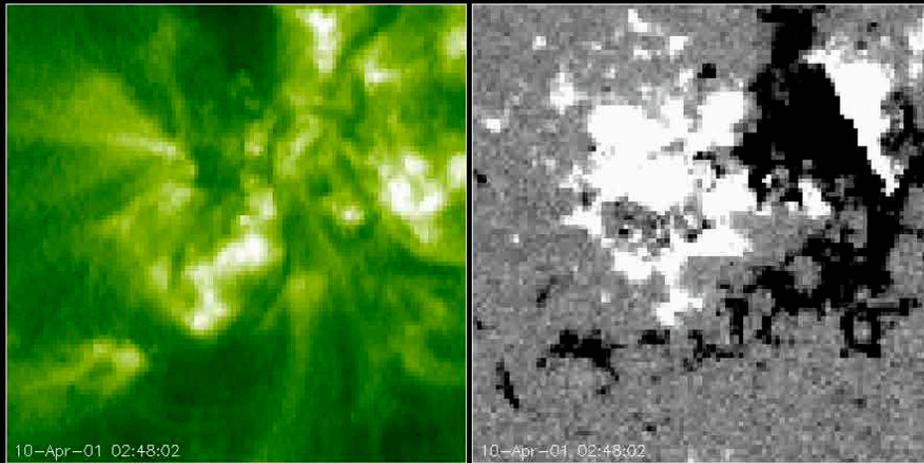
- Components of event:
 - CME observed as coronal dimming
 - Filament/prominence ejection
 - Flare

CME Observations

- Filament: long, narrow, cool
- Relation to rest of corona not clearly observed
- Flare loops perpendicular to filament
- Filament field strongly non-potential (large free energy), only place in corona where field has high stress!
- Filament rises before onset of flare heating
- Timing wrt CME onset not clear

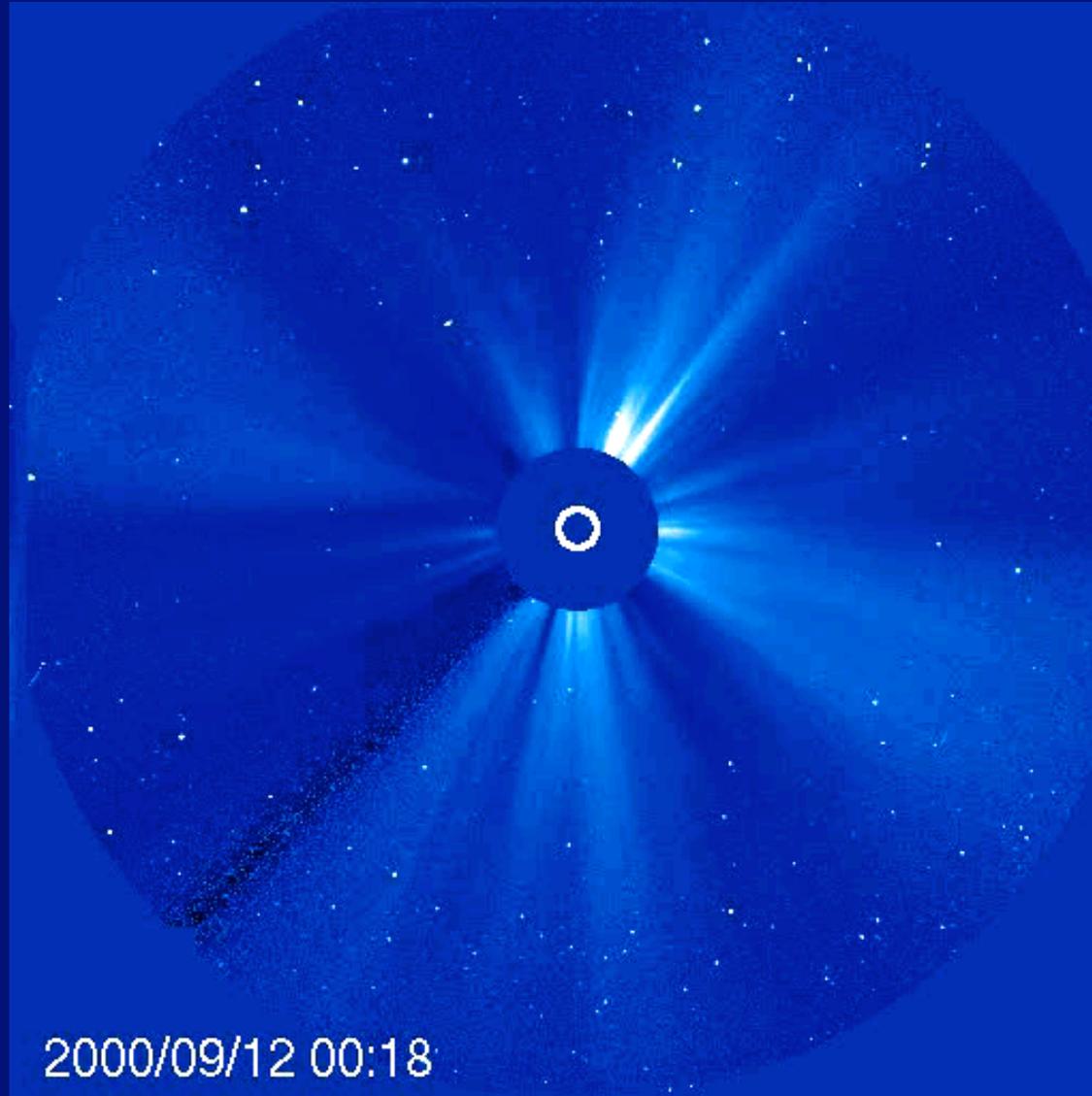


CME Observations



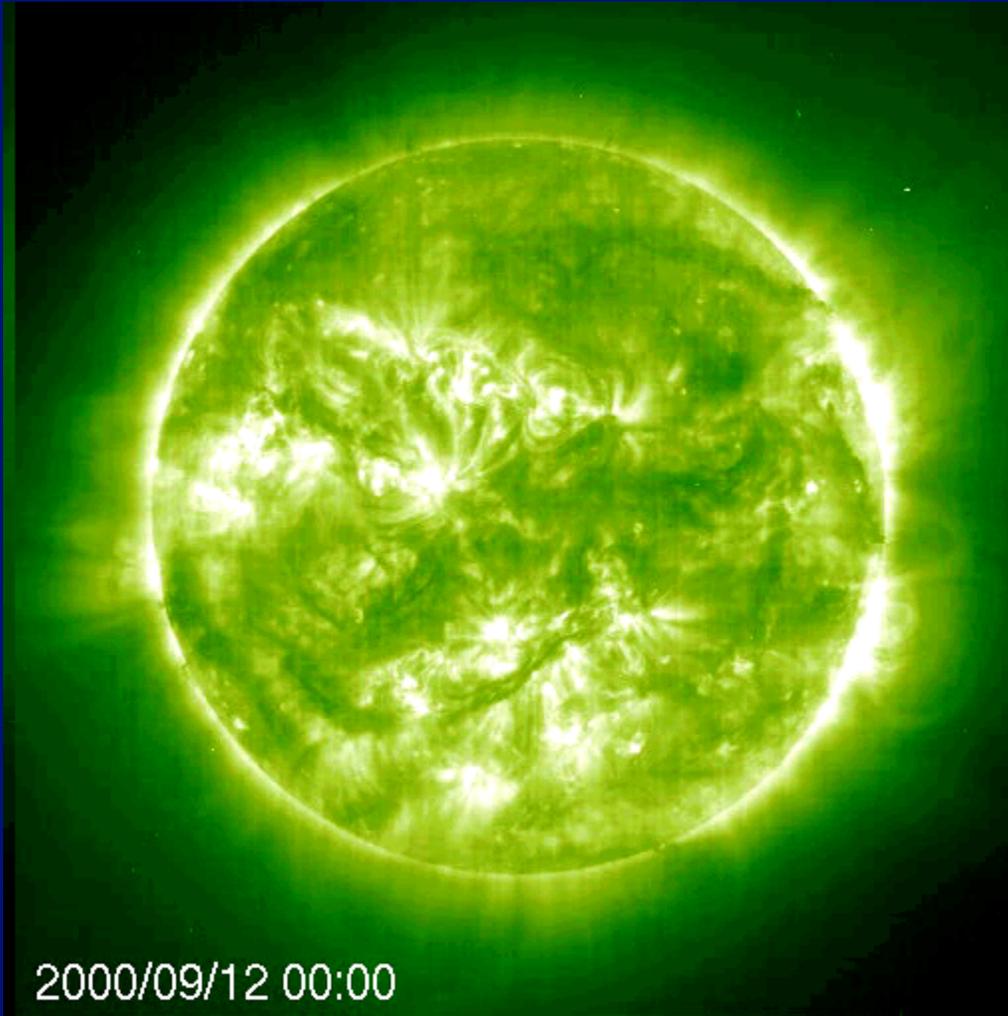
- Filament overlies polarity inversion line (PIL) – low lying
- Photospheric B-field does not evolve during eruption
- Energy buildup slow compared to eruption – 1 km/s

09/12/00 LASCO Observations: 5 - 30 R_☉



- Slower, non-active region, halo CME

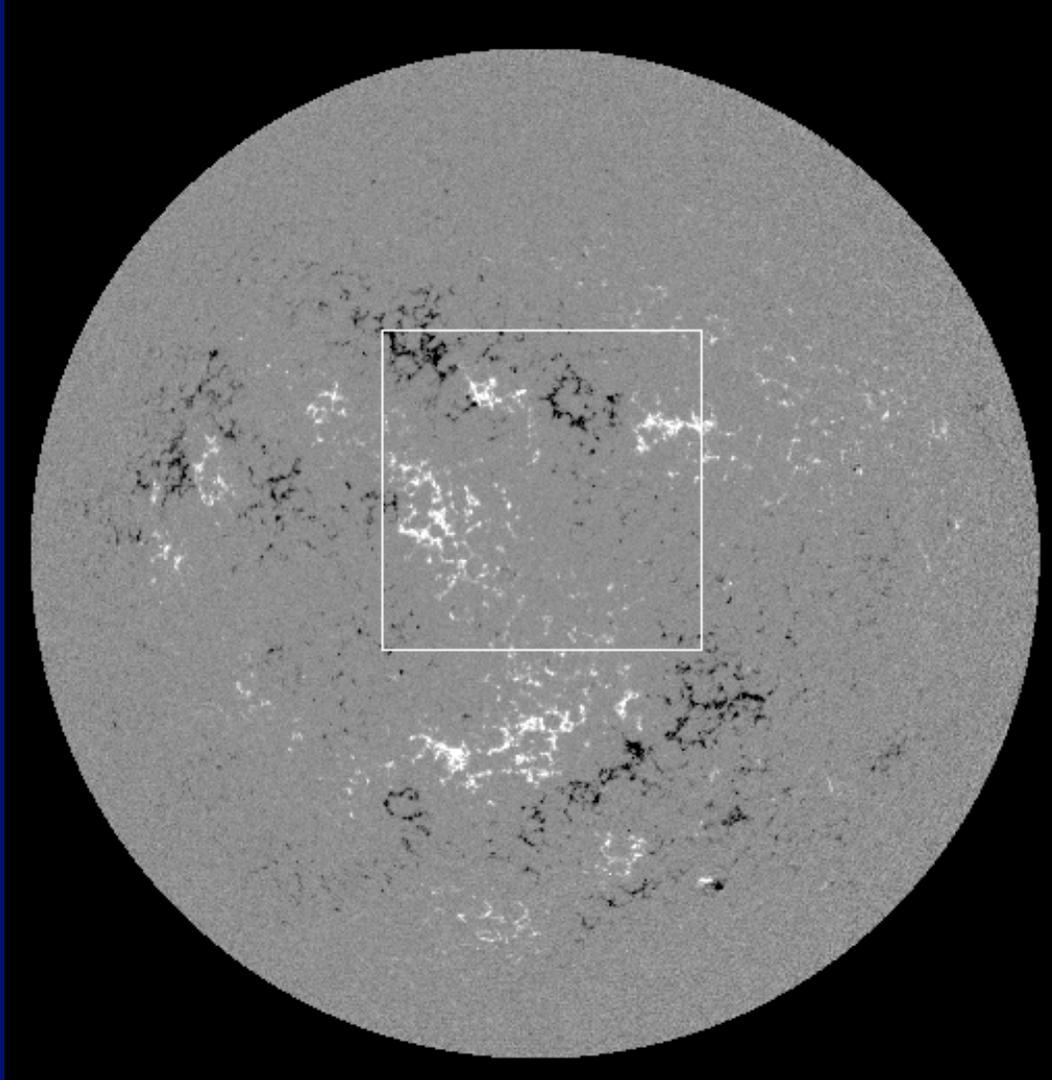
09/12/00 EIT Observations



- Ejection of filament followed by flare

O9/12/00 MDI Observations

SOHO/MDI Magnetogram
12-Sep-2000 05:30



Observational Numbers

- Energy must be stored in corona
 - $E \sim 10^{32}$ ergs, $\tau \sim 10^3$ s, Power $\sim 10^{29}$ ergs/s
 - $L \sim 10^{10}$ cm, $W \sim 10^9$ cm, $\Rightarrow F \sim 10^{10}$ ergs/cm²/s
 - Poynting flux $\sim E_B V$, if $B \sim 10^3$ G, $\Rightarrow V \sim 10^{.5}$ km/s -- easily seen
 - note that $F \sim 10^3$ active region heating -- also much larger than chromospheric heating
 - if twist filament ends only, require all solar luminosity
- Plasma plays negligible role in energetics
 - *active region*: $T \sim 10^{6.5}$ K, $N \sim 10^{10.5}$ /cm³, $E_G \sim 10$ ergs/cm³
 - $B \sim 10^{2.5}$ G, $E_B \sim 10^{3.5}$ ergs/cm³
 - also gravitational potential energy, $M g_{\text{sun}} H \sim E_G \ll E_B$

Observational Numbers

- Energies
 - Three flux systems -- filament, active region, quiet background
 - For bipolar field, $B \sim r^{-3}$, $E_B \sim r^{-6}$
 - *filament*: $L \sim 10^{10}$, $W \sim 10^9$, $H \sim 10^9$, $B \sim 10^3$, $\Rightarrow E_B \sim 10^{32.5}$
 - *act. reg.*: $L \sim 10^{10}$, $W \sim 10^{10}$, $H \sim 10^9$, $B \sim 10^3$, $\Rightarrow E_B \sim 10^{33.5}$
 - *quiet*: $L \sim 10^{11}$, $W \sim 10^{11}$, $H \sim 10^{10}$, $B \sim 10^1$, $\Rightarrow E_B \sim 10^{32.5}$
 - *quies. fil.*: $L \sim 10^{11}$, $W \sim 10^9$, $H \sim 10^{10}$, $B \sim 10^1$, $\Rightarrow E_B \sim 10^{30.5}$
 - AR filament channel has sufficient energy for fast eruption
 - Can open background field, but only small fraction of overlying active region field
 - Flux however must be due to background field

Conclusions

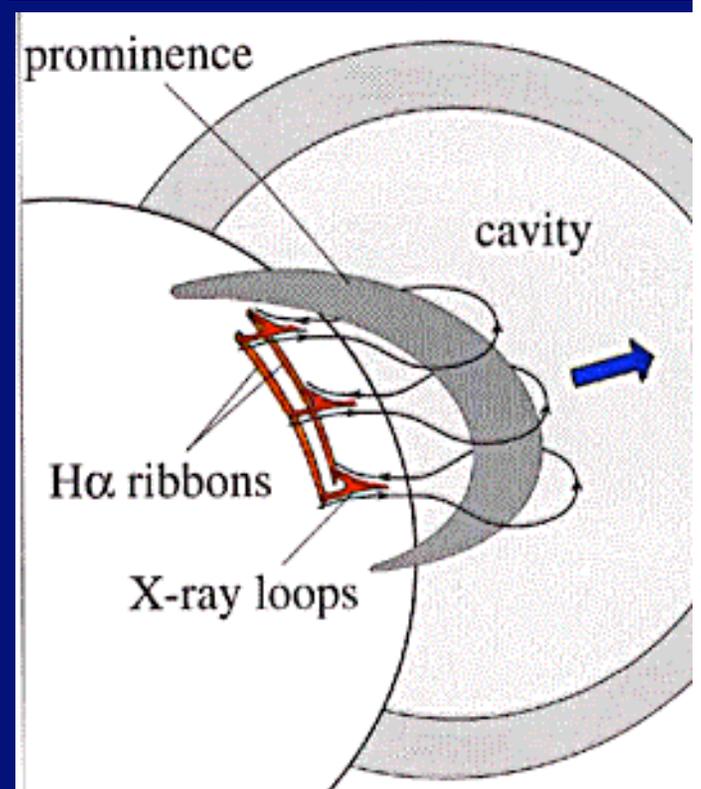
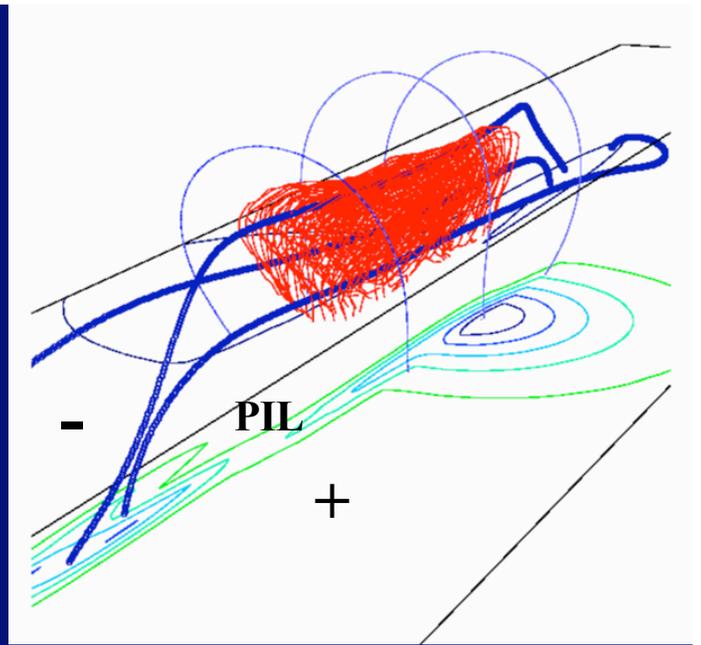
- Energy stored in strongly non-potential field of filament channel
- Held down by approximately-potential overlying coronal field
- Provides pre-eruption force balance

(Antiochos et al.)

- Force balance breaks down and field expands outward explosively
- Field reconnects below eruption to a potential state yielding flare

- How do filament channels form and what is their structure?
- How do they disrupt?

(T. Forbes, UNH)



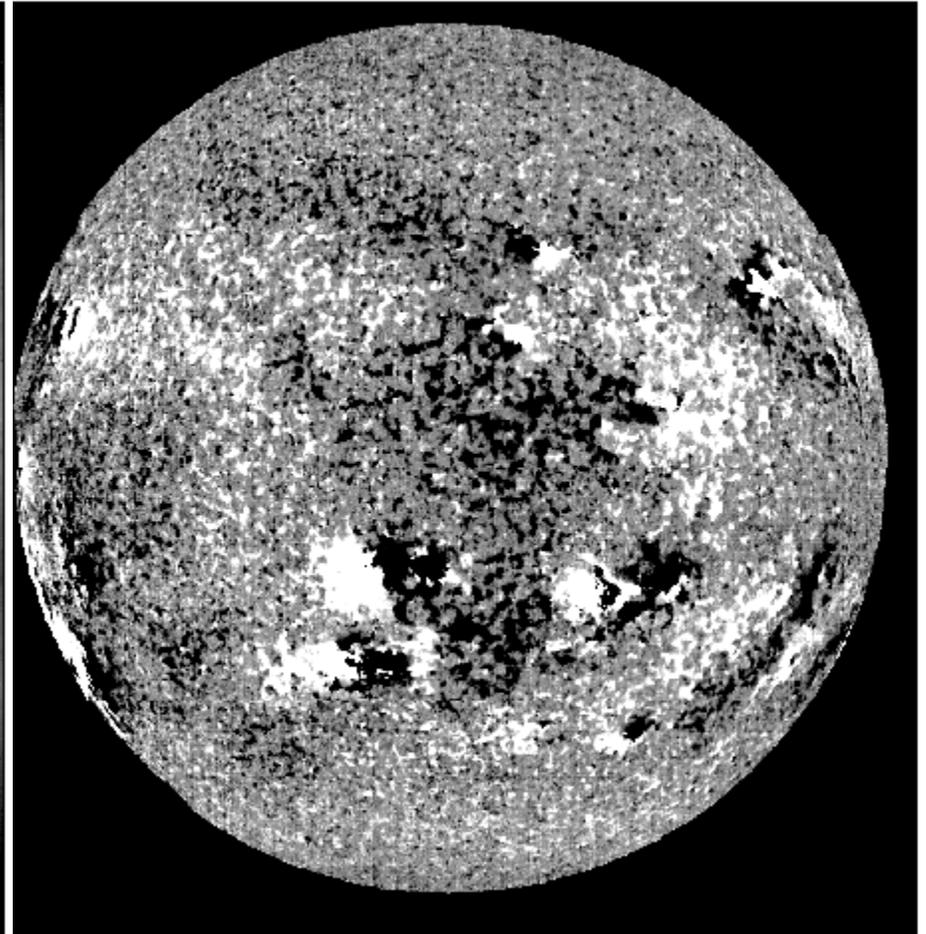
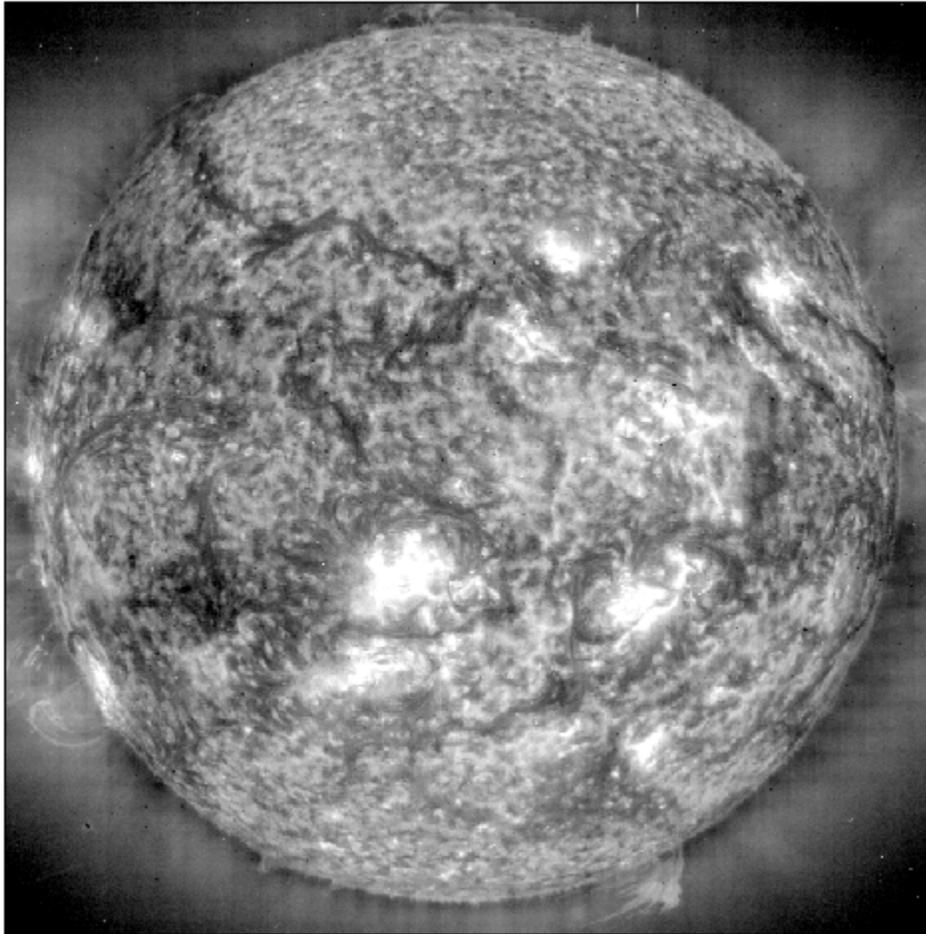
Filament Observations

10/02/00 observations by EIT/SOHO and Kitt Peak

He II 304

8688 Å

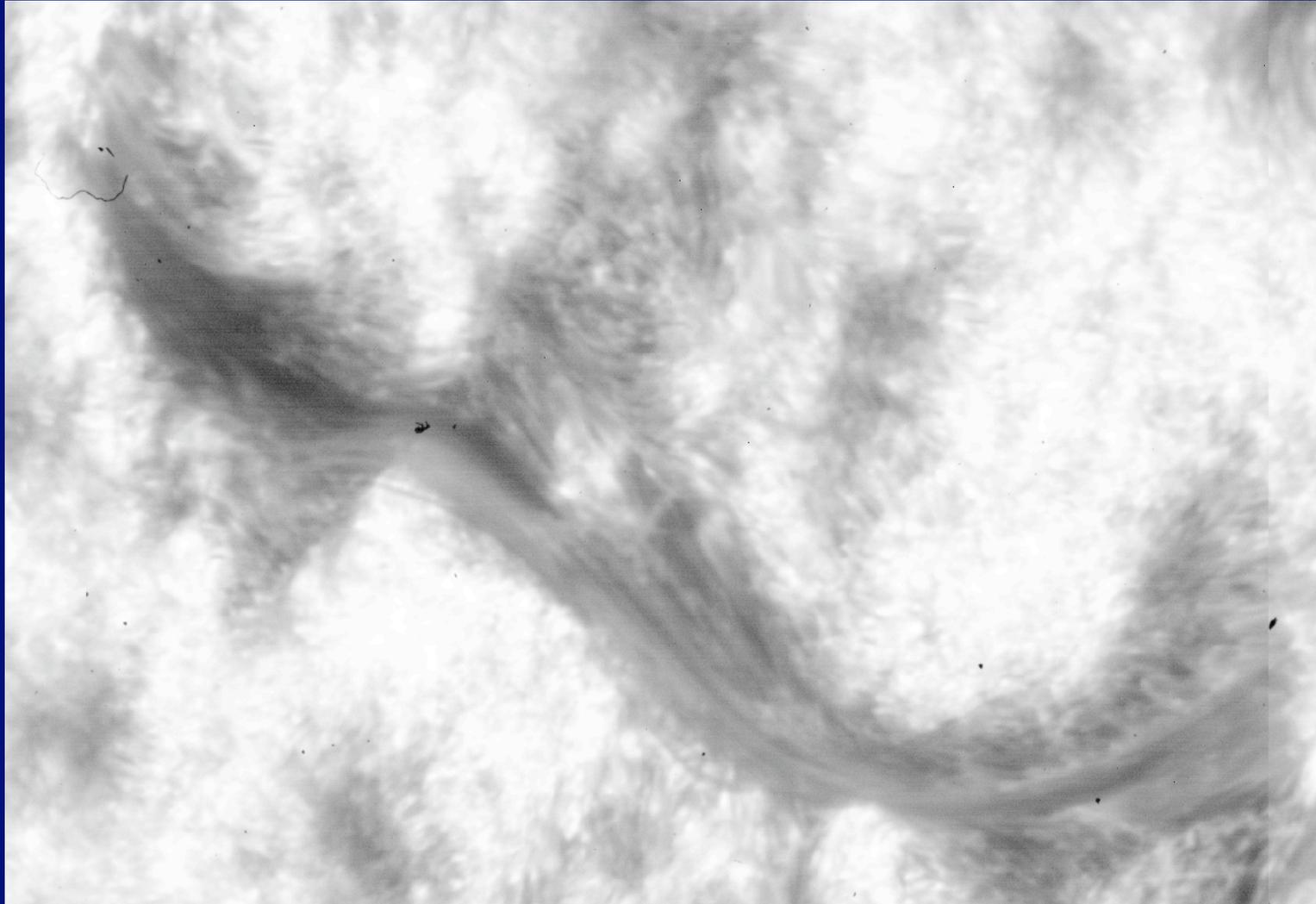
19:19



- Always lie above photospheric polarity inversion line
- Fairly common, ~ 30 % coverage, both active & quiet

Filament Observations

NRL VAULT image of 06/16/02, 20K material, spatial resolution < 200 km

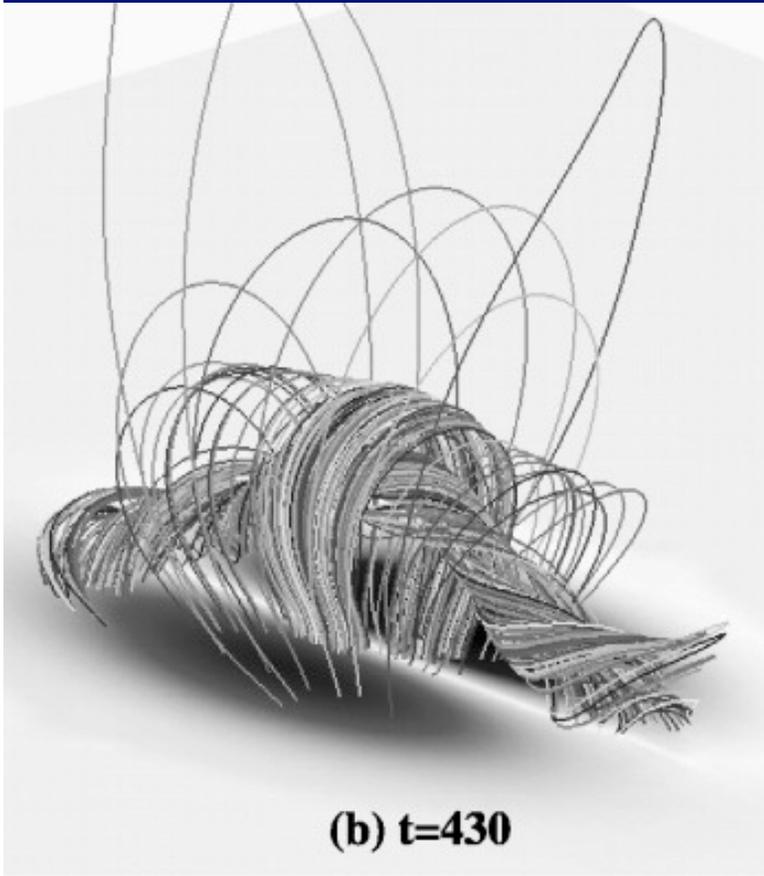


- Little evidence for twist in structures or motions before eruption

Models for Filament Structure

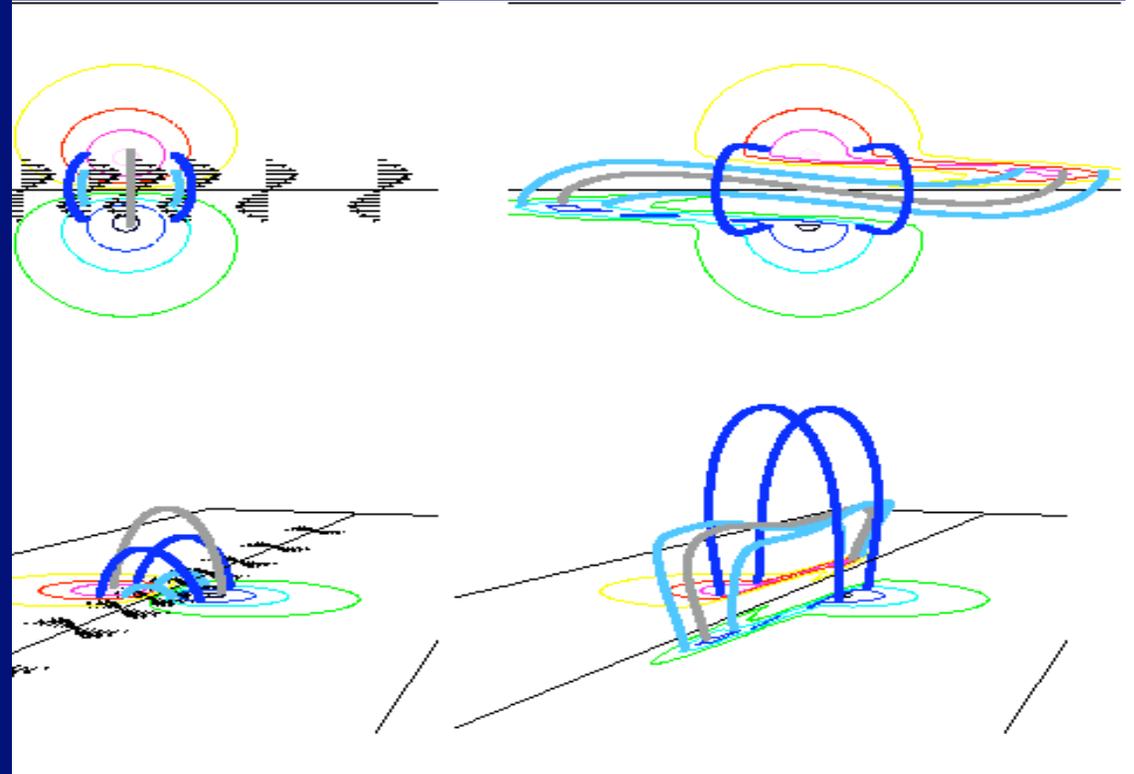
- **Twisted flux rope**
 - Can naturally support cool material in field line dips
 - Originally proposed (Kuperus-Radu) to account for observation of inverse polarity
 - Motivated by three-part structure, helmet-streamer & cavity
 - Twist appears to be present in erupting structures
- **Sheared 3D arcade**
 - Simplest possible structure that can support cool material
 - Also agrees with observation of inverse polarity

Models for Filament Structure



Amari et al
Twisted Flux Rope

- Need better observations (in corona!) to determine which, if either, is correct – SOLIS, ATST?

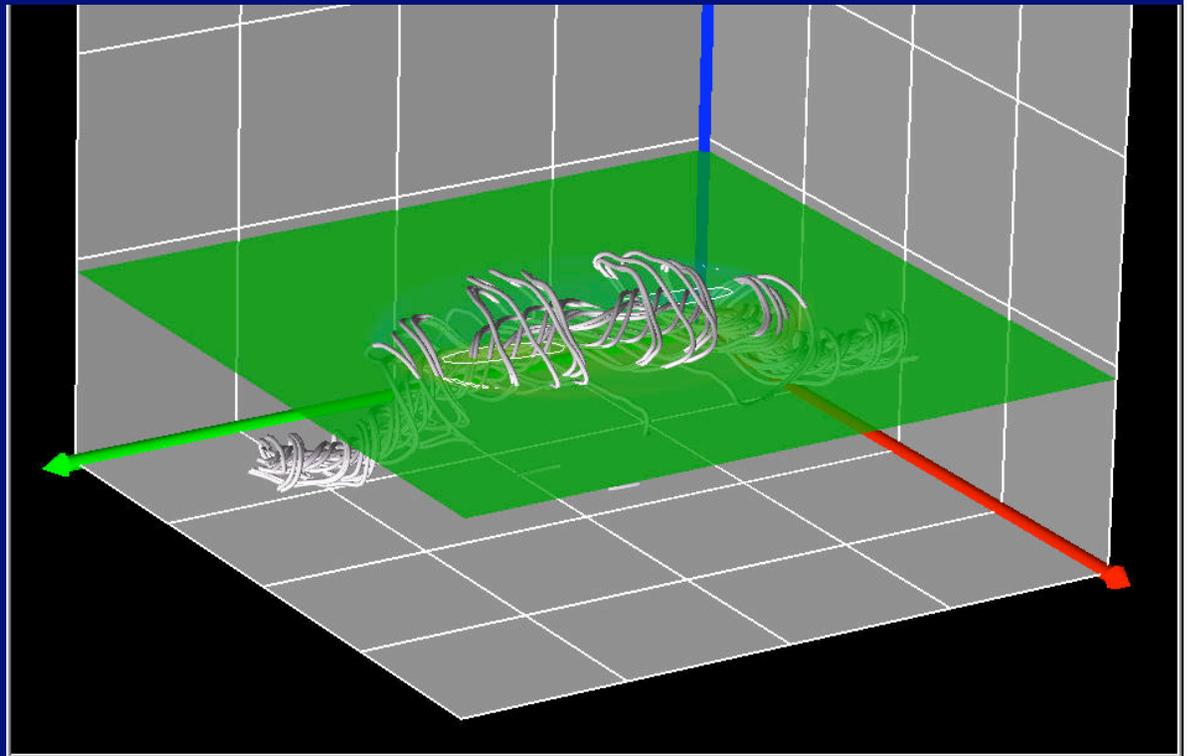
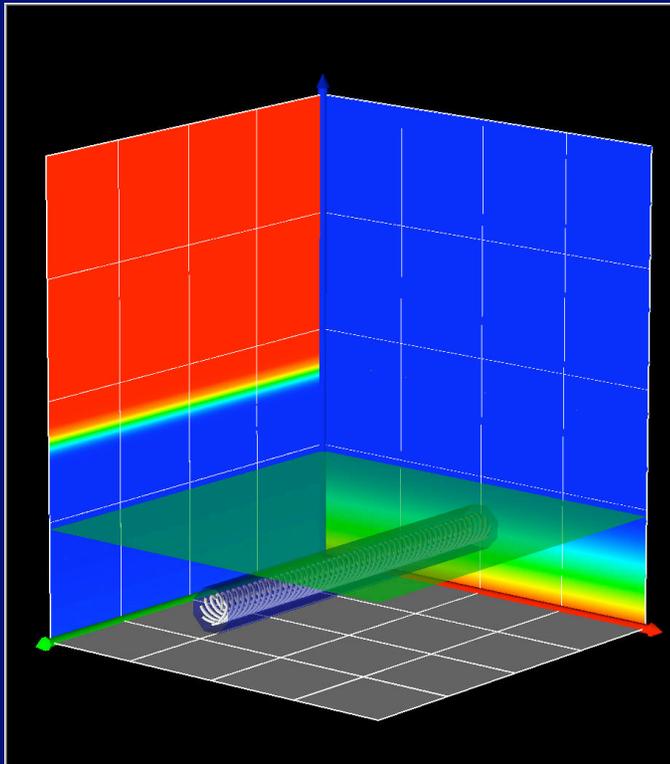


Antiochos et al
Sheared 3D Arcade

Models for Filament Formation

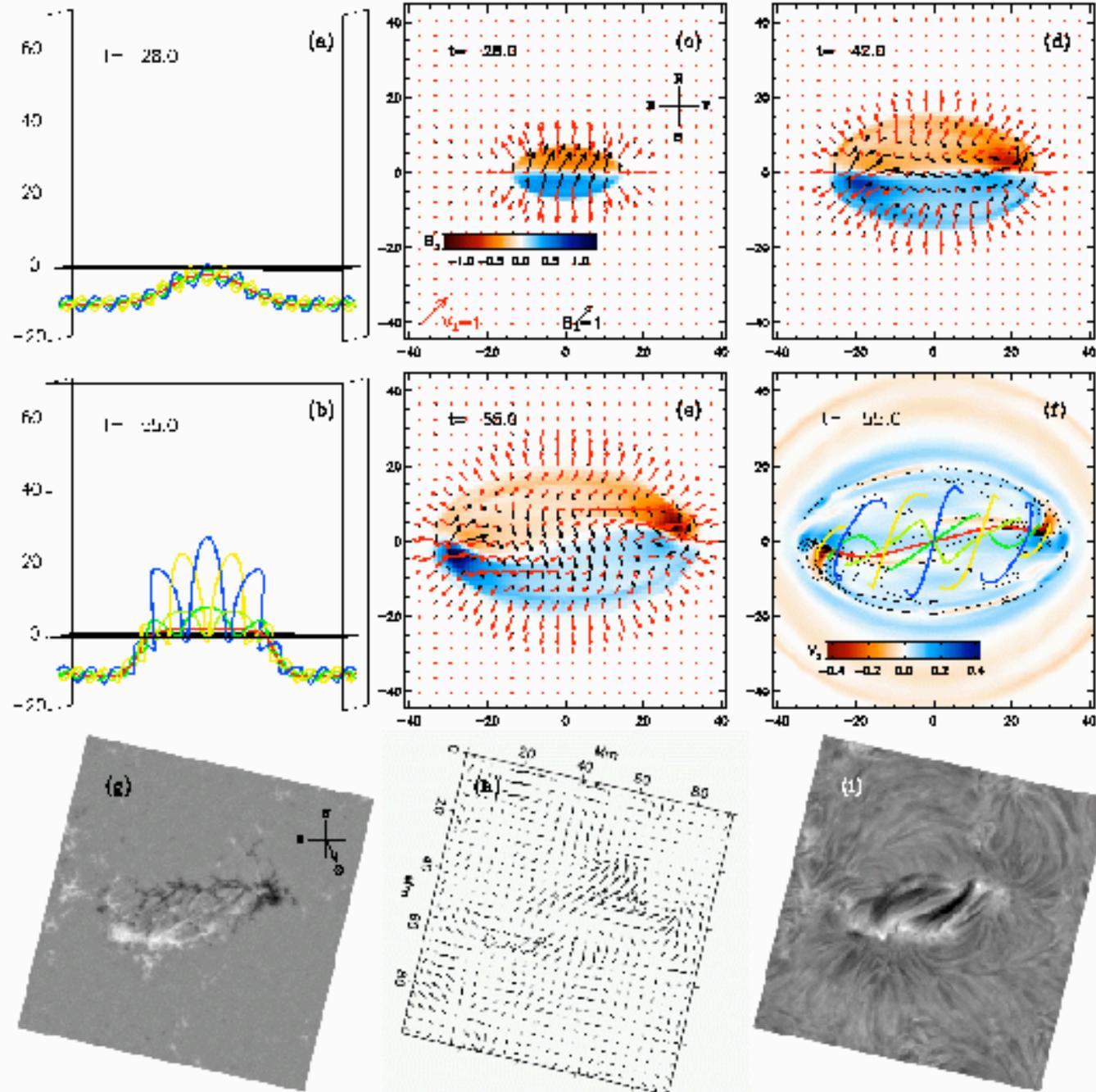
- Must produce large shear in all types of solar regions
- Must concentrate shear near PIL
- Must produce twist, if believe in rope model
- Flux emergence – shear originates below surface (Monday WG1 talks, Fisher's talk)
 - Assume twisted flux rope below photosphere
 - Expected both observationally and theoretically
 - Easily yields sheared arcade
 - Obtaining twisted flux rope requires further evolution, reconnection/cancellation at photosphere

Models for Filament Formation



(Magara et al 2005)

- Left: Flux tube below photosphere (green plane), left side shows temperature profile, right pressure
- Right: Field after emergence, resembles observed filaments and has the structure of sheared 3D arcade model
- Similar results by Fan and others



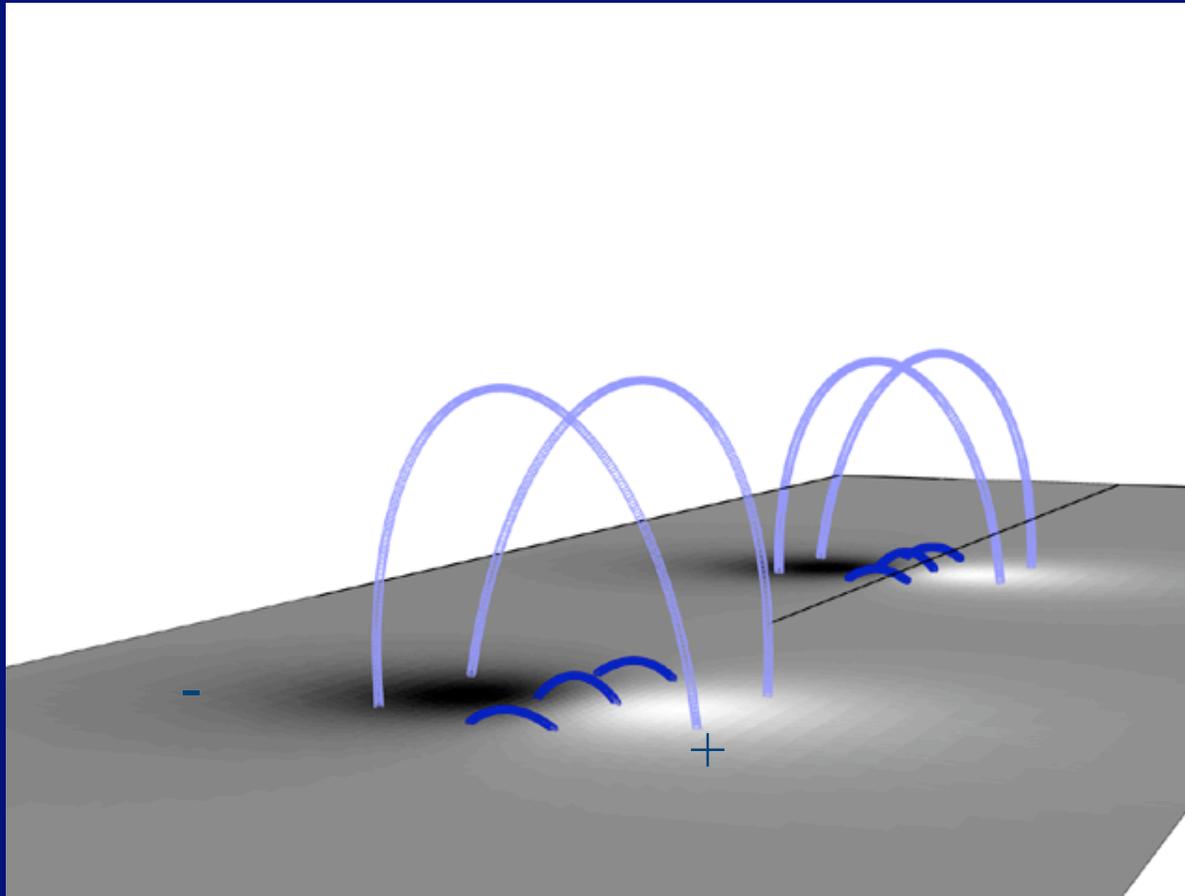
(Fan 2001)

Models for Filament Formation

- **Photospheric motions**

- Origin still sub-surface flows, but flux already emerged
- AR spots sometimes show rotations, shear
- But is not always observed
- Differential rotation may shear quiescent filaments
- But need mechanism to concentrate shear at PIL
- Reconnection likely to play important role – (van Ballegooijen's talk)

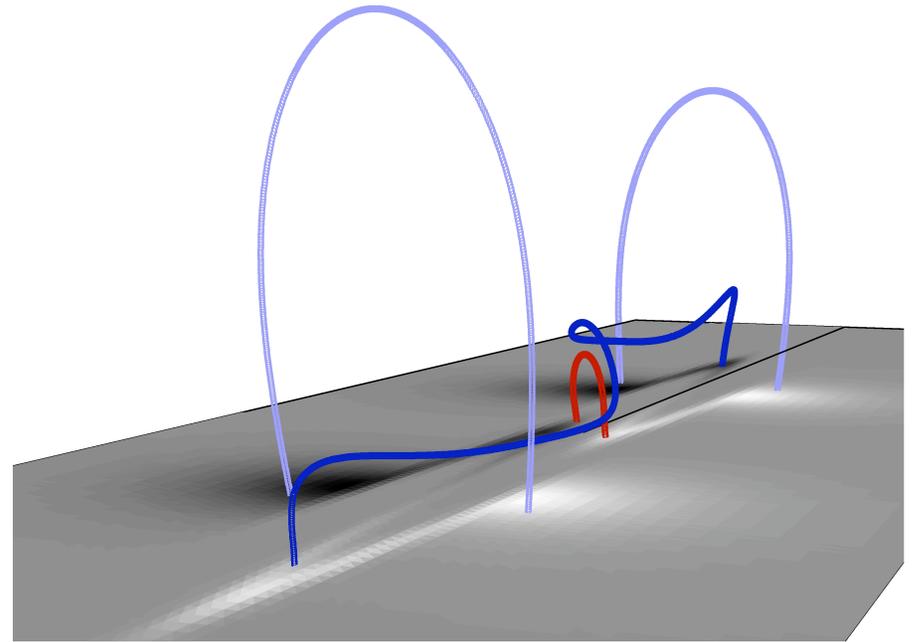
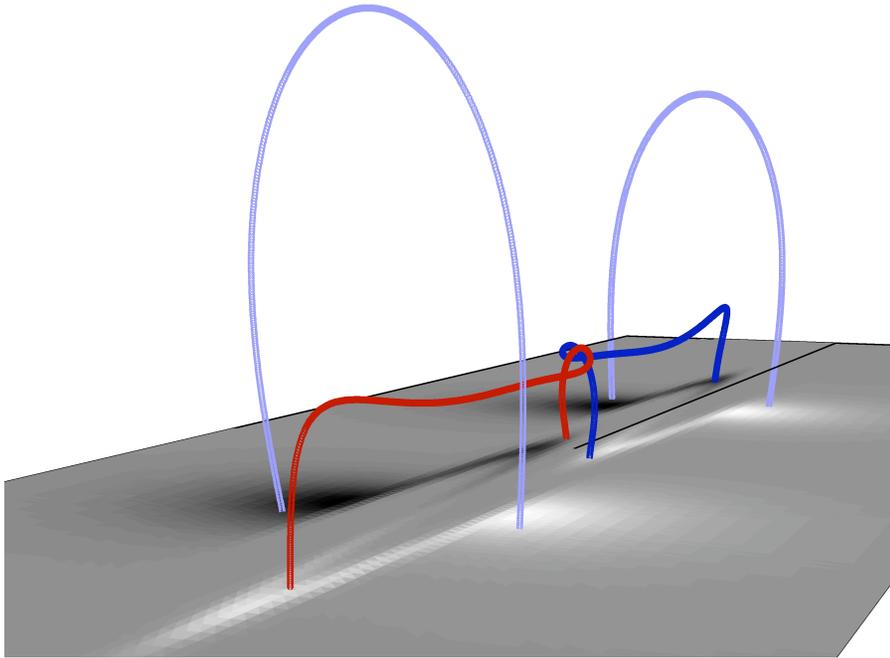
Models for Filament Formation



(from, DeVore et al, 2005; Aulanier et al, 2005)

- Filament channel formation by shear and reconnection
- Bipolar (one polarity inversion line) initial magnetic field
- Modest footpoint motion, shear amplification by reconnection

Models for Filament Formation



- Short fibrils reconnect to form long filaments (e.g., Martin, Title, ...)
- Resulting structure has observed geometry of filaments/prominences

Models for Filament Formation

- **Bottom Line:**

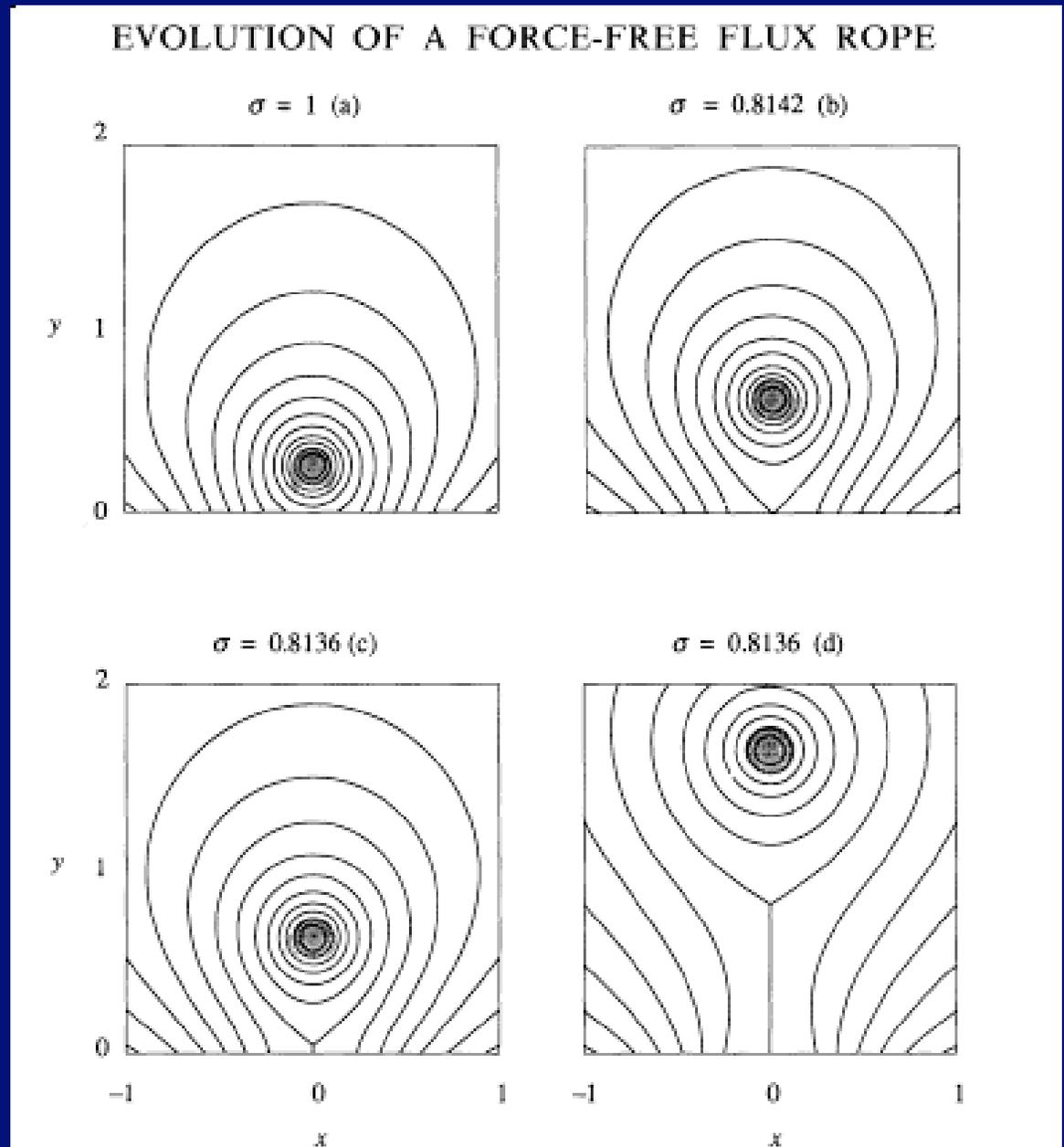
- At present have no robust model that explains formation in generic cases
- Need more work on photosphere-corona interaction
- Should get major input from combination of SOLAR-B and STEREO
- Great problem to work on, both observationally and theoretically!!

Models for CME Initiation

- All models need explosive removal of overlying field (see Tuesday WG1 talks)
- Twisted flux rope models: (e.g., Forbes et al, Low, van Ballegooijen et al, Sturrock, Mikic & Linker, Roussev et al, Fan et al, ...)
 - Twist is essential element of pre-eruption state
 - Generally invoke an ideal instability/loss-of-equilibrium (e.g., a kink)
 - May include effects of mass loading
 - Reconnection often invoked to create initial state and accelerate eruption – flare

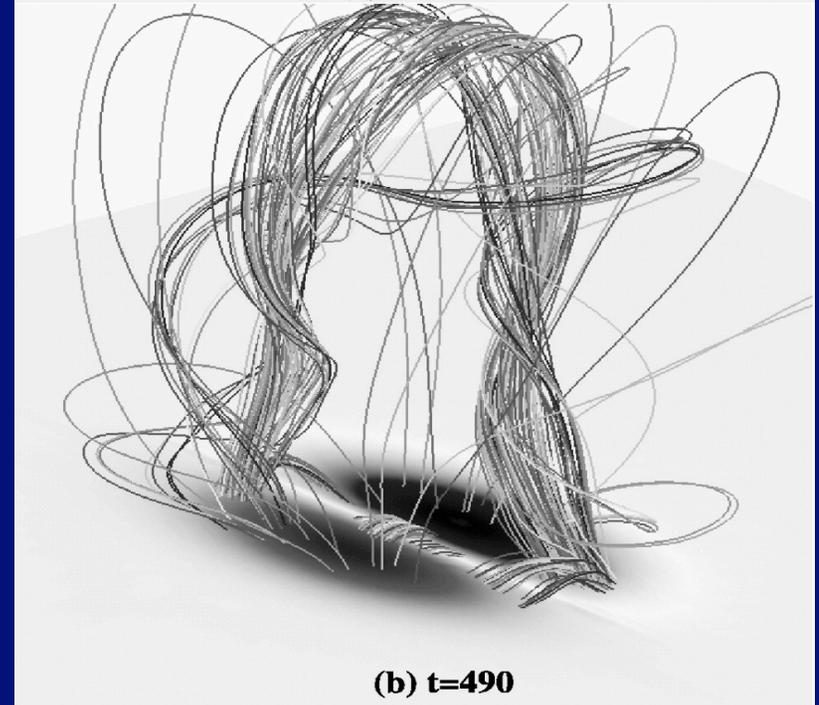
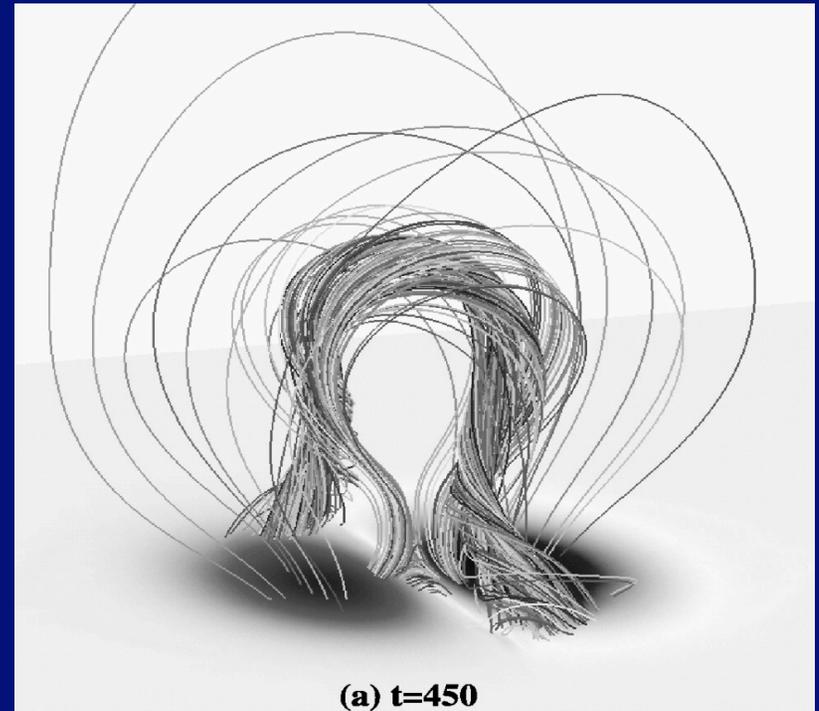
2.5D Twisted Flux Rope Model (Forbes et al)

- Simple bipolar polarity region
- Rope forms by cancellation & reconnection at photosphere
- Growth leads to loss of equilibrium
- Current sheet forms below rope
- Should erupt in spherical system or 3D



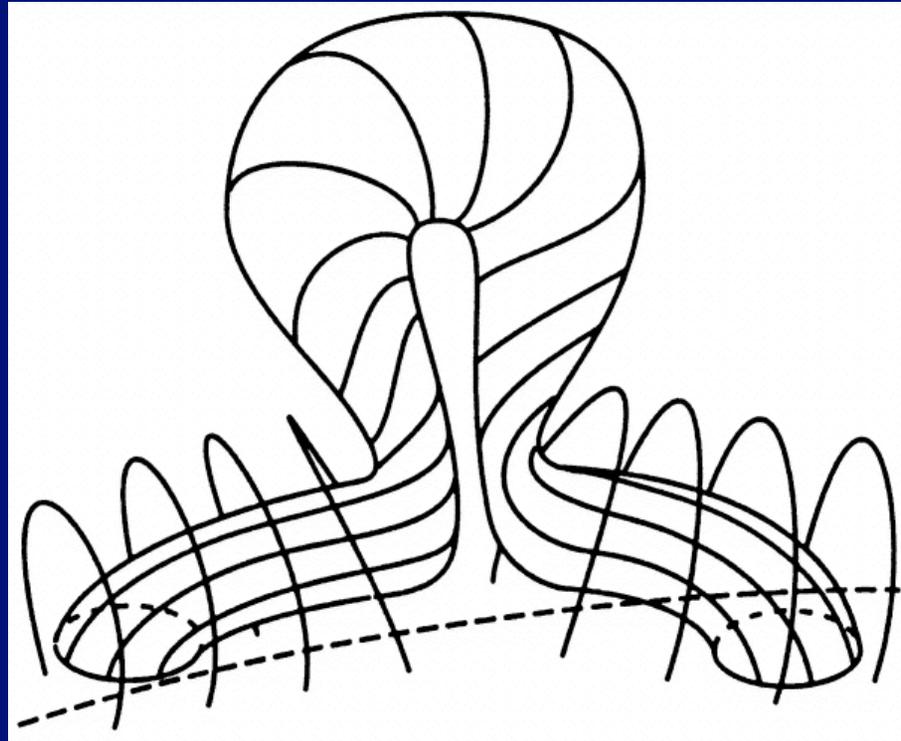
3D Flux Rope Model

- 3D simulation by Amari et al, 2000, (also Mikic & Linker et al, also Fan 2005, ...)



3D Twisted Flux Rope Model

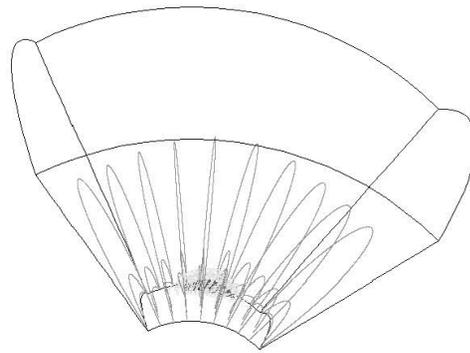
- Role of reconnection not clear
- May simply be due to ballooning-like mode
 - similar behavior observed in Fan simulation



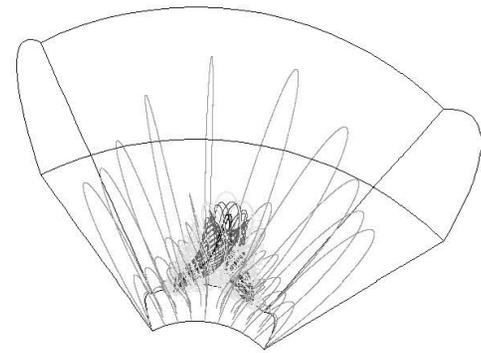
(Sturrock, 2002)

3D Rope Model

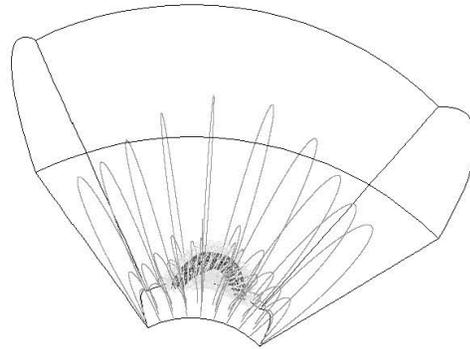
- Fan, 2005



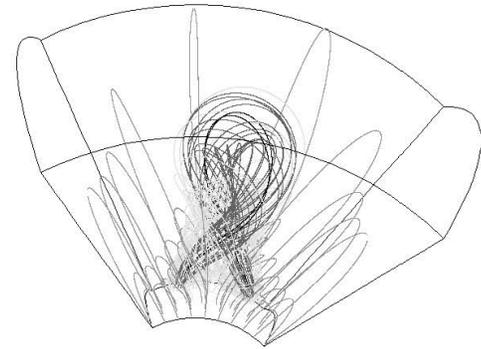
t=45.



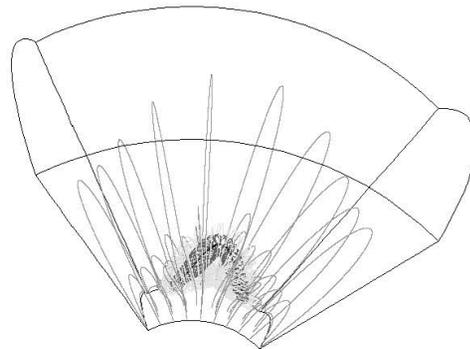
t=90.



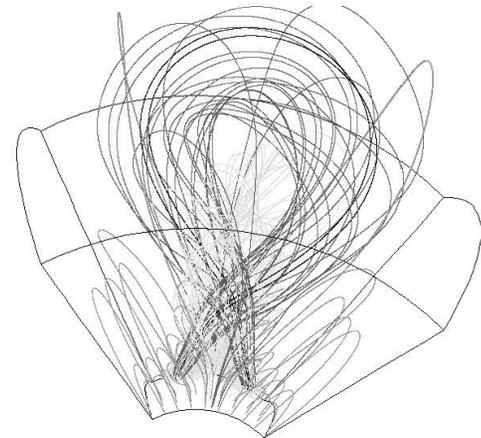
t=70.



t=97.



t=83.



t=103.

Models for CME Initiation

- Reconnection models (Resistive) (e.g., Sturrock, Moore et al, Antiochos et al, Aulanier, MacNeice et al, ...)
 - Use reconnection to change topology, removing overlying field
 - Reconnection in filament channel
 - Tether-cutting (doesn't actually remove overlying B)
 - Reconnection outside filament channel
 - Breakout
 - Breakout needs multi-polarity system, but always present in corona (see poster by Lynch et al)

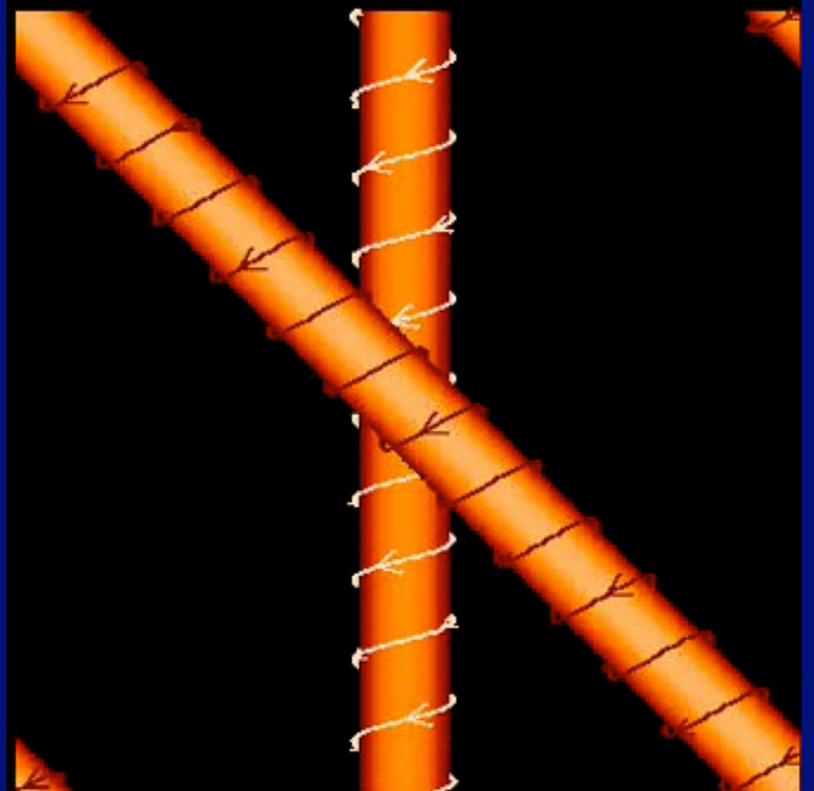
Magnetic Reconnection

- Physics:
 - In cosmic plasmas, magnetic field lines act like material lines
 - Field stores energy, but also constrains structure and evolution
 - Reconnection “breaks” field lines, producing fast energy transfer from field to plasma
 - Drives CMEs, solar flares, coronal heating, geomagnetic storms, laboratory disruptions, ...

Basic Reconnection Process:

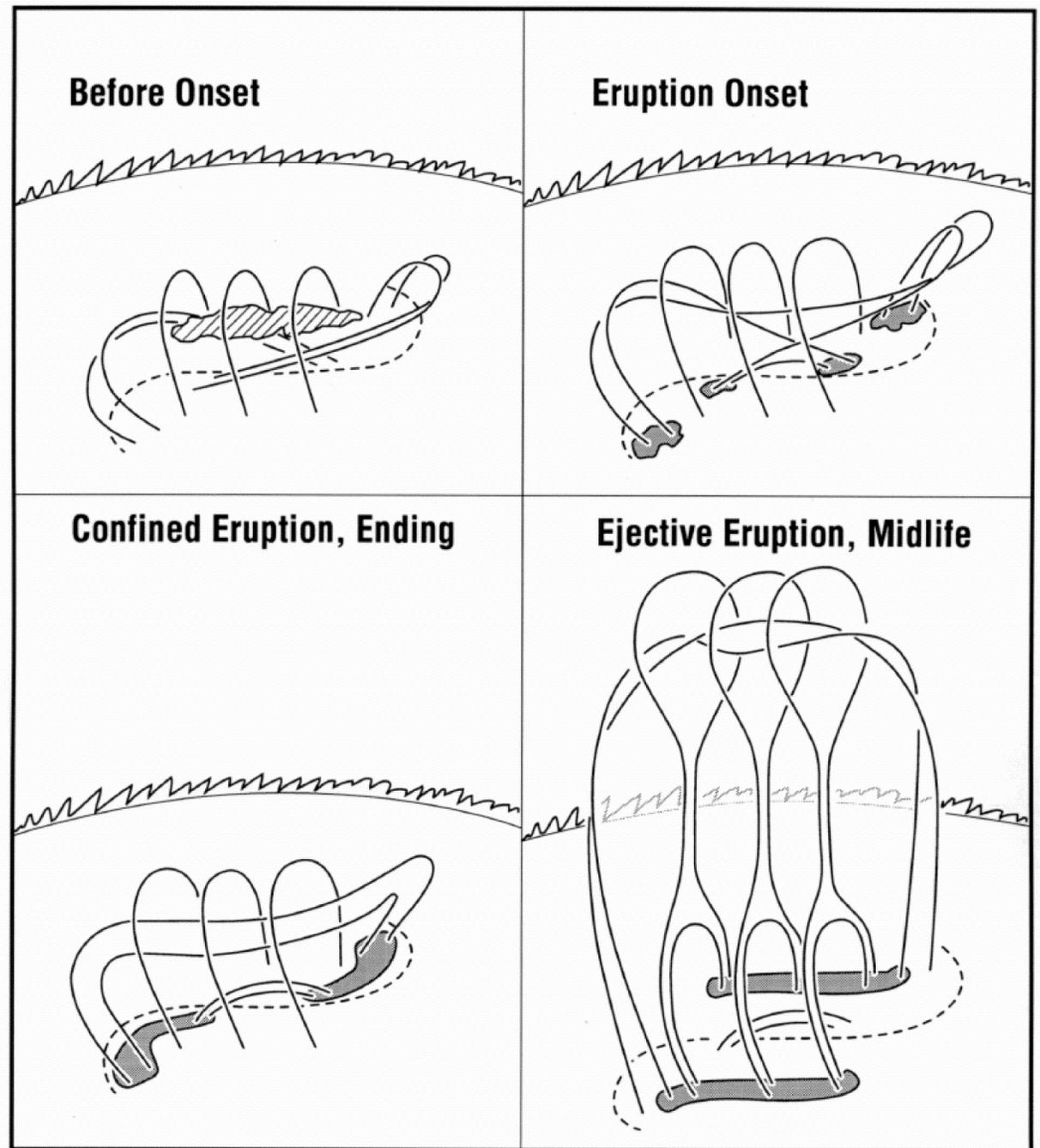
- Collision of two initially-isolated, twisted flux tubes
- Restructuring of tubes releases $> 50\%$ of magnetic energy to plasma

Isosurface of field strength
(Linton et al 2002)



Tether Cutting Model

- Field topology is differentially sheared bipolar arcade
- Reconnection within sheared field destabilizes system
- But not observed in simulations

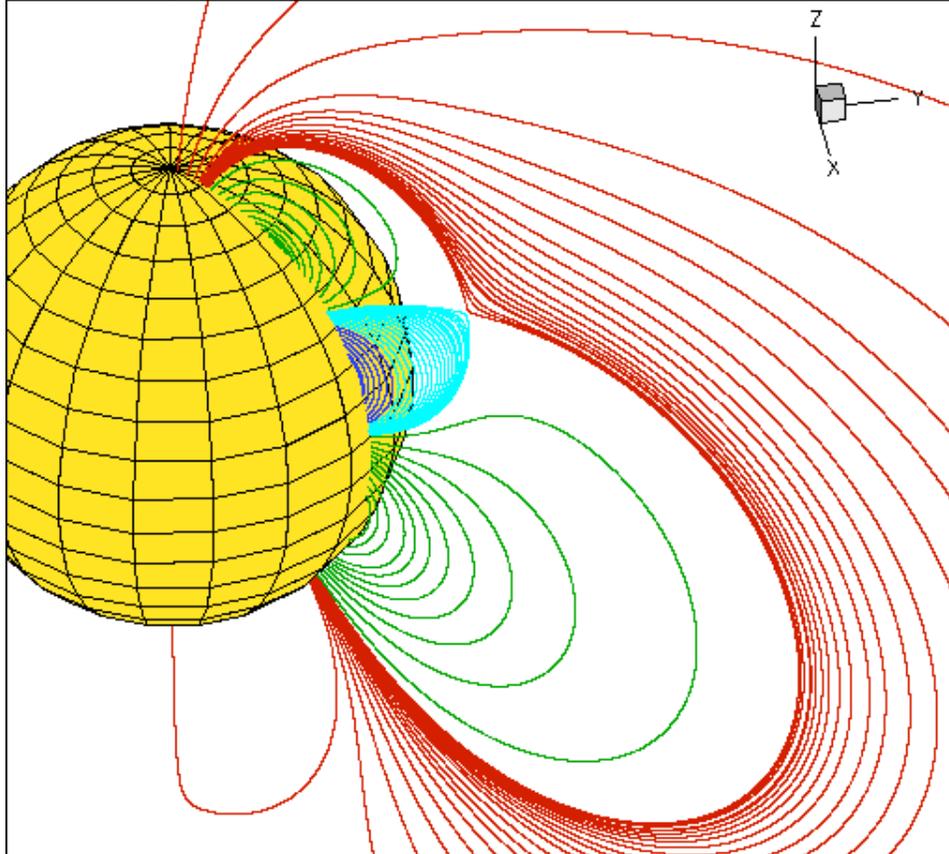


Breakout Model

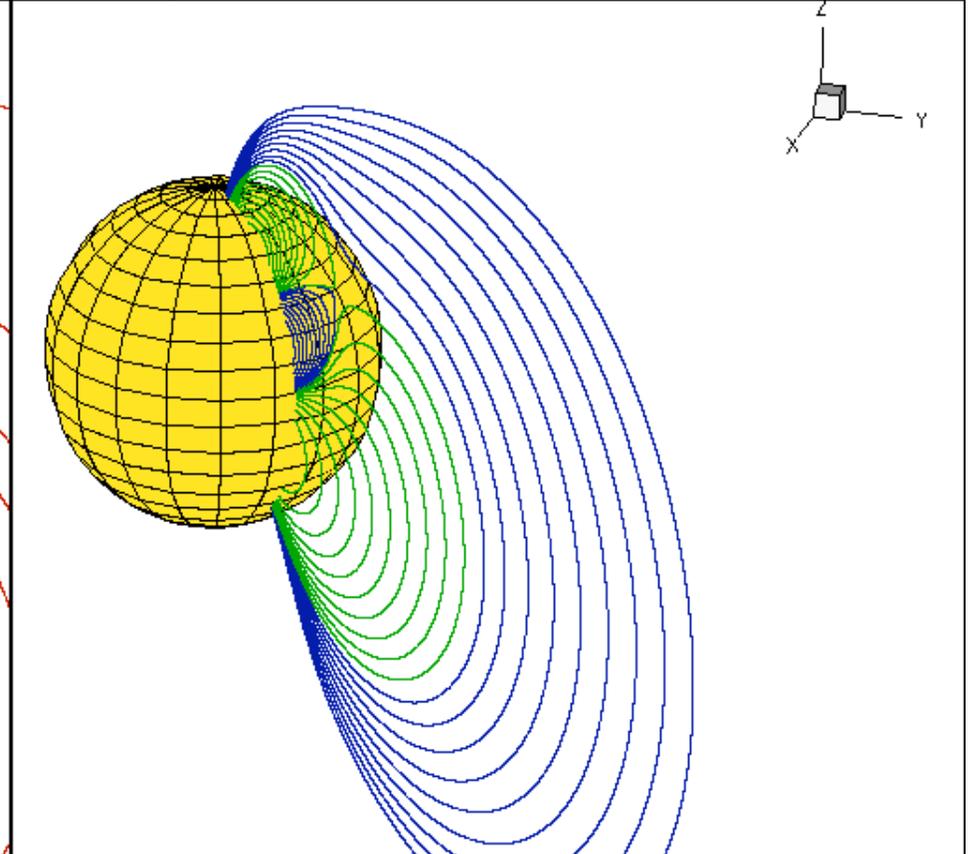
- Multi-polar system with coronal null
- Filament channel could be sheared arcade or twisted rope
- Reconnection removes overlying flux producing explosive expansion – (see Lynch for 3D version)

(Gao, PhD Thesis, 2005)

Frame 001 | 12 May 2005 | Field-lines time = 0.00000000000000D+000



Frame 001 | 12 May 2005 | Field-lines time = 0.00000000000000D+000



Models for CME Initiation

- **Bottom Line:**
 - Have two types of models that produce explosive CMEs in 3D simulations
 - Twisted rope needs certain topology for filament channel
 - Breakout needs certain topology for coronal field
 - Both need more work to understand exact requirements for fast ejection
 - Both need more testing against experiments
 - Interesting area of research!