Solar eruptions and their manifestations in the solar wind

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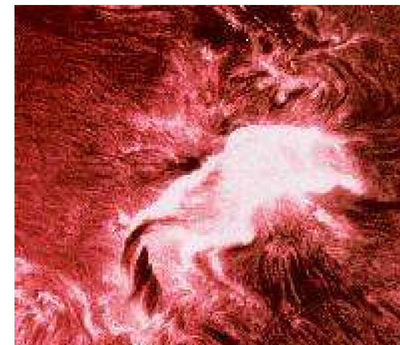
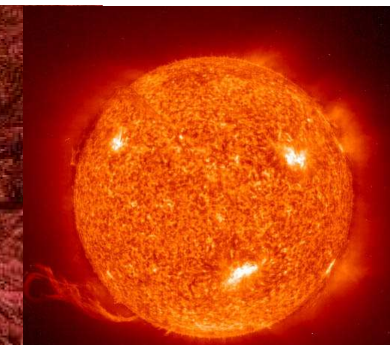
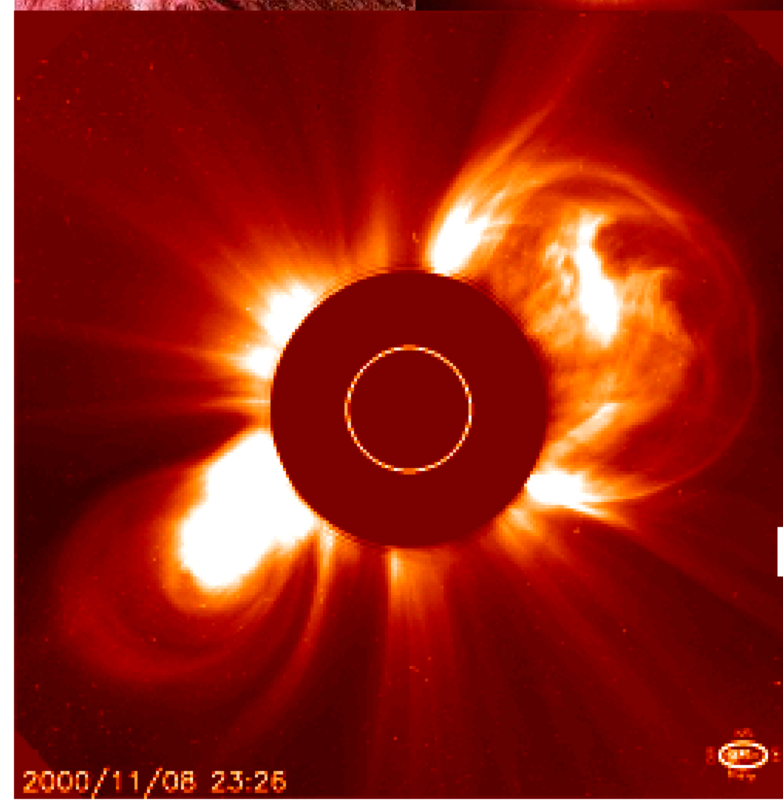
Research Seminar on Sun–Earth Connections
Spring 2006

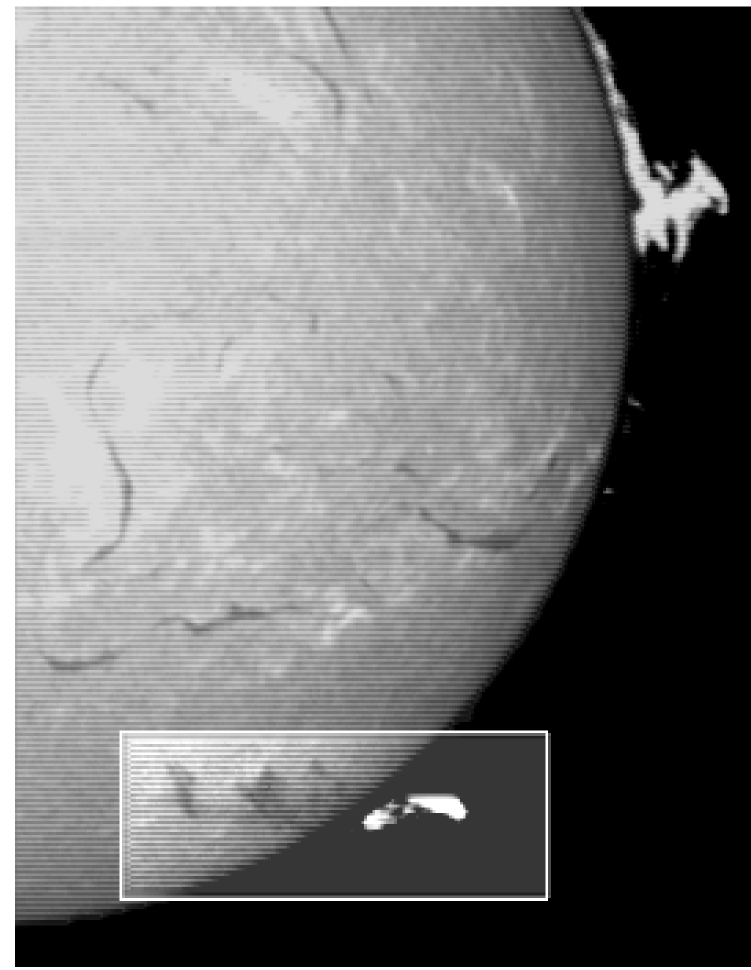
Outline

- Solar Eruptions:
  - prominences
  - flares and CMEs
- Manifestations in the SW
  - ICMEs (or magnetic clouds, MCs)
  - IP shock waves
- Some open questions
- Main references:
  - Antiochos (2005)
  - van Ballegooijen (2005)

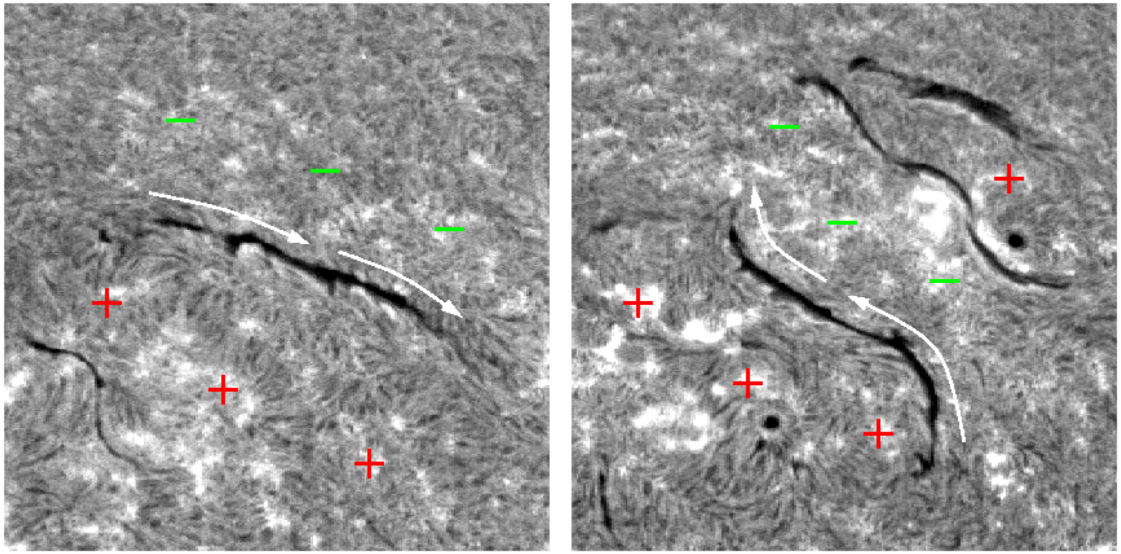
Prominences/filaments

- Prominences (a.k.a. filaments): cool plasma (~ 10^4 K) embedded in hot corona (~ 10^6 K) above **polarity inversion lines** (PIL).
- B-fields provide support, and insulate the prominence from the hot surroundings.
- Prominences are **non-potential** structures in the solar corona and, thus, important for understanding solar **flares** and **CME**s.



Filament channels

figure: van Ballegooijen (2005)



Dextral Sinistral

- Filaments are located in channels co-aligned with chromospheric fibrils
- Dextral channels:
  - axial field to the right as seen from the + polarity region
  - filaments have right-bearing legs
- Sinistral channels:
  - axial field to the left as seen from the + polarity region
  - filaments have left-bearing legs

"Standard" model for explaining filament observations

- Plasma supported by a dip in a twisted magnetic field
- Note, however:
  - legs extend downward from the main body of the filament
  - plasma on inclined field lines
  - support mechanism unknown

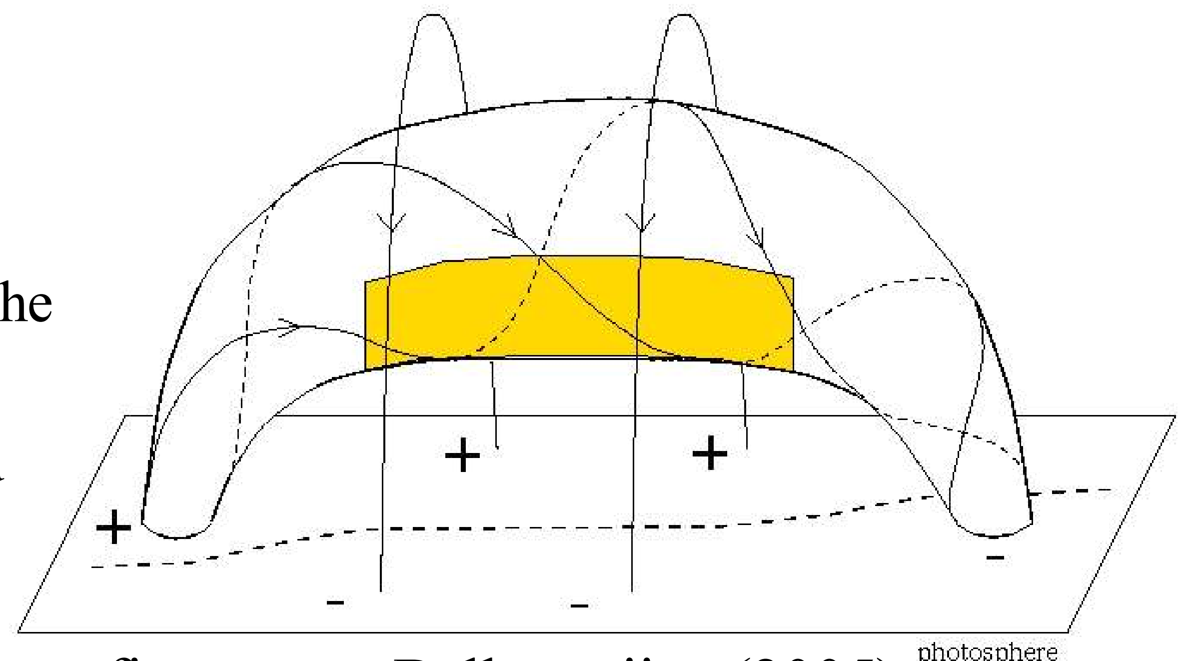
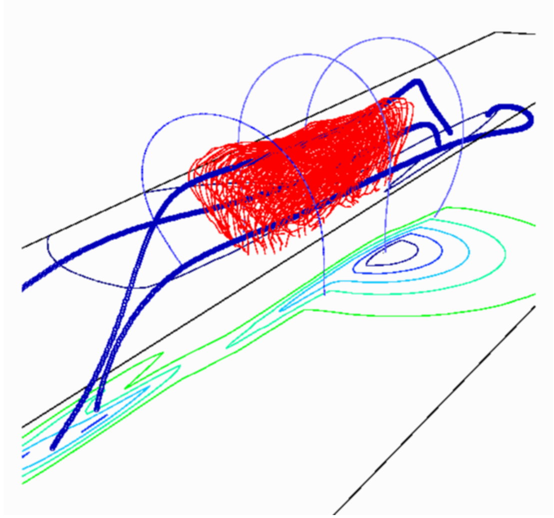


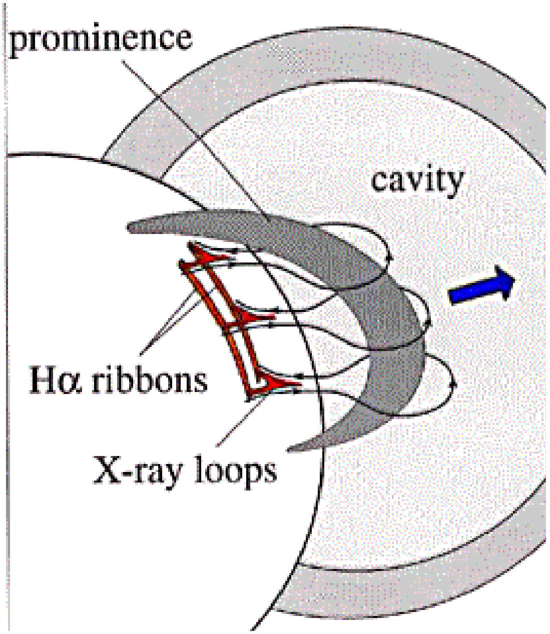
figure: van Ballegooijen (2005)

Solar eruptions

DeVore et al.



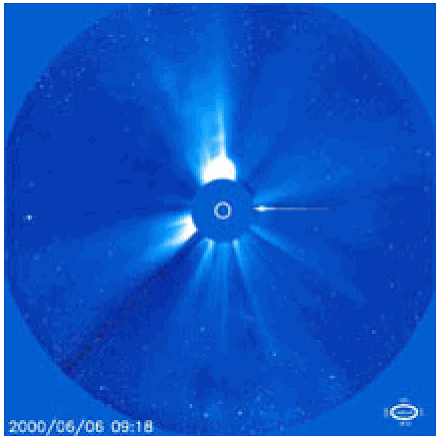
- Occur in sheared filament channels
- Non-potential field created above the PIL
  - Strong field provides the necessary energy for eruption
  - Held down by the overlying coronal (potential) field
- Force balance breaks leading to an explosive expansion of the field
  - CME
- Field reconnects below into a potential structure
  - flare

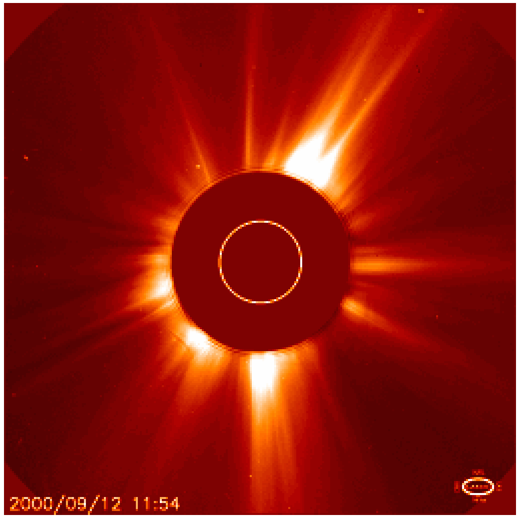


T. Forbes

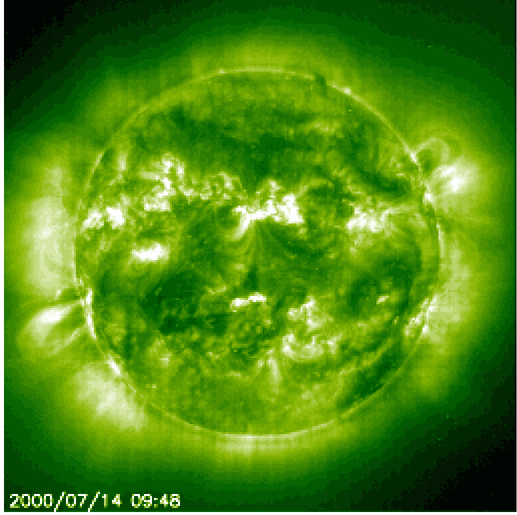
Key observations of CMEs

- Limb: Three-part structure
  - Bright front
  - Dark cavity
  - Bright core
  - Helical structures?
- Disk: halo
- Velocities 50–2500 km/s
- Two main categories
  - impulsive: fast (> 400 km/s), decelerating
  - gradual: slow (< 400 km/s), accelerating

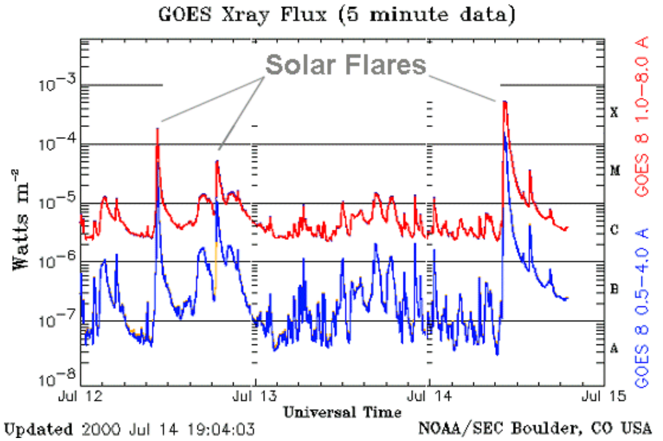




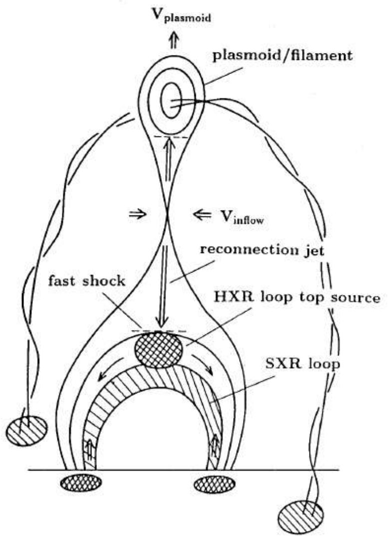
Key observations of flares



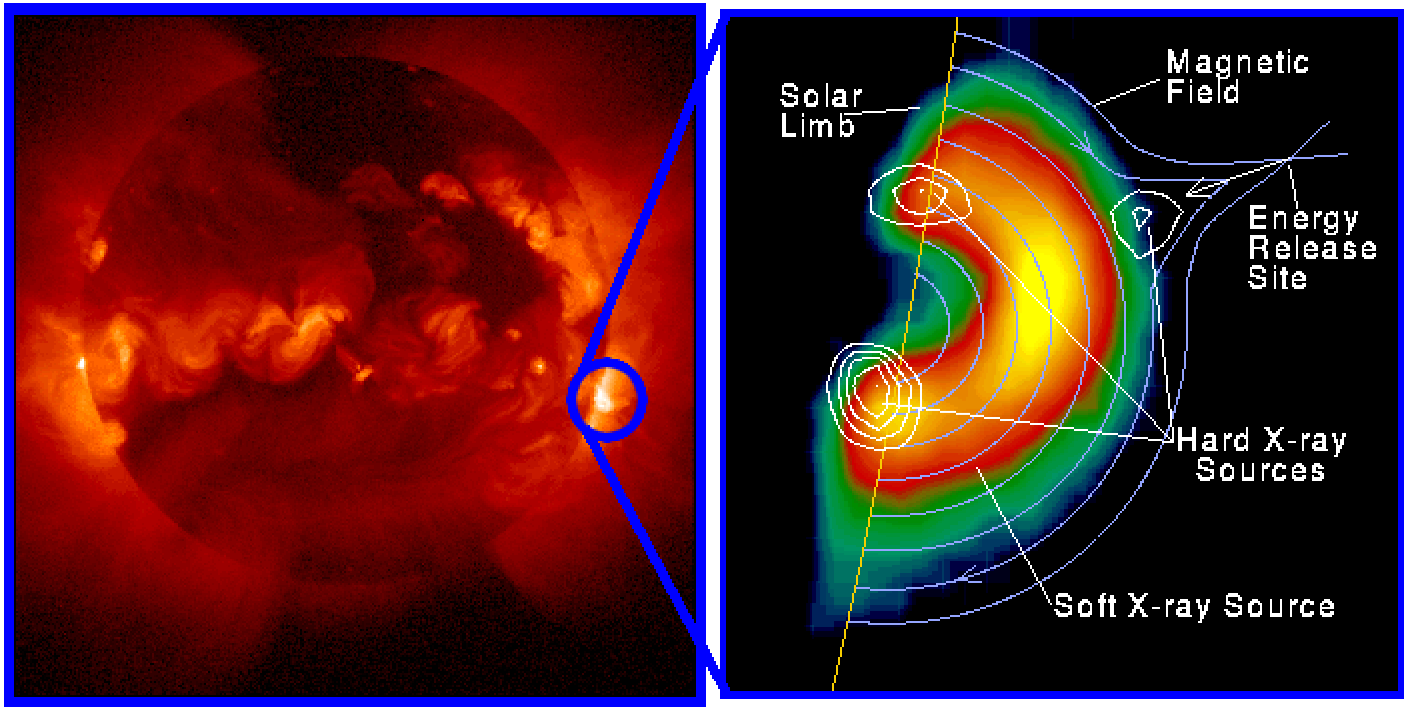
- Optical, radio, **EUV**, **X-rays**, SEPs
- Compact
  - impulsive flares (< 10 min), single loop
  - hard and soft X-rays
  - loop-top and foot-point sources
  - narrow, slow CMEs; “X-ray plasmoids”



- Two-ribbon (or multi-ribbon) flares
  - long duration (>10 min) events, arcades above PIL
  - soft X-rays, seldom hard X-rays
  - related to fast CMEs and erupting prominences (disrupting arcades)

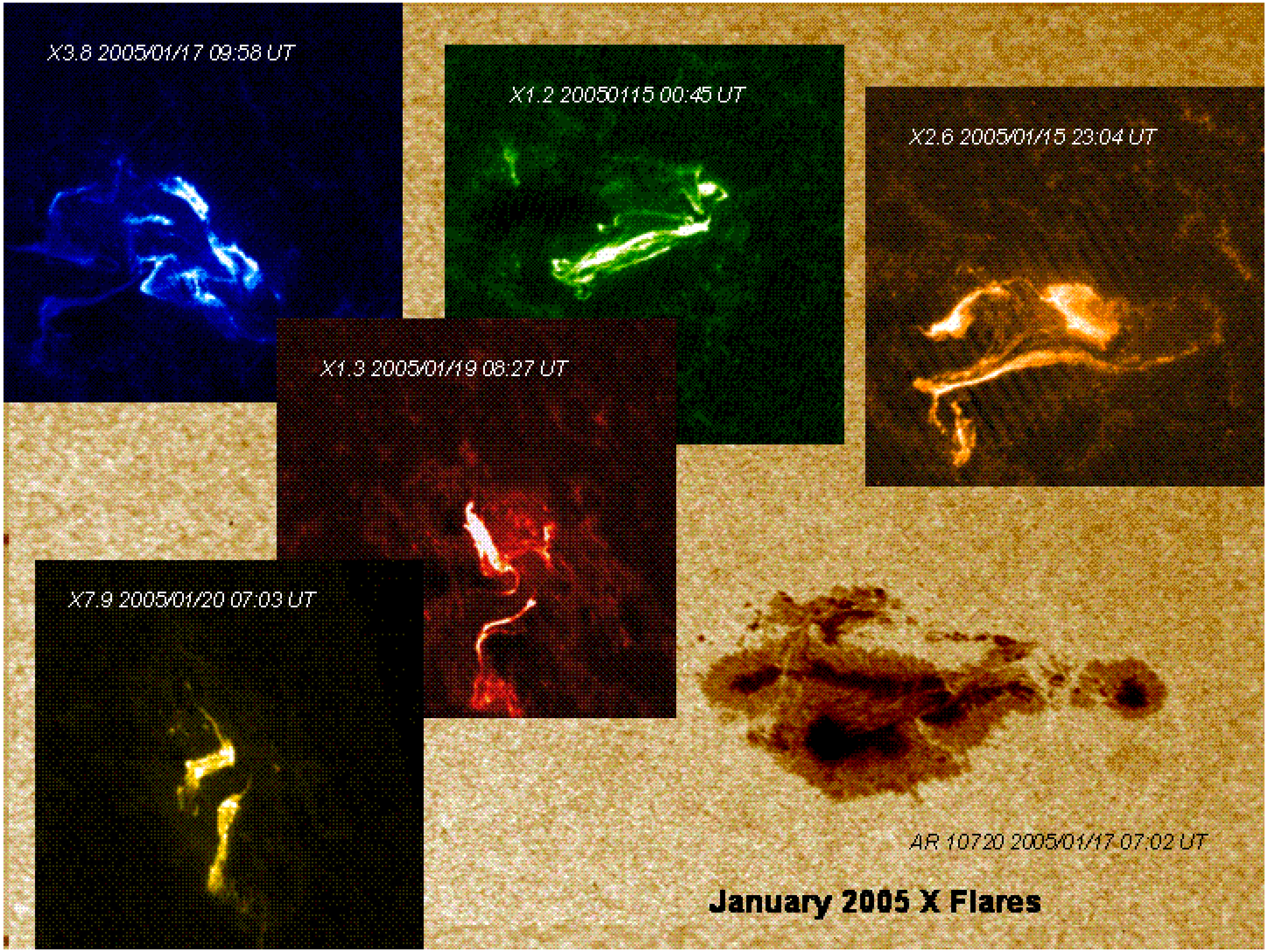


Impulsive X-ray flare (Yohkoh)



Yohkoh X-ray Image of a Solar Flare, Combined Image in Soft X-rays (left) and Soft X-rays with Hard X-ray Contours (right). Jan 13, 1992.

Gradual flares (Trace)



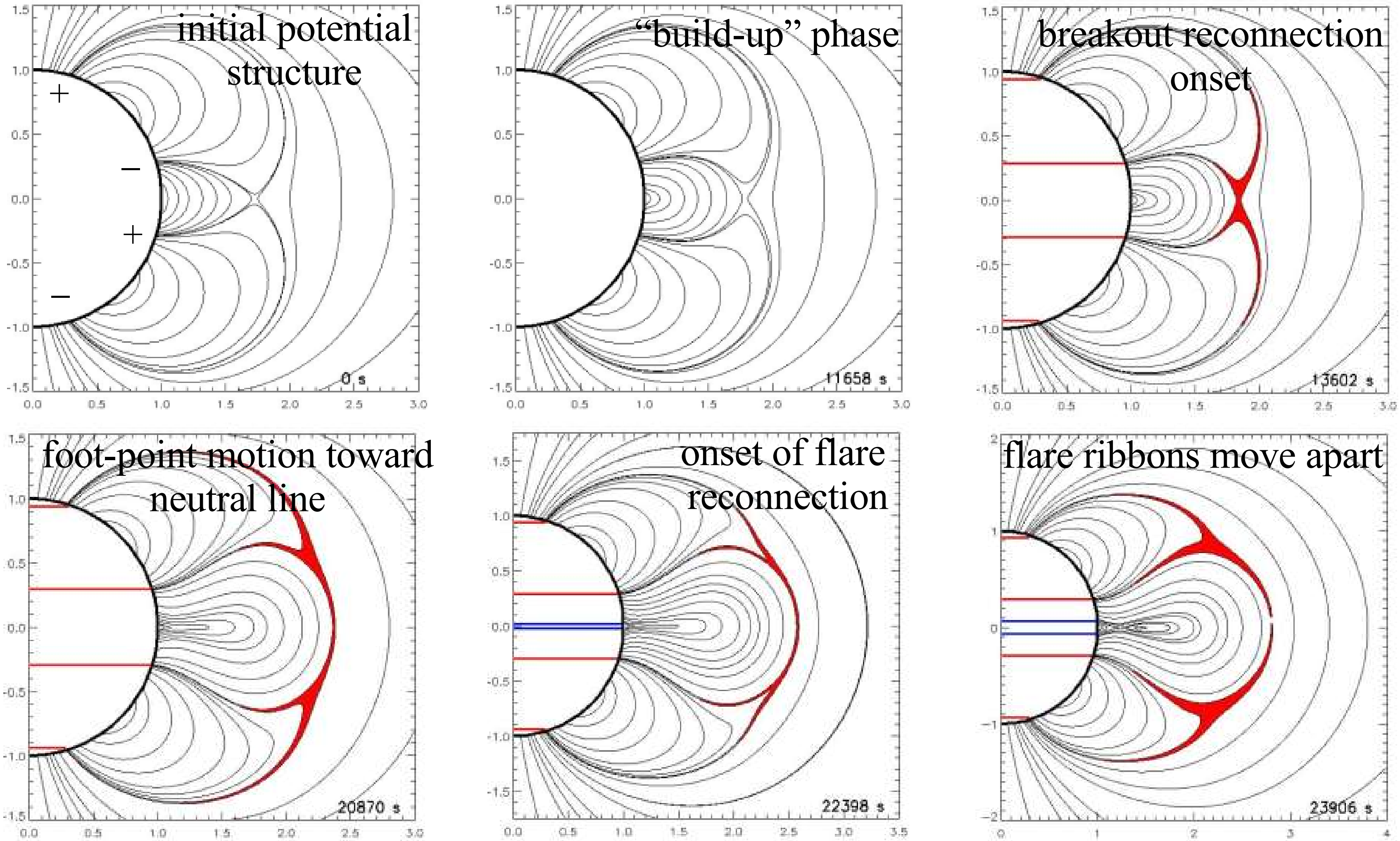
Models for CME Initiation

- Reconnection models (Resistive):
  - Sheared 3D arcade topology (but not essential)
  - Reconnection removes overlying field
  - Tether-cutting: reconnection inside filament channel
  - Breakout: reconnection outside filament channel
    - Needs multi-polarity system
- Twisted flux rope models (Ideal):
  - Twist is essential to pre-eruption topology
  - Generally bipolar polarity region (not essential)
  - Ideal (kink-like) instability/loss-of-equilibrium moves aside overlying field

Antiochos (2005)

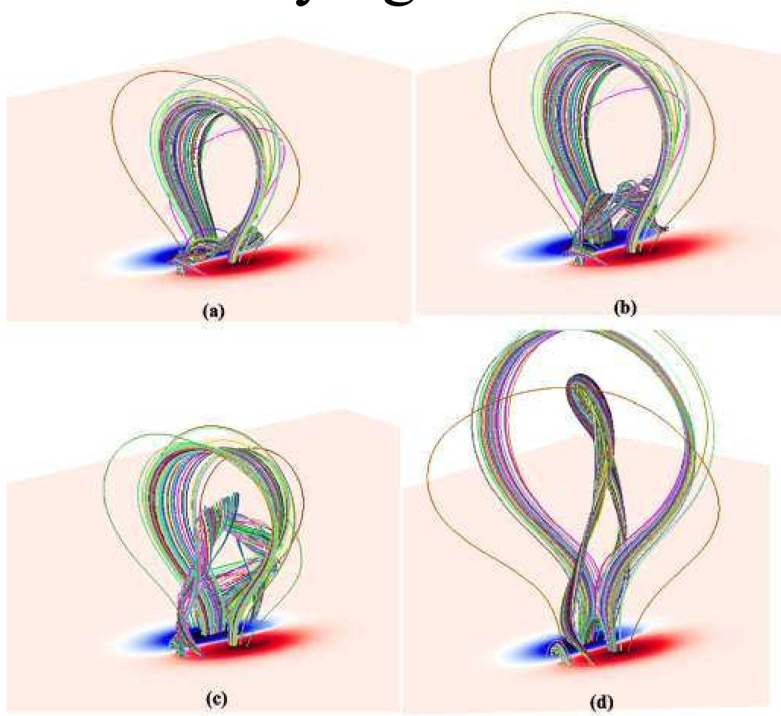
Breakout model (Antiochos et al)

- Multi-polar field & foot-point shear
- Reconnection removes overlying flux

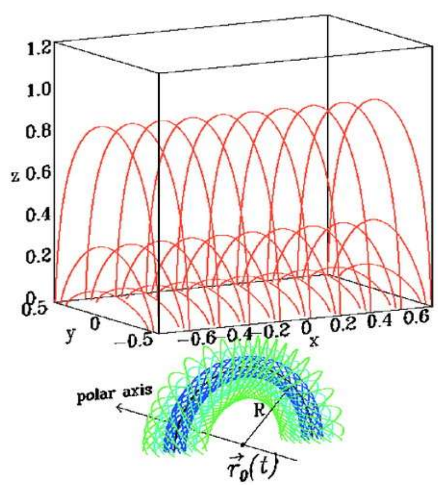


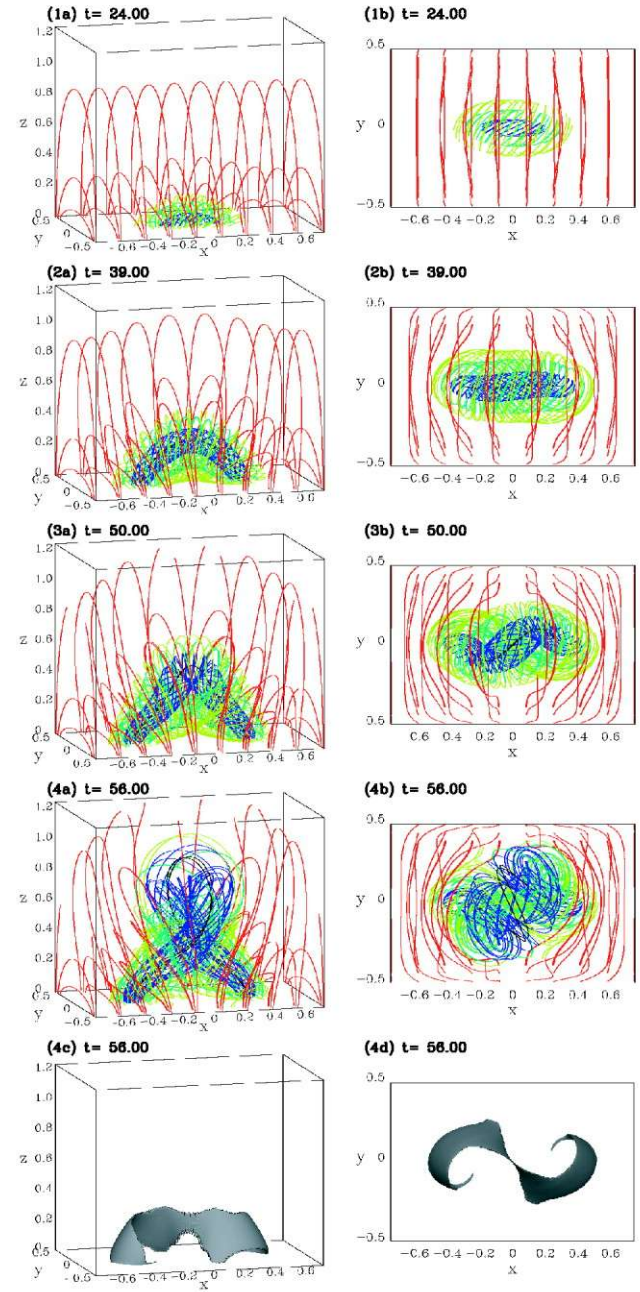
Twisted Flux Rope Model

- Bipolar field with some process to form twisted rope
- Rope lifts/kinks for some critical twist, overlying field moves aside



Amari et al. (2003, “flux cancellation”)





Gibson et al. (2004, “flux emergence”)

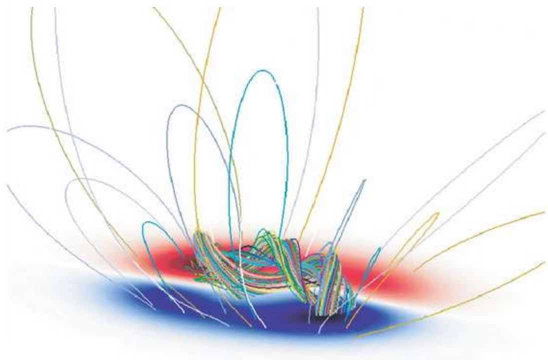
Flux emergence model of Amari et al. (2004)

$$B(r, t) = B_0(r_0) \cdot \nabla_0[r_0 + v(r_0)t\hat{z}]$$
$$= B_0(x, y, Z) + [B_{0\perp}(x, y, Z) \cdot \nabla_{0\perp}v(x, y)]t\hat{z}.$$

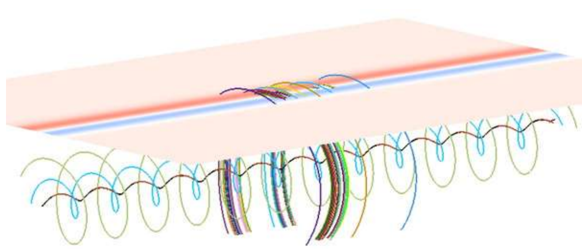
$$Z = z - v(x, y)t$$

$$E_s = v(x, y)B_s \times \hat{z}$$

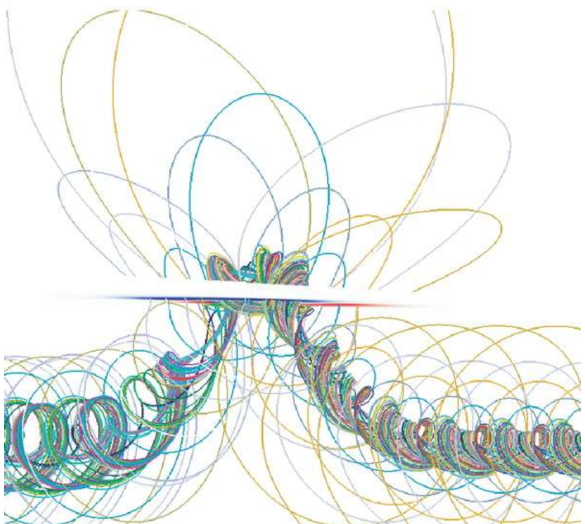
$$B_0 = B_0 e^{-[y^2+(z-z_0)^2]/a^2}[\hat{x} - q(z - z_0)\hat{y} + qy\hat{z}]$$
$$v(x, y) = v_0 e^{-\{[(x-x_c)^2/\sigma_x^2]-[(y-y_c)^2/\sigma_y^2]\}},$$



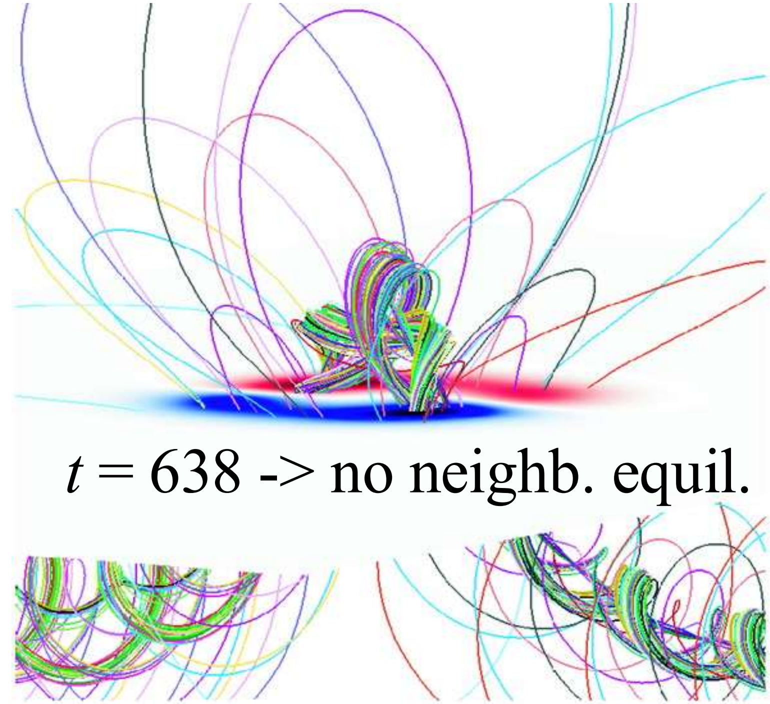
(a) $t = 618$



$t = 0.05$

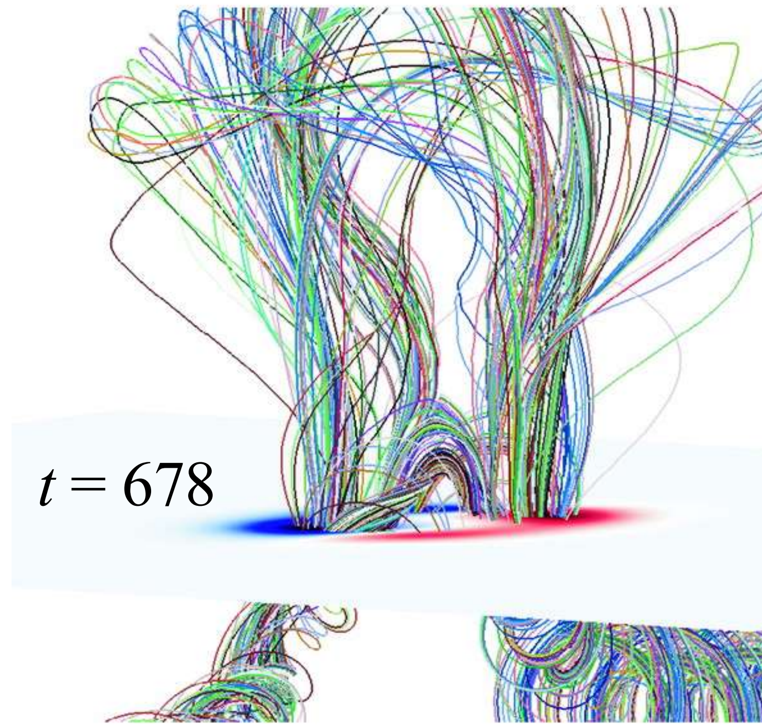


(b)



$t = 638$ -> no neighb. equil.

(a)



$t = 678$

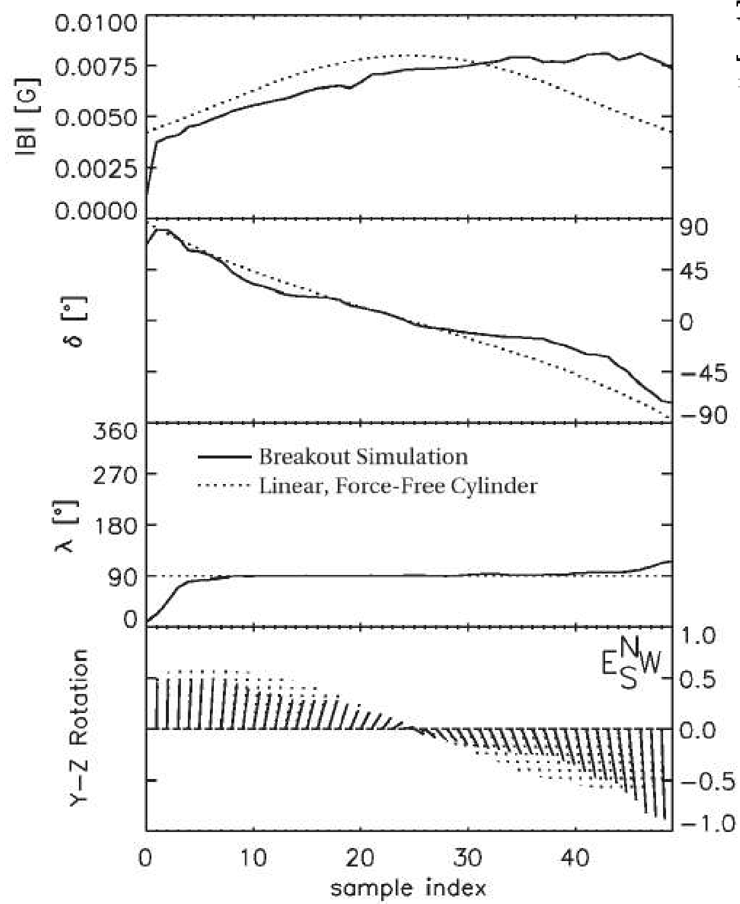
(b)

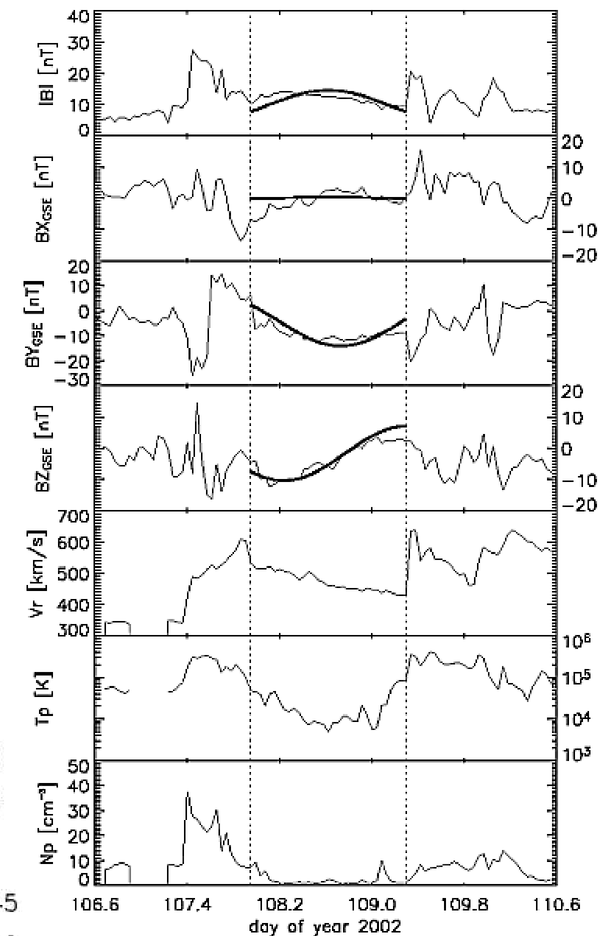
Interplanetary CMEs, magnetic clouds (MCs)

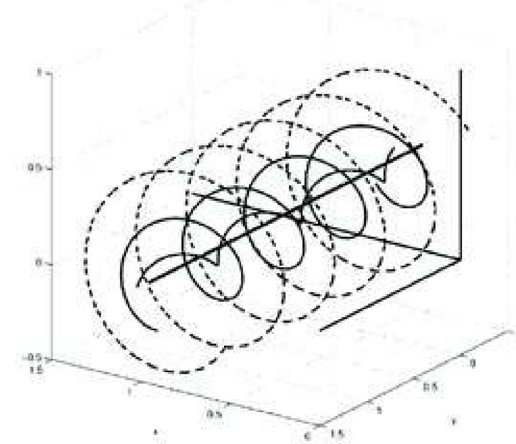
- CME flux ropes observed in the solar wind
- Well fitted with an axisymmetric linear force-free field

$$\boldsymbol{B} = HB_0 J_1(\alpha\,\rho)\hat{\boldsymbol{\phi}} + B_0 J_0(\alpha\,\rho)\hat{\boldsymbol{z}}$$

- Modeled breakout CME can be fitted with the MC model, as well

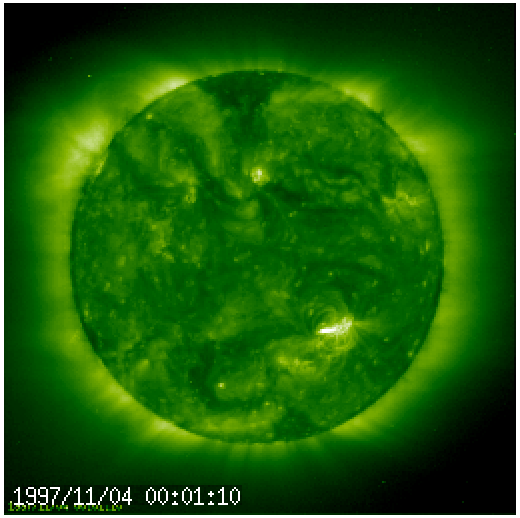


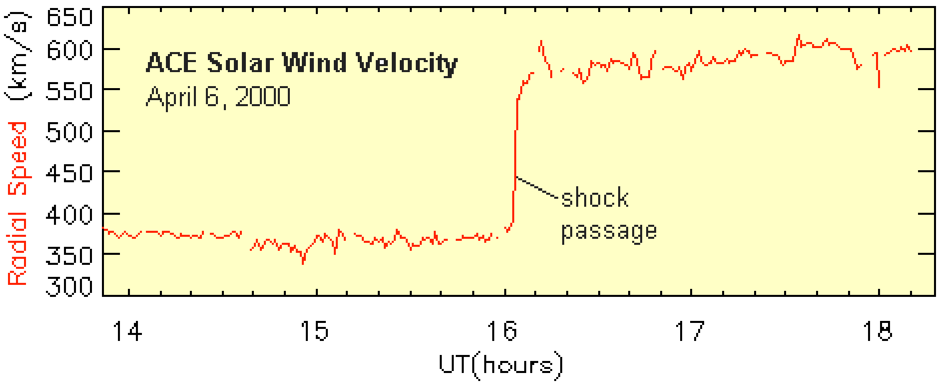


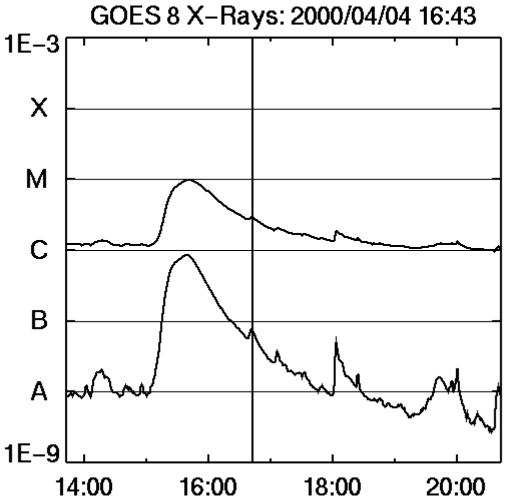


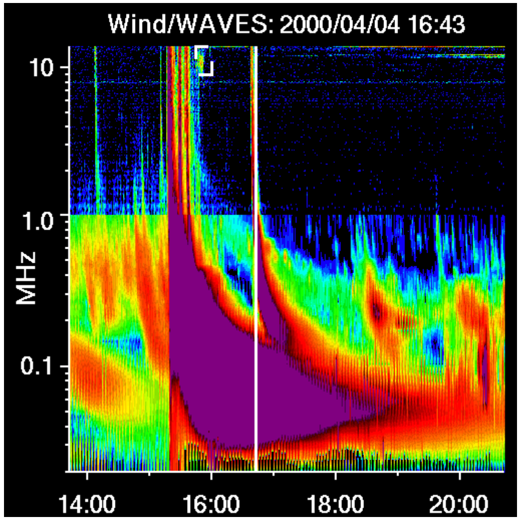
Coronal and interplanetary shocks

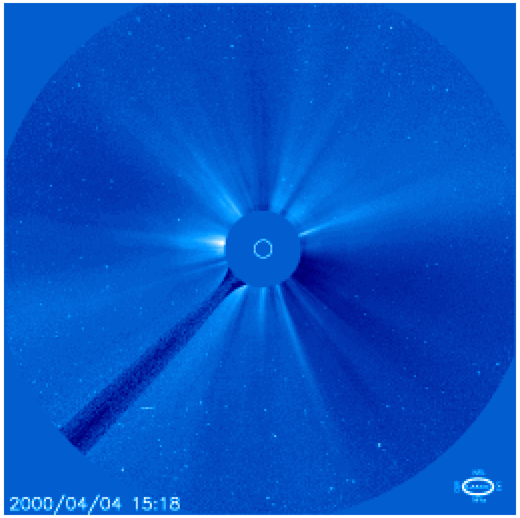
- Fast CMEs super-fast-magnetosonic => drive fast-mode shock waves
  - compress the magnetic field
  - amplify turbulence
  - accelerate particles
  - large angular span

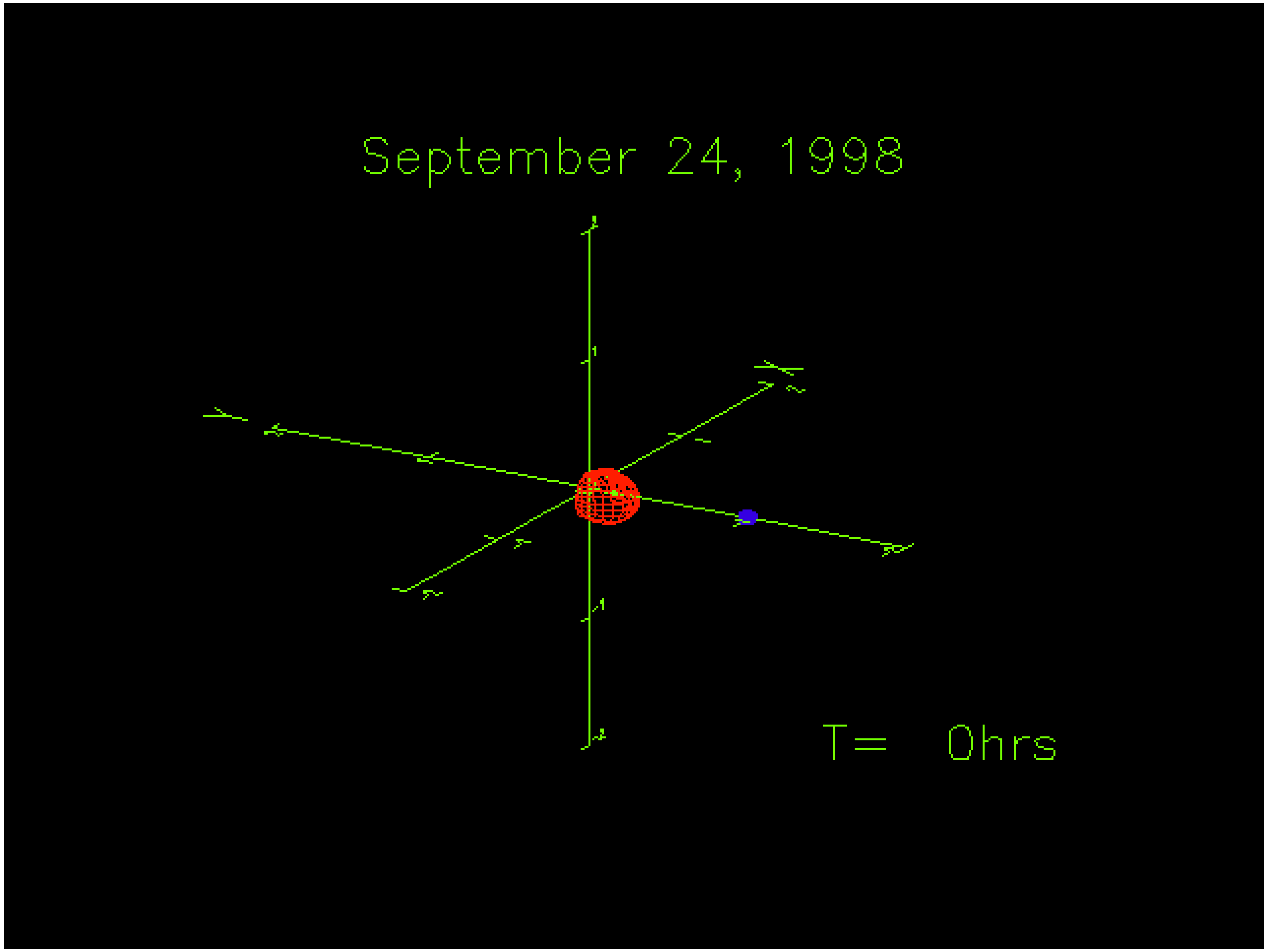











September 24, 1998
T= 0hrs

Some challenges for future

- Relation between flares, CMEs, coronal shocks and SEPs
  - Where does the radio burst come from
    - blast-wave vs. driven shock
  - How does the shock propagate through corona (refraction)
    - EIT waves vs. shocks
  - Where and how are SEPs accelerated (Arto tells more)
- Three-part structure vs. ICMEs
- How to get to the extremes
  - shearing, twisting and flux emergence loads the corona with magnetic energy, but how do you get a fast enough eruption?