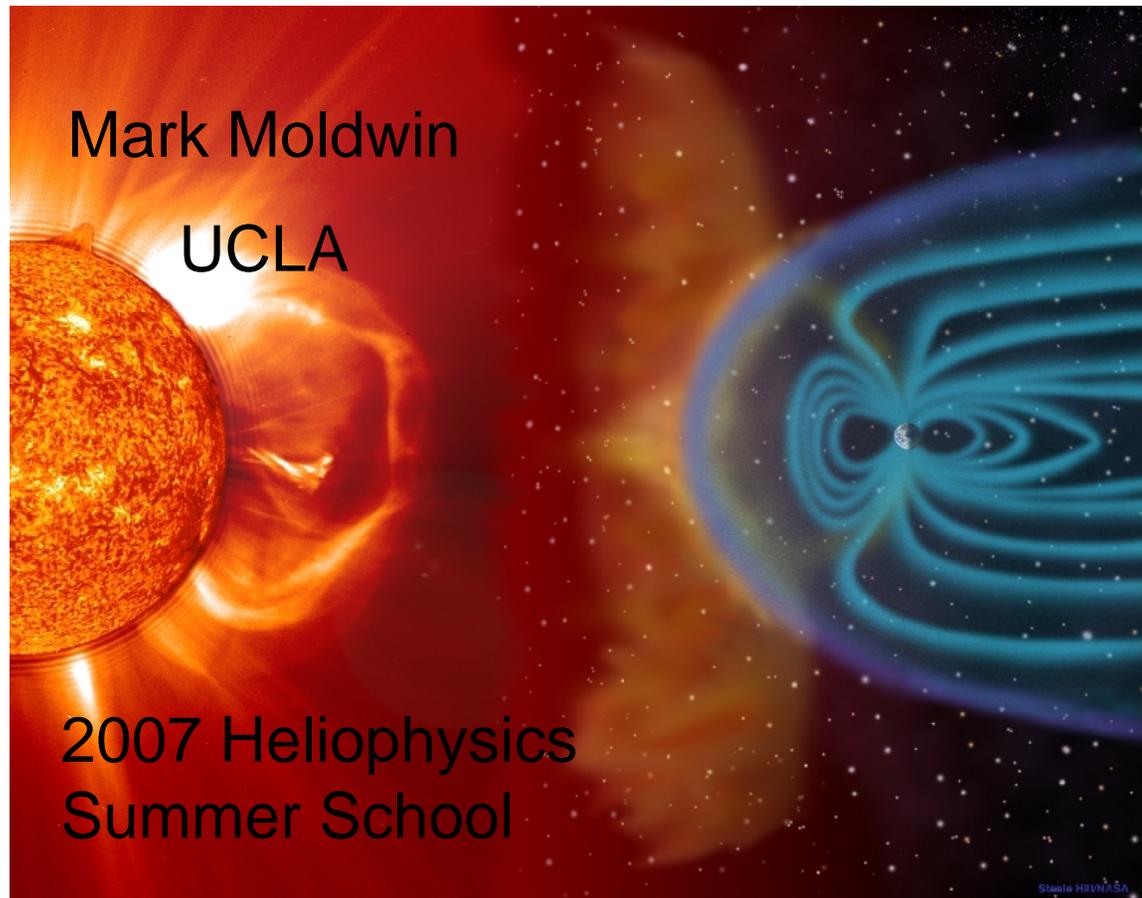


Magnetic Flux Ropes in Space Plasmas



With thanks to Mark Linton at NRL

Goal of Lecture

- Introduce one of the most ubiquitous features in space plasmas
- Describe their Origin, Evolution, Structure, and impact
- Will present combination of simulations, observations, and synthesis models

What is a Flux Tube?

- Ideal MHD's frozen-in flux condition
- Equation of motion has the pressure gradient and Lorentz term on RHS
- Magnetic force has two components - magnetic pressure term acting perpendicular to field and a tension term along field.
- Can think of flux tubes as mutually repulsive rubber bands

Pop Quiz

- **BACKGROUND:** Spacecraft X observes a magnetic field change over Y units of time.
- How do you know if the observed change in B is due to the relative motion of a boundary past the spacecraft or dynamics/global change/transient in the background configuration?

Lesson

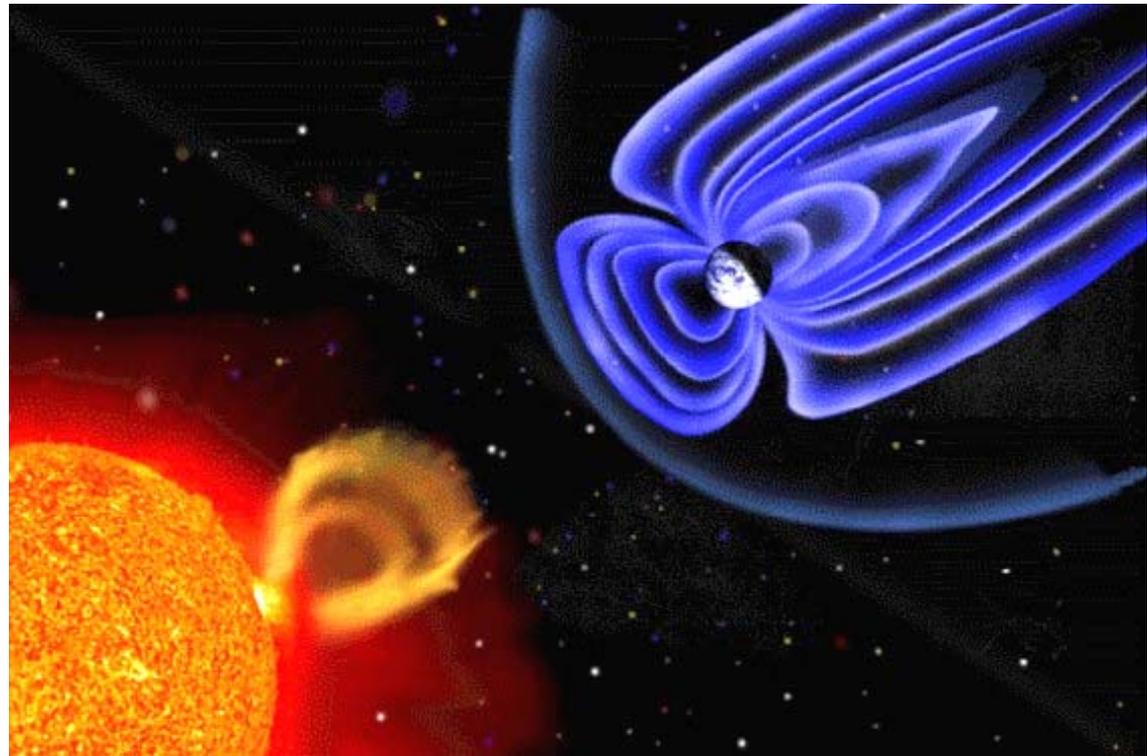
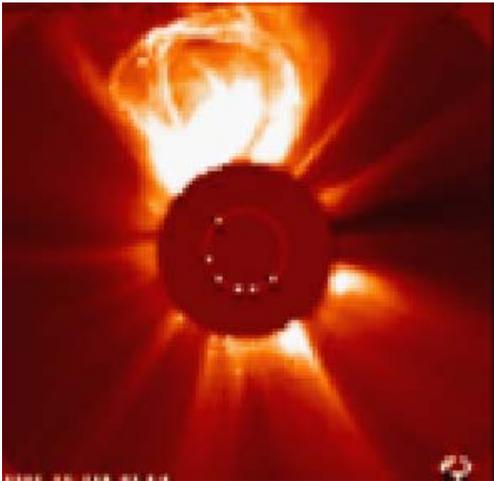
- Must make models to understand global structure and dynamics
- Must use statistics to understand global structure and dynamics
- Must make multiple, simultaneous, distributed measurements to understand global structure and dynamics

What are Flux Ropes, and Who Cares?

- Magnetized plasmas can form structures on various scales - shocks, discontinuities, waves, flux tubes, current sheets etc.
- Some are created by magnetic reconnection and can have sharp and clear boundaries
- Provide evidence of dynamics AND can give rise to significant energy and momentum flow from one region to another

Coronal Mass Ejections are the primary driver of major
Geomagnetic storms

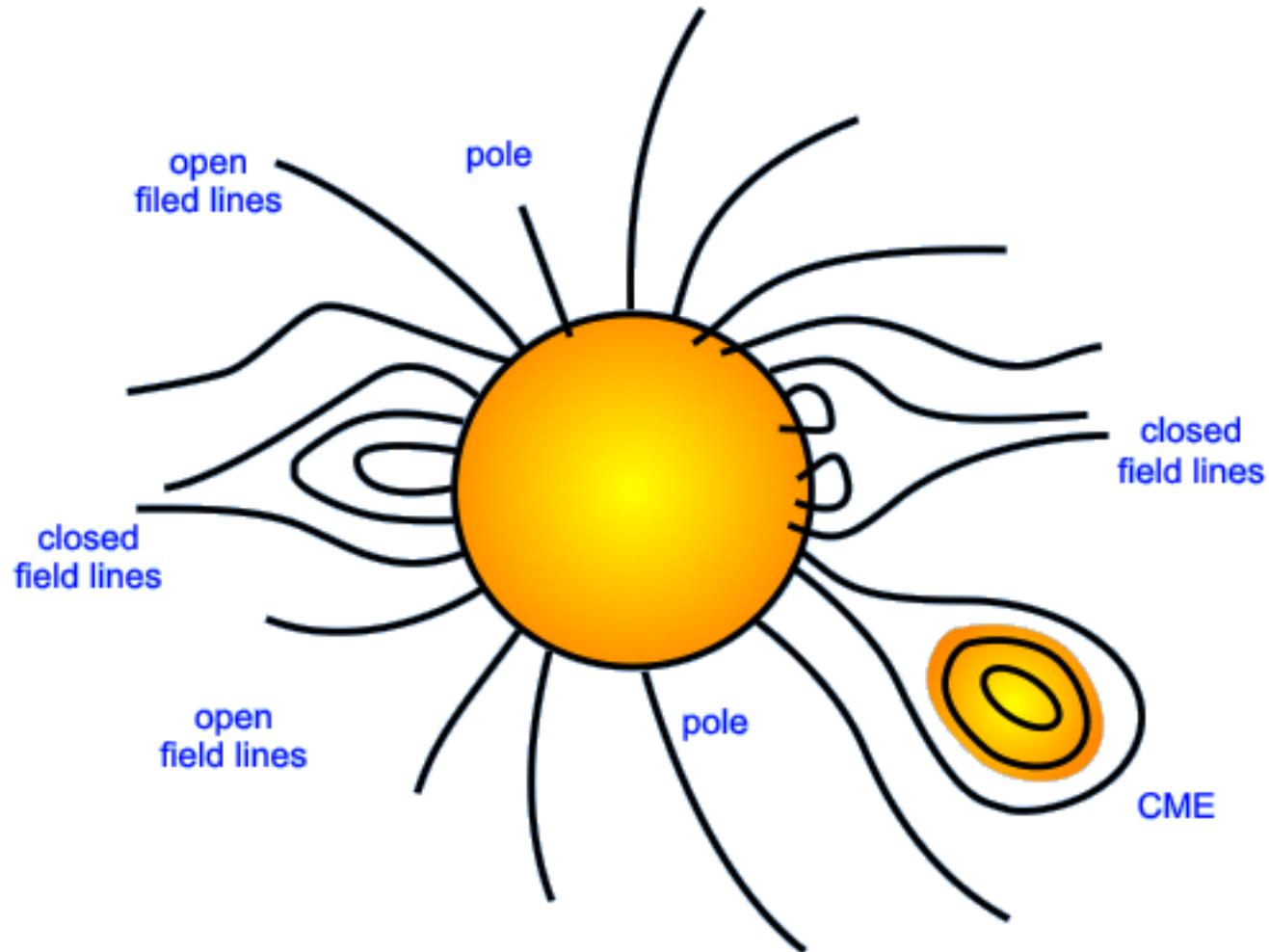
Their structure determines their geomagnetic effectiveness



Pop Quiz

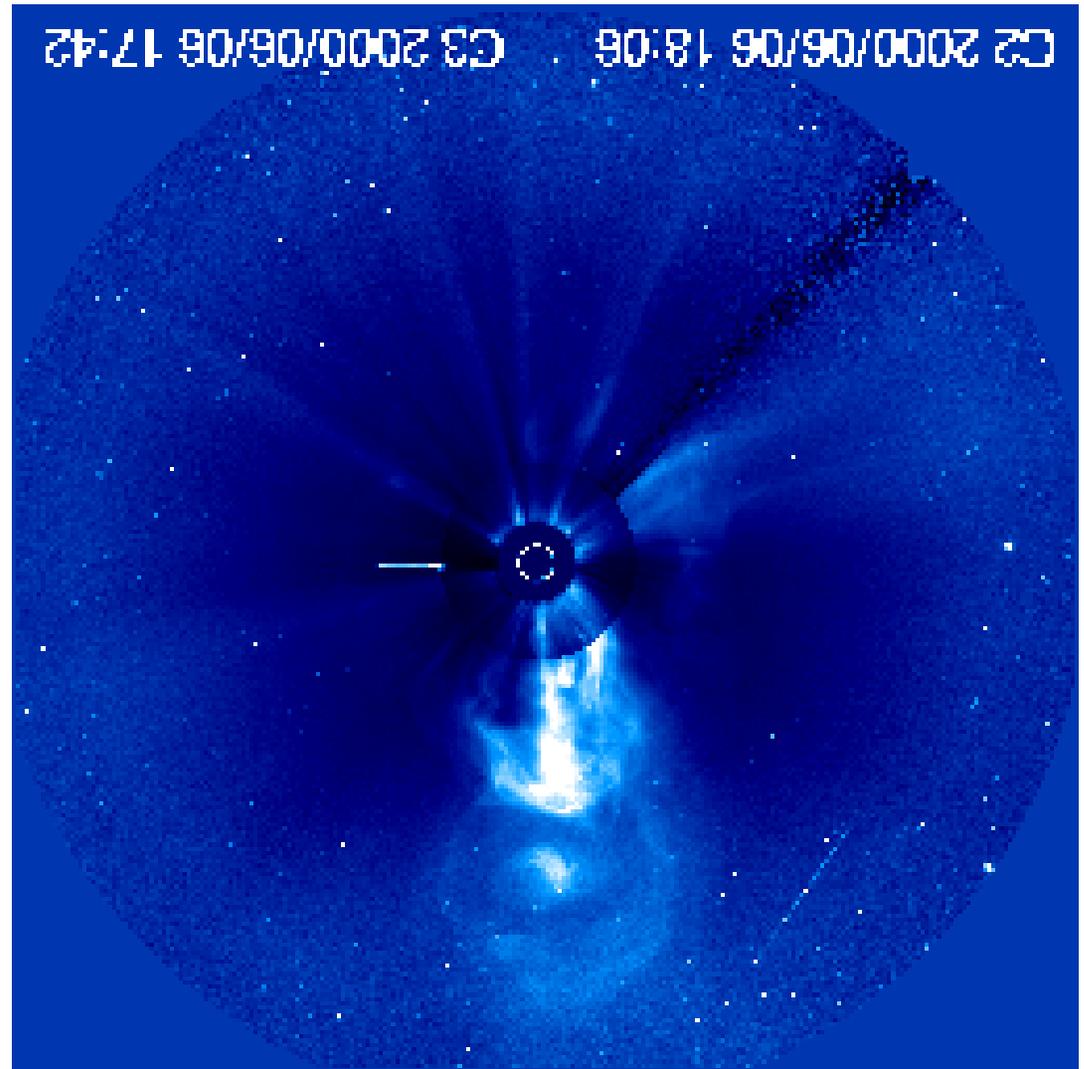
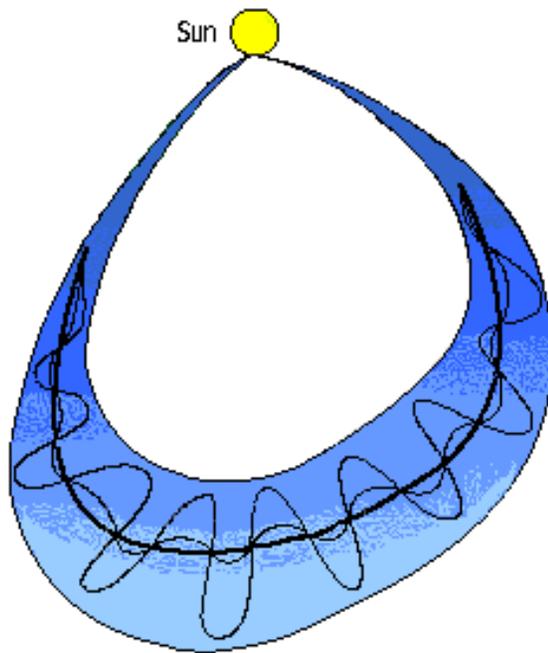
- Draw a cartoon model of the structure produced by magnetic reconnection in the lower corona to make a CME.
- What does it look like?
- How would you describe it without using technical words?

Creation of Coronal Mass Ejection by Reconnection in Solar Magnetic Fields



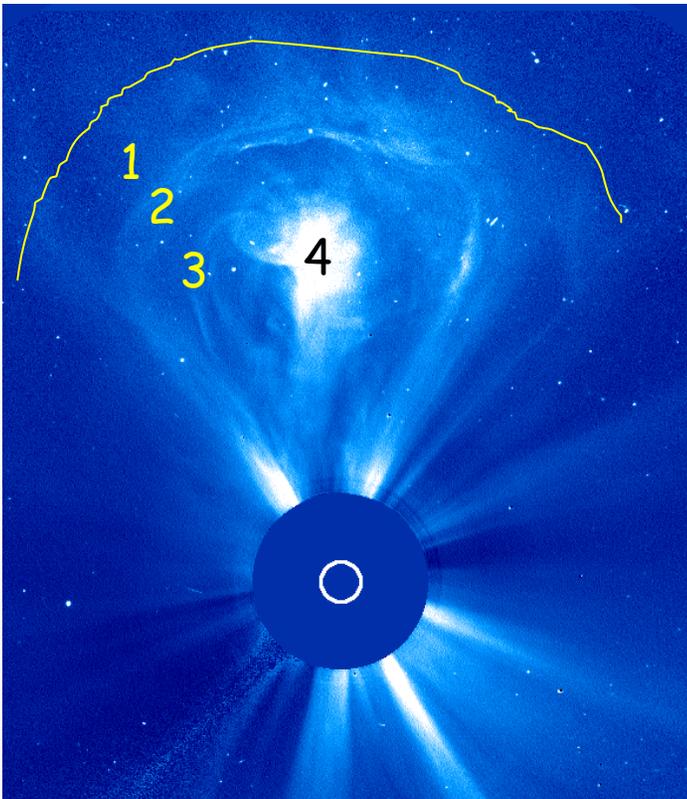
What is wrong with this picture?

CME Structure

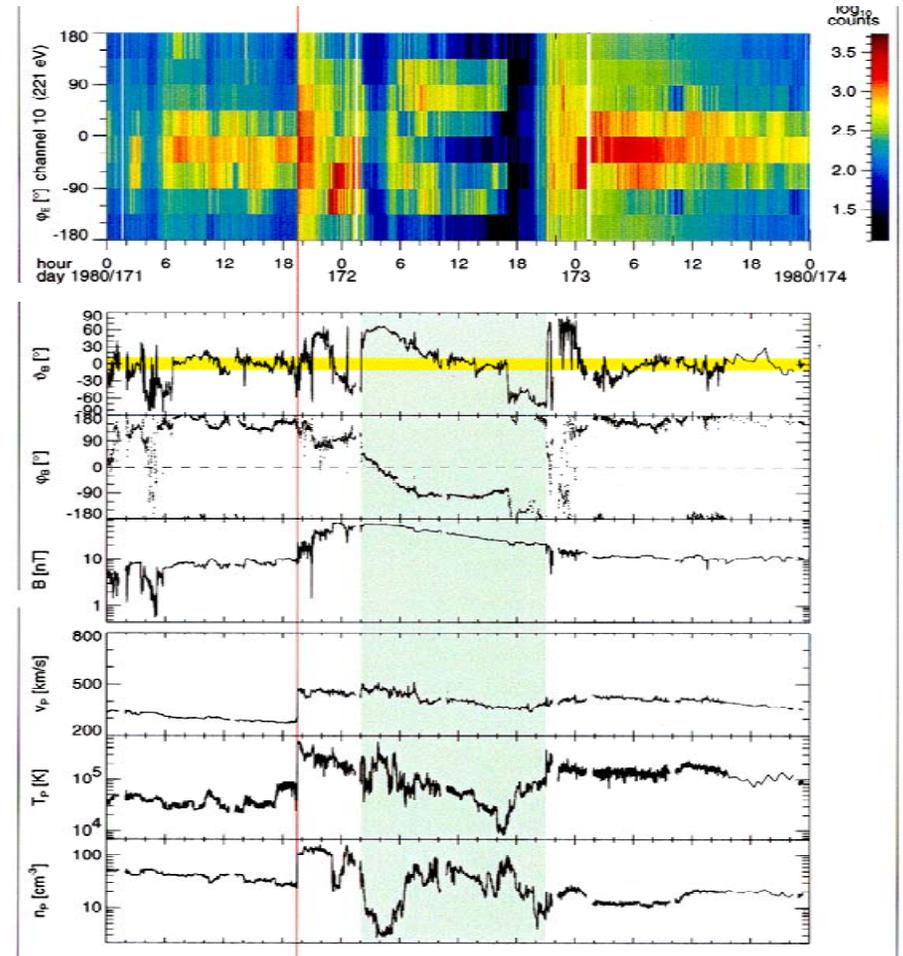


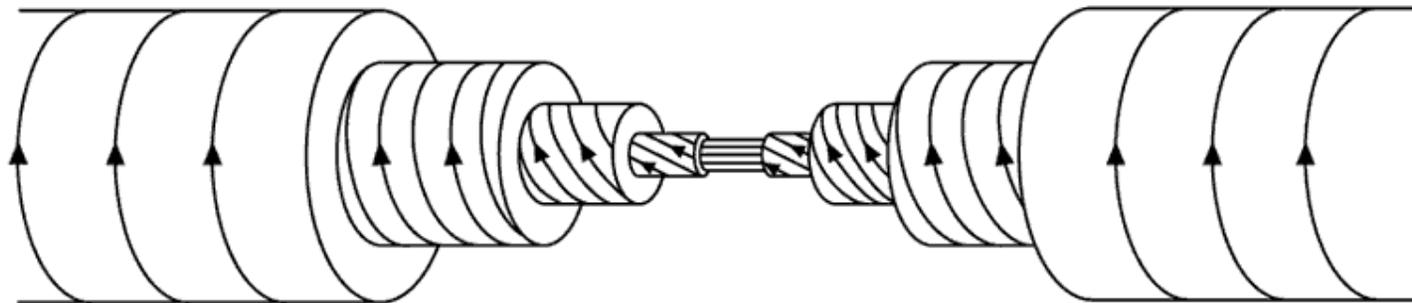
How to transform CMEs into ICMEs?

The majority of CMEs has a clearly discernible multi-part structure. But most ICMEs exhibit a very different two-part structure: a shock-compressed sheath layer followed by a rather homogeneous low beta plasma, with several other characteristic signatures.



From Schwenn





Interior Structure of Flux Rope

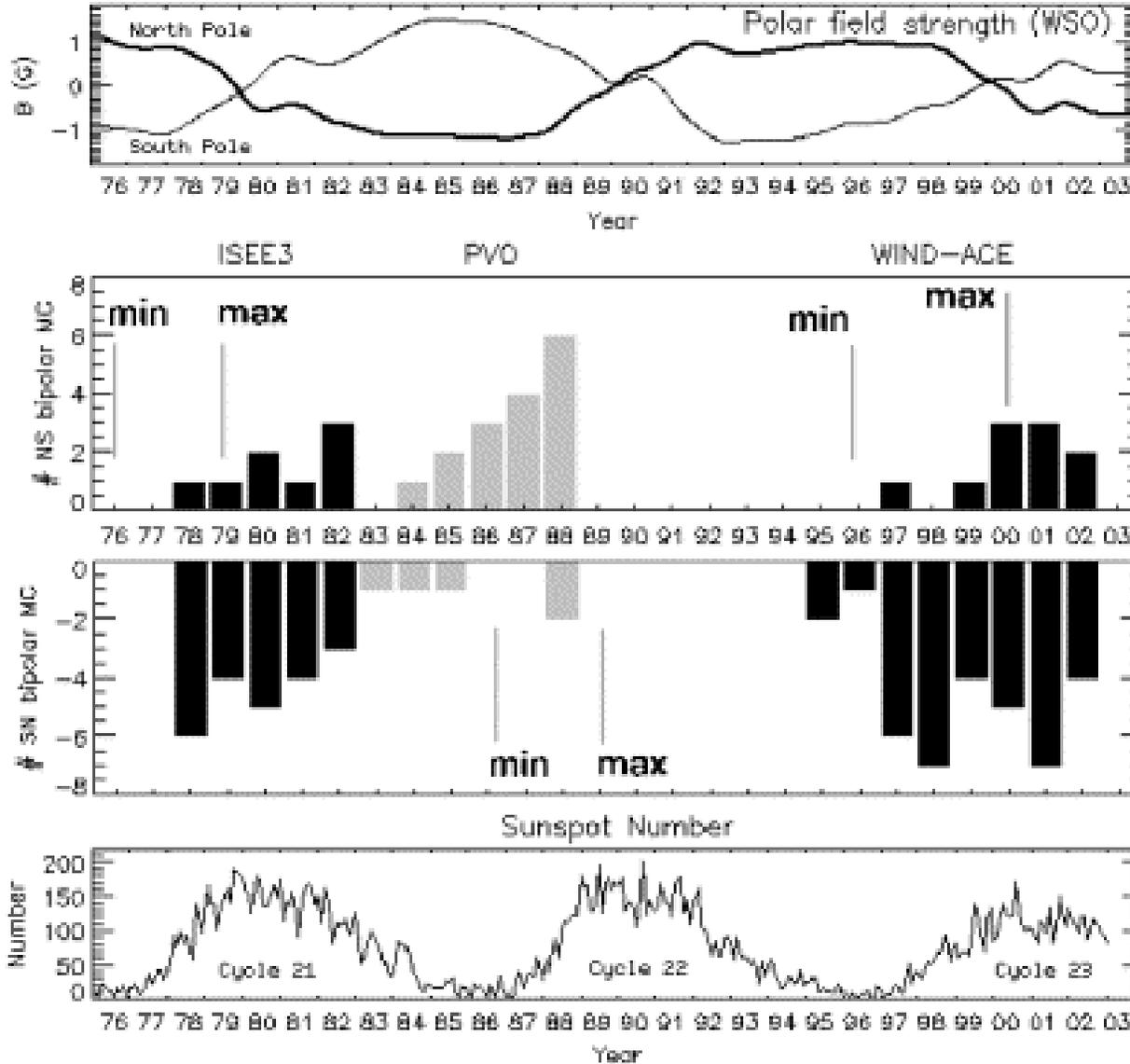
Russell and Elphic

Magnetic clouds have flux rope structure and polarity

Magnetic Rope Types Lying In Ecliptic Plane

Magnetic Cloud Type				
	SEN	SWN	NES	NWS
Leading Field	South (-Bz)	South (-Bz)	North (+Bz)	North (+Bz)
Axial Field	East (+By)	West (-By)	East (+By)	West (-By)
Trailing Field	North (+Bz)	North (+Bz)	South (-Bz)	South (-Bz)
Helicity	LH	RH	RH	LH

Bothmer and Schwenn and Mulligan et al



Li and Luhmann, 2004 Polarity has solar cycle dependence

Formation of Coronal Mass Ejection

- **Breakout CME:**
reconnection in front of CME allows it to erupt
- **Most models:**
reconnection behind CME, cuts fieldlines connecting it to the Sun, and causes flaring and particle acceleration
- **In some models,**
reconnection below CME is main driver of eruption

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

MacNeice et al. 2004

3D Model of CME

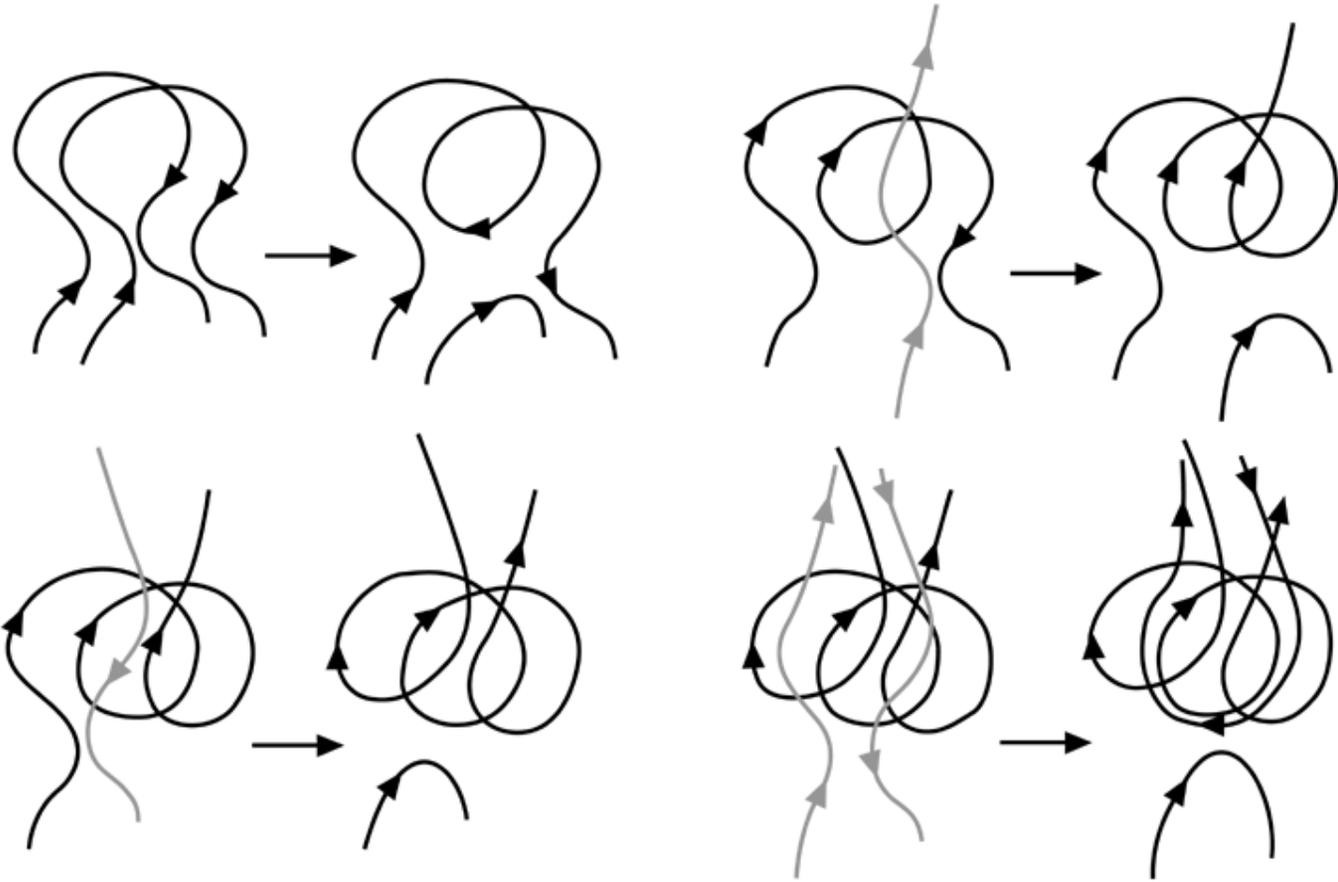
(Lynch et al)

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

Legs of CME collide at an oblique angle.
Flare reconnection forms tangled arcade below,
3D flux rope/knot above.

Reconnection with guide field is key to understanding CME's.

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



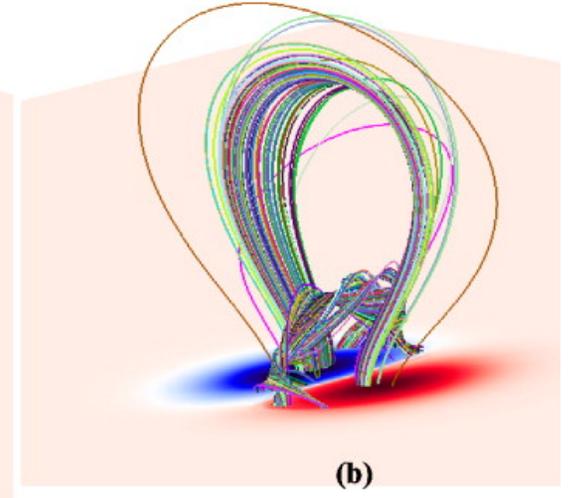
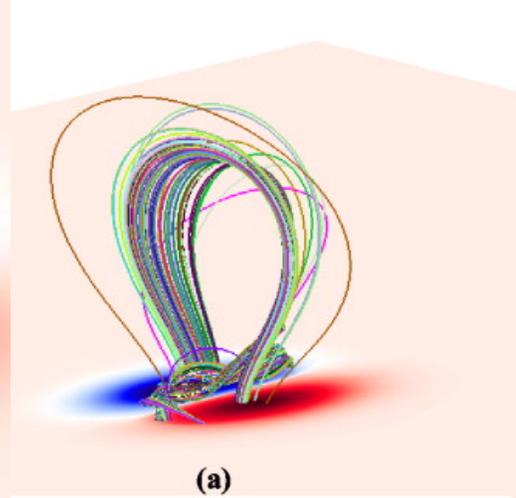
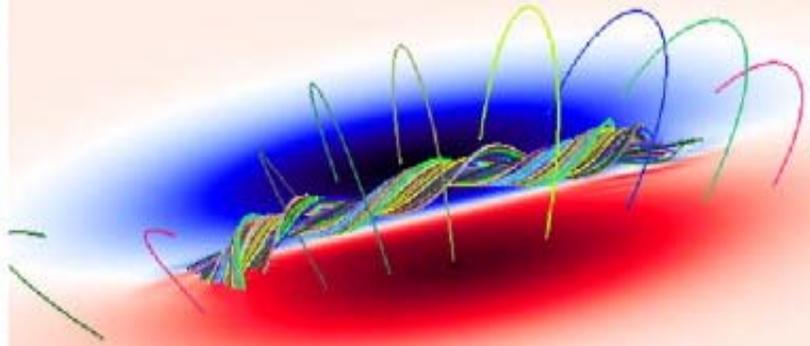
Russell

CME Current Sheet Evolution

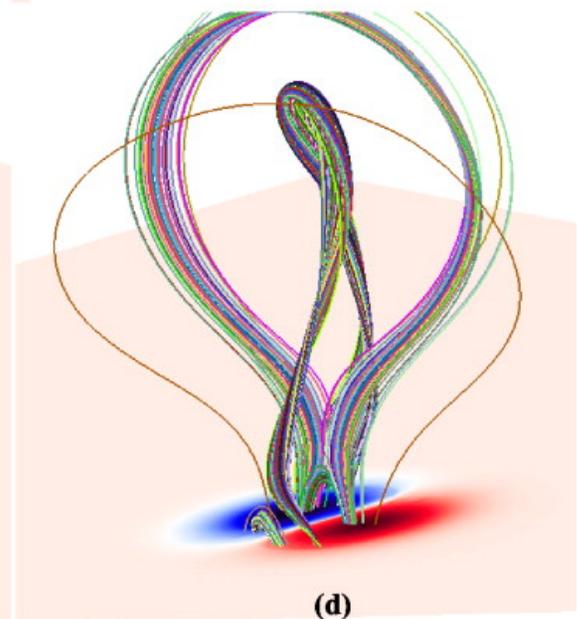
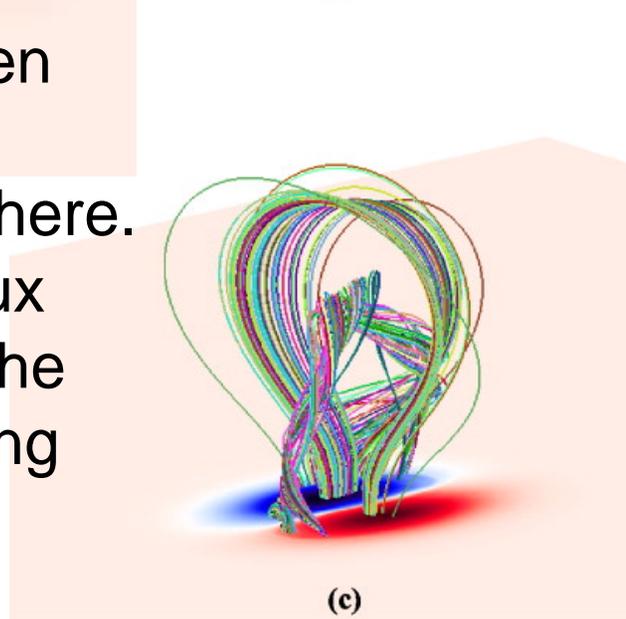
- CME erupts with the field still attached to the photosphere
- Eruption brings CME legs together – forces a current sheet to develop
- Reconnection is then initiated in the current sheet, cutting the fieldlines which attach the CME to the photosphere

3D Model of CME – Flux Cancellation

(Amari et al 2003)



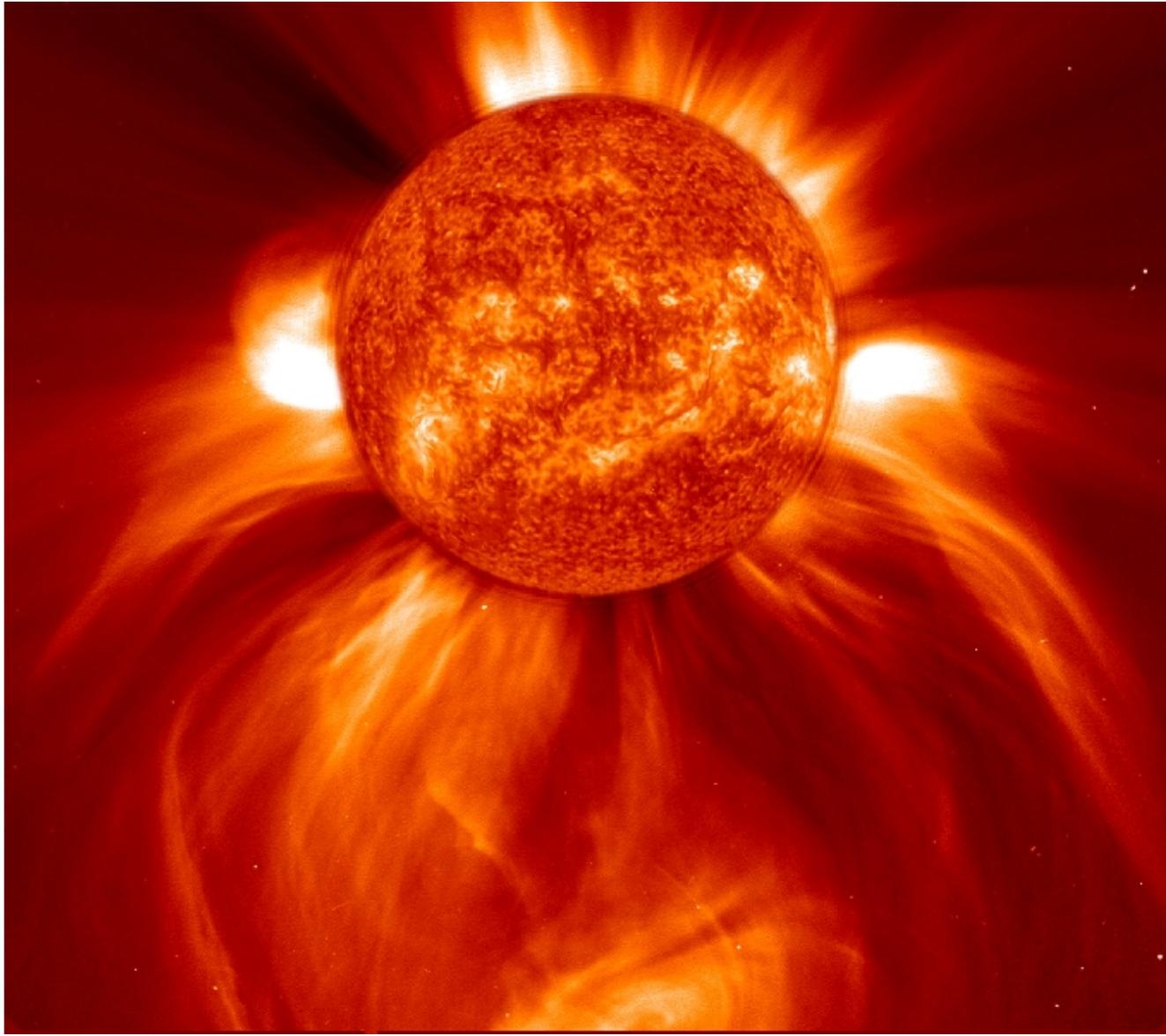
Shear magnetic field, then cancel flux by diffusion, reconnection at photosphere. This creates a twisted flux rope. For strong shear, the Rope erupts, reconnecting with overlying field.

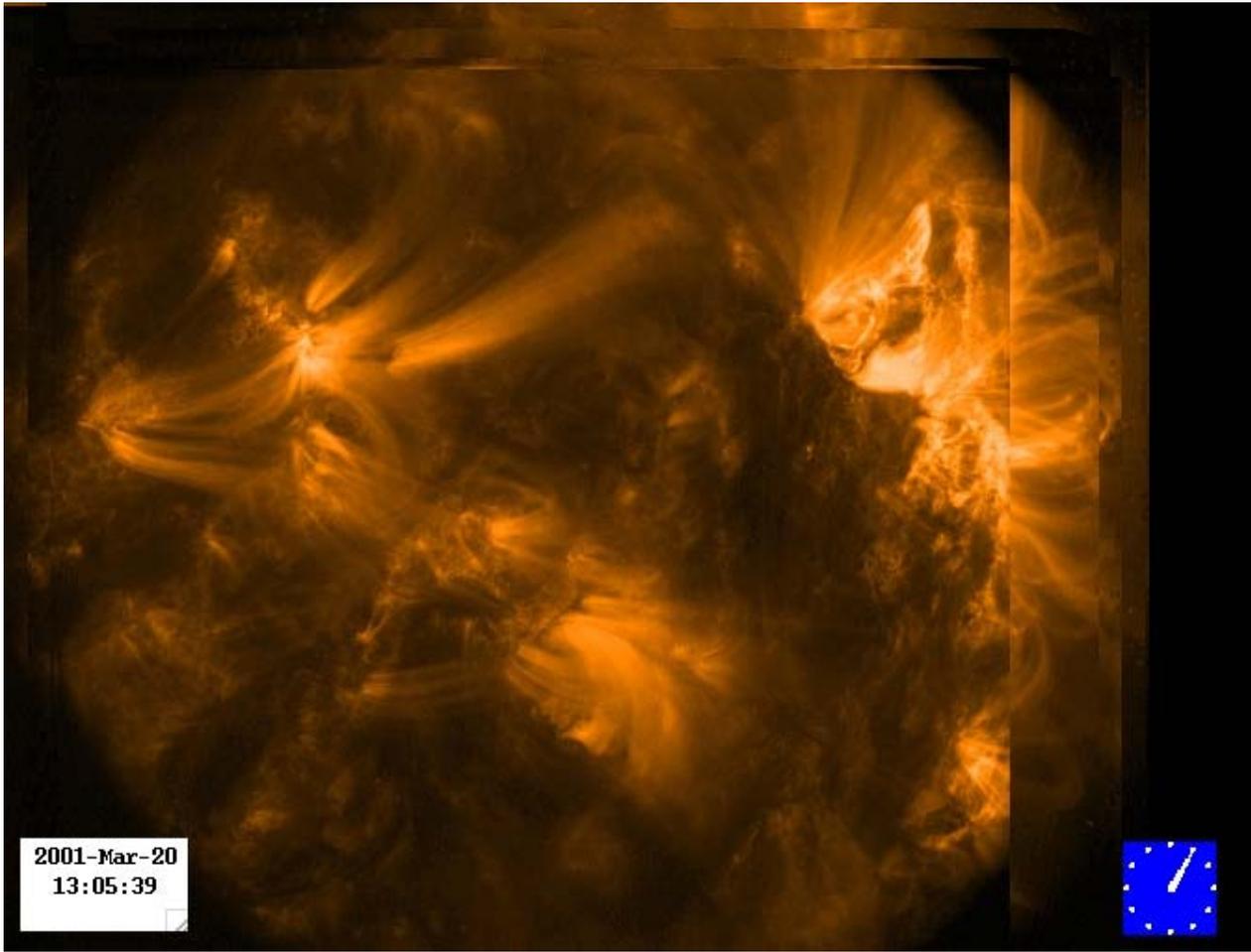


Note: In this scenario, formation of flux rope happens **before** eruption. In “breakout” flux rope forms **during/after** eruption.

3D effects in CME Generation

- Guide field is likely to be common in current sheets behind erupting CME and in the magnetotail
- Reconnection will be “component” rather than exactly anti-parallel
- Resulting flux rope will have twist wrapping around the guide field
- Tangling of CME field-lines will result if more than one reconnection region is excited





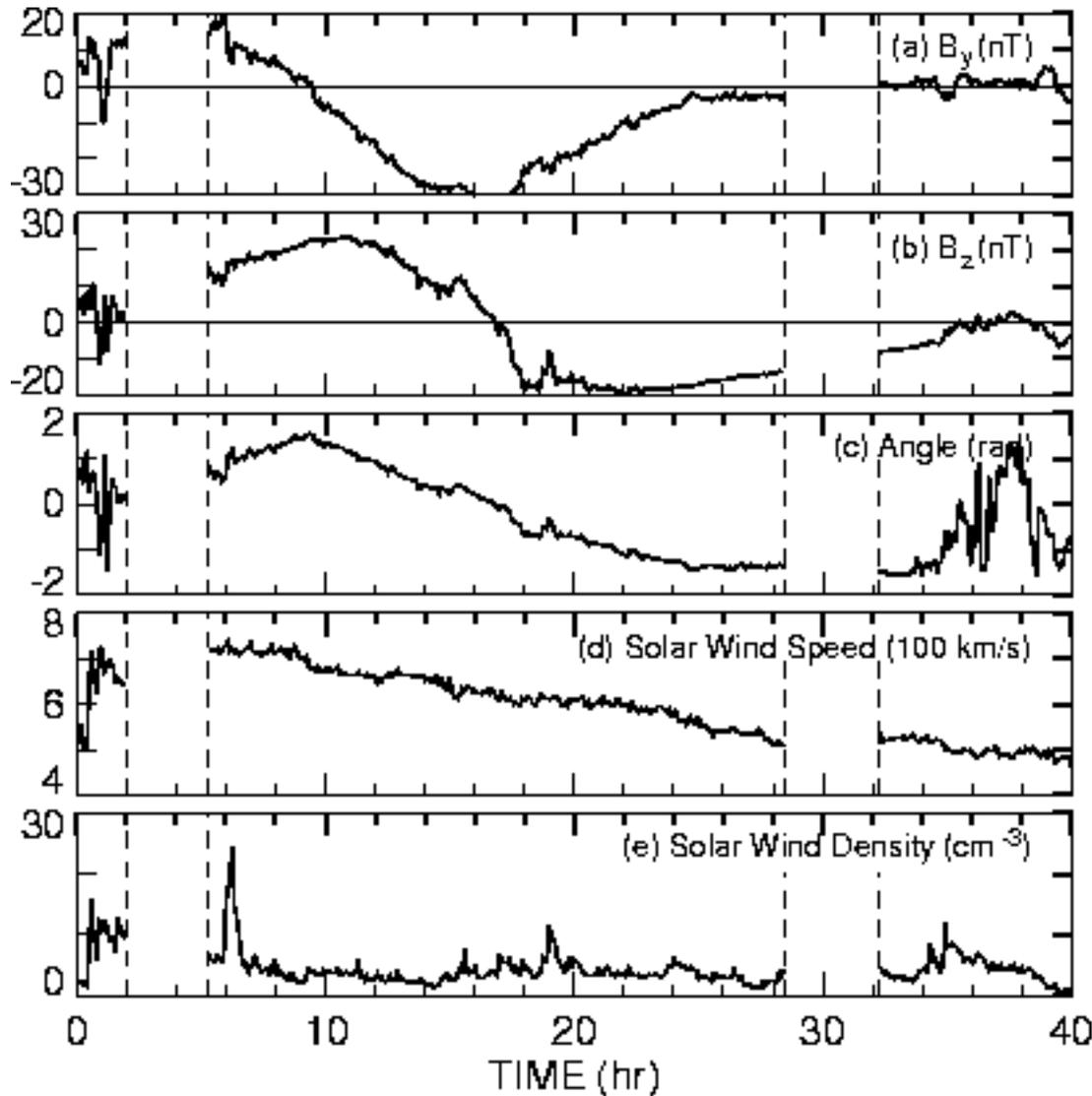
Observation of Coronal Mass Ejection

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

- **Eruption from Corona of magnetic field and plasma**
- **Magnetic field bulges out, then pinches together behind eruption, leading to post-CME reconnection**
- **Coronagraph and in-situ measurements both consistent with twisted flux rope magnetic structure**

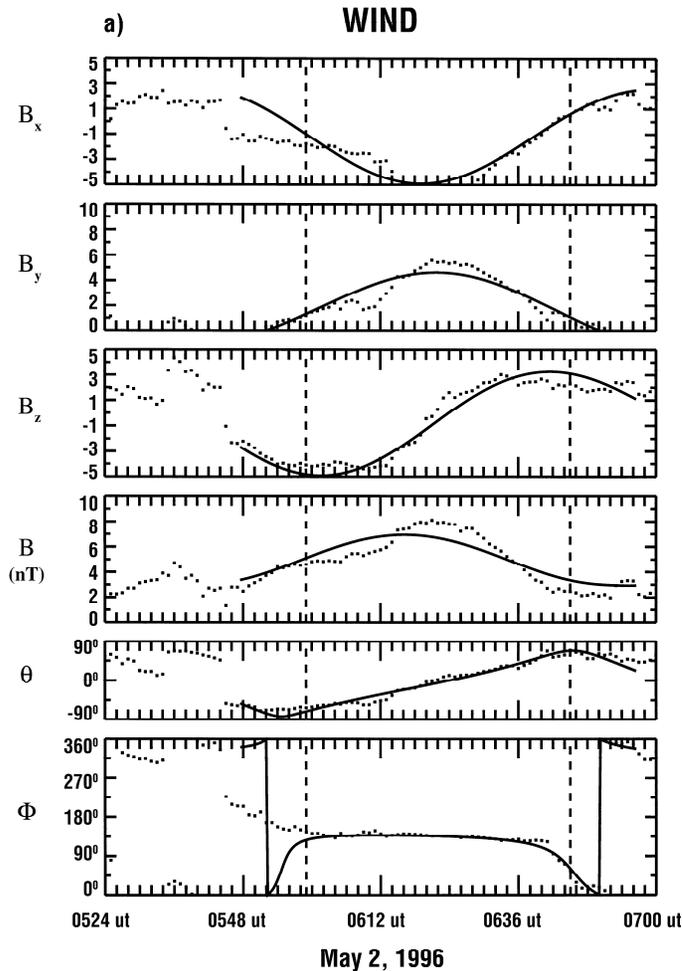
LASCO C2 Coronagraph

ICME Magnetic Signatures



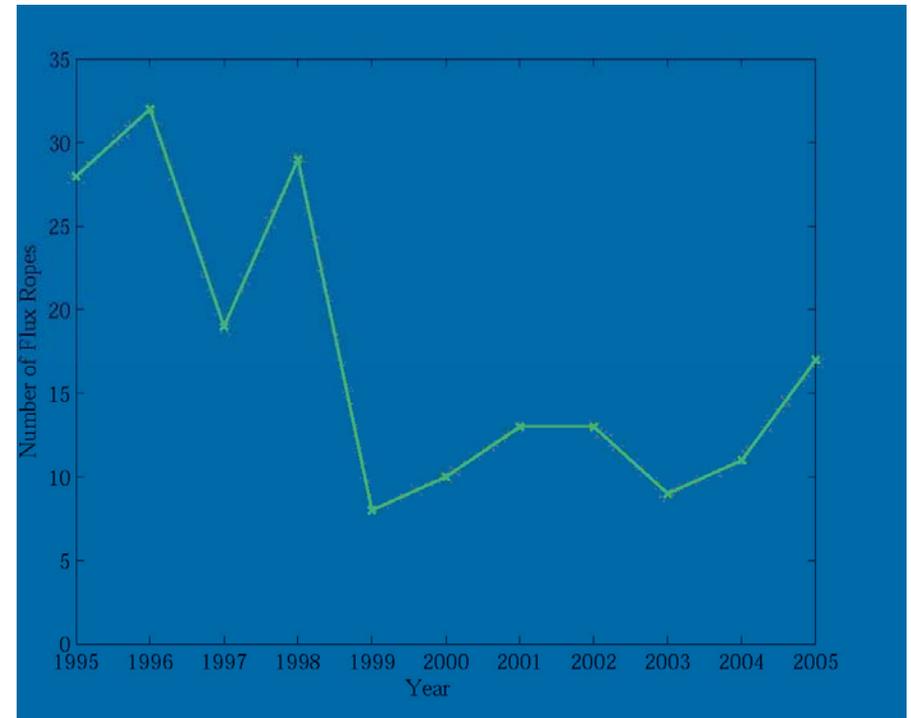
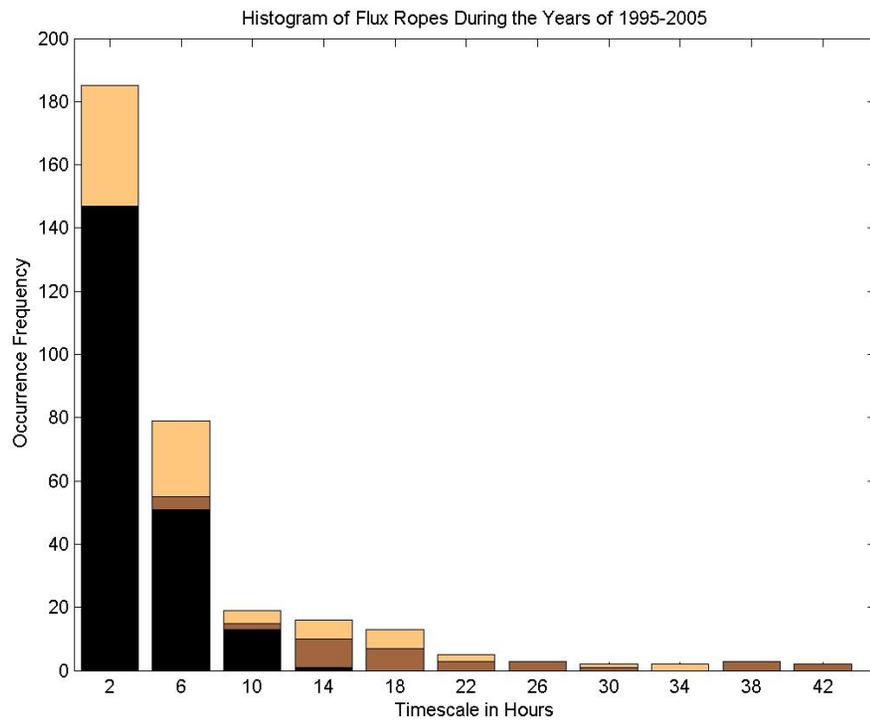
Flux rope signature: Increase in magnetic field strength within flux rope. Strong component of twist (B_z) and guide field (B_y) are both present.

Reconnection across HCS?



- New class of flux ropes discovered in solar wind (Moldwin et al., 2001)
- Scale order of an hour

Small Flux Rope Properties

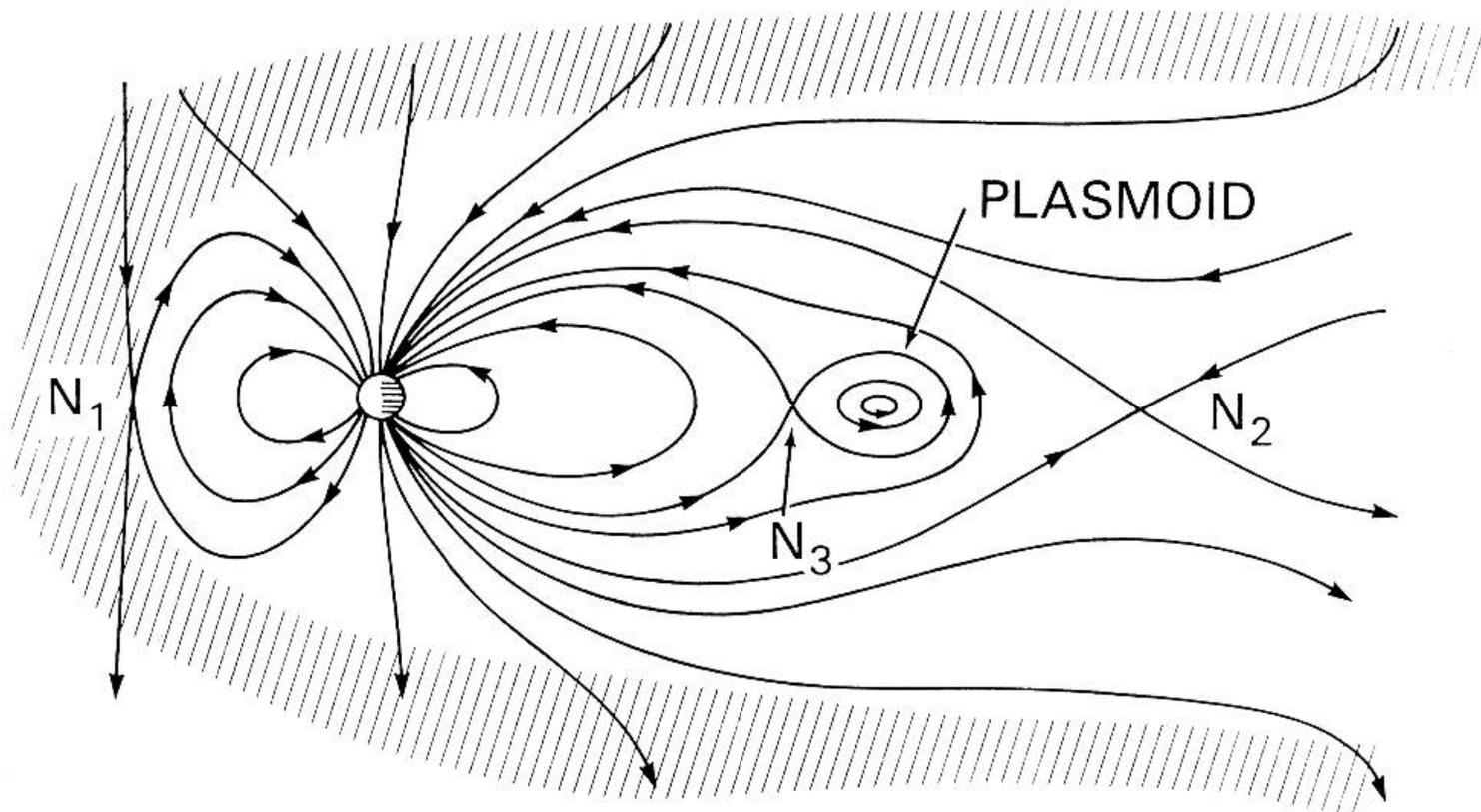


Cartwright and Moldwin, 2007

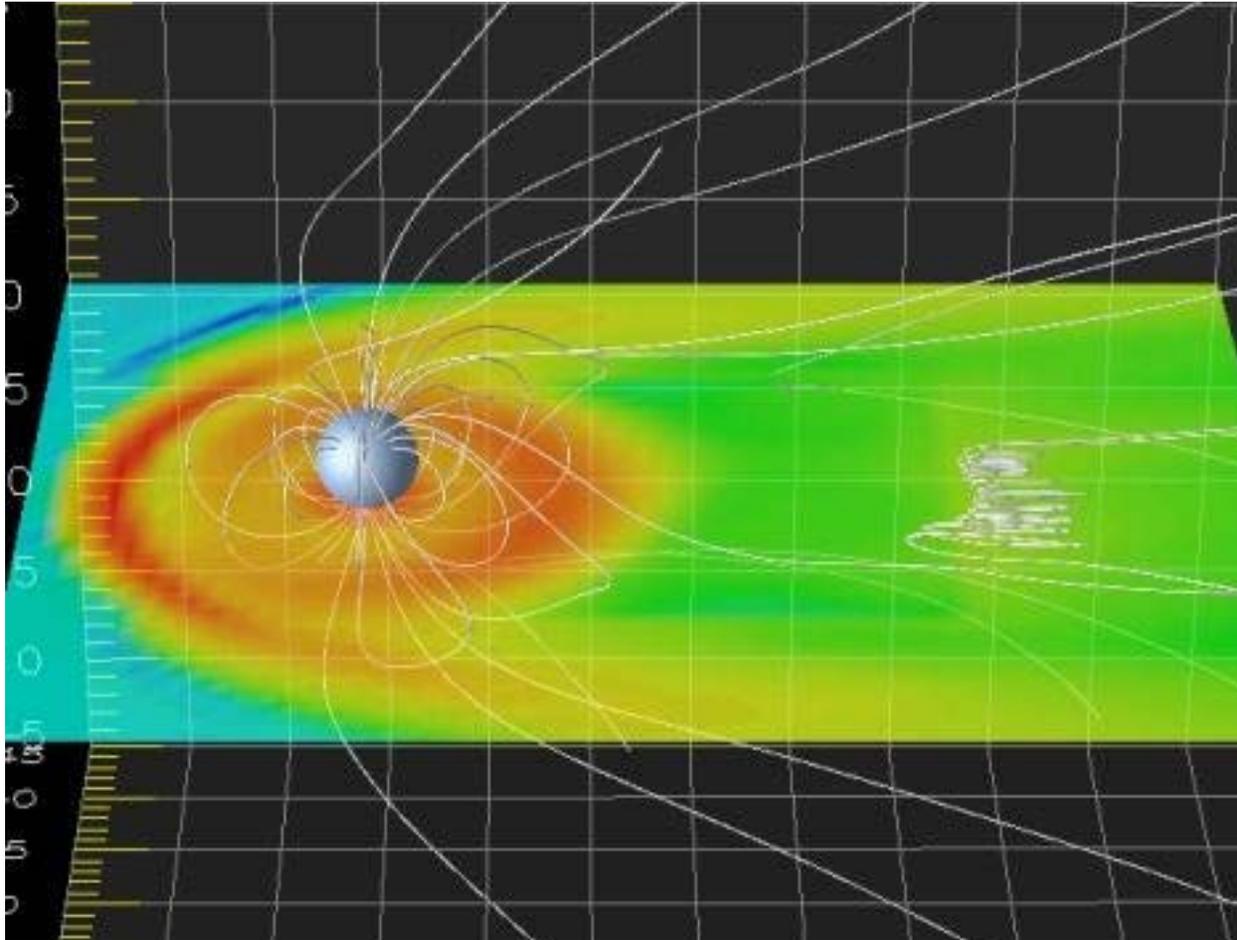
Magnetotail Current Sheet Evolution

- Solar wind extends Magnetotail on night side of Earth
- Disturbance in solar wind, sets off reconnection in Magnetotail
- Plasmoid forms between reconnection site and pre-existing tailward X-point
- Plasmoid is ejected from Magnetotail

Creation of Plasmoid by Magnetic Reconnection in Earth's Magnetotail

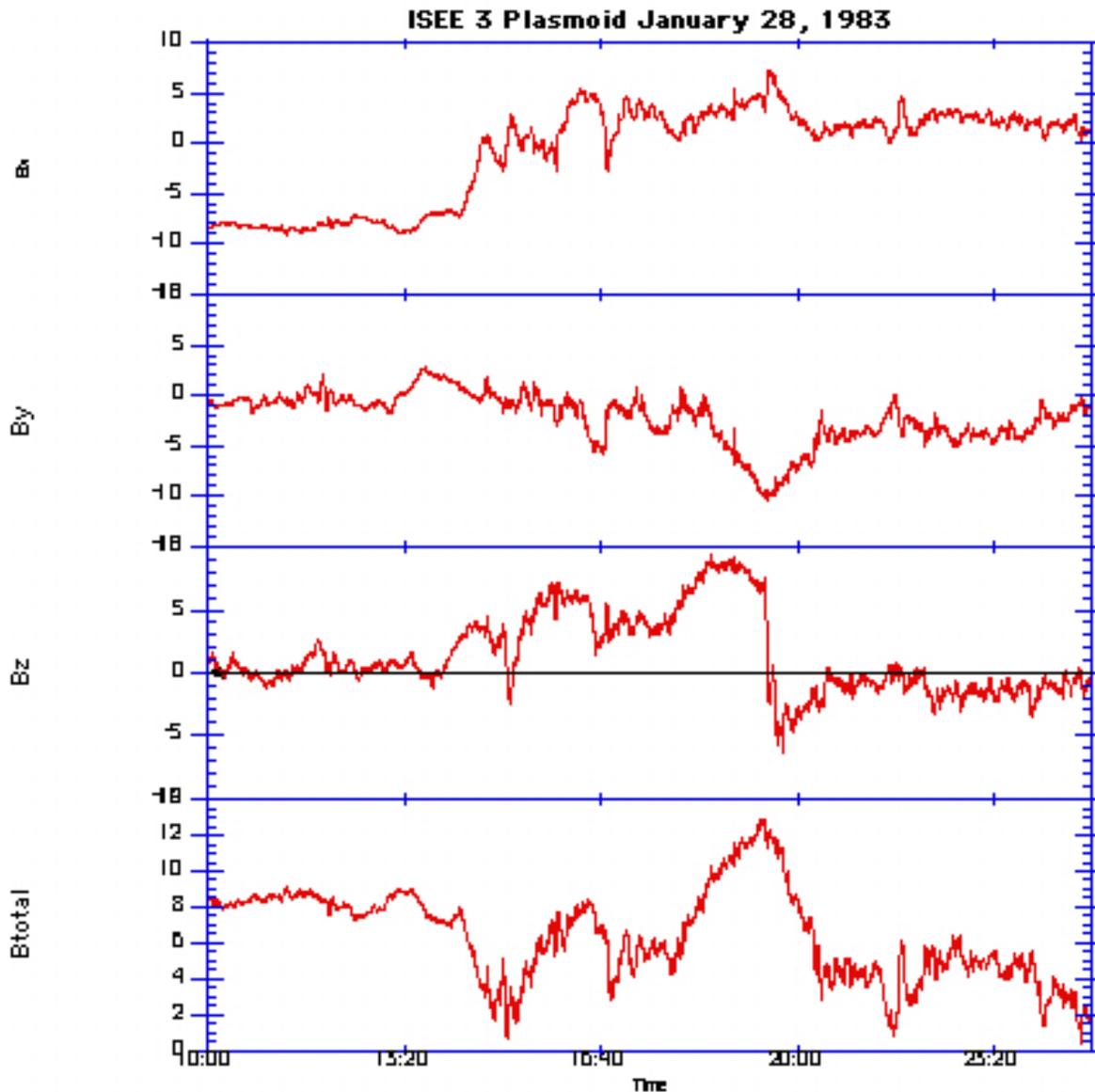


Formation of Plasmoid



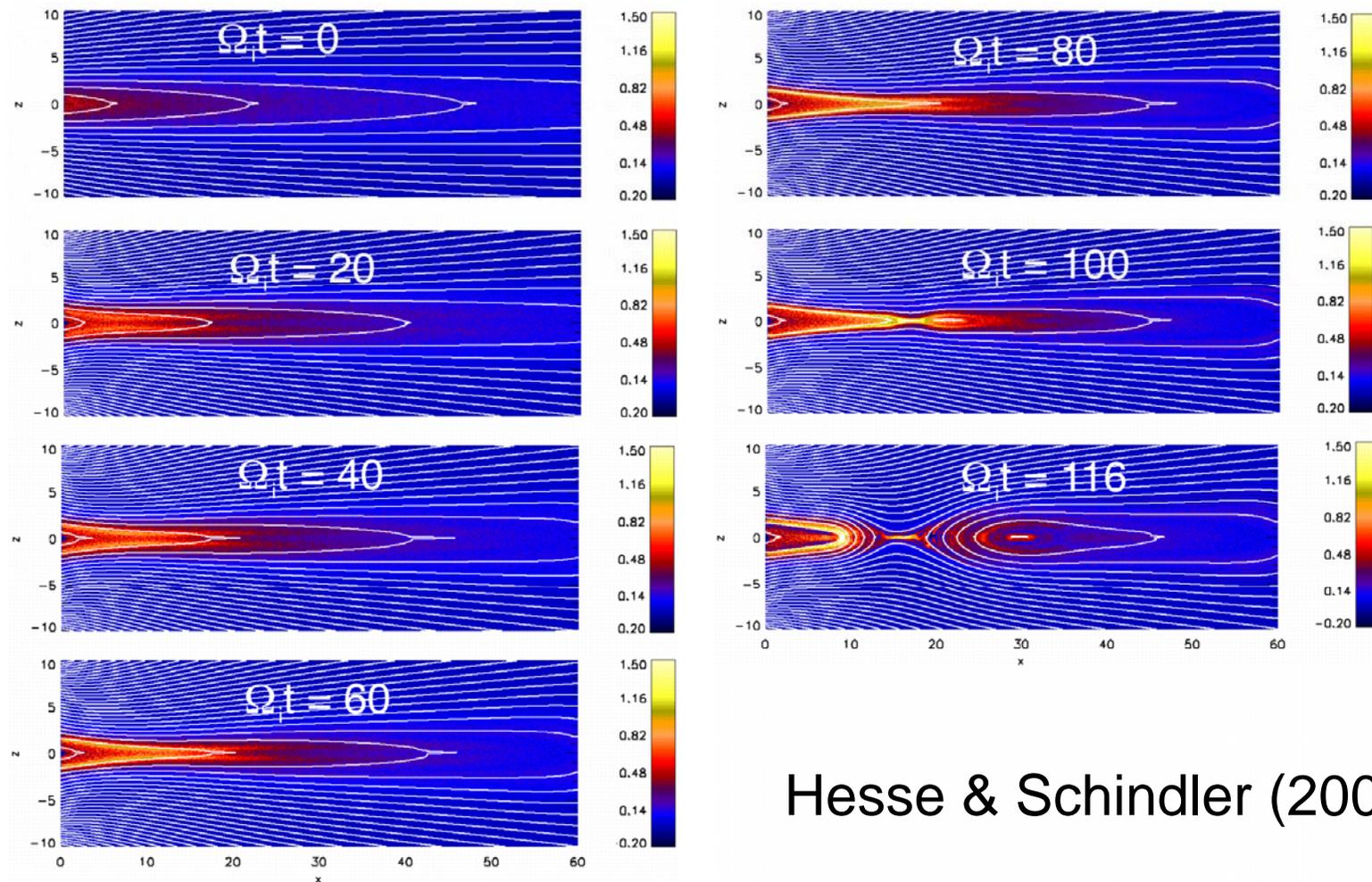
Magnetotail current sheet forms – similar to Post-CME current sheet. Localized reconnection forms plasmoid, tearing mode can lead to tangling, multiple plasmoids, as in post CME flare.

Plasmoid Magnetic Signatures



Magnetotail plasmoid structure: magnetic features show same flux rope twisted structure with guide field as is seen in CME fields.

Plasmoid Formation in Magnetotail



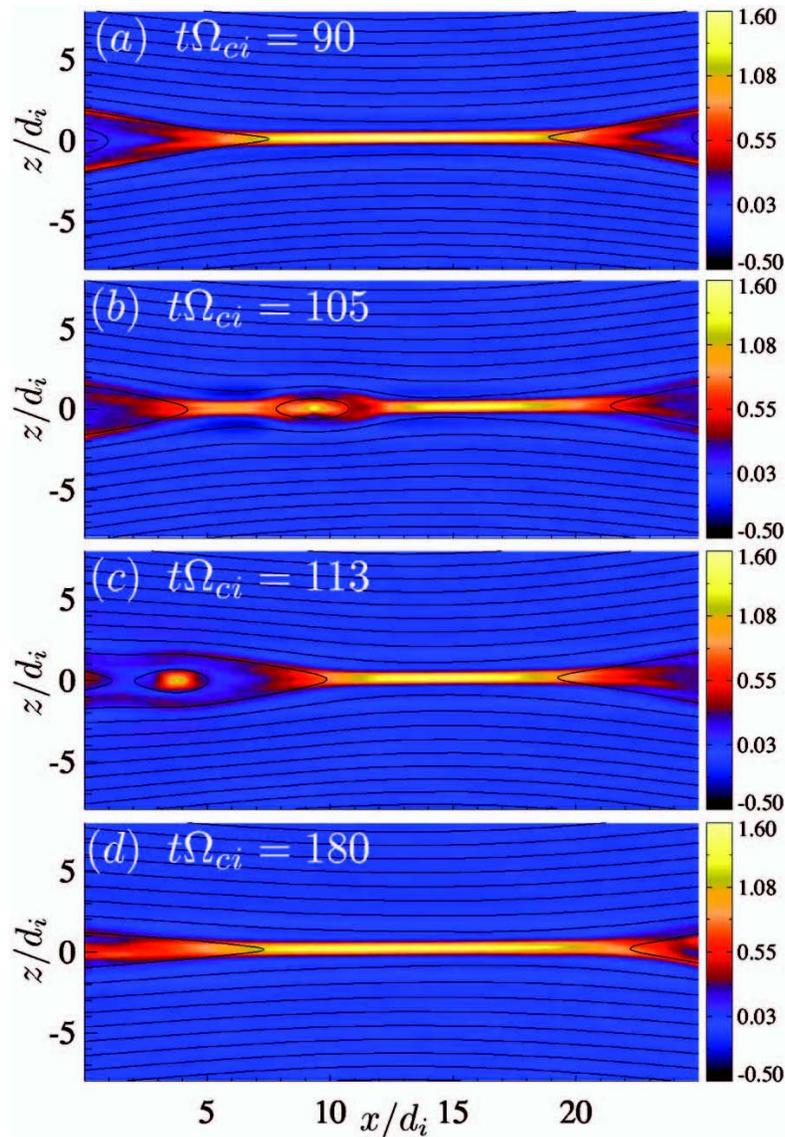
Hesse & Schindler (2001)

Start with magnetotail-type configuration.

Perturb the equilibrium, pinch off region in tail, creating X-point.

Reconnection at X-point generates disconnected island/plasmoid.

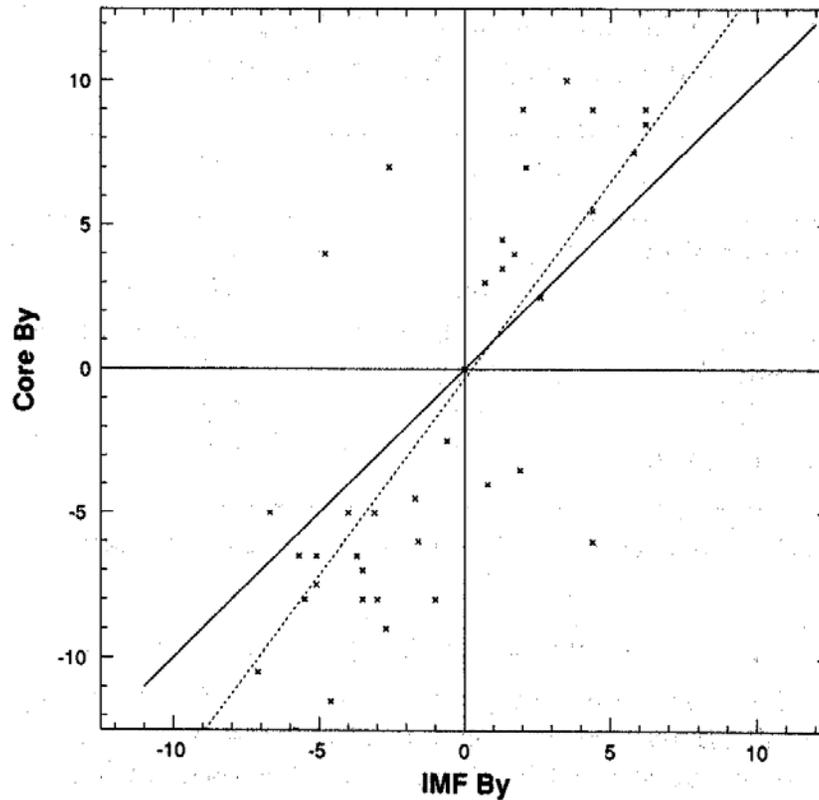
Generation of Multiple Islands/Plasmoids under Magnetotail conditions



Long current sheet, with open boundaries, e.g. Magnetotail, is unstable to spontaneous tearing. Leads to generation and ejection of multiple magnetic islands/plasmoids

**Daughton, Scudder,
& Karimabadi, 2006**

Plasmoid Core Field correlation with IMF By Direction
(same as Magnetic Cloud Core Field
correlated with source field)



Properties of Flux Ropes

- Helical field structures with core fields
- Often current sheets at edges
- Wide range of scales
- Magnetic Reconnection needed for formation
- Carry significant energy, mass, momentum

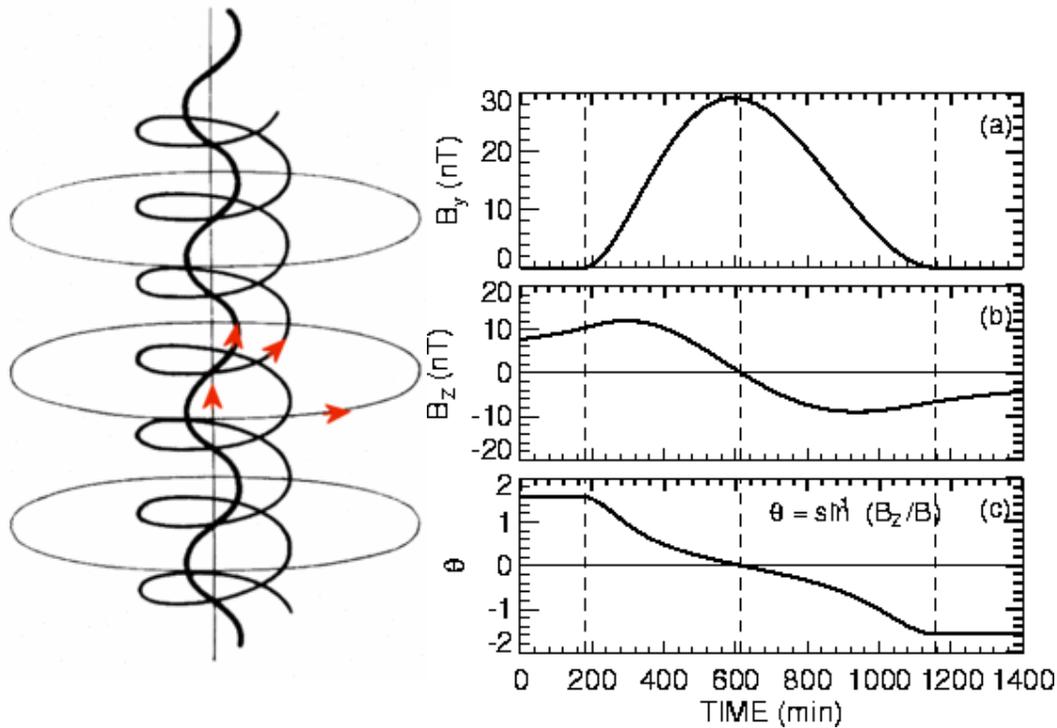
Flux Rope Model

- Simplist model is a force free cylindrical model that can be represented by Bessel functions
- Force Free $\mathbf{J} \times \mathbf{B} = 0$
- What is a none trivial or potential field solution to this equation?

Lundquist Soln

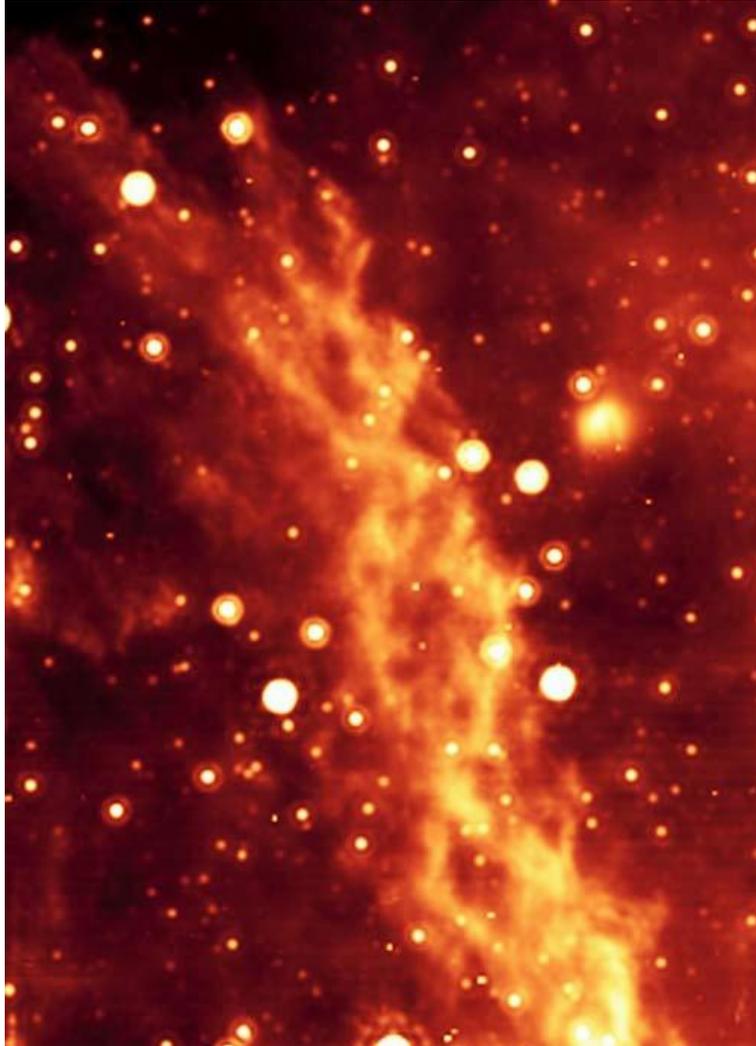
- $\mu_0 \mathbf{J} = \alpha \mathbf{B}$
- So \mathbf{J} has to be parallel to \mathbf{B} and α is some scalar function of position and time
- If α is constant then from Ampere's law get a Helmholtz Equation whose solution are Bessel functions.

Flux Ropes



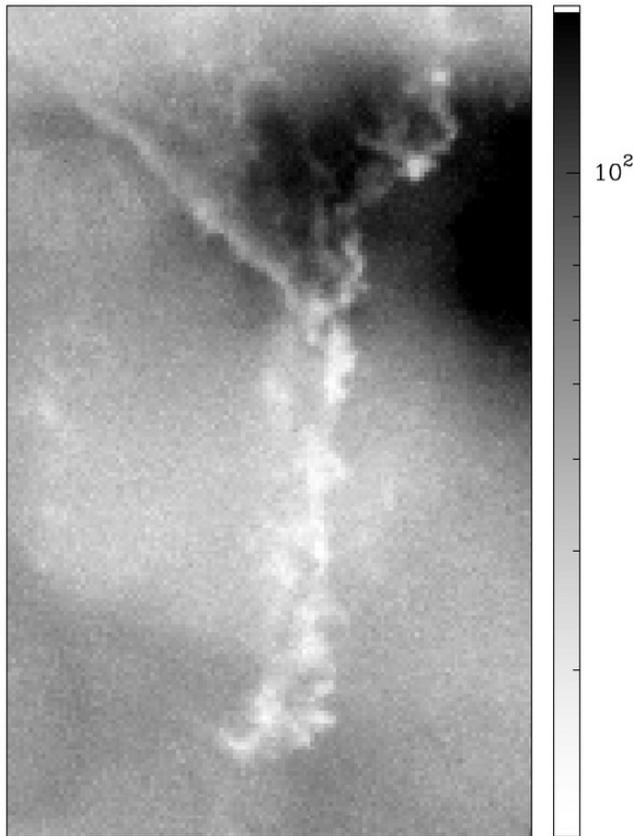
- The center of the rope is the core field
- Edges of rope often have current sheets to separate it from surrounding plasma

Double Helix Nebule



- IR image
 - Near center of Milky Way
 - About 80 LY long
- Morris et al. Nature, 2007

Hubble Image of Planetary Nebula



- Twisted knots suggestive of flux ropes
 - Scale 100s of AU
- Dahlgren et al., 2007

Take Home Message

- Flux Ropes are formed by reconnection or strong shearing of magnetic fields
- Observed throughout space
- Guide field is often present – creates twisted flux rope, with twist field wrapped around an axis of guide field
- Play significant role in energy, mass, and momentum transfer in Sun-Earth relationship (CMEs and storms, magnetotail flux rope plasmoids and substorms)