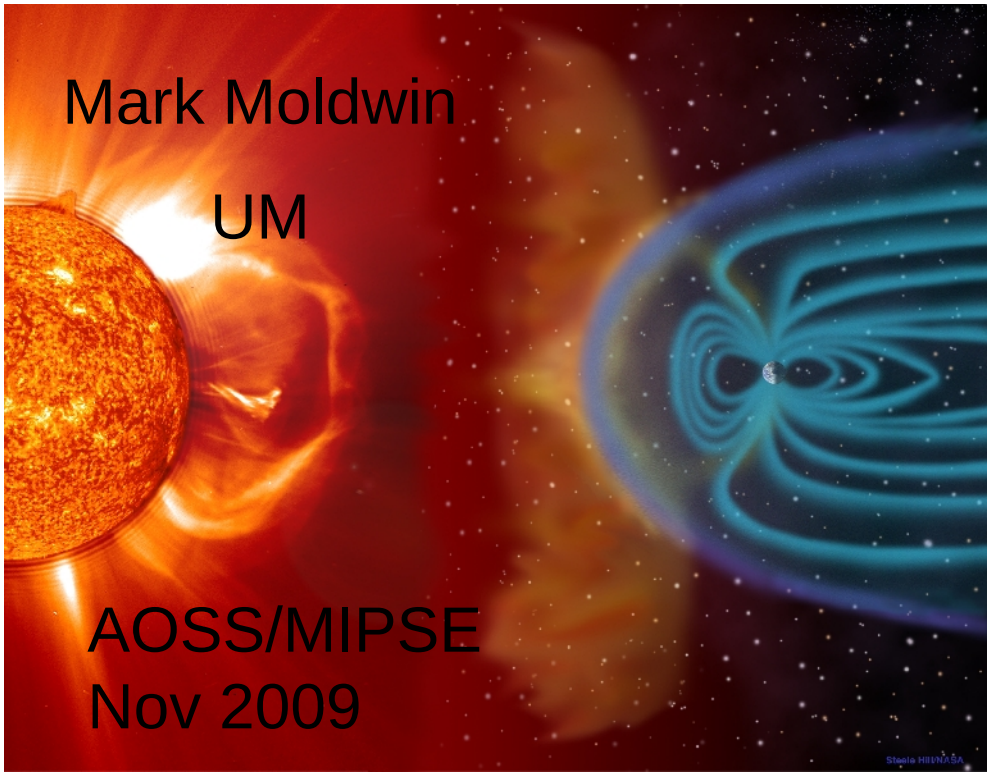
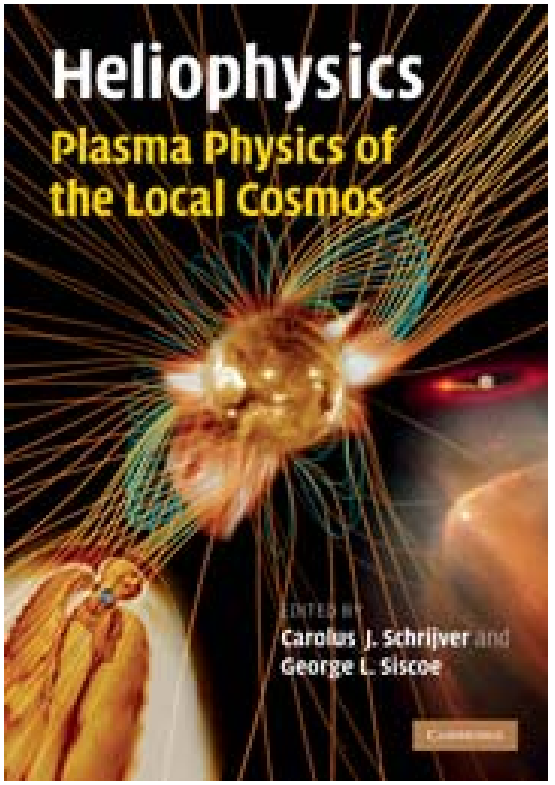
Universal Magnetic Structures



With thanks to Mark Linton at NRL
Linton and Moldwin, JGR, 2009



Cambridge Univ Press, 2009

Goal of Seminar

- Introduce one of the most ubiquitous features in magnetized plasmas
- Describe their Origin, Evolution, Structure, and Impact
- Organizing magnetized plasma domains by their structure reveals that there are universal structures that span all scales and tell us about universal processes that create them.

Universal Magnetic Structures

- Magnetized plasmas form a FINITE set of structures seen over wide range of scales
- For this seminar, I posit that there are only three groups – flux tubes, cavities, current sheets.
- What does this tell us about magnetized plasmas? Why only three?

Pop Quiz for Grad Students

- 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 (or take pictures and invert)
- Will show results using these approaches

Examples of Three Groups

- Cavities: Magnetospheres, heliospheres
- Current Sheets: Heliospheric Current Sheet, magnetospheric current sheets
- Flux Tubes: What I will focus on today

What is a Flux Tube?

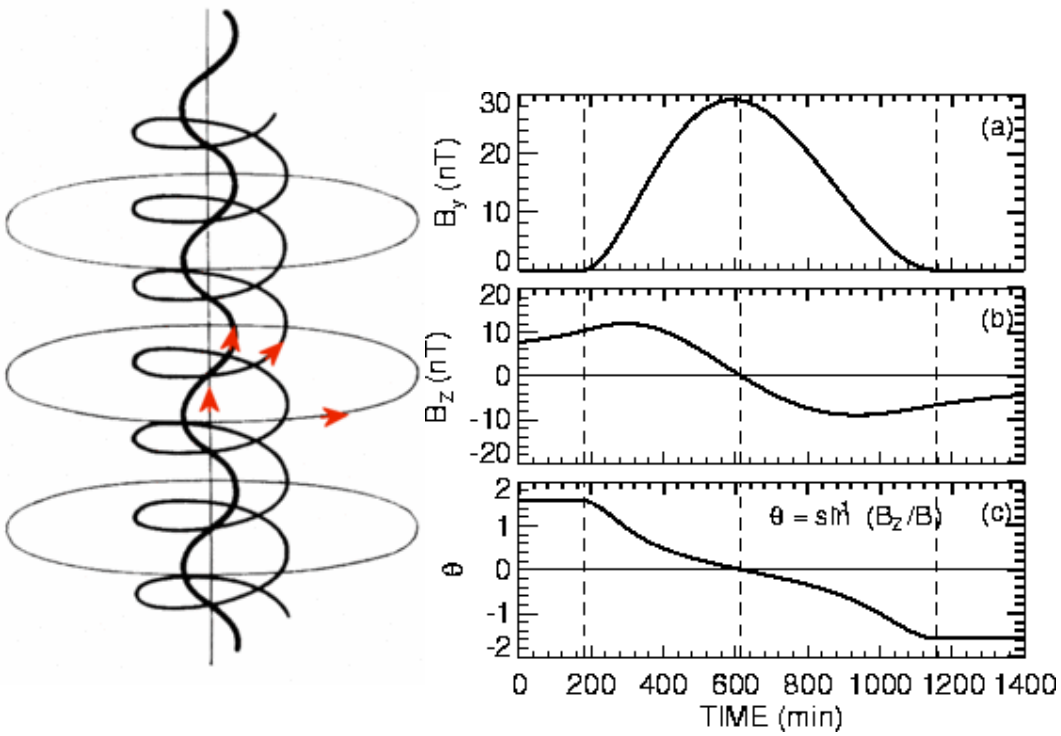
- Ideal MHD's frozen-in flux condition
- Equation of motion has the pressure gradient and Lorentz term on RHS
- Magnetic force has two components - magnetic pressure term acting perpendicular to field and a tension term along field.
- Can think of flux tubes as mutually repulsive rubber bands
- They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

What are Flux Ropes, and Who Cares?

- Currents can cause the field to twist – hence the term “rope”

- Some are created by magnetic reconnection and can have sharp and clear boundaries. Due to topology change allow exchange of Energy/momentum/mass between flux tubes

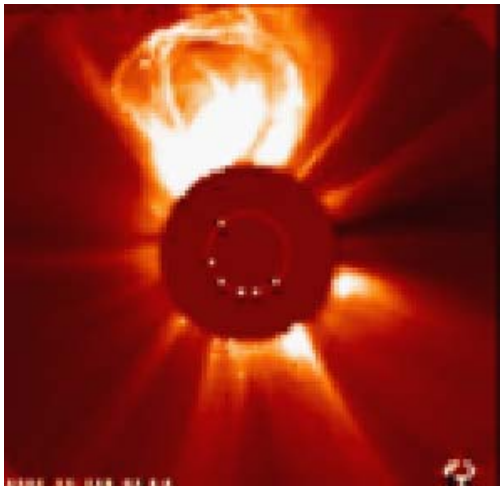
Flux Ropes

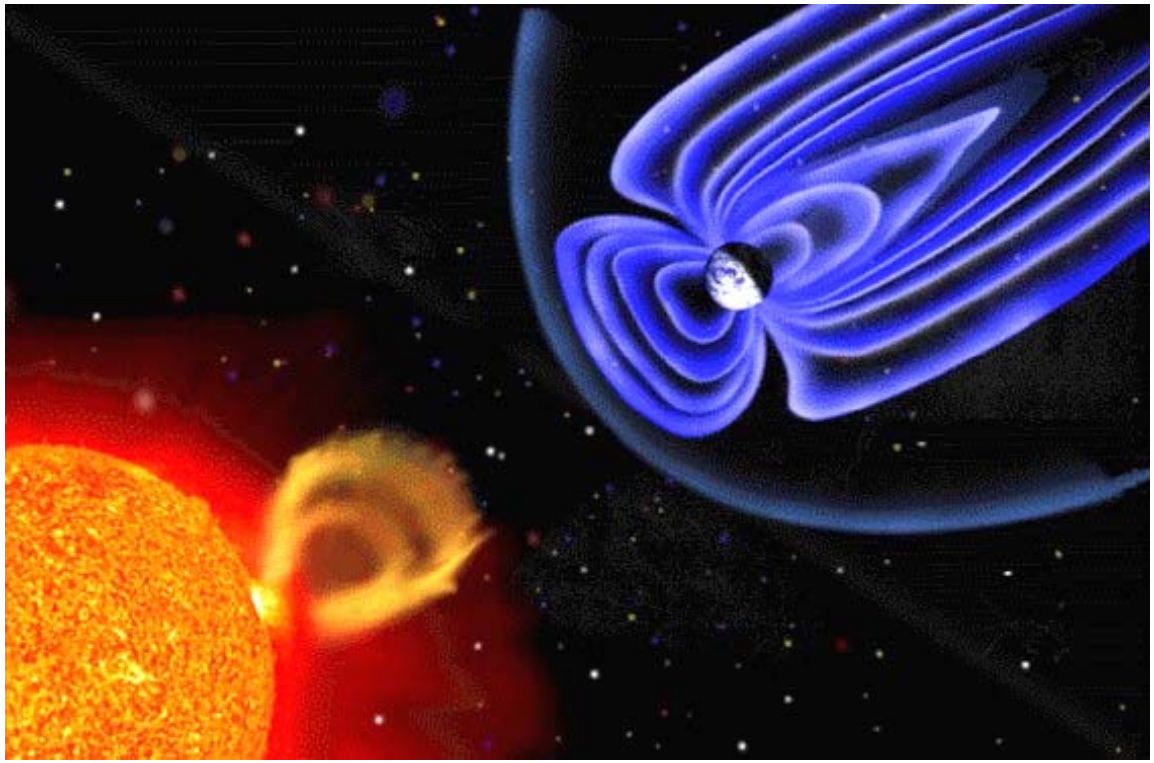


- The center of the rope is the core field
- Edges of rope often have current sheets to separate it from surrounding plasma

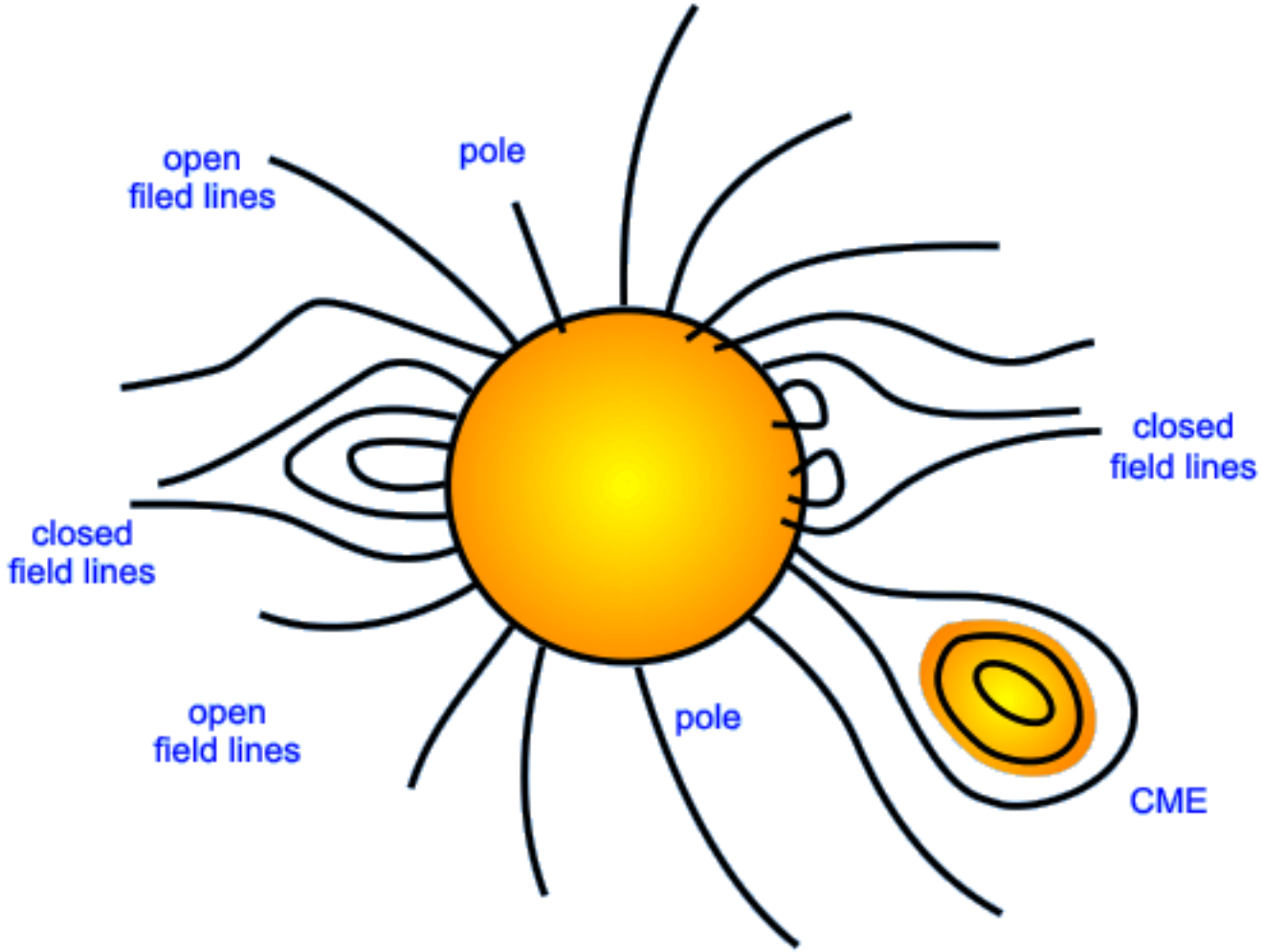
Coronal Mass Ejections are the primary driver of major Geomagnetic storms

Their structure determines their geomagnetic effectiveness
The are magnetic flux ropes



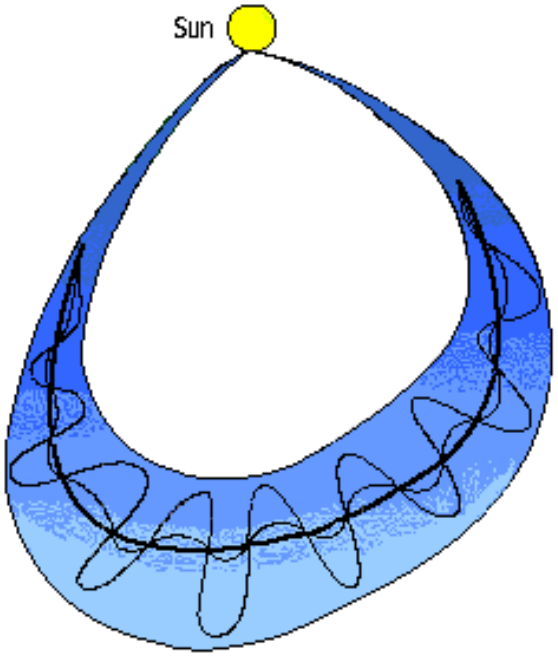


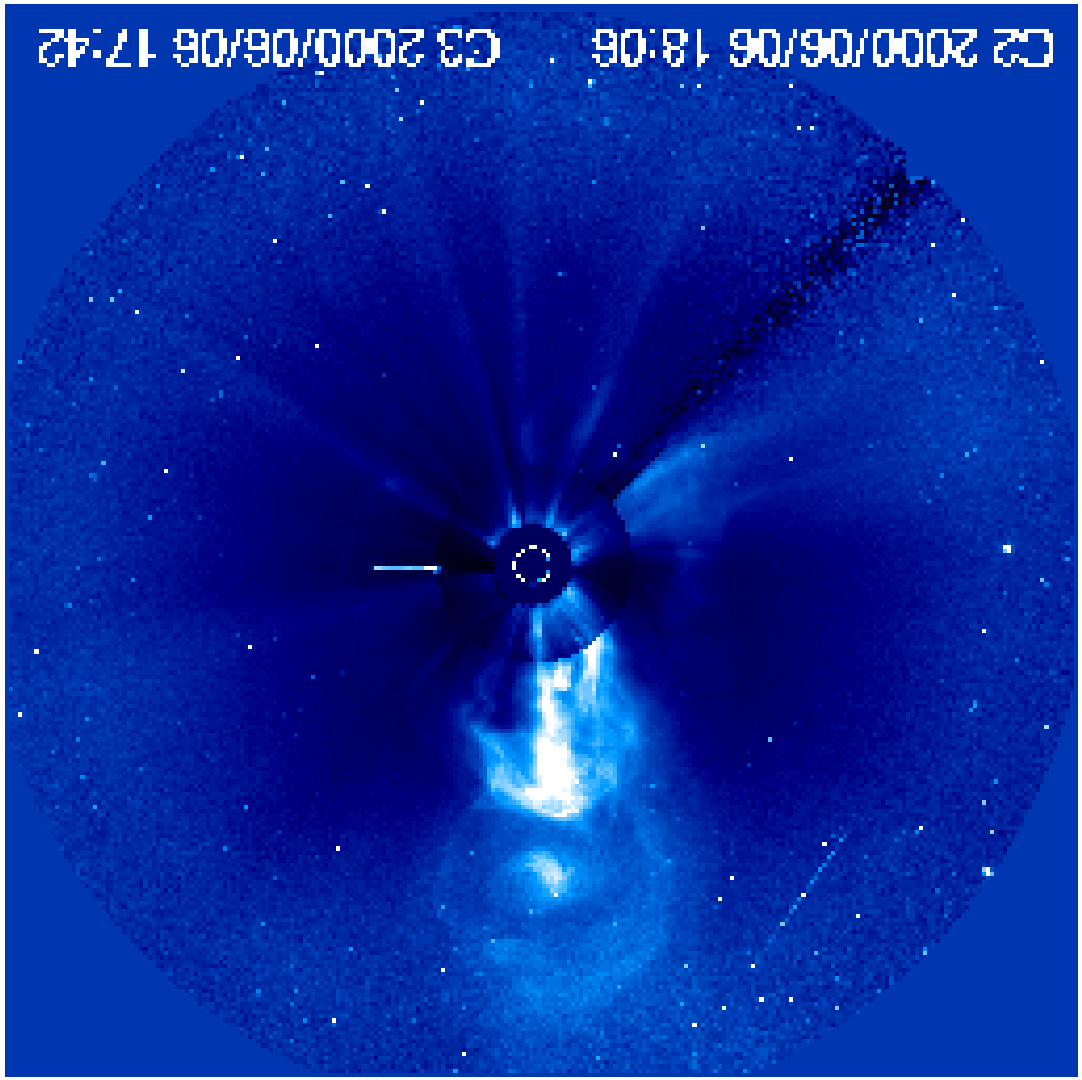
Creation of Coronal Mass Ejection by Reconnection in Solar Magnetic Fields



What is wrong with this picture?

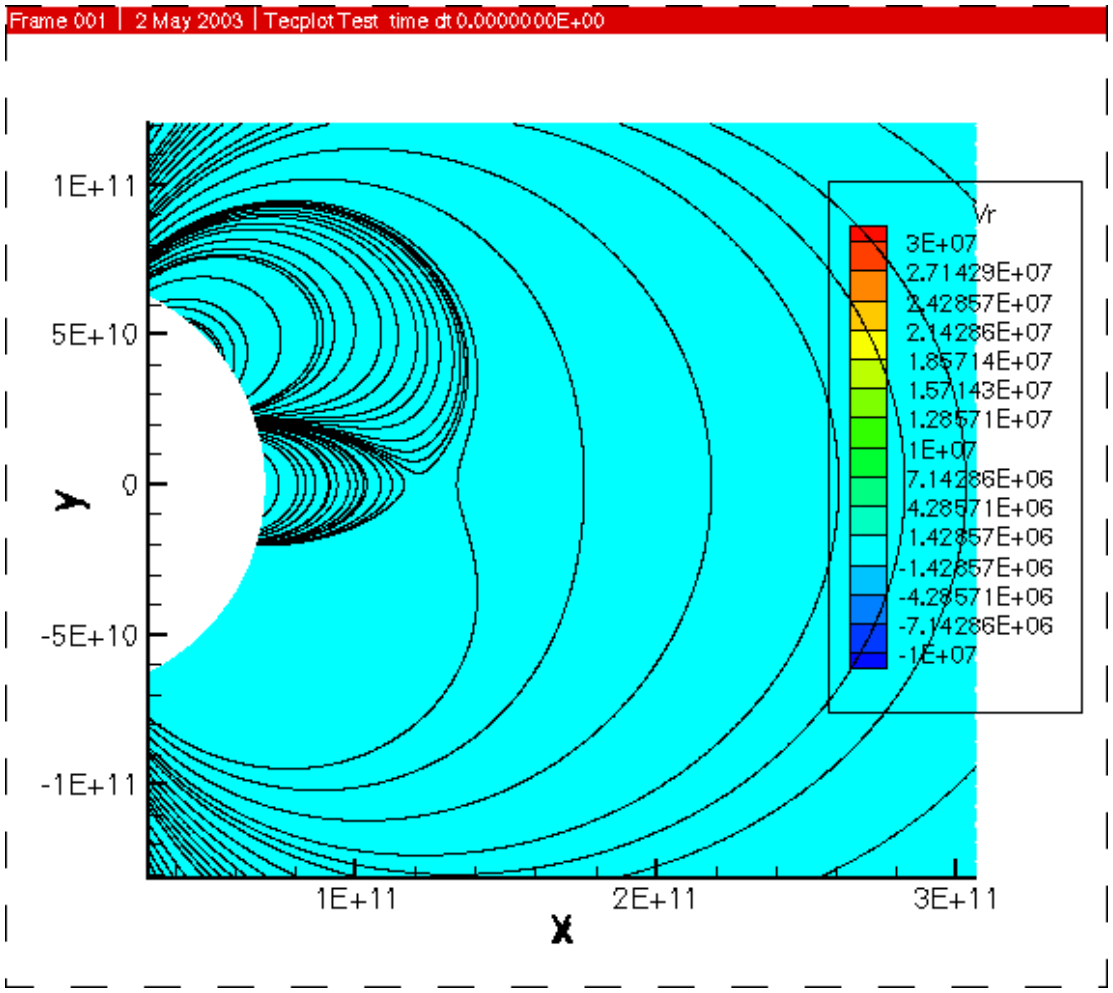
CME 3D Structure





Formation of Coronal Mass Ejection

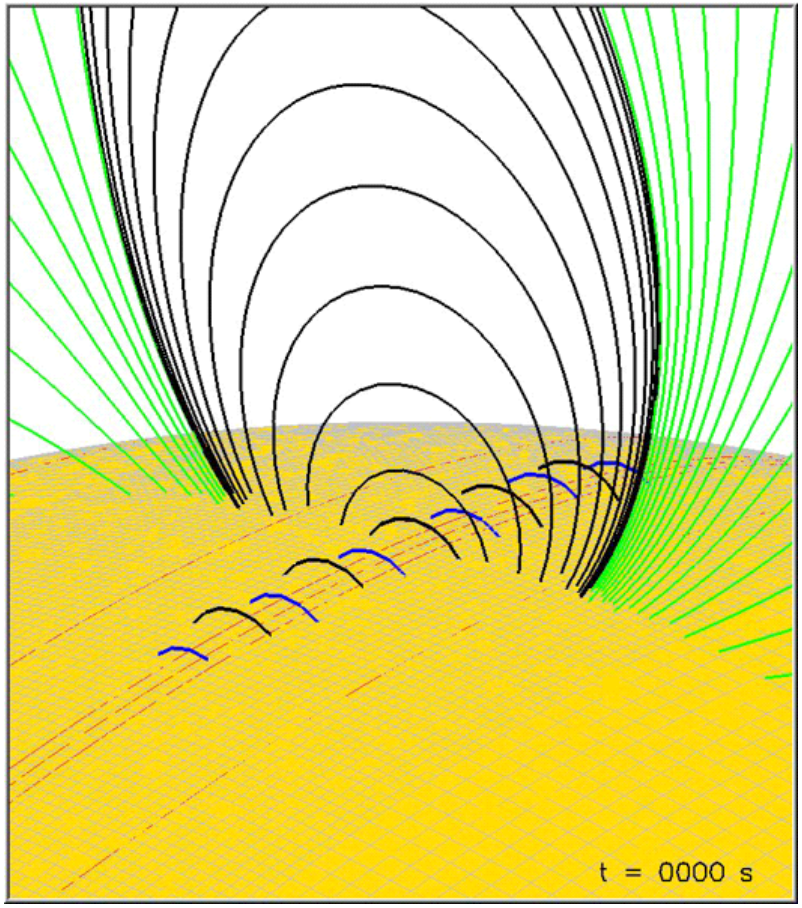
- **Breakout CME: reconnection in front of CME allows it to erupt**
- **Most models: reconnection behind CME, cuts fieldlines connecting it to the Sun, and causes flaring and particle acceleration**
- **In some models, reconnection below CME is main driver of eruption**
- **Work by Manchester et al here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



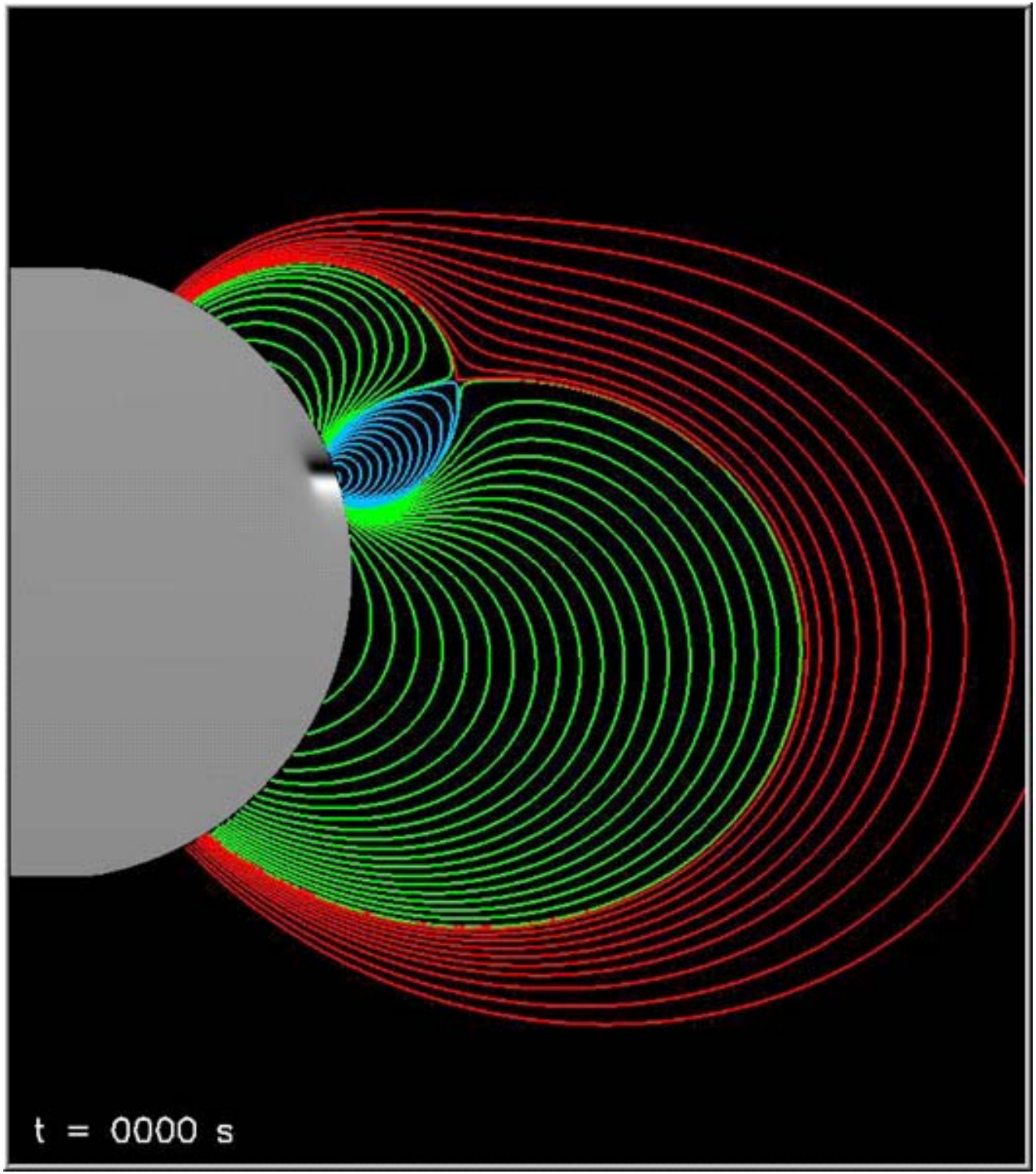
MacNeice et al. 2004

3D Model of CME

(Lynch et al)



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.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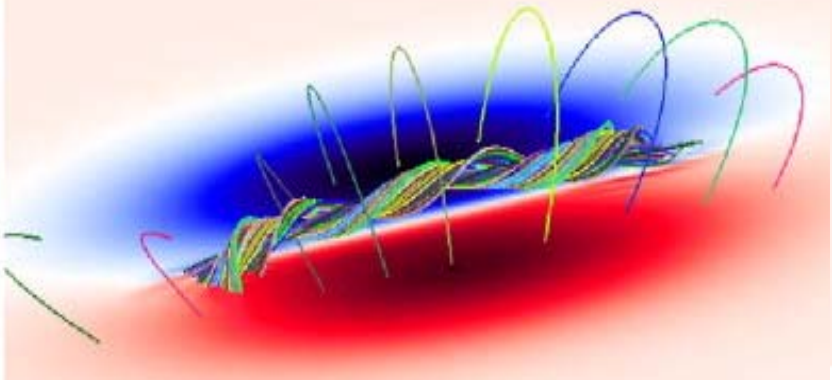
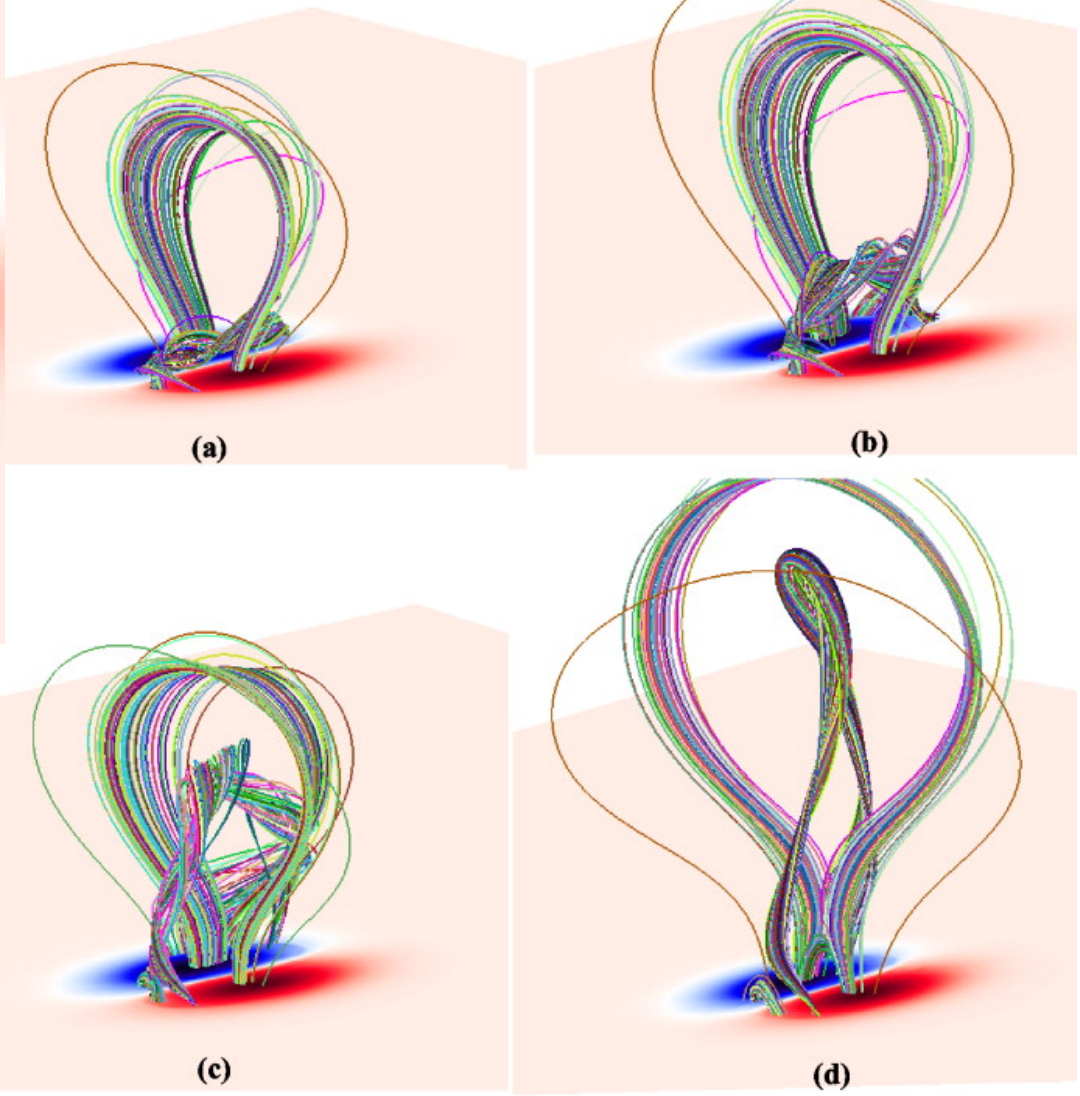
3D Model of CME – Flux Cancellation

(Amari et al 2003)



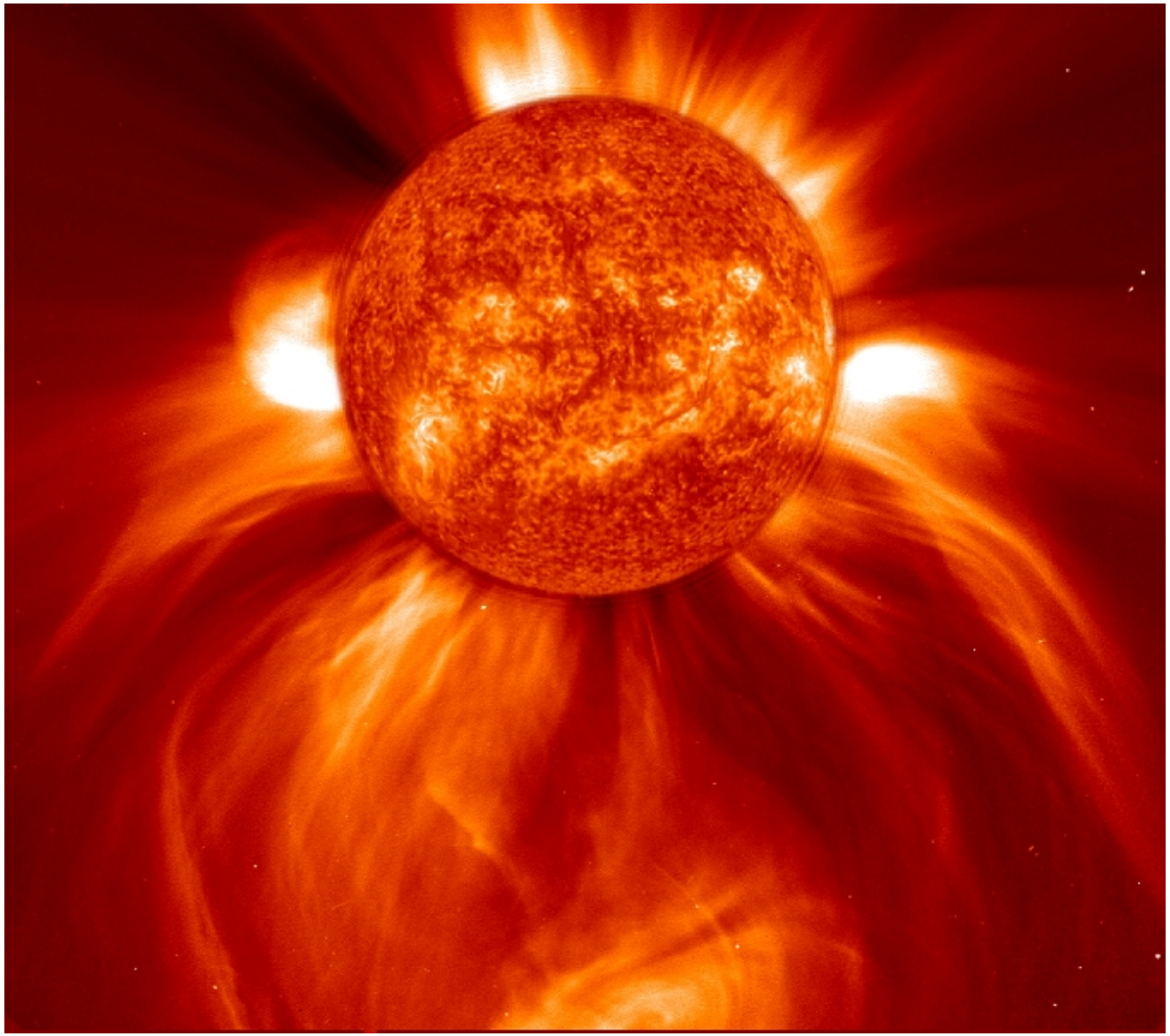


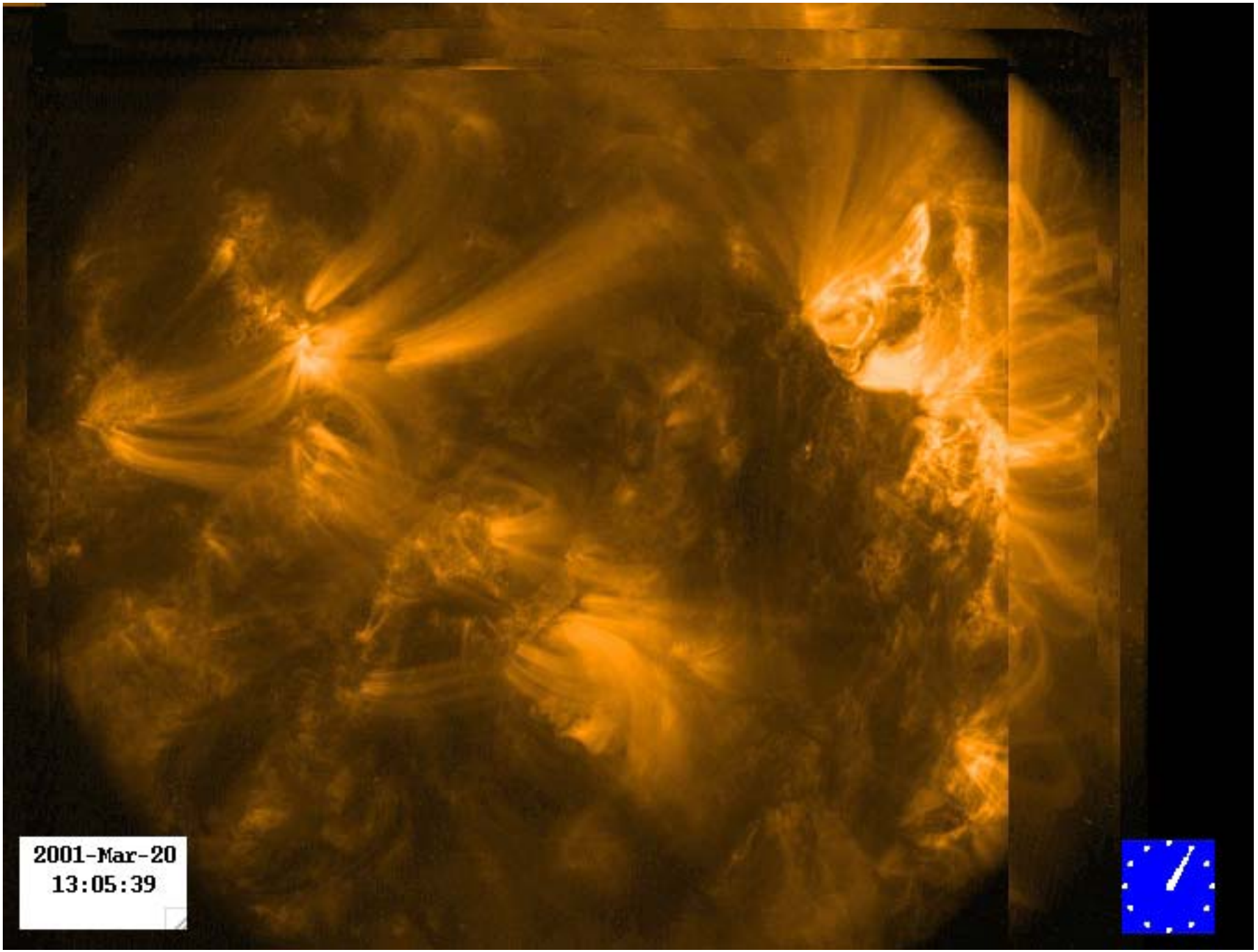
Shear magnetic field, then cancel flux by diffusion, reconnection at photosphere. This creates a twisted flux rope. For strong shear, the Rope erupts, reconnecting with overlying field.

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
- BOTTOM Line – Often COMPLICATED Structures

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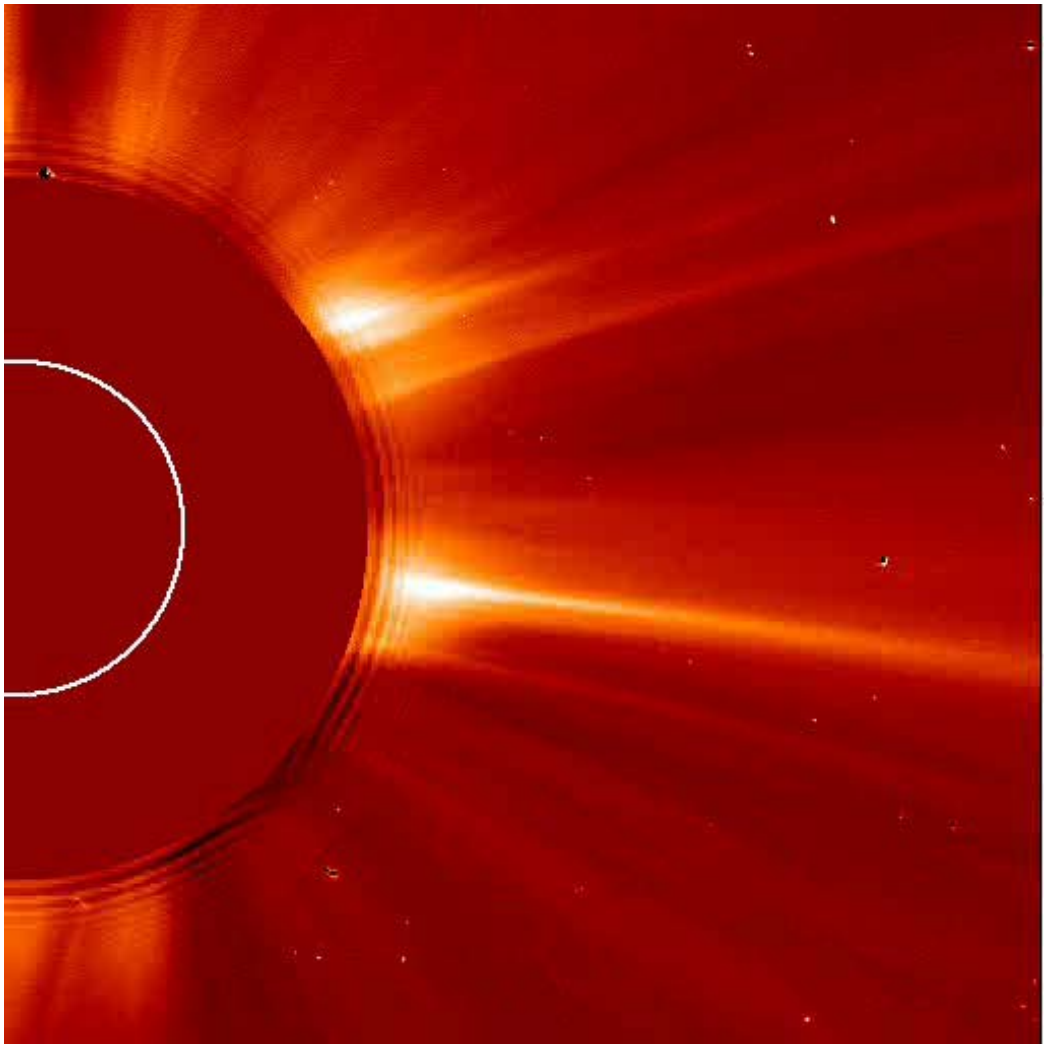
Observation of Coronal Mass Ejection

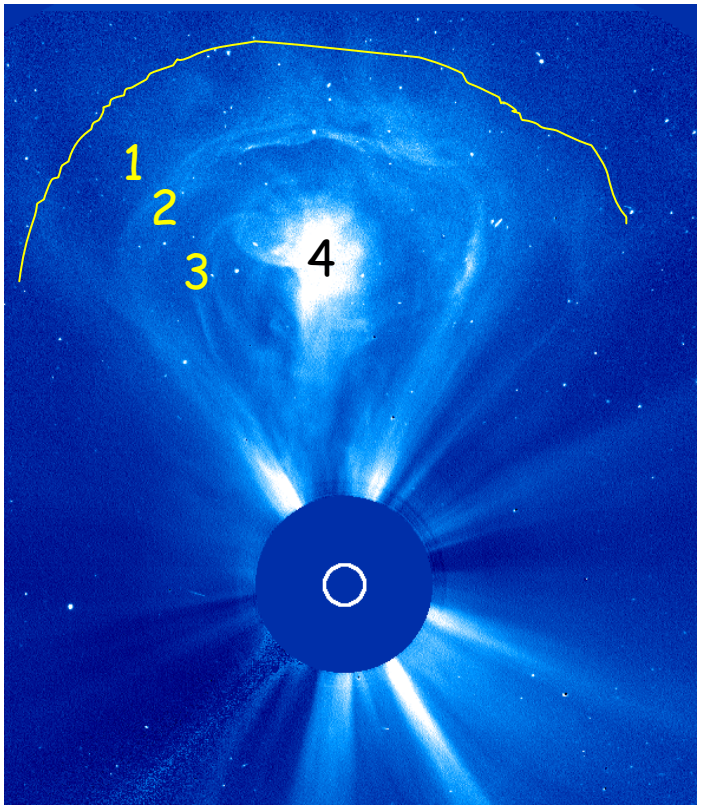


LASCO C2 Coronagraph

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



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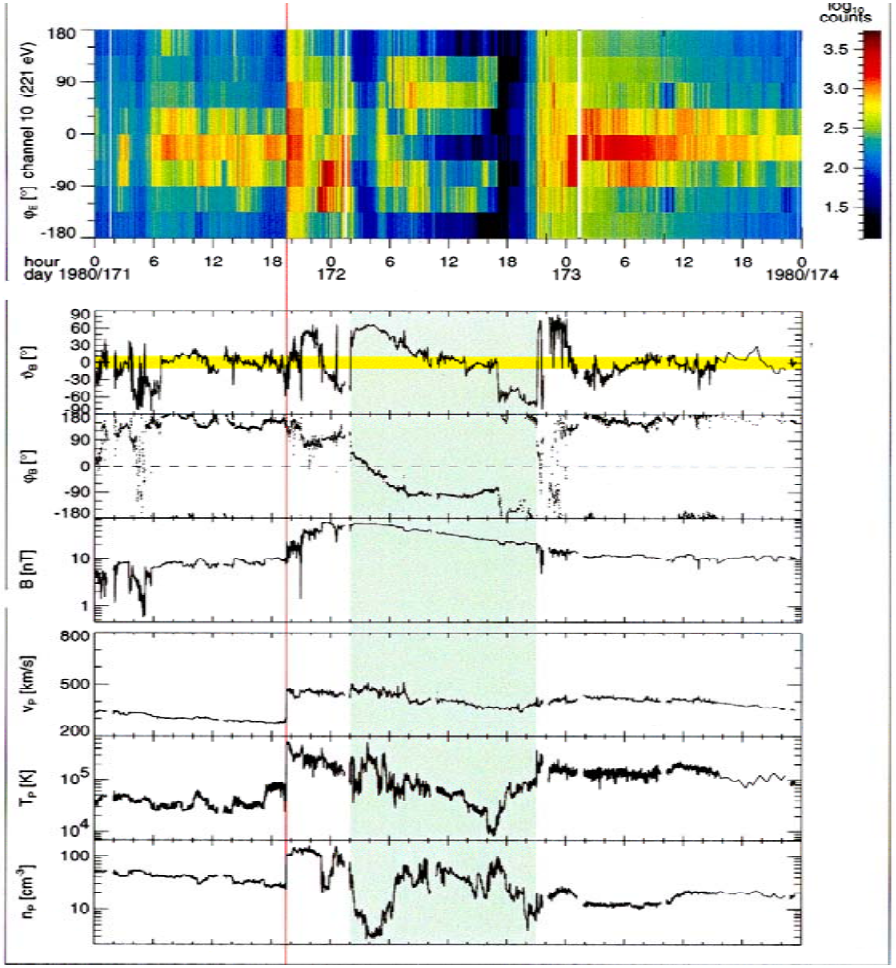
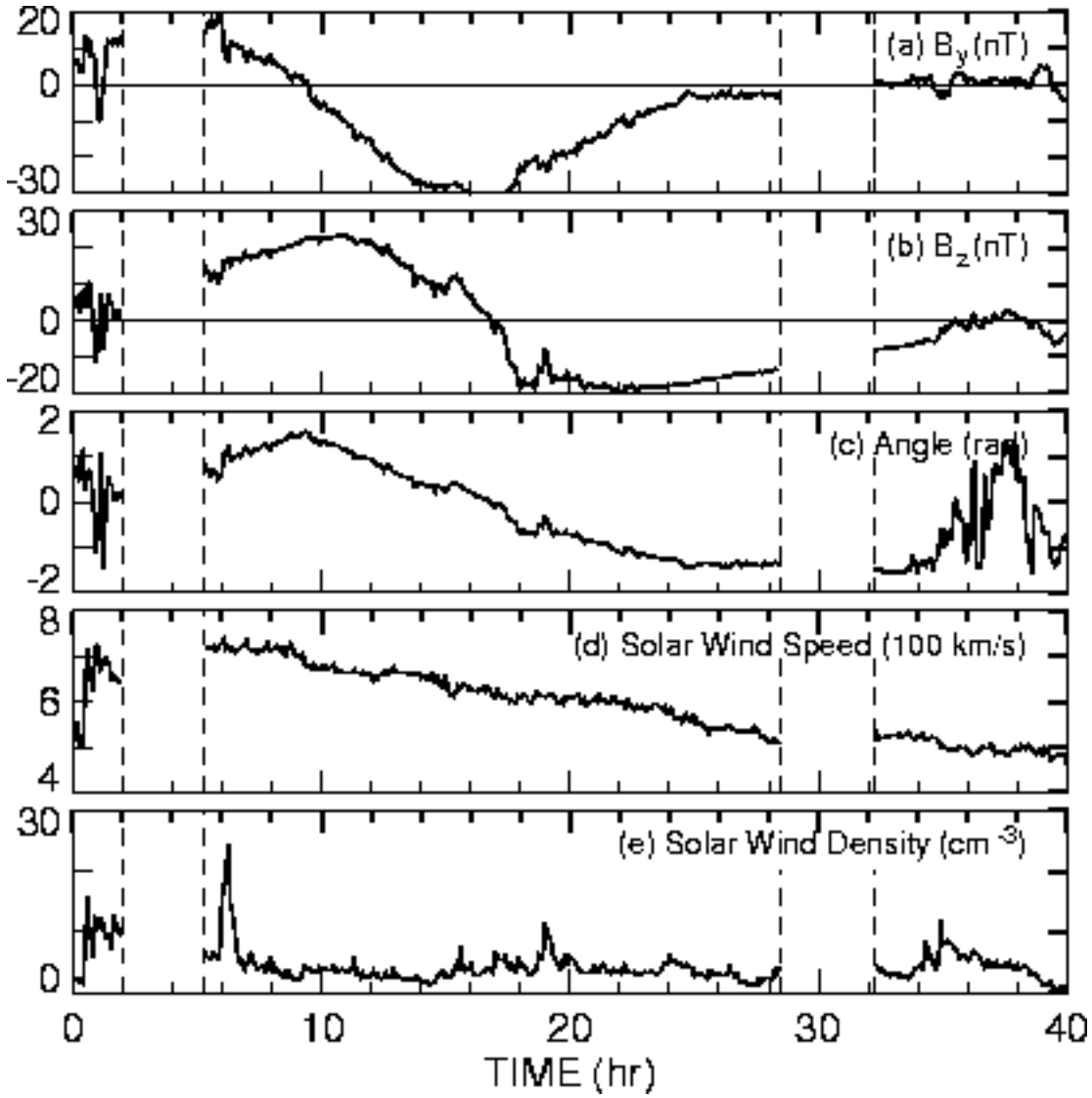
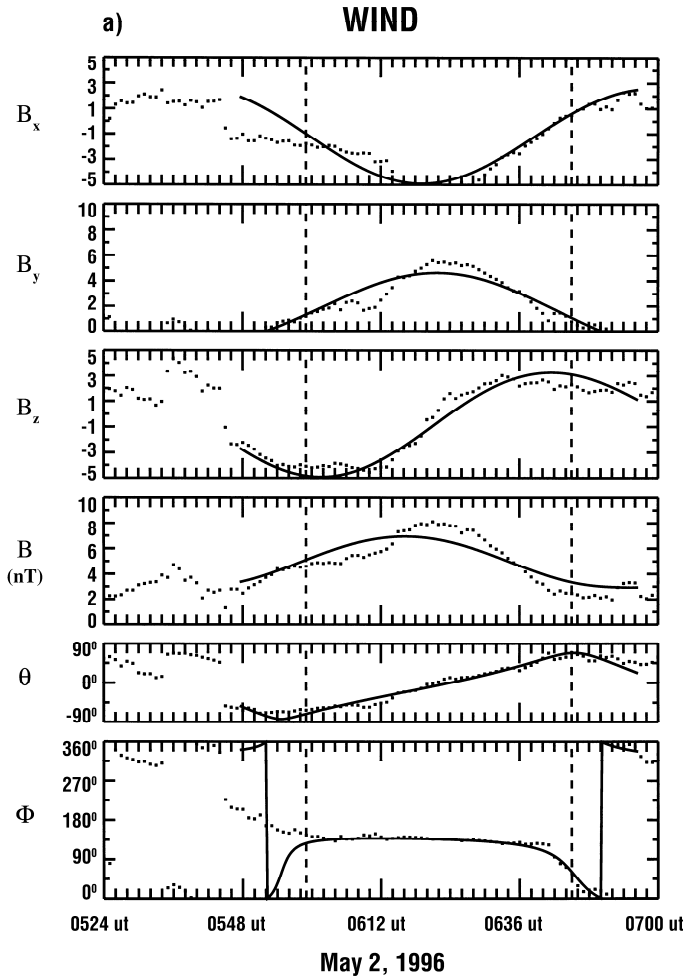


ICME Magnetic Signatures



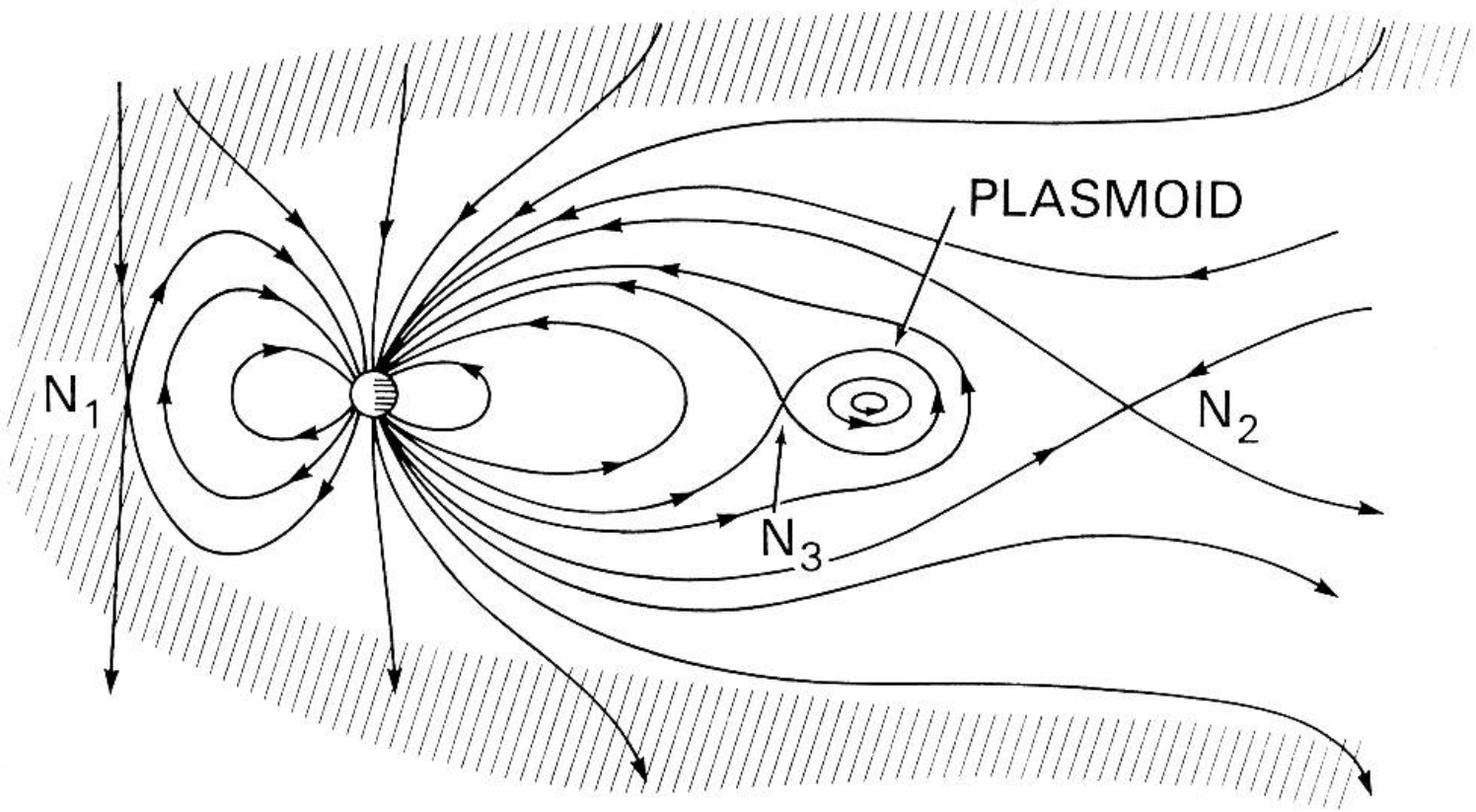
Flux rope signature: Increase in magnetic field strength within flux rope. Strong component of twist (Bz) and guide field (By) are both present.

Reconnection across HCS?

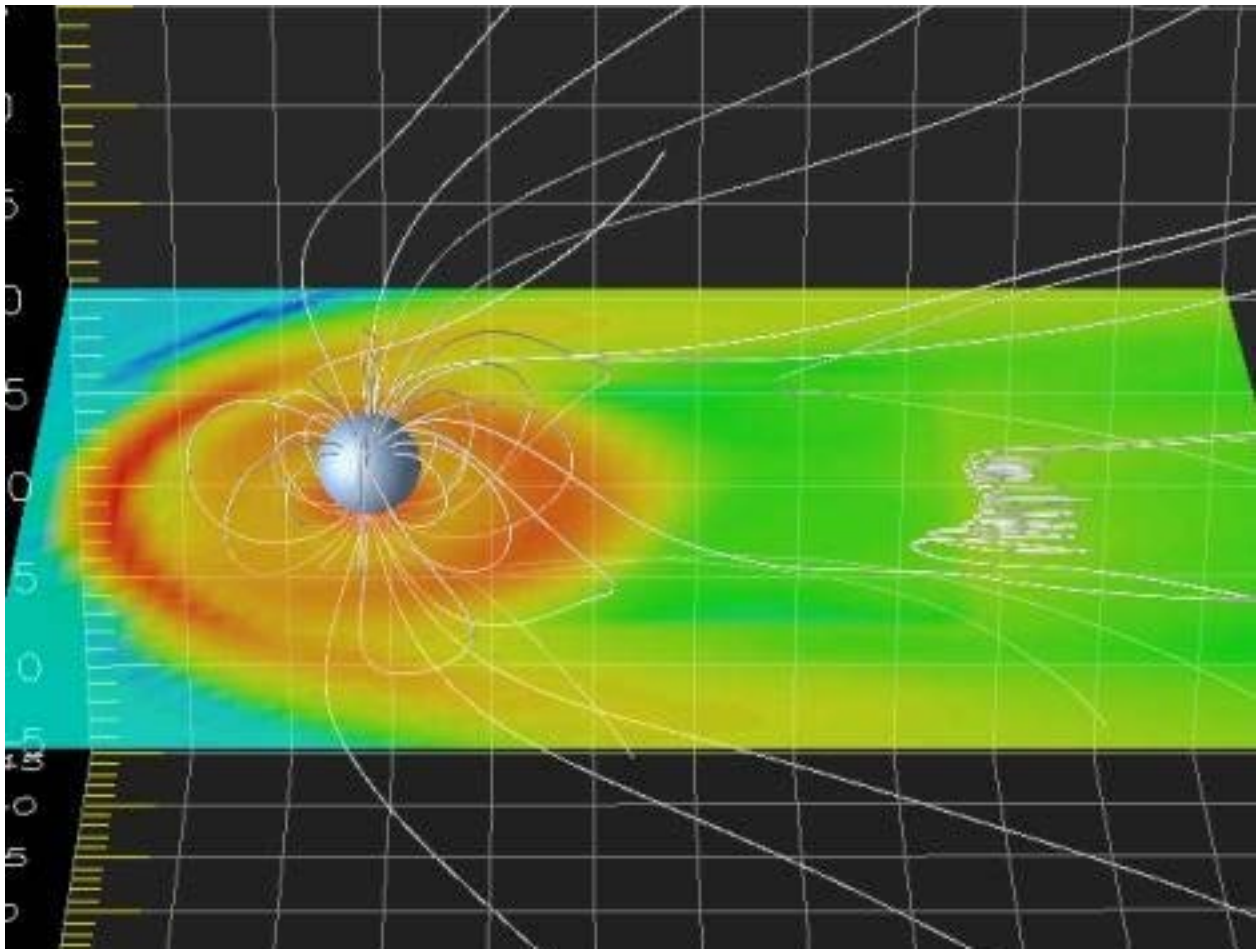


- New class of flux ropes discovered in solar wind (Moldwin et al., 2001)
- Scale order of an hour (Cartwright and Moldwin, 2008)

Creation of Plasmoid by Magnetic Reconnection in Earth's Magnetotail

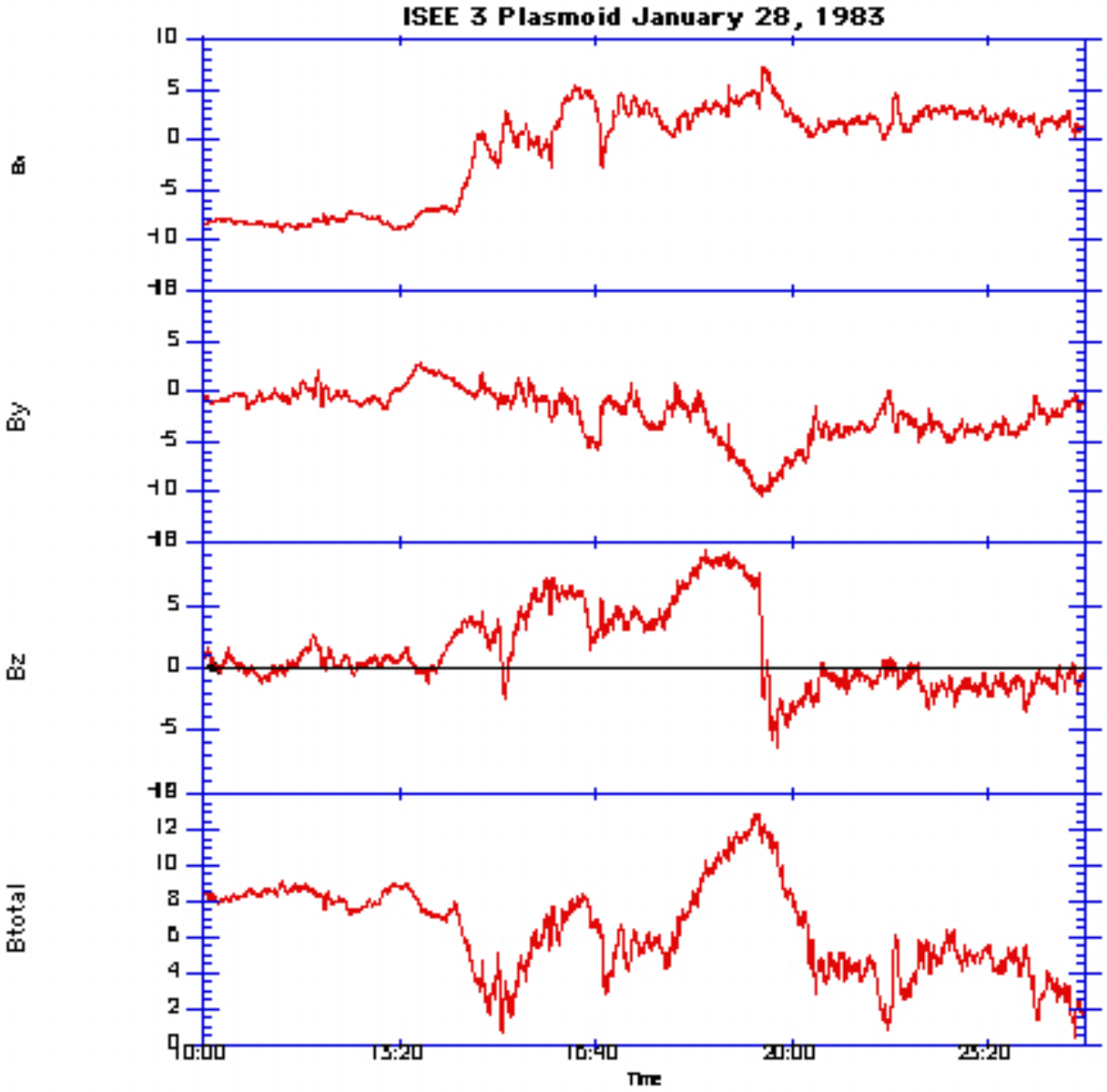


Formation of Plasmoid



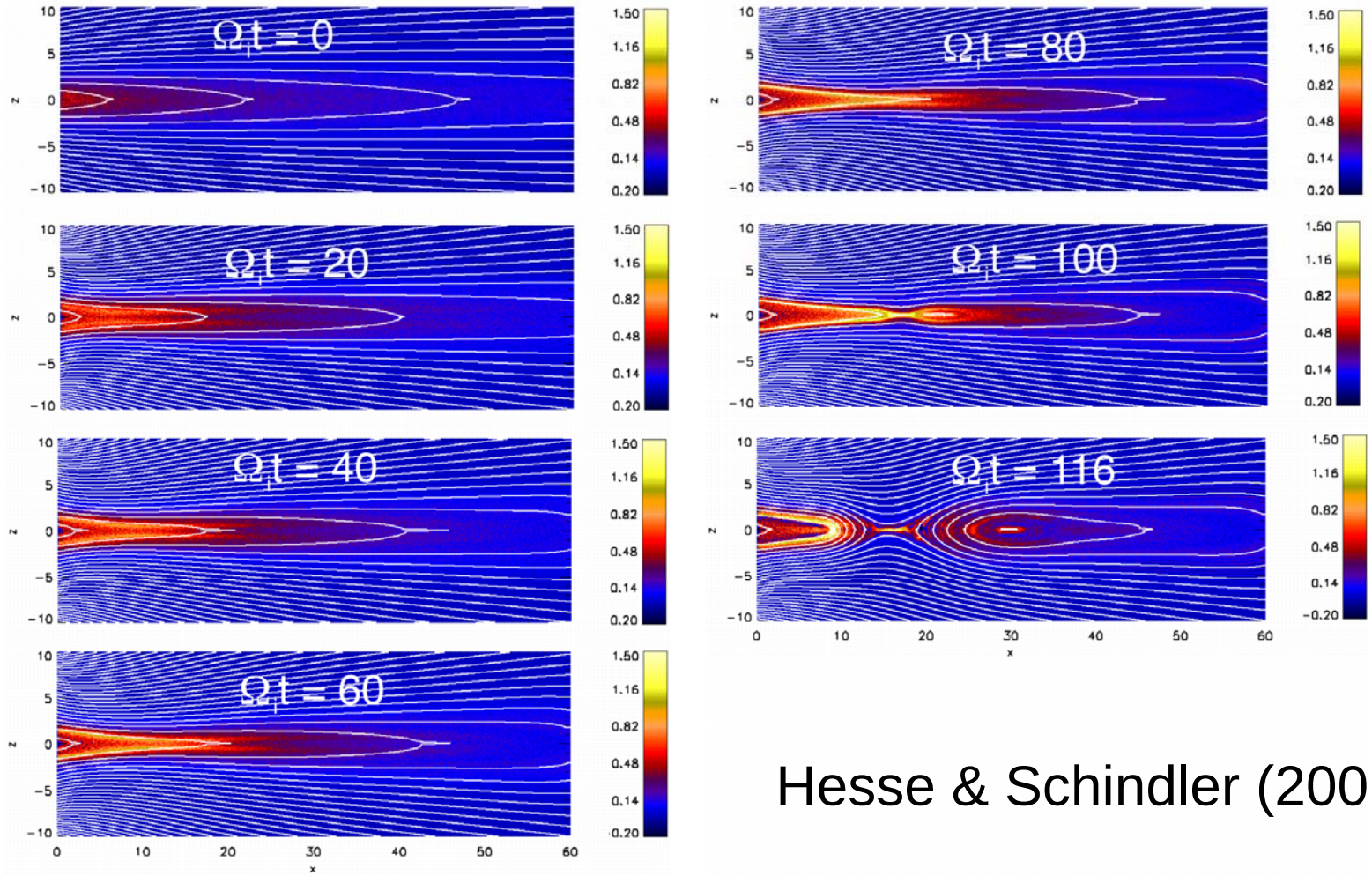
Magnetotail current sheet forms – similar to Post-CME current sheet. Localized reconnection forms plasmoid, tearing mode can lead to tangling, multiple plasmoids, as in post CME flare.

Plasmoid Magnetic Signatures



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

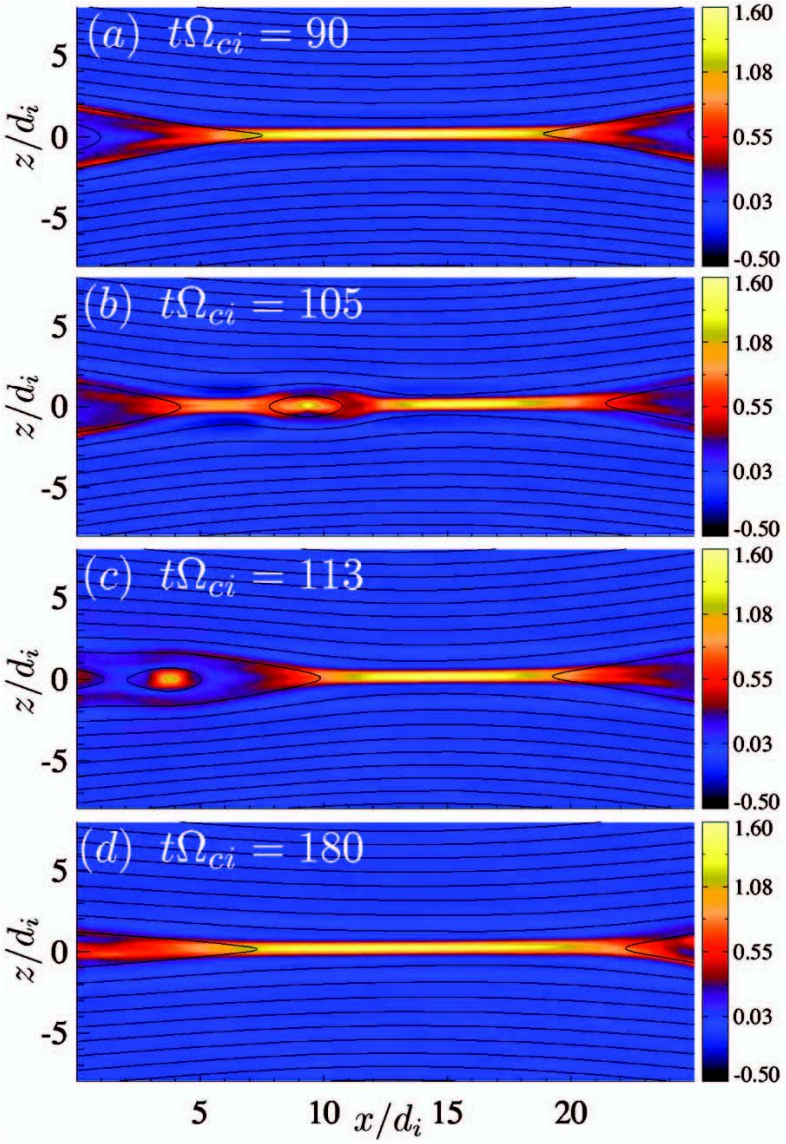
Plasmoid Formation in Magnetotail



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



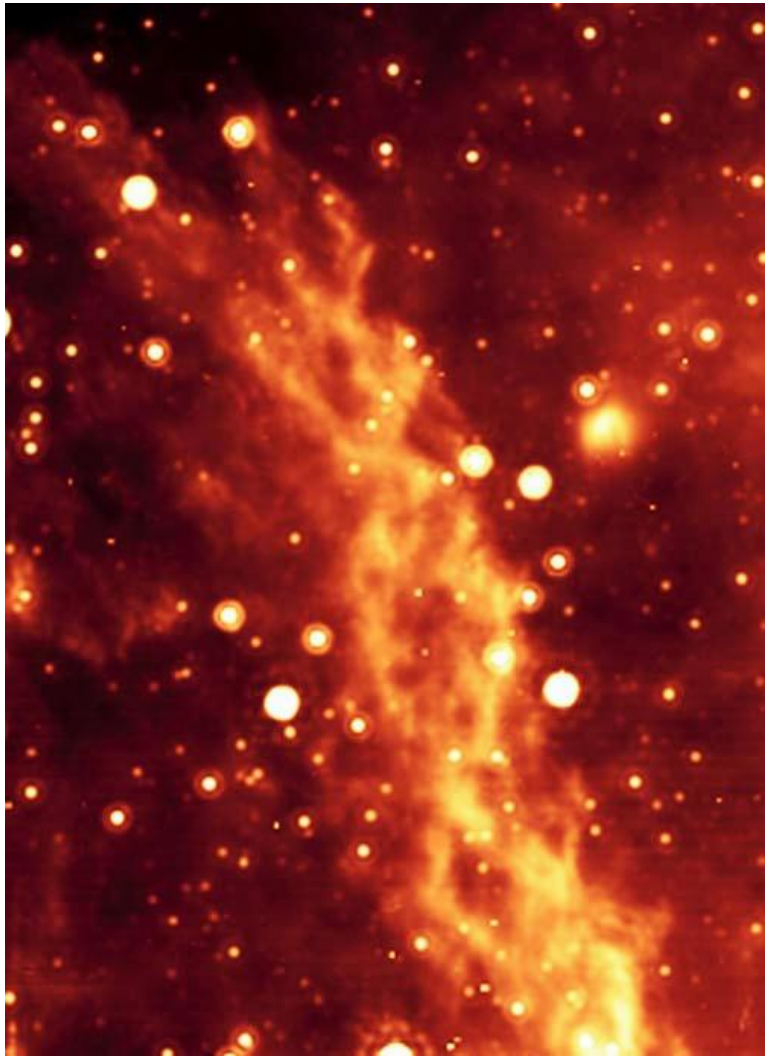
Long current sheet, with open boundaries, e.g. Magnetotail, Is unstable to spontaneous tearing. Leads to generation and ejection of multiple magnetic islands/plasmoids

Daughton, Scudder, & Karimabadi, 2006

Properties of Flux Ropes

- Helical field structures with core fields
- Often sharp current sheets at edges
- Wide range of scales
- Magnetic Reconnection needed for formation
- Carry significant energy, mass, momentum
- Seen on Sun, in solar wind, in magnetospheres (and ionosphere of Venus)

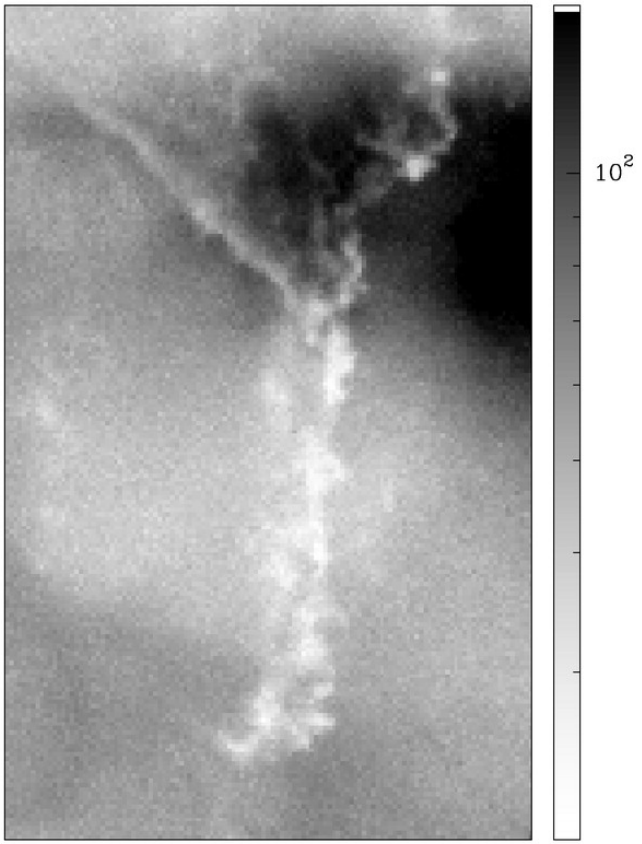
Double Helix Nebule



- 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)
- Universal Magnetic Structure is due to formation by magnetic reconnection.
- Want to understand Heliosphere – need to understand magnetic reconnection