MODELING SOLAR ACTIVE REGIONS WITH FLUX ROPES

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NASA Summer School

Ausgust 4, 2022, Section 1

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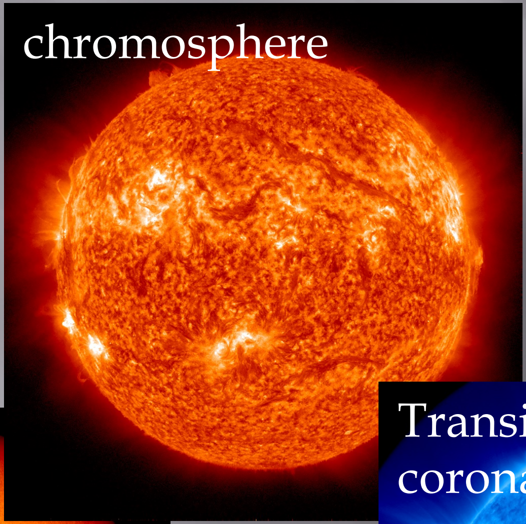
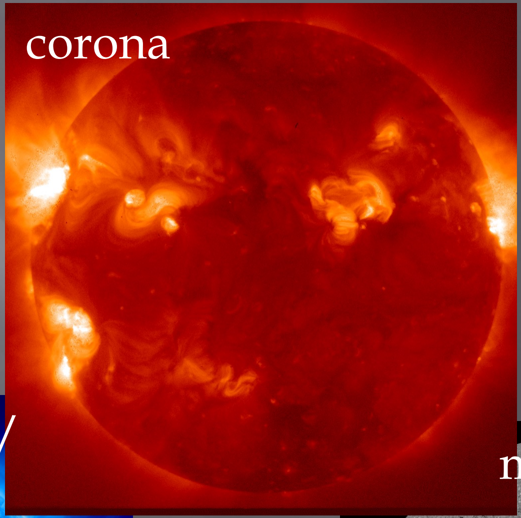
Outline

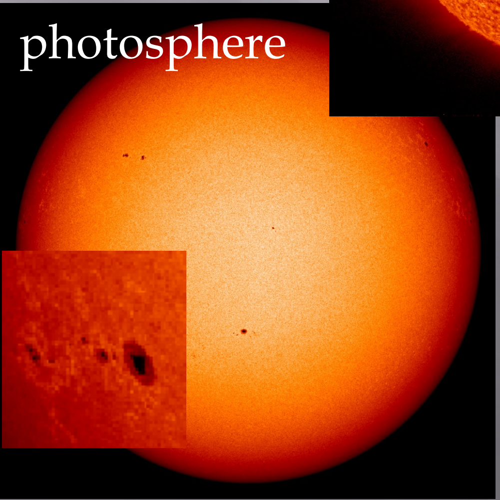
- Solar Active regions and sigmoids
- General questions to be answered
- Sigmoid models for formation and evolution
- Eruption models
- Magnetic modeling of sigmoidal regions
- Field topology analysis
- The instability-reconnection feedback scenario
- Some questions of common interest

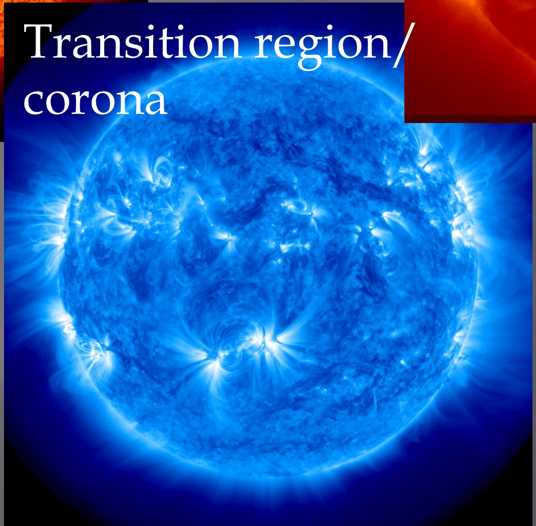
Solar active regions (AR)

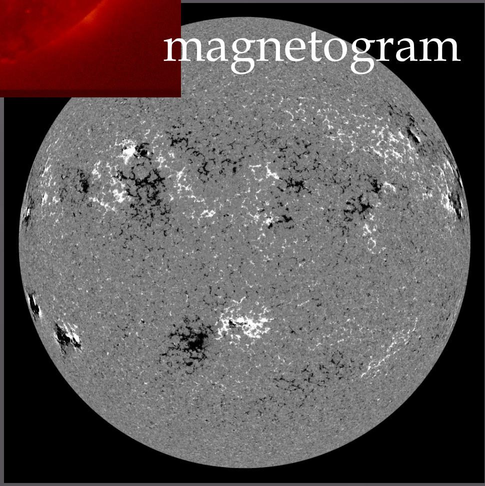
- Magnetic in nature
- Flux tubes from the interior rise via buoyancy
- AR in different parts of the solar atmosphere





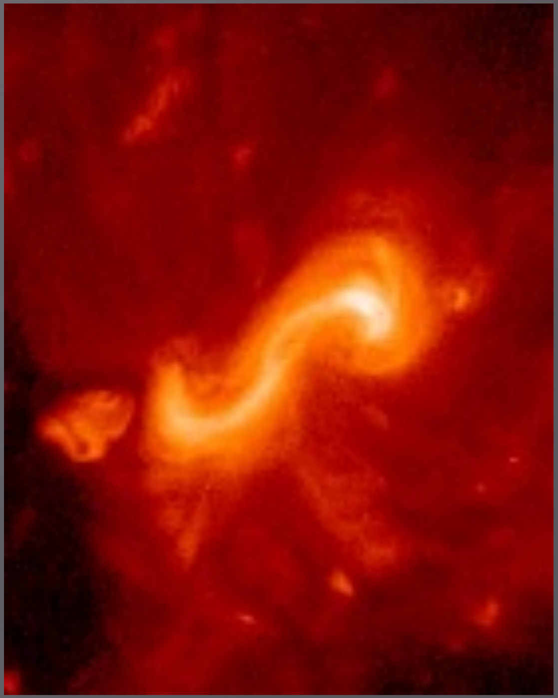


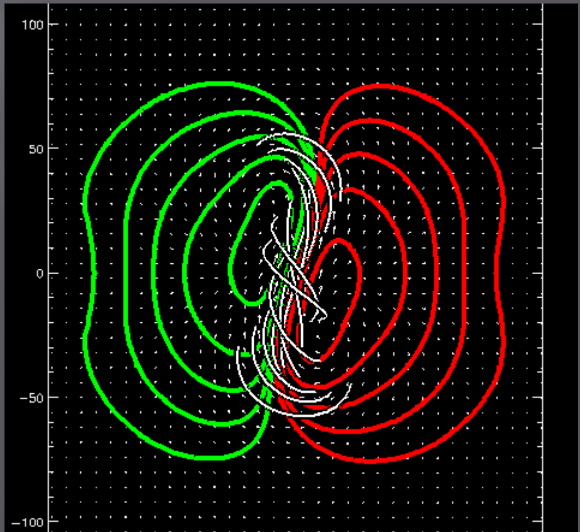




Sigmoids – an overview

- Transient or long-lasting S (south) or inverse-S (north) shape active regions
- Twisted and sheared magnetic field structures – great for storing magnetic energy
- Canfield et al. (1999, 2007) - 68% of eruptions originate in sigmoidal regions
- Often associated with H_α filaments, in dips of twisted flux ropes
- Best modeled by a weekly twisted flux rope in the core, held down by a potential arcade – Titov & Demoulin (1999)





Some questions

- How do sigmoids form? – How is the flux rope build up?
- What is their magnetic field structure?
- What is the free energy contect and how is it stored?
- What is the topology of the field?
- What instabilities play a role in the eruptions?
- Is reconnection important?
- Locating probable sites for reconnection and instabilities?

Models for formation and evolution

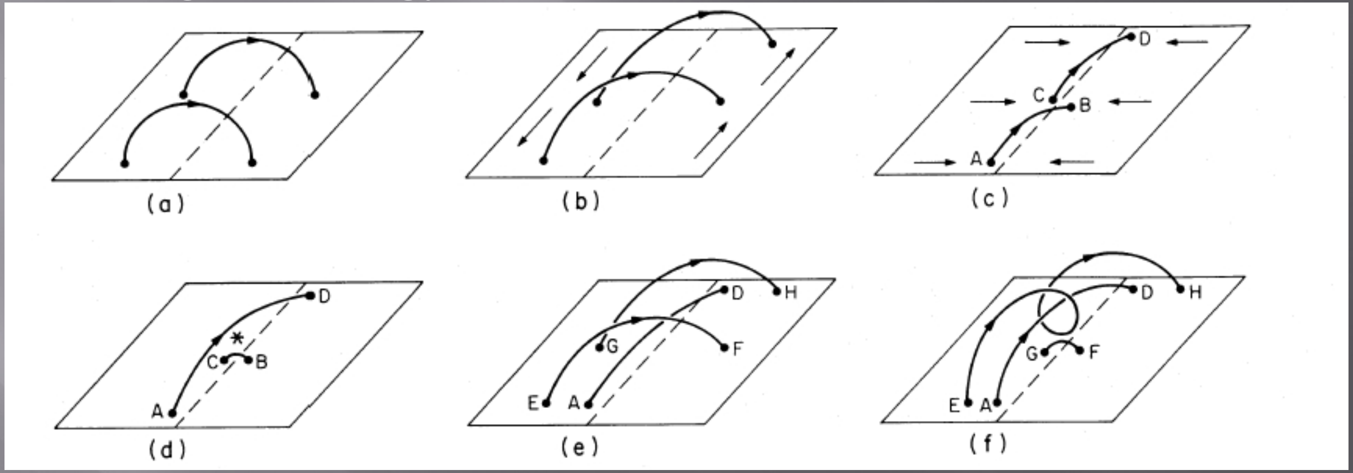
1. Flux emergence through the photosphere of already twisted flux rope (Fan & Gibson '04, '06, '07, Archontis et al. '09)
   - If plasma is included (β~1) flux rope is destroyed by the plasma it drags along
   - MHD simulations cannot stabilize the flux rope before eruption – it erupts almost instantaneously
   - Simulations of transient sigmoids in emerging flux regions

2. Shearing footpoint motions inject twist and shear in an initially potential field (Aulanier et al. '10, Amari et al. '00)
   - Requires large scale rotation or relative motion of polarities
   - Not always observed

Models for formation and evolution

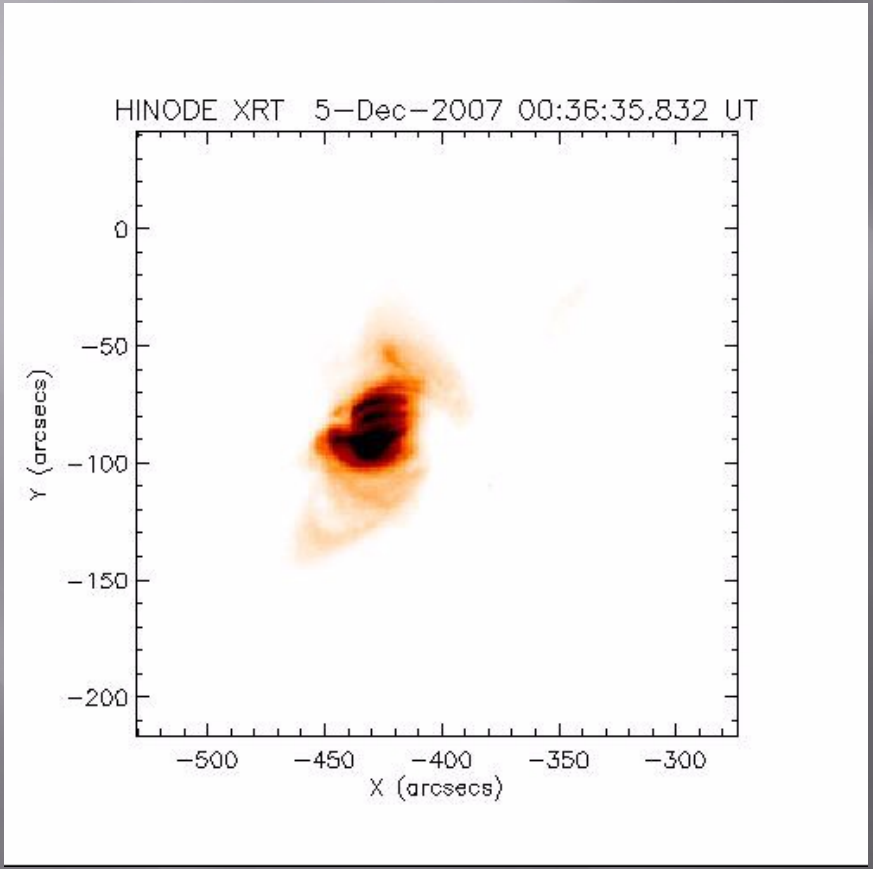
3. Flux cancellation in decaying active region

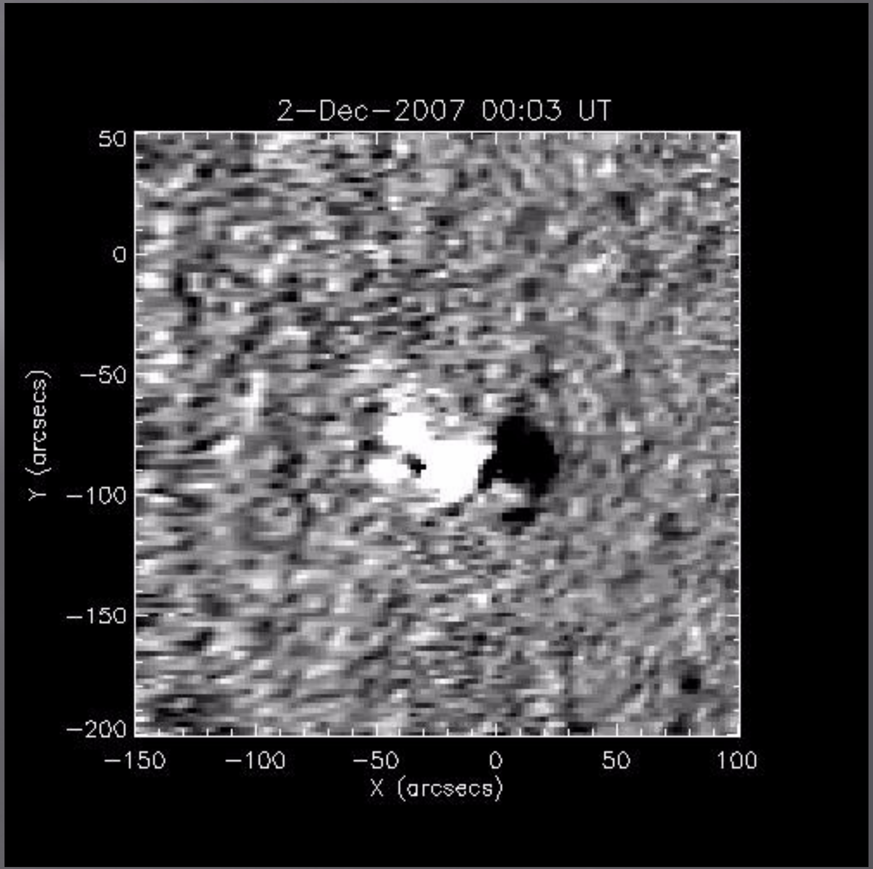
- Van Ballegooijen & Martens (1989) picture for building flux ropes and storage of energy



- Shear flow + converging motions → short submerging loops + long helical field lines (FL)
- Build of free energy (definition) - Potential field to field with free energy

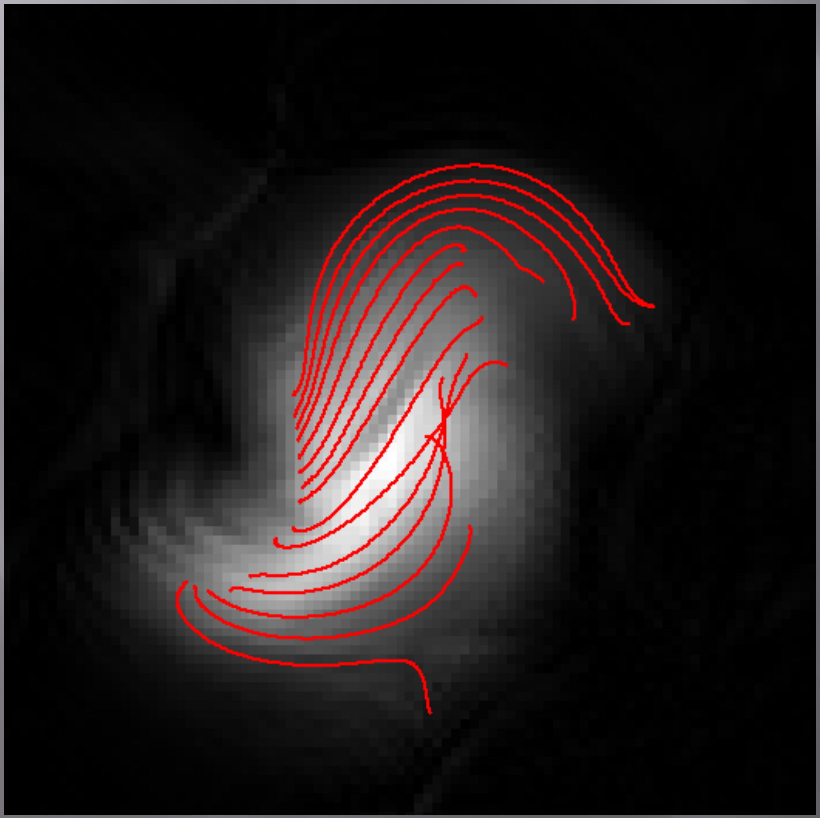
An example of flux cancelation for building flux ropes

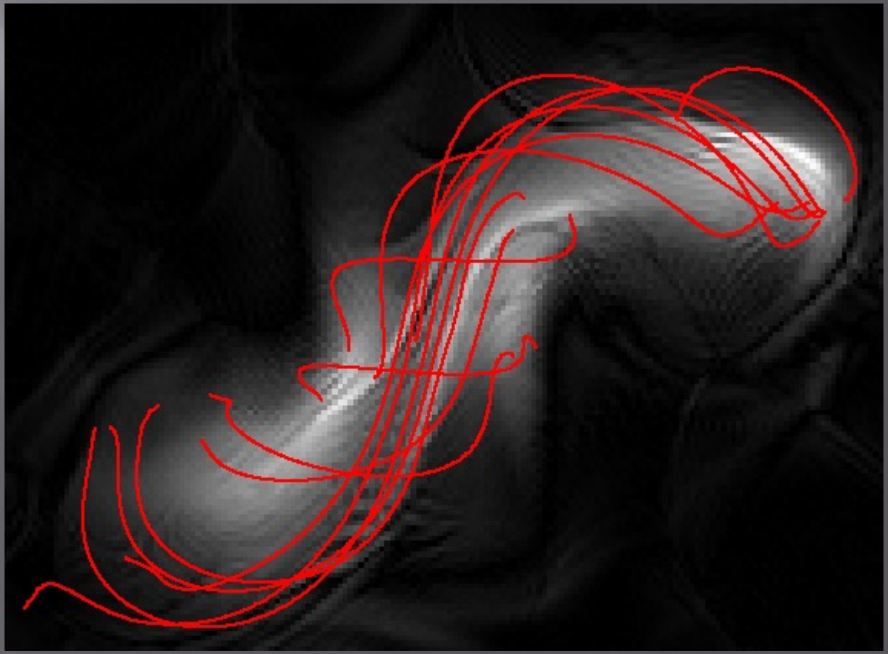




Sheared arcade to full FR

- Little flux – sheared arcade - earlier in the evolution
- More flux – 2J to S FLs – 1 day to few days before eruption





Eruption models

- The standard model
- Need loss of equilibrium
- Ideal instabilities – kink, torus
- Reconnection

Kink and torus instability

- Equations

Magnetic field modeling – Motivation

- Need model of the magnetic field when region is on disk
- Static or quasi-static from observed B field, extrapolates the field to the corona
- Can match to observed loops and associate loops with parts of the field structure
- Field topology, current build-up, energy storage
- Can estimate flux and energy budgets
- Study flux build-up prior to eruptions
- Conditions for instability
- Study region formation, evolution, eruption
- Comparison with dynamical MHD models

Magnetic Models

- Euler Euqation or equation for motion in the corona

$$\rho\frac{d\mathbf{V}}{dt} = \rho(\frac{\partial\mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}) = -\nabla p + \rho\mathbf{g} + \mathbf{j}\times\mathbf{B} + \mathbf{F}_{\text{visc}} + \mathbf{F}_{\text{friction}} = 0$$

- Mening that the magnetic pressure and tension in the configuration
- must balance

$$-\nabla(\frac{B^2}{2\mu}) + \frac{1}{\mu}(\mathbf{B}\cdot\nabla)\mathbf{B} = 0$$

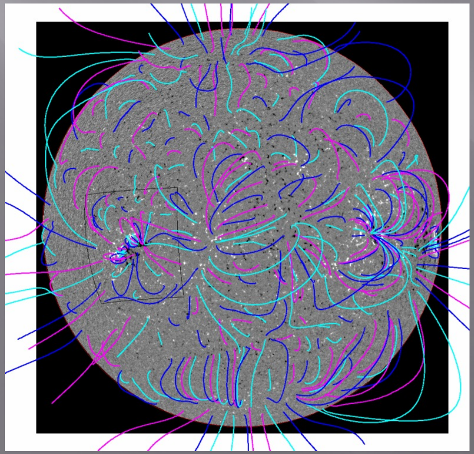
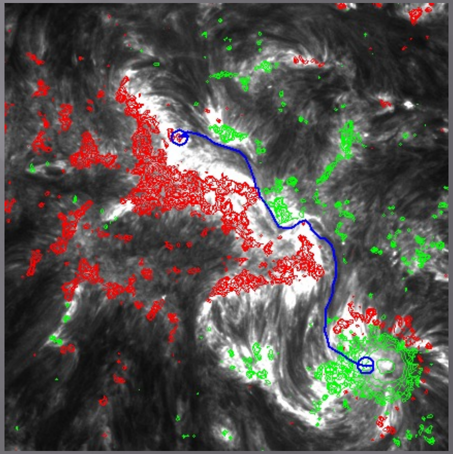
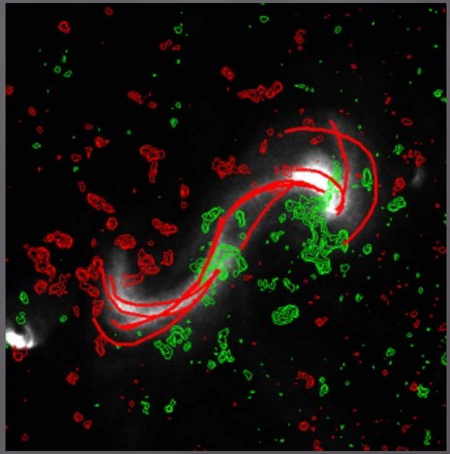
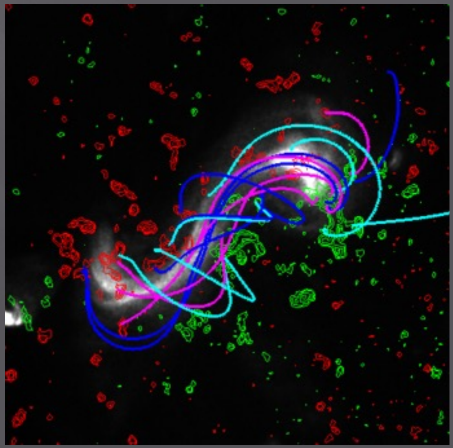
- Corona in equilibrium – force-free, **J||B**

$$\nabla\times\mathbf{B}\approx\alpha\mathbf{B}$$

- Potential field when torsion parameter $\alpha=0$
- Linear force free field (LFF) when $\alpha=$const everywhere
- NLFFF - $\alpha=$const along field lines, but different for different FLs
- NLFFF models most accurately describe the sheared and twisted core AND the potential arcade
- Schriver et al. (2006, 2008) – review of NLFFF models

The flux rope insertion method

- van Ballegooijen (2000, 2004)
- Global potential field extrapolation from SOLIS/HMI Carington magnetogram for global B.C.
- Potential field extrapolation from a HiRes LoS magnetogram (MDI or HMI)
- Clear up a cylindrical cavity with no B where FR will be
- Insert flux rope as a combination of axial and poloidal flux – use filament path as guidance - from dat
- Relax by magneto-friction with hyperdiffusion
- Fit model to observed coronal loops

Magnetofriction

- EquationsWe iterate the induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E},$$

where the electric field is expressed by the the resistive MHD condition:

$$\mathbf{E} = -\mathbf{v} \times \mathbf{B} + \eta \mathbf{j}$$

- With frictioanl coefficients and current terms

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left(\upsilon \times \mathbf{B} - \eta_i \nabla \times \mathbf{B} + \frac{\mathbf{B}}{B^2} \nabla \cdot (\eta_4 B^2 \nabla \alpha) \right)$$

- Casted in vector potentioanl to preserve the divergence of B

$$\frac{\partial \mathbf{A}}{\partial t} = \upsilon \times \mathbf{B} - \eta_i \nabla \times \mathbf{B} + \frac{\mathbf{B}}{B^2} \nabla \cdot (\eta_4 B^2 \nabla \alpha) + \nabla(\eta_d \nabla \cdot \mathbf{A})$$

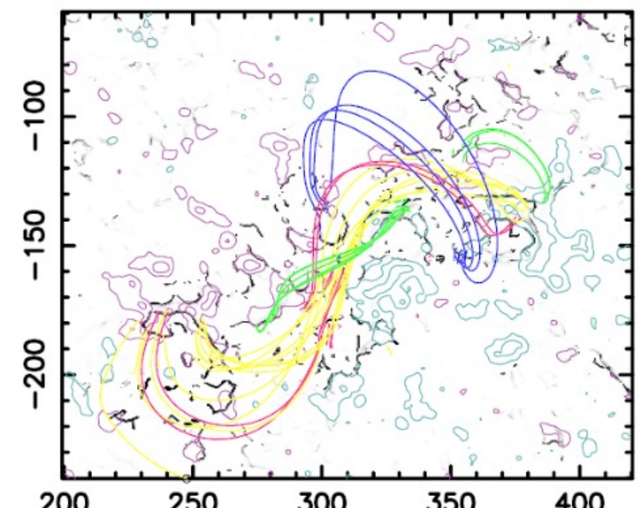
XRT Sigmoid from Feb 2007

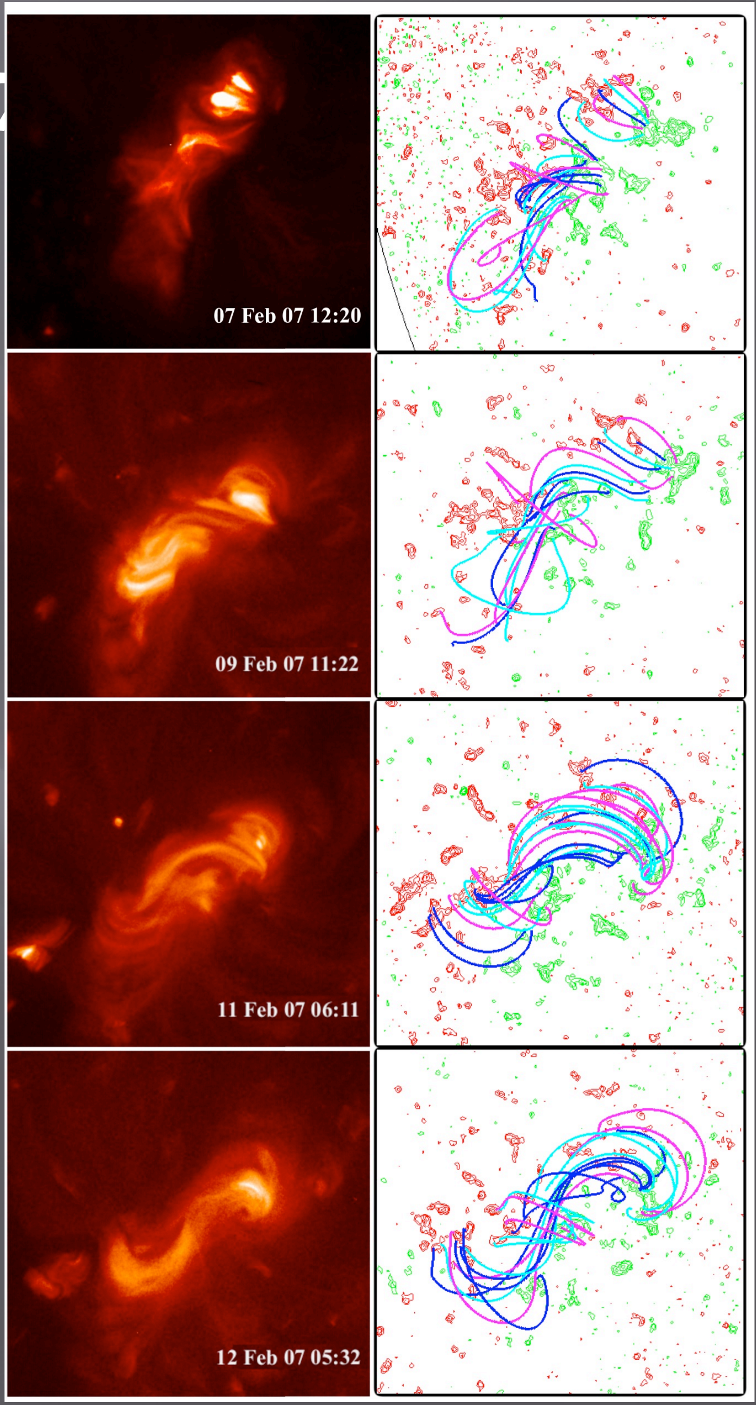
Evolution over 7 days

2 eruptions – Feb 07, 12

Types of field lines:

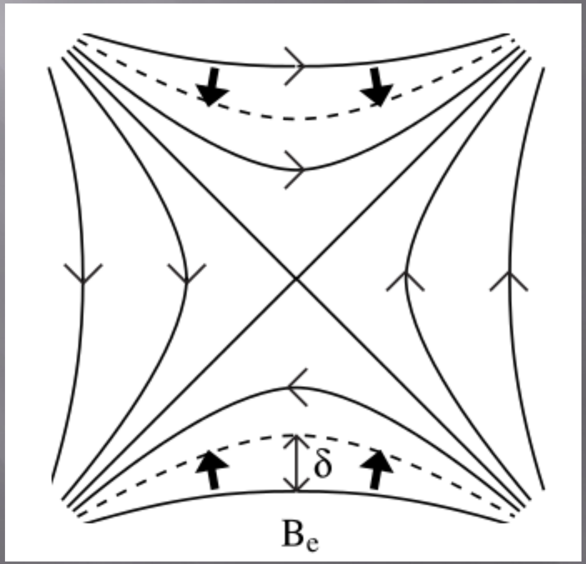
- J - shaped
- S- shaped
- Sheared arcade
- Potential arcade
- Post-flare-like loops

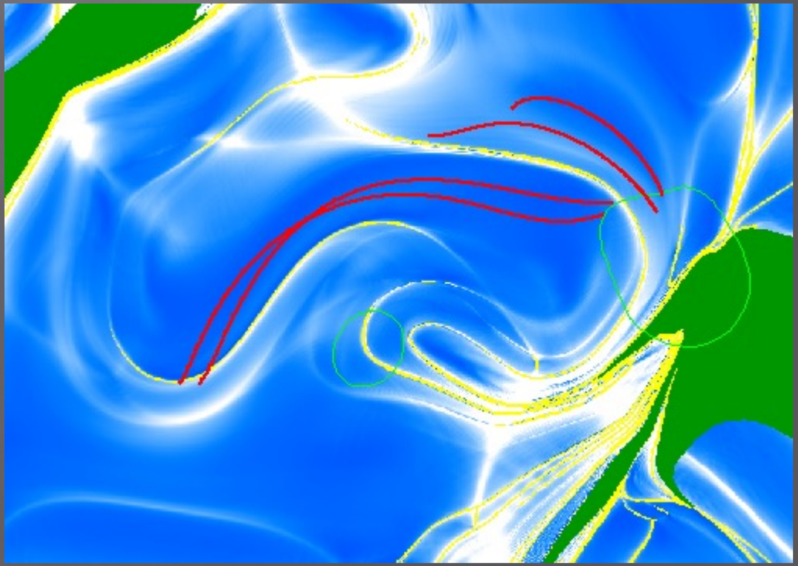




Magnetic field Topologies

- Connectivity domains – topology under smooth deformations
- Gradient of the mapping from one set of neighboring footpoints to the other – Priest & Demoulin ‘95, Demoulin et al. ‘96, ‘97
- Circle generally maps onto ellipse - squashing factor (Q) – Titov '99, ‘07
- Separatrices – discontinuous mapping, infinite Q
- Quasi-Separatrix Layers (QSLs) – where FL linkage drastically changes but is still continuous, large but finite Q,
  3D generalization of topology **add contours by hand**





Squashing factor

- The gradient of the field line mapping is given by the Jacobian magtrix (Demoulin ''95, 99)

$$M = \begin{pmatrix} \frac{\partial X}{\partial x} & \frac{\partial X}{\partial y} \\ \frac{\partial Y}{\partial x} & \frac{\partial Y}{\partial y} \end{pmatrix} = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$$

The covariant form of Q, applicable to any system of coordinates and shapes of the boundaries, was derived by Titov (2007). The squashing factor, Q, quantifies the strength of a QSL and is given by $Q = N^2/|\Delta|$, where $N^2 \equiv a^2 + b^2 + c^2 + d^2$ and the Jacobian $\Delta \equiv ad - bc$. Assuming flux conservation, the Jacobian is also the ratio

QSLs and current sheets

- Separatrices and QSLs + footpoint motions → locations for build-up of sharp/dense current sheets, probable sites for reconnection
- Slip-running reconnection – FLs slip through plasma at $>V_A$
- Theoretically Q is inversely proportional to the thickness of current sheet
- Sharp current sheets → explosive release of energy in reconnection
- Not so sharp → store free energy

General properties of QSLs

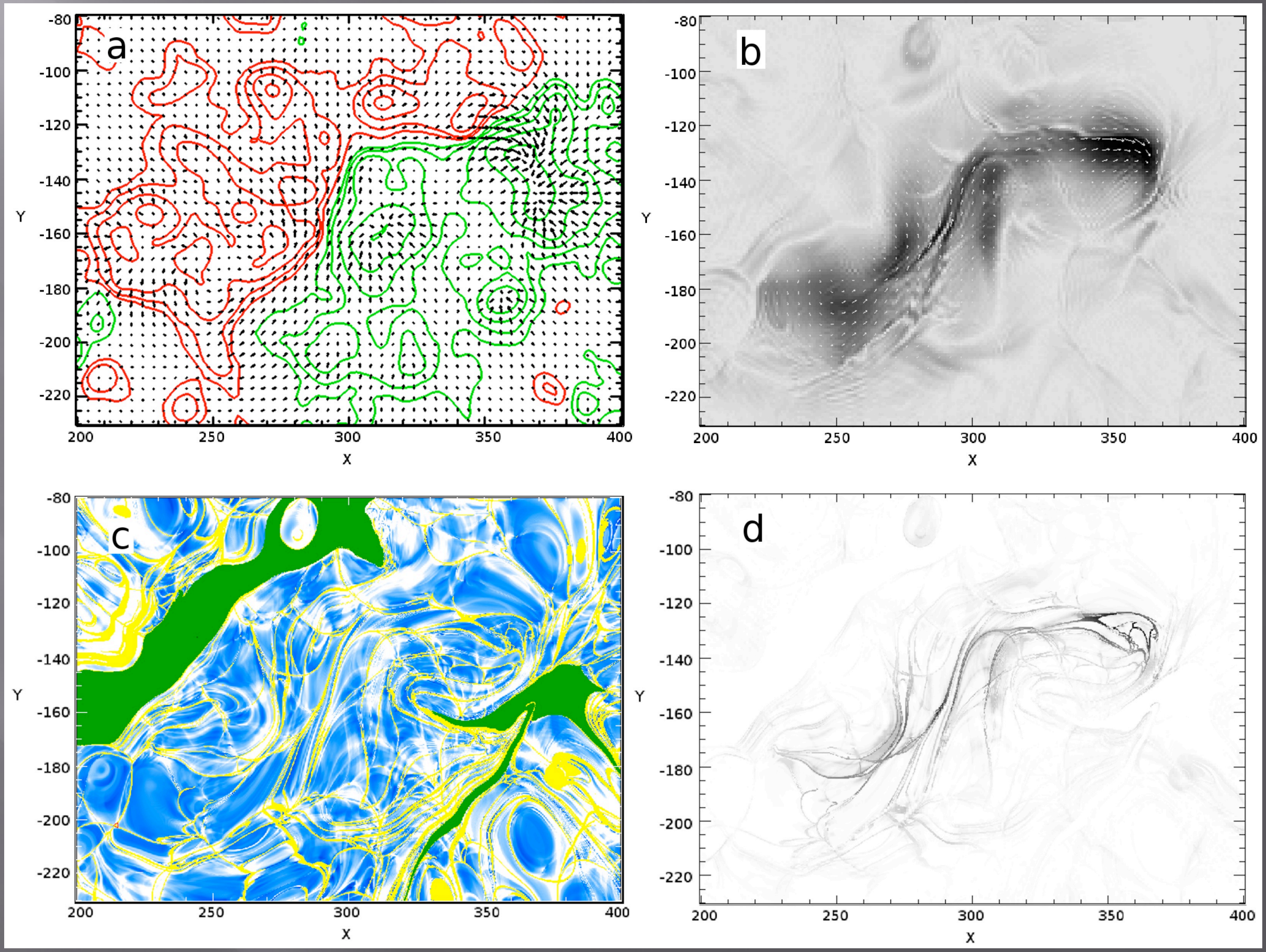
Large complexity in B flux

Large complexity in low-res QSL map

Prominent QSLs are aligned with B-field

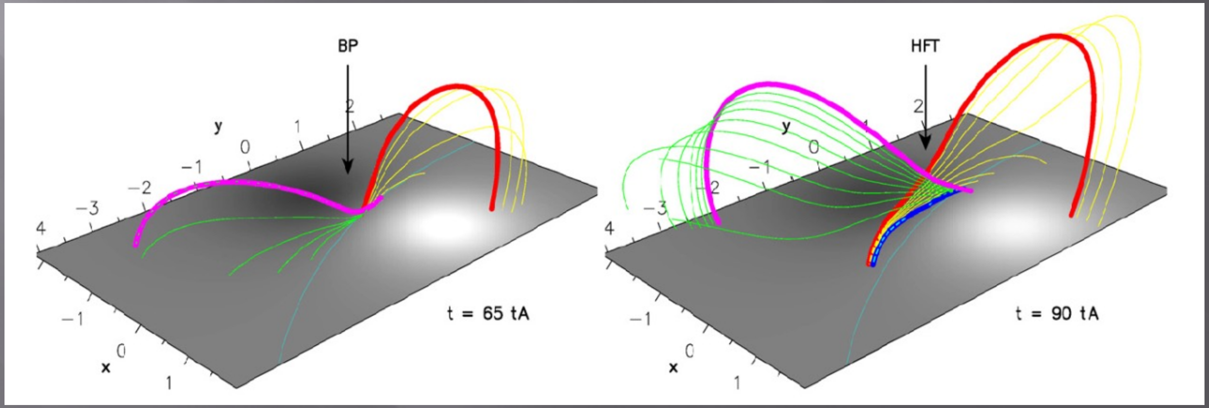
Correspond to large current concentrations

JQ plots – product of J and Q plots – to pick out prominent QSLs



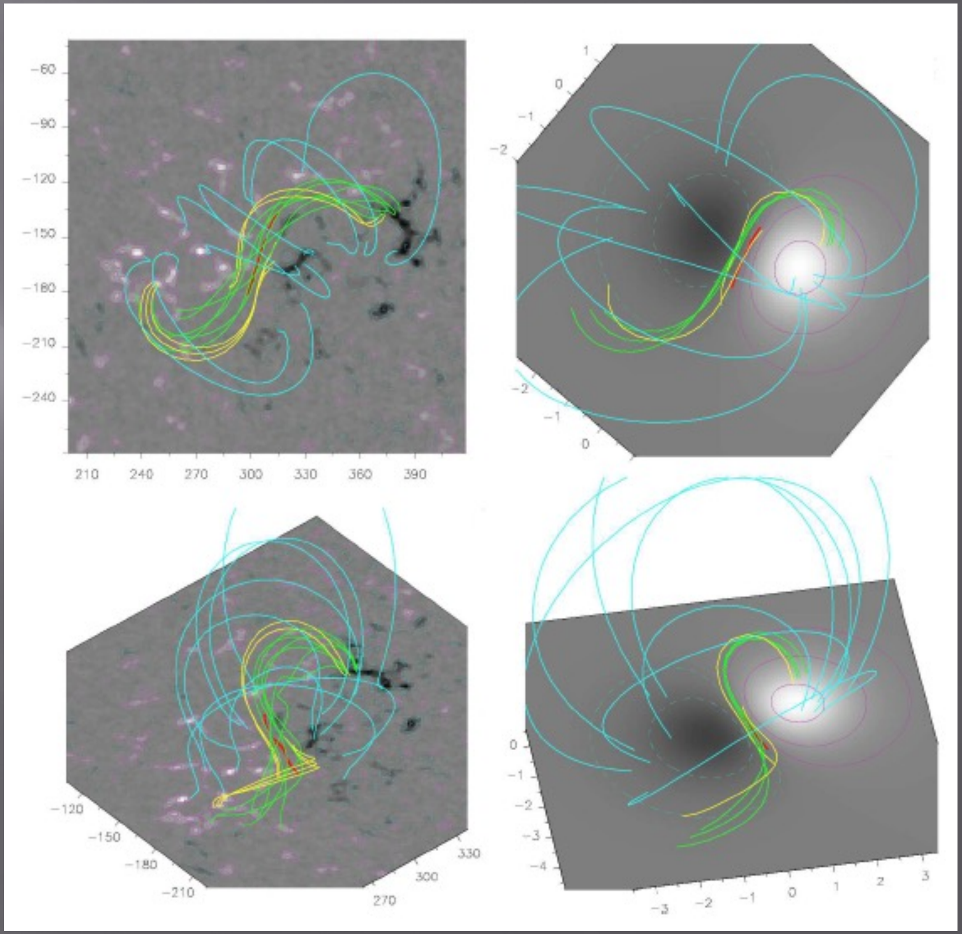
Idealized MHD simulations

- Zero-β 3D MHD code (Aulanier et al. 2005, 2010)
- Initially a potential field from two smooth asymmetric polarities
- Shearing motions at the PIL
- Diffusion of B – flux cancellation at PIL
- Build flux rope
- The flux rope (FR) develops BPSS but does not erupt
- Later develops an inverted tear drop shape
- The elevated flux rope enters into the torus instability domain and lifts off



The 3D magnetic field

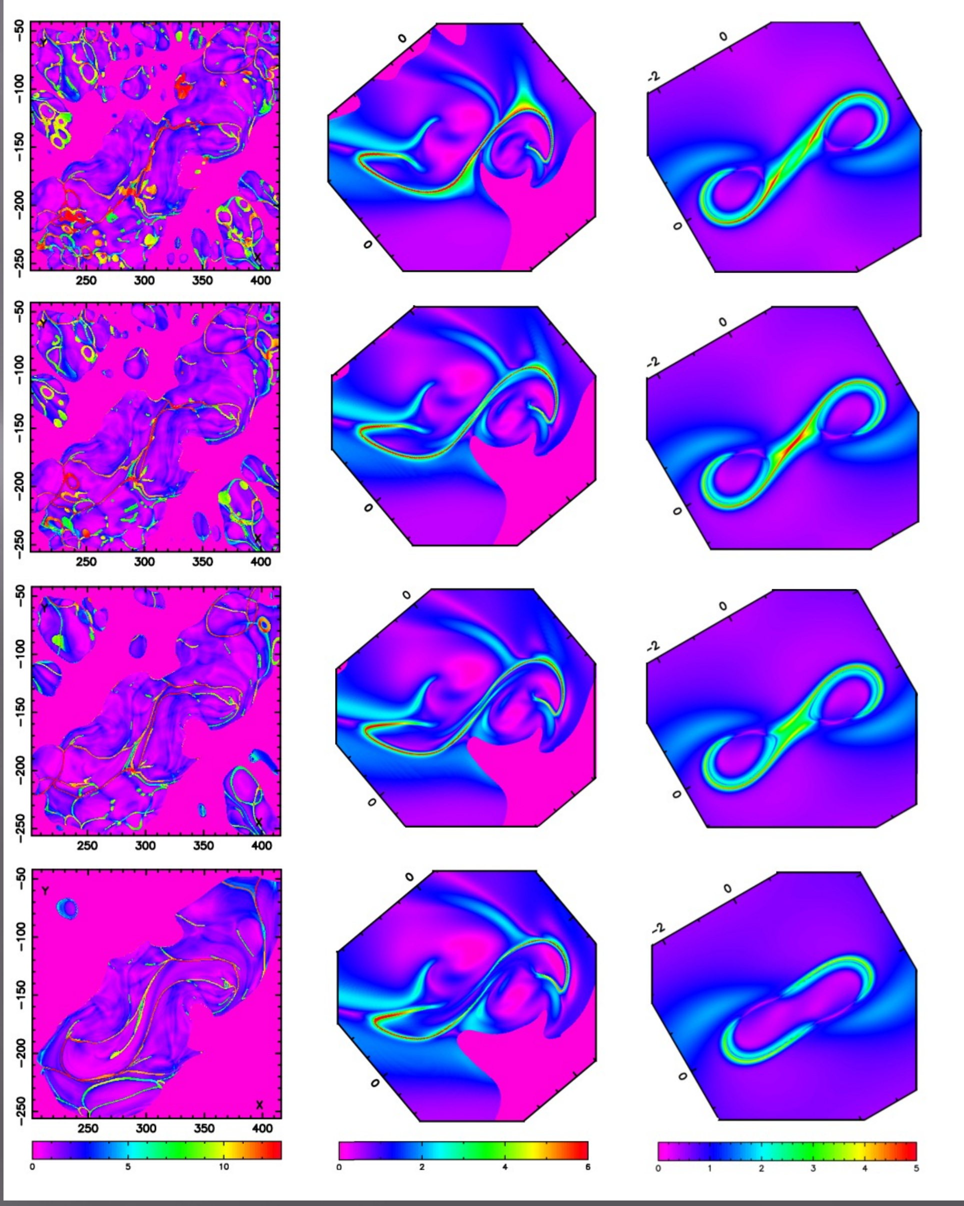
- All 4 types of field lines exist in both models
  - S-shaped (green) – from the inside of the flux rope
  - J-shaped (yellow) – connect under the FR
  - Short red field lines under the HFT
  - Overlaying arcade (blue)
- The FR in the MHD simulation is much thinner w.r.t. length



Horizontal QSL maps

- Higher complexity in the QSL maps of the NLFFF model – intrinsic to the large fragmentation of the real B distribution
- In MHD model – single diffuse QSL – due to extended diffuse polarities
- S-shaped QSL in MHD model due to incomplete FR
- Recovers TD topology for a HFT configuration FR

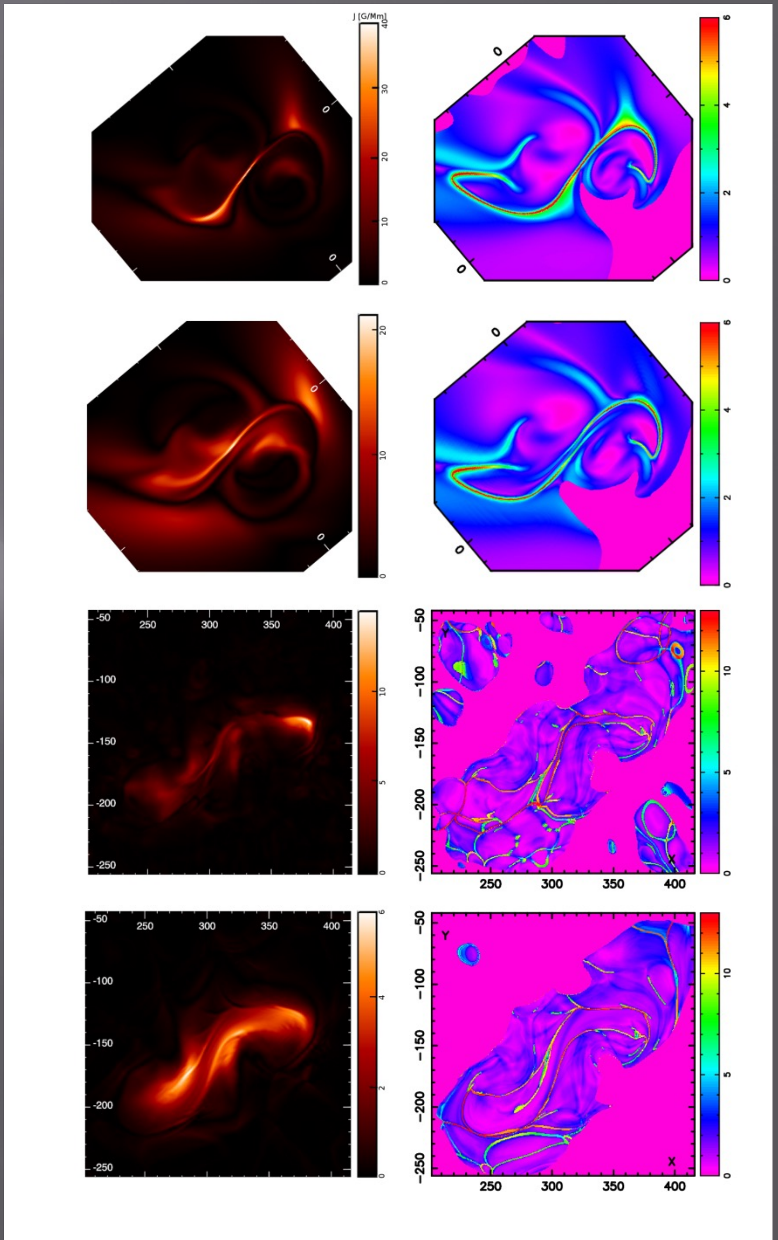
- **Label columns**
- **Add arrows for guidence**



Current distributions

- QSLs coincide with ridges in the current density
- Both QSLs and current concentrations outline the FR cavity
- Current is more diffuse in NLFFF model due to relaxation process
- MHD simulation has footpoint motions – hence sharp currents at QSLs

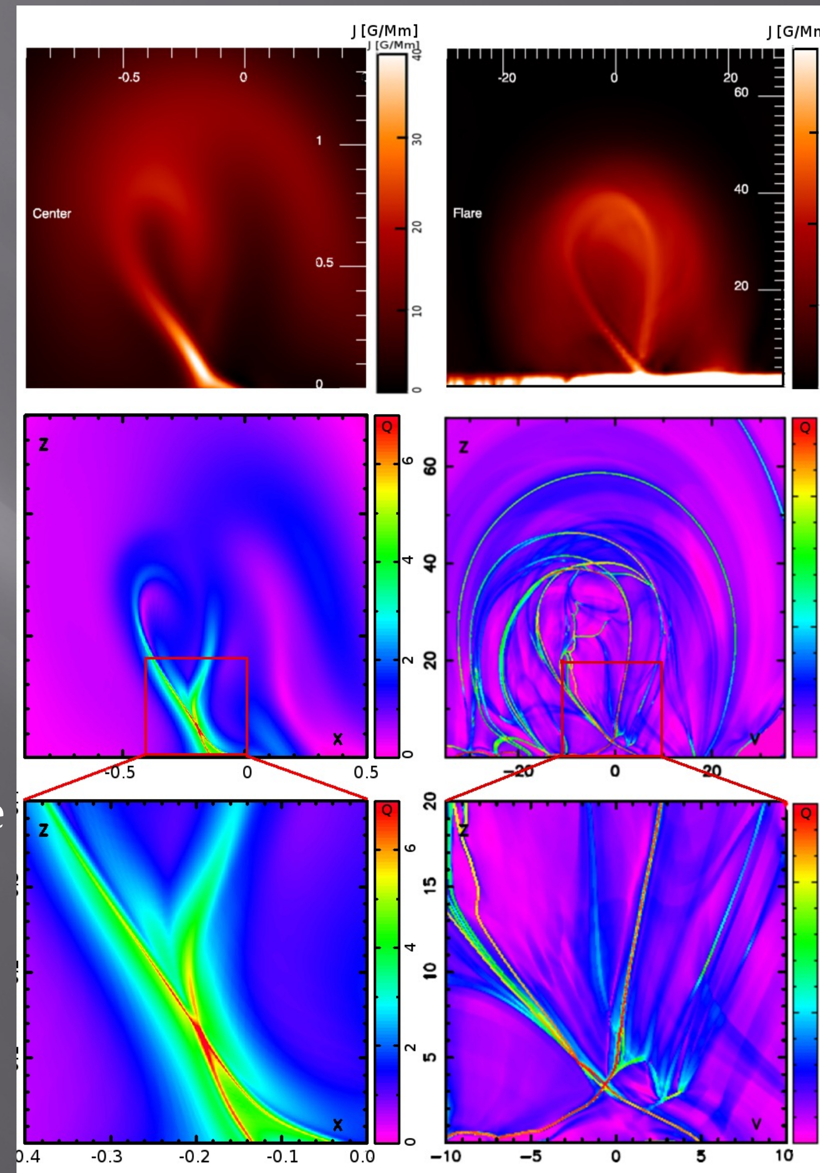
- **Same**



The Hyperbolic Flux tube

- **Add cartoon, eq. for HFT**
- **Outline HFT**

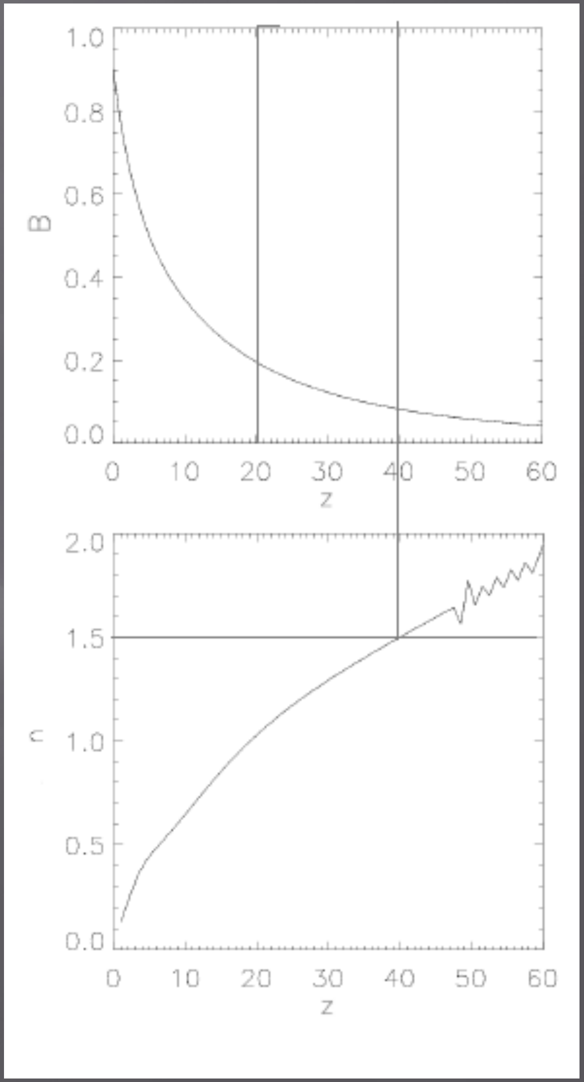
- QSLs and current on the edge of the FR
- Asymmetric expansion and current distributions in both cases
- HFT configuration in both models
- Highest value of Q
  - 10^{13} – NLFFF model
  - 10^{8} – MHD simulation
- Explosive reconnection can take place for $Q>10^{6}$ (Demoulin et al. 96)
- HFT appears at the location of the eruption in both cases



The torus instability

- **Increase thickness lines**

- Not enough twist for kink instability ~ 1-1.5 turns, need at least 3.5π
- Tether-cutting reconnection at the HFT elevates the FR more and it enters the torus instability regime in the MHD simulation (Aulanier et al. 2010)
- Torus instability when the potential arcade falls off with heights as n=dlnB/dlnz=1.5, depends on aspect ratio
- Evidence for possible torus instability in the modeled 3D magnetic field
- n=1.5 at the edge of the FR, continued expansion will lead to torus instability



Discussion

- Need to study the formation mechanism of sigmoids – flux emeregence/cancellation, footpoint motions
- How to gain a handle on the eruption mechanism?
- What instabilities contribute and what are the conditions?
- What are the relevant stability limits? What are the effects of the magnetic field configuration? (i.e., the ratio of toroidal to poloidal field in the flux rope)
- What properties define marginally stable configurations? What can be observed?
- Resistive instabilities have not been fully explored
- How do kink and torus play together to produce an eruption

More questions

- Do we need reconnection and how does play with the instability?
- What leads to the onset of reconnection – on small and large scales
- What are the global properties of the field and where might reconnection occur?
- How does reconnection occur in partially ionized plasmas? – relevant to chromospheric reconnection