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The Pre-eruption Behavior of an XRT Sigmoid – NLFFF Model and an MHD Simulation

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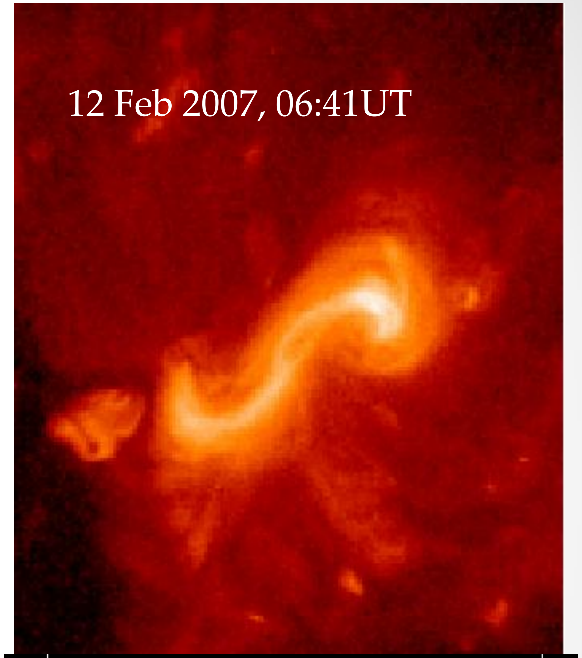
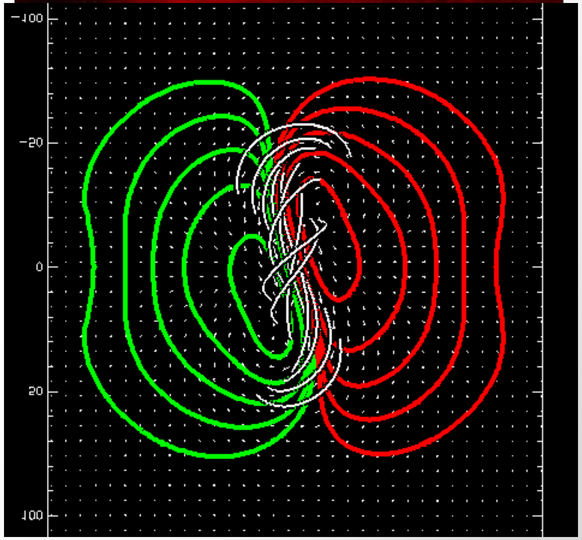
Outline

- Motivation
- The NLFFF model
- The MHD simulation
- The role of flux cancelation
- Topology analysis – a comparison
- The role of the torus instability

Sigmoids – an overview

- Transient or long-lasting S (south) or inverse-S (north) shape
- Twisted and sheared magnetic field structures – great for storing magnetic energy
- Canfield et al. '99, '07 - 68% of eruptions originate in sigmoidal regions
- Need to study the formation and evolution phases as well as the eruption mechanism
- Best modeled by a weakly twisted flux rope in the core, held down by a potential arcade – Titov & Demoulin 1999
- Model an XRT sigmoid observed on Feb12, 2007, flare and CME at 7:40UT – McKenzie & Canfield '08



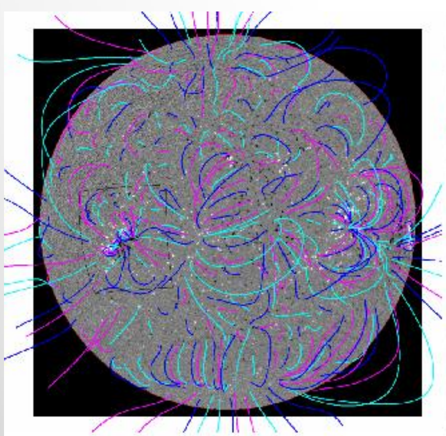
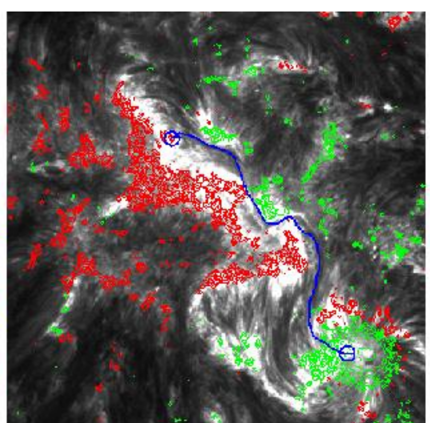
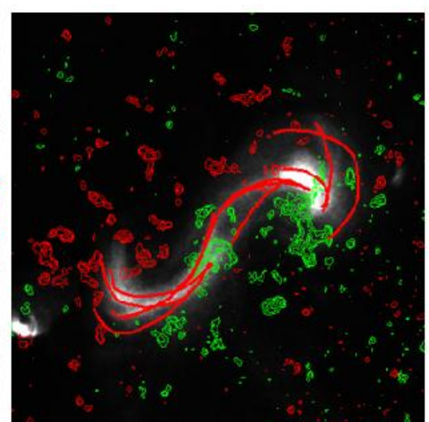
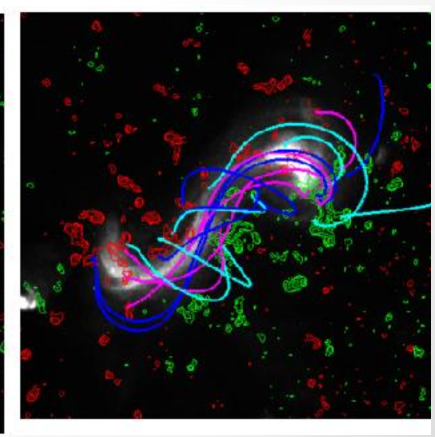


NLFFF models vs MHD simulations

- Need model of the magnetic field when region is on disk
- NLFFF models most accurately describe the sheared and twisted core AND the potential arcade
- For one snapshot of the magnetic field, we can study:
  - Field topology and current build-up
  - Can estimate flux and energy budgets
  - Conditions for instability, probable reconnection sites
- Dynamical MHD simulation
  - Not based on specific data
  - Tries to reconstruct the evolution and eruption of solar AR
- Arrive at consistent picture through the comparison of magnetic models and dynamic MHD simulations

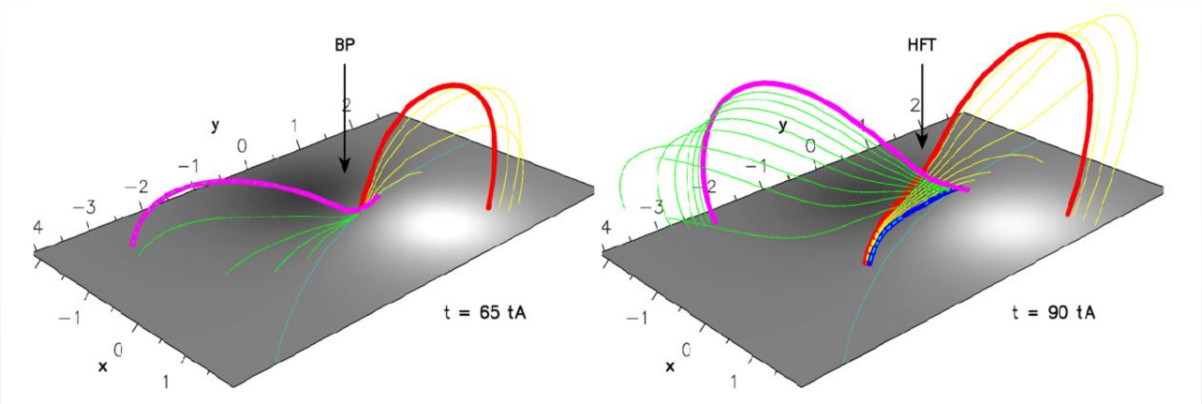
The NLFFF model –
the flux rope insertion method

- van Ballegooijen ‘00, ‘04, ‘07, Savcheva, van Ballegooijen & DeLuca ‘11
- Global potential field extrapolation from SOLIS Carington magnetogram B.C.
- Potential field extrapolation from a HiRes LoS MDI magnetogram
- Clear up a cylindrical cavity with no B
- Insert flux rope as a combination of axial and poloidal flux – use filament path as guidance
- Relax by magnetofriction with hyperdiffusion
- Fit model to observed coronal loops in XRT

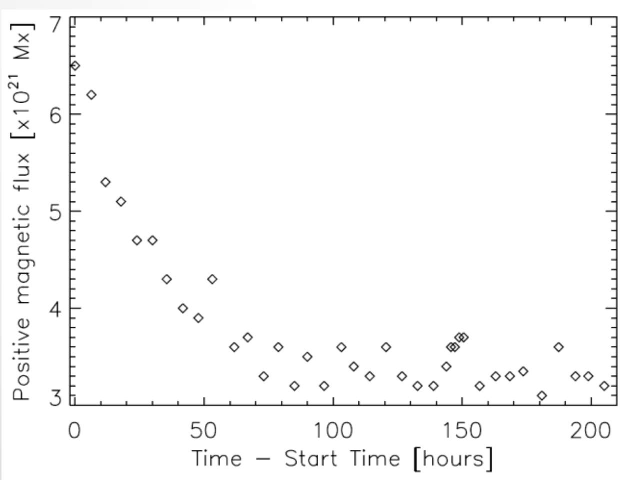
The MHD simulation

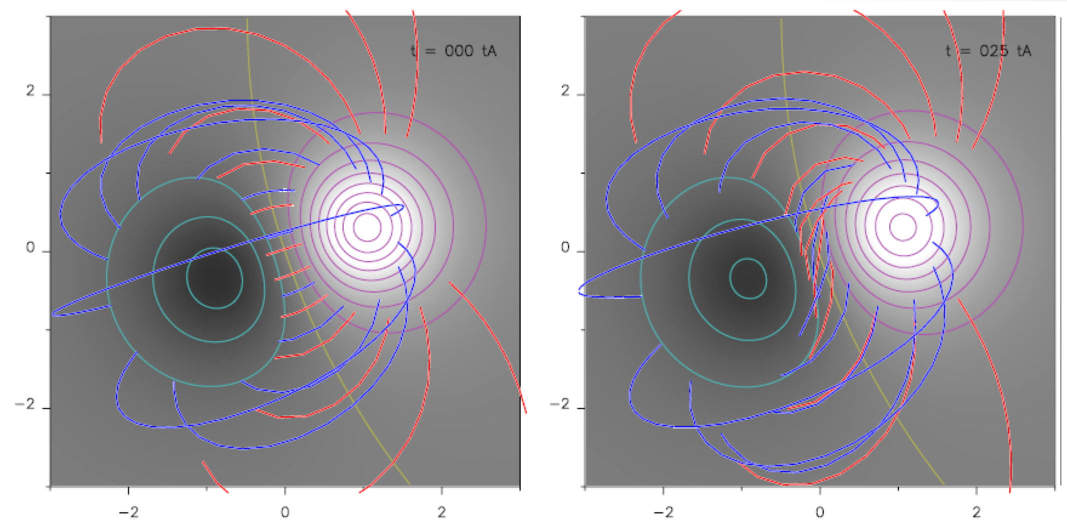
- Zero-β 3D MHD code (Aulanier et al. 05, Aulanier et al. 10)
- Initially a potential field from two smooth asymmetric polarities
- Shearing motions at the PIL
- Diffusion of B – flux cancellation at PIL
- Build flux rope
- The flux rope (FR) develops BPSS but does not erupt
- Later develops an inverted tear drop shape
- The elevated flux rope enters into the torus instability domain and lifts off



The flux rope development

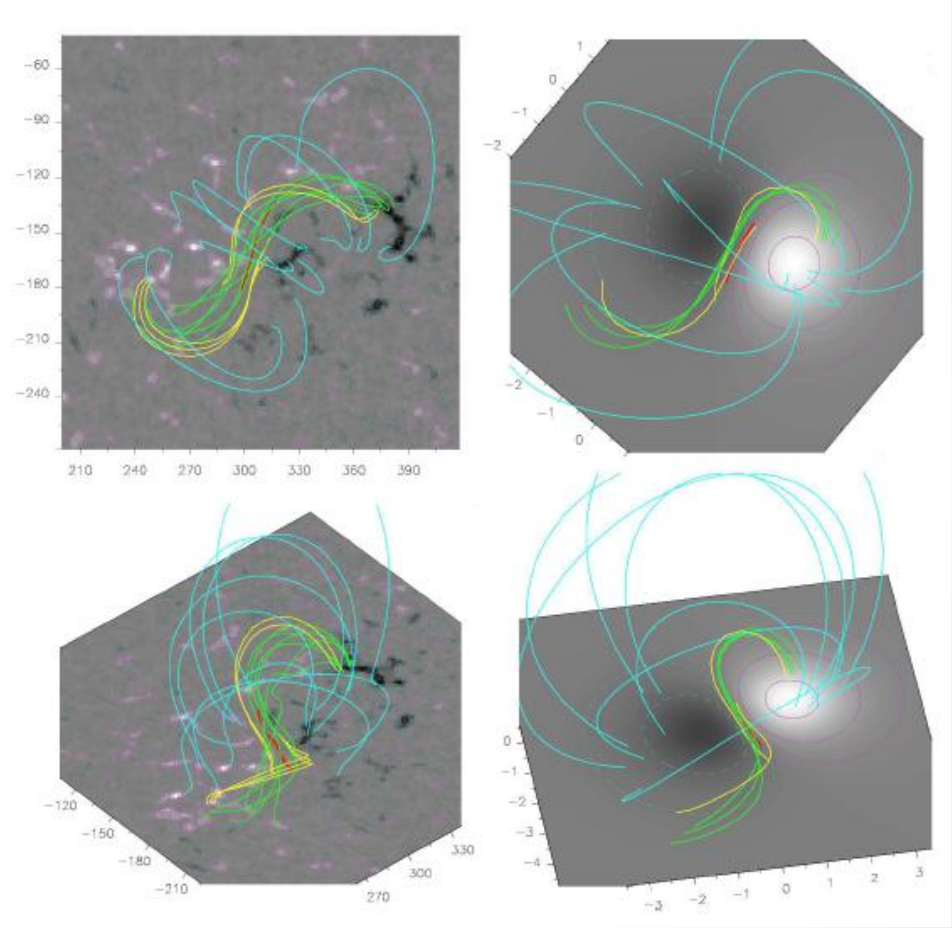
- Flux cancelation in both models
  - 50% in the observed sigmoid
  - 10% in the MHD simulation
- Shearing motion
  - Relative linear motion of two semi-detached regions in the observed region
  - Rotation of the two polarities in MHD simulation





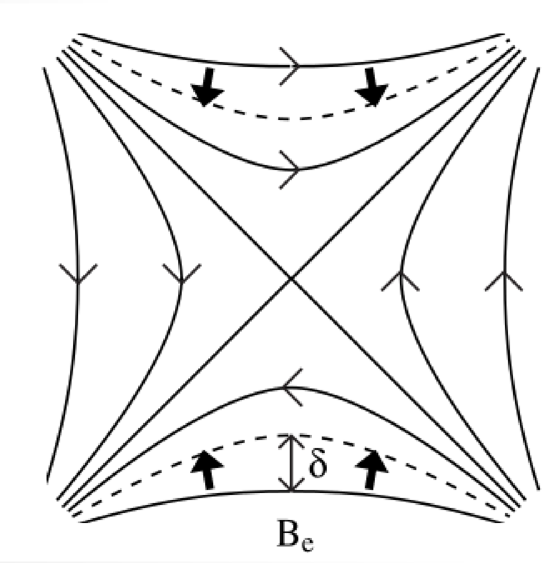
The 3D magnetic field

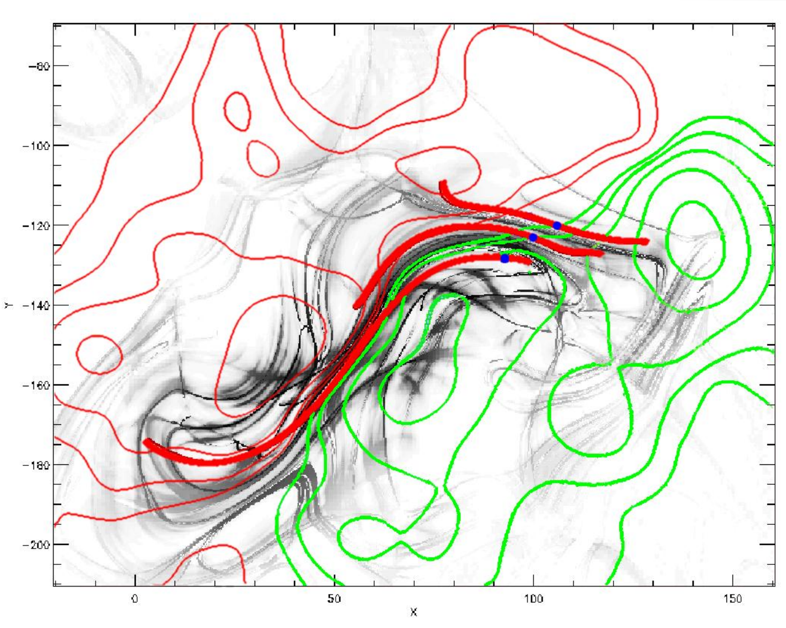
- All 4 types of field lines exist in both models
  - S-shaped (green) – from the inside of the flux rope
  - J-shaped (yellow) – connect under the FR
  - Short red field lines under the HFT
  - Overlaying arcade (blue)
- The FR in the MHD simulation is much thinner w.r.t. length – not fully developed



Topology analysis

- Generally, Quasi-Separatrix Layers (QSLs, Priest & Demoulin 95, Démoulin et al. 96) – gradient of the mapping of field lines
- Strong connectivity gradients but mapping is continuous
- Strength of QSLs defined by squashing factor Q – Titov 02, 07



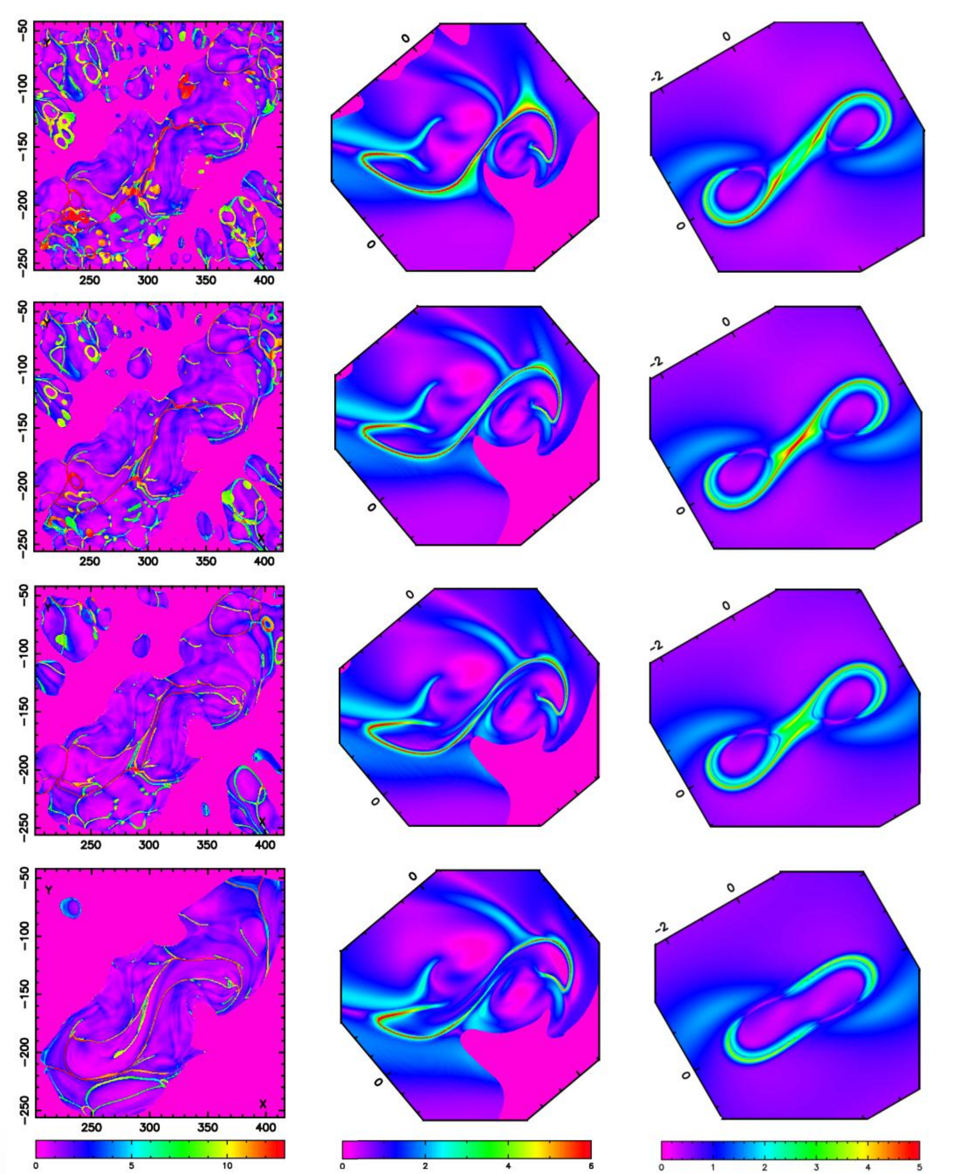


QSLs and current sheets

- Separatrices and QSLs + footpoint motions – formation of sharp current sheets
- Value of Q inversely proportional to thickness of current sheet
- Reconnection at QLSs – explosive release of energy

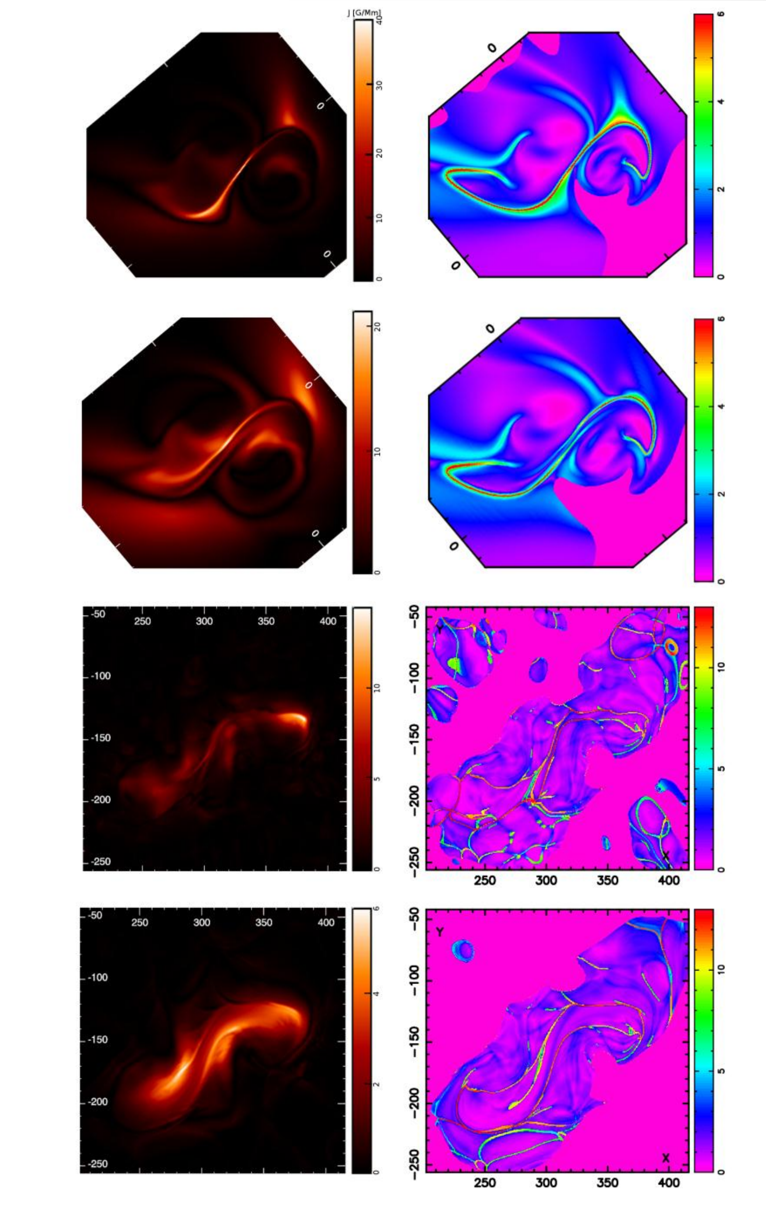
Horizontal QSL maps

- 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



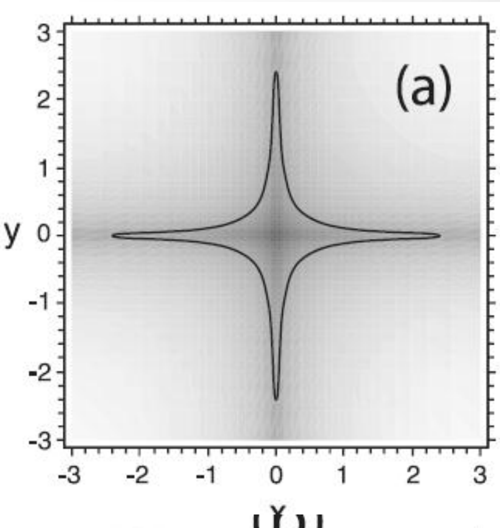
Current distributions

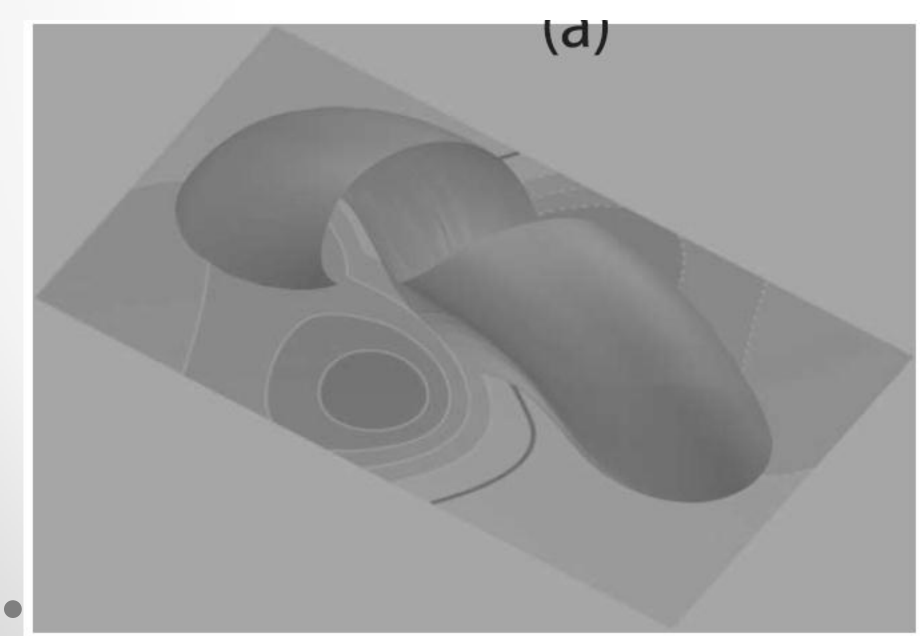
- QSLs coincide with ridges in the current density
- Both QSLs and current concentrations outline the FR cavity
- Current is more diffuse in NLFFF model due to relaxation process
- MHD simulation has footpoint motions – hence sharp currents at QSLs

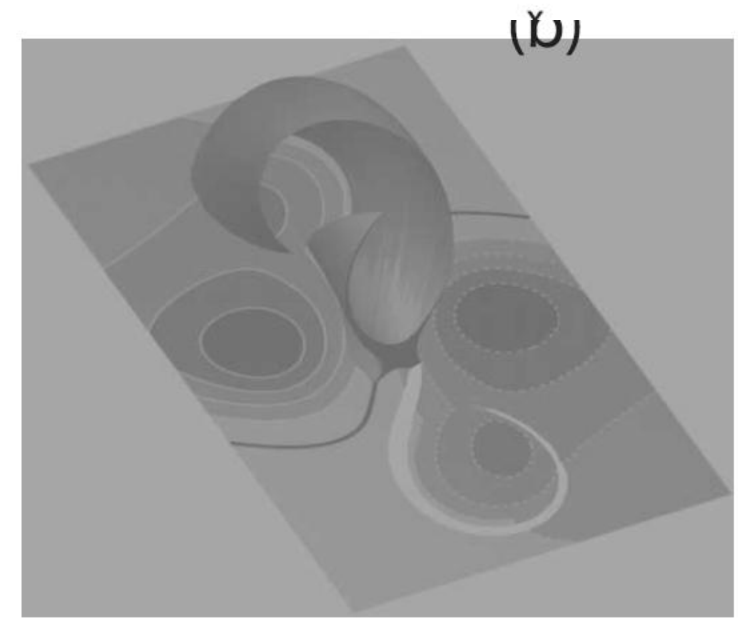


Hyperbolic Flux Tube (HFT)

- Highest Q region in the volume (Titov '07)
- QSL folds on itself
- 4-way saddle point – like an X-line
- Reconnection can happen if $Q>10^6$

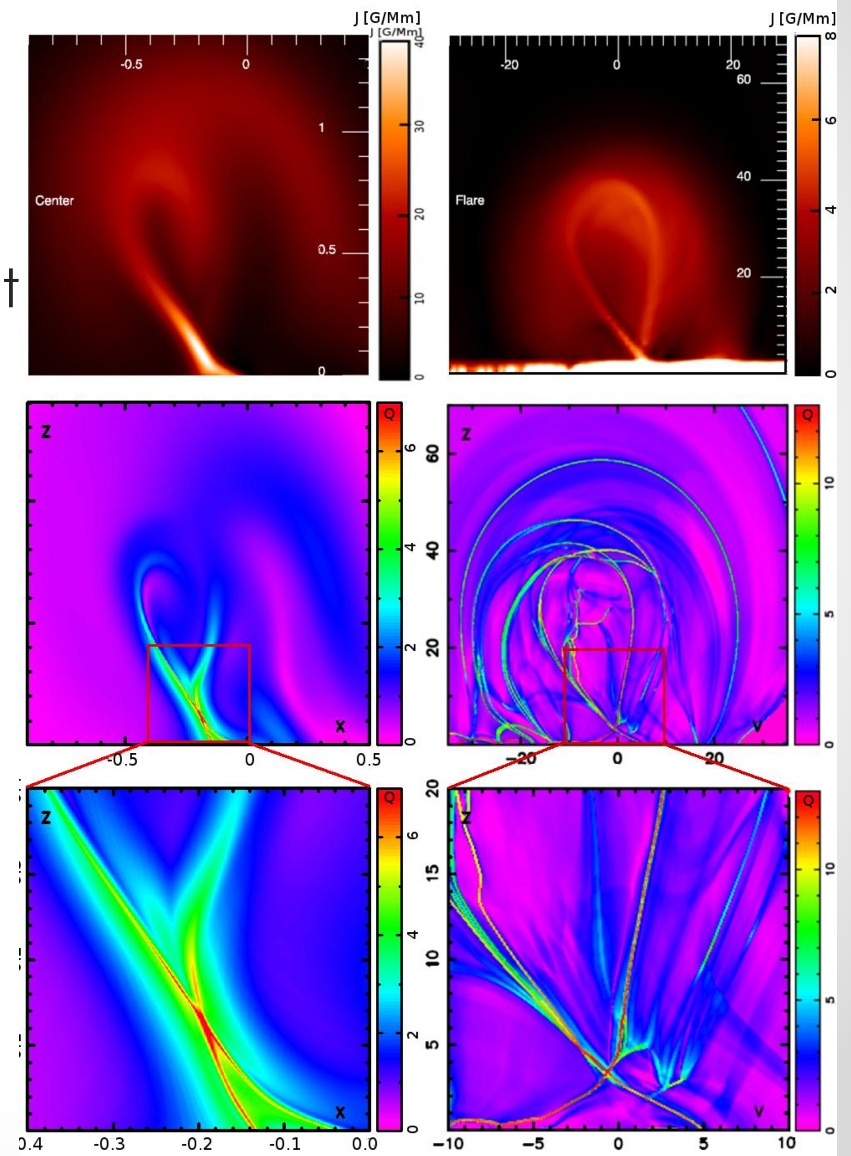






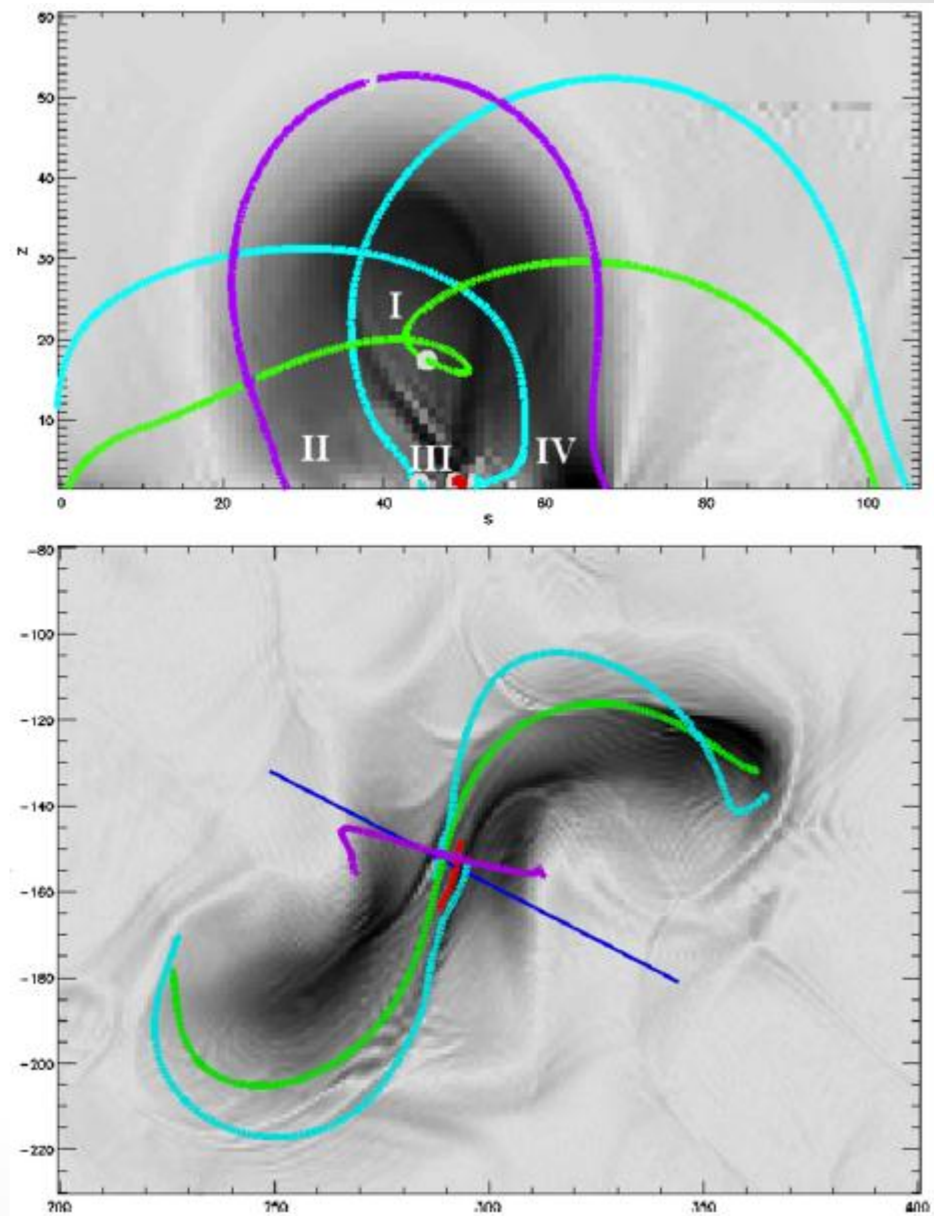
The HFT

- 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



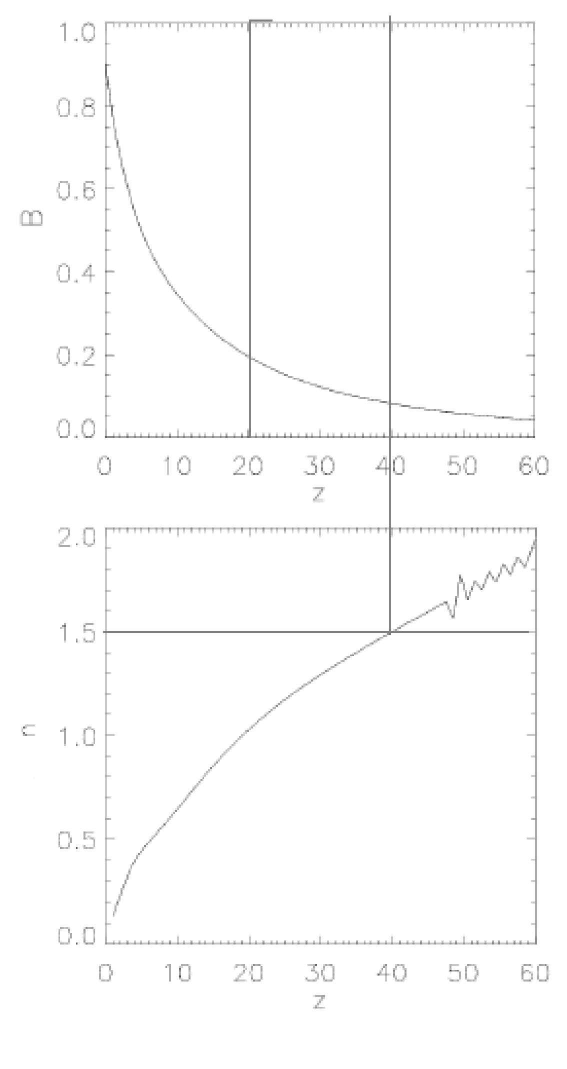
Field lines at the HFT

- 2 J-shaped field lines meet at HFT – reconnect
- Flux is transferred to flux rope
- Weakens arcade and strengthens the flux rope
- Flux rope is elevated



The torus instability

- Reconnection at the HFT elevates the FR more and it enters the torus instability regime in the MHD simulation (Aulanier et al. 10)
- Torus instability when the potential arcade falls off with heights as n=dlnB/dlnz=-1.5
- 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



Conclusions

- NLFFF models of a XRT sigmoid – the flux rope insertion method
- Dynamical MHD simulation with shearing motions and diffusion of B
- A consistent picture of the evolution and eruption of the sigmoid
  - Similarity in the FR development process
  - Topological similarities
  - HFT at the location of the flare
  - Current concentrations coincide with QSLs on the edge of the flux rope
  - Evidence for torus instability