Magnetic Field Modeling and Topology Analysis in Sync with MHD Simulations to Understand the Evolution and Eruption of Solar Active Regions

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Sesssion2

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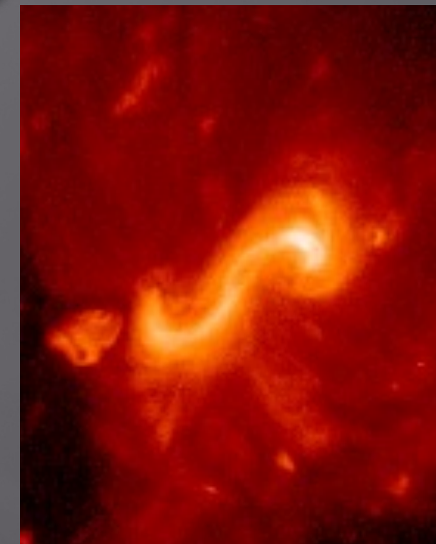
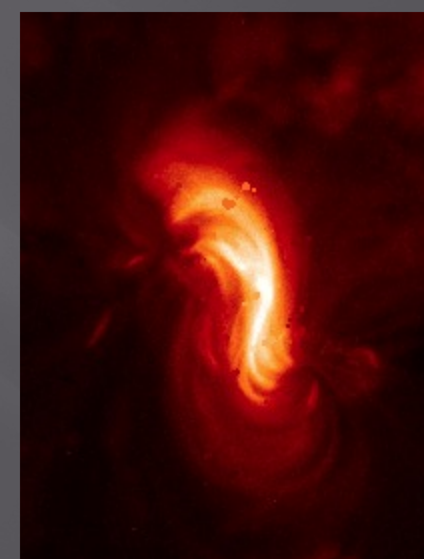
Outline

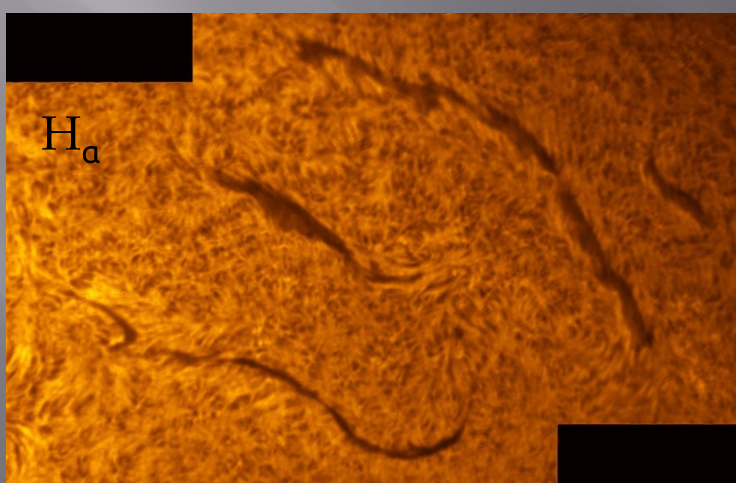
- Motivation and sigmoidal active regions in general
- Magnetic field modeling – the basics
- The flux rope insertion method
- Flux cancellation and sigmoidal flux ropes
- Basics of topology analysis
- Data- constrained and data-driven MHD simulations
- The Inoue MHD simulation 09/02/13
- The KT MHD simulation of 12/07/12
- The MAS global thermodynamic simulation of 12/07/12
- The KT MHD simulation and topology analysis of the 10/04/08
- The SWMF global thermodynamic simulation of 10/04/08
- Summary and Conclusions

Sigmoidal active regions

- Majority of eruptions in sigmoidal active regions (ARs)
- Observed in the solar corona in X-rays →
  - Rust & Kumar '96
- S or inverted S-shape
- Transient or long-lasting
- Often associated with H_{α} filaments

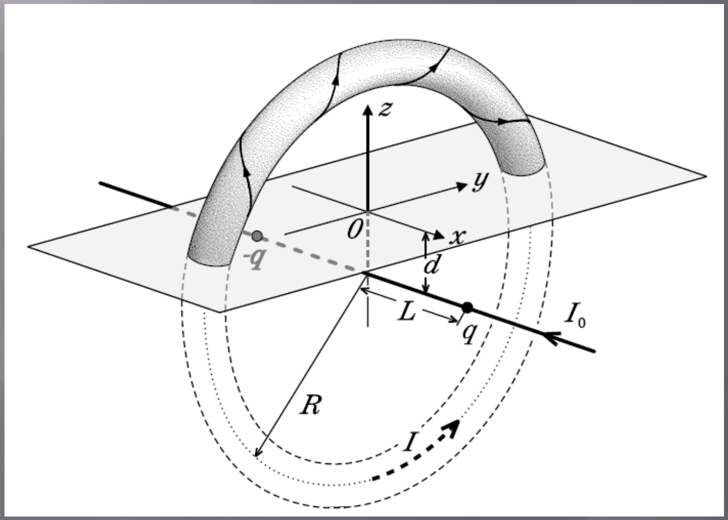


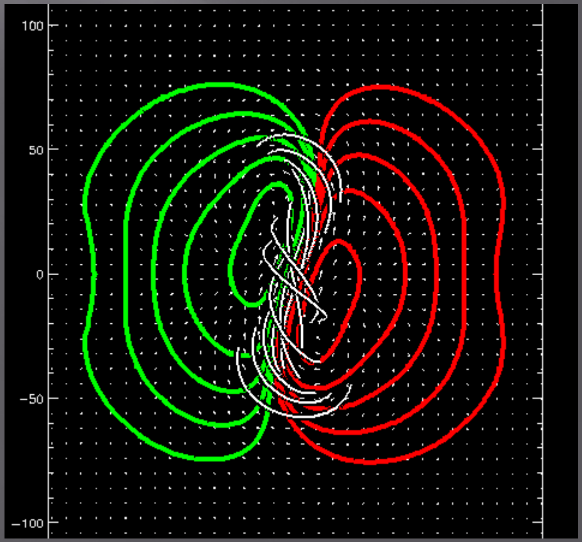




Sigmoidal active regions

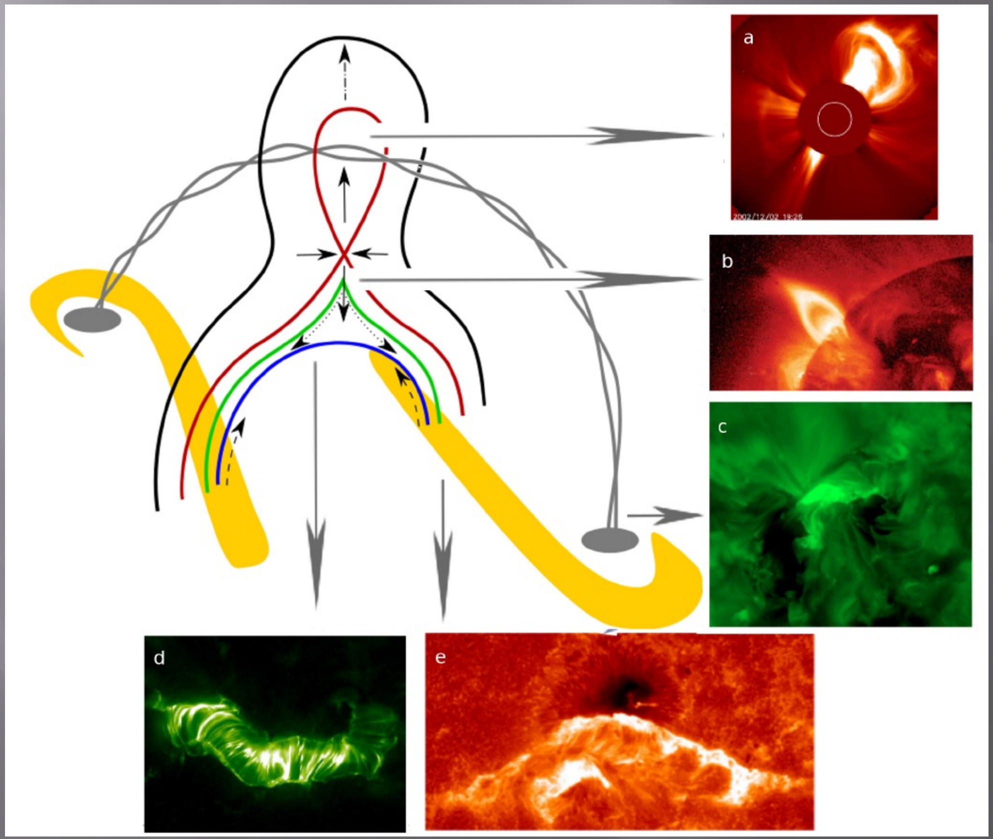
- Twisted and sheared magnetic field structures
- Great for storing magnetic free energy
- Canfield et al. '99, '07; Savcheva et al. '14, '21 68-74% of eruptions in sigmoidal ARs
- Best modeled by a flux rope in a potential arcade
- Titov & Demoulin '99 flux rope model





The standard flare/CME model

- Requires pre-existing magnetic flux rope (FR)
- Need loss of equilibrium via instabilities and/or reconnection
- This model produces all observed flare/CME features
- Study erupting sigmoids as laboratory – high probability for eruption



Schematic of Standard flare/CME model with Observed (post)-flare and CME features (Savcheva et al. ‘16, Kazachenko et al. 21)

Some questions about sigmoidal ARs

- How do sigmoids form? – How is the flux rope built up?
- **What is their magnetic field structure?**
- What is the free energy content 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?**
- **Eruption mechanisms**

Magnetic field modeling

- Need a model of the 3D magnetic field when region is on disk
- Coronal field constrained by photospheric B
- Can estimate flux and energy budgets
- Current distributions
- Field topology by tracing millions of filed lines
- Conditions for kink and torus instabilities
- **Follow formation, evolution, and eruption of region in data-constrained and data-driven MHD and magnetofrictional (MF) simulations**

Magnetic field modeling

- Potential field
- $\mu \mathbf{J} = \nabla \times \boldsymbol{B} = \alpha \mathbf{B}$
  - When $\alpha=0$, no currents, no free energy, min energy state - cannot power an eruption
- Linear Force-Free Field (LFFF)
  - When α=const everywhere, unphysical
- Non-Linear Force-Free Field (NLFFF)
  - When $\alpha=f(r)$, but constant along given field line
  - Most realistic, represents core of AR, and more potential arcade/restraining field

NLFFF modeling
The flux rope insertion method

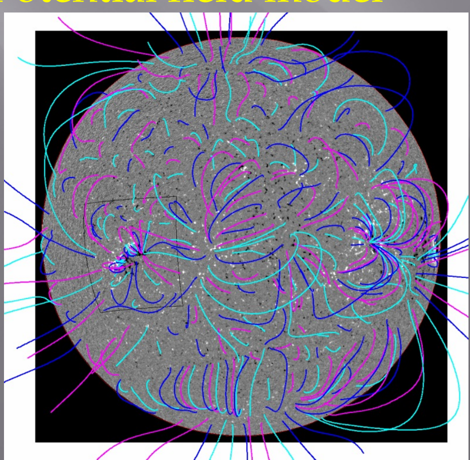
- van Ballegooijen '04 , Savcheva et al. '16 **– the Coronal Modeling System (CMS)**
  - Global potential field extrapolation from SOLIS/HMI synoptic (full sun) magnetogram
  - Potential field extrapolation from partial LoS MDI/HMI magnetogram
  - Insert magnetic flux rope (FR) along observed filament path – grid of models with combinations of axial and poloidal flux
  - Relax by magnetofriction with hyperdiffusion – η_4

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

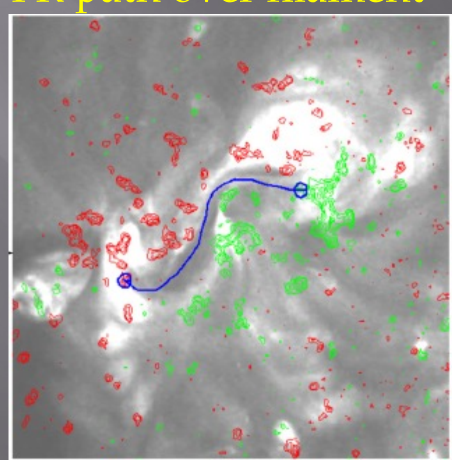
$$v = (f\mathbf{j} - v_1 \hat{\mathbf{r}} \times \mathbf{B}) \times \frac{\mathbf{B}}{B^2},$$

  - Match grid of models to observed coronal loops

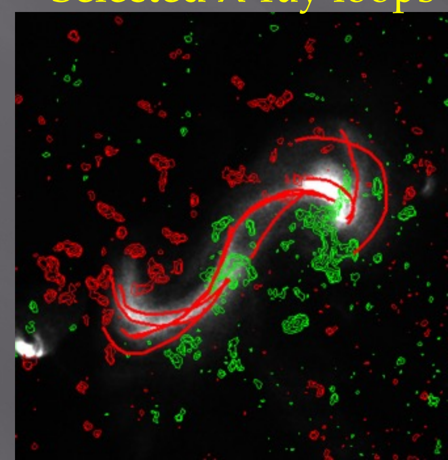
Potential field model



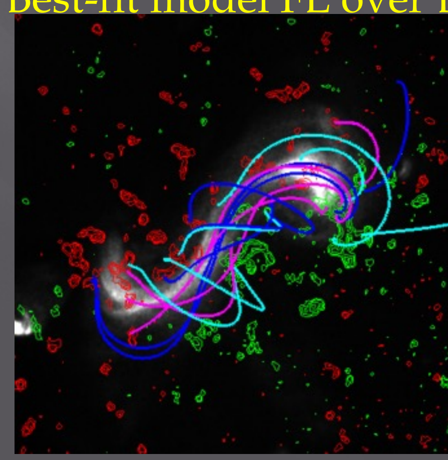
FR path over filament



Selected X-ray loops



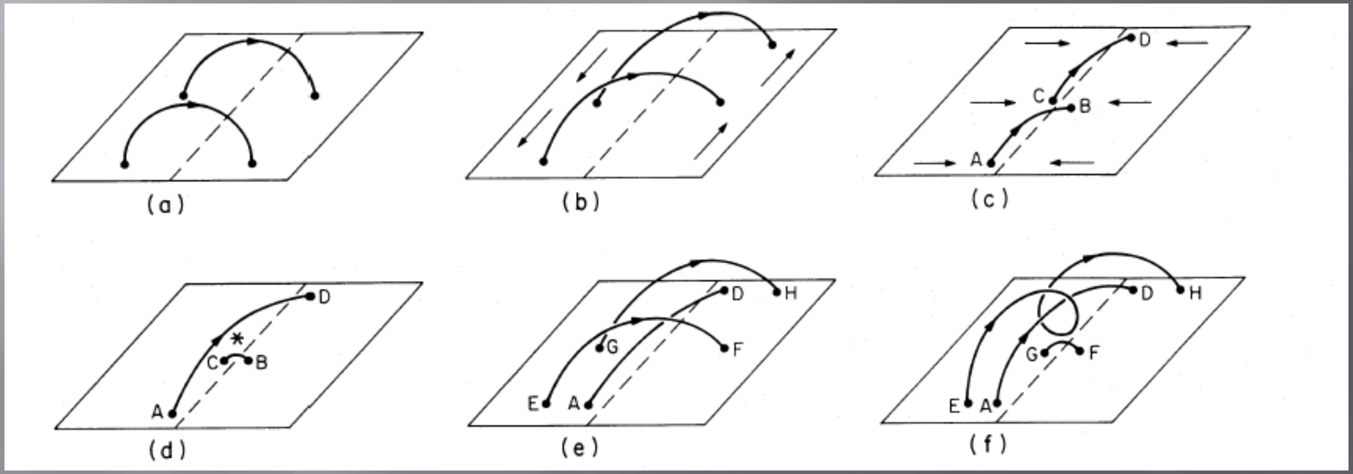
Best-fit model FL over B



Magnetic Flux Cancellation Model for formation and evolution of FRs

Flux cancellation in decaying active regions

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



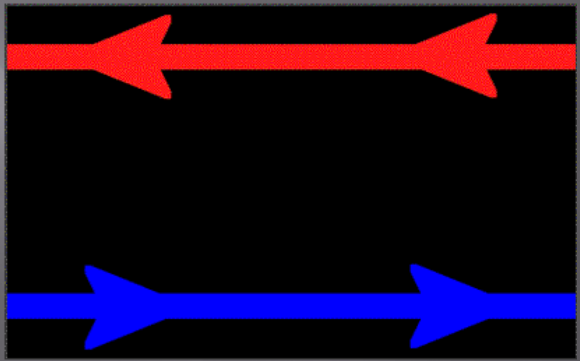
Magnetic Flux Cancellation Schematic from Van Ballegooijen & Martens (1989)

- Shear flow + converging motions → short submerging loops + long helical field lines (FL)
- Build-up of free energy - Potential field converts to field with magnetic free energy, i.e FR

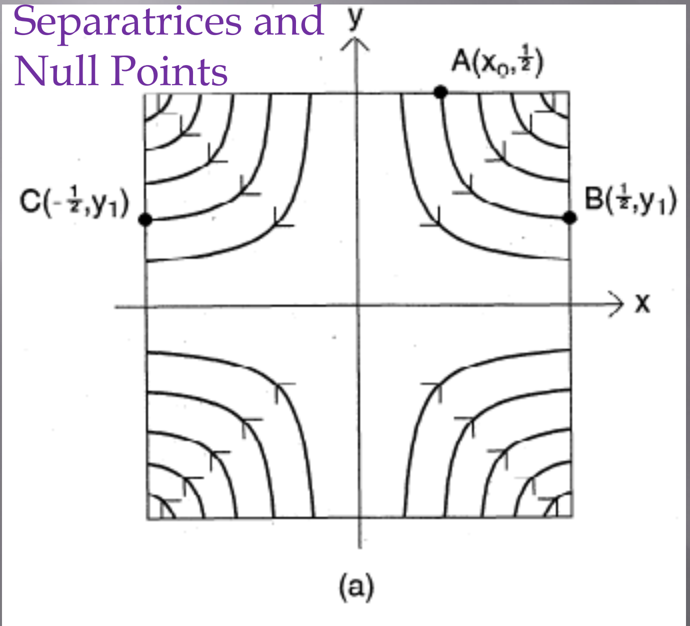
Basics of Magnetic Field Topology

- Topology: persists under smooth deformations
- Separates 3D field into *connectivity or quasi-connectivity domains*
- Gradient of the mapping of a set of neighboring footpoints from one boundary to the other – Priest & Demoulin '95, Demoulin et al. '96, '97
- Circle of FL footpoints generally maps onto ellipse – squashing factor (*Q*) –
  - Titov et al '99, '07
- Quasi-Separatrix Layers (QSLs) – where field-line linkage drastically changes, large but finite Q
- Currents can accumulate at QSLs

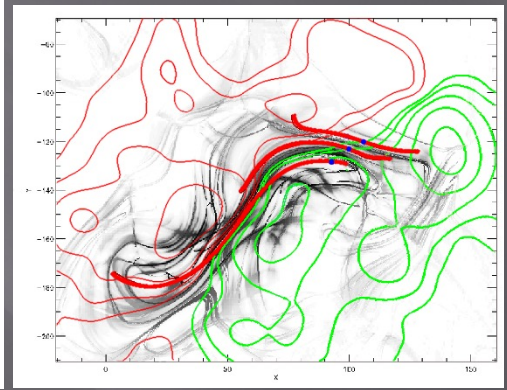
Reconnection

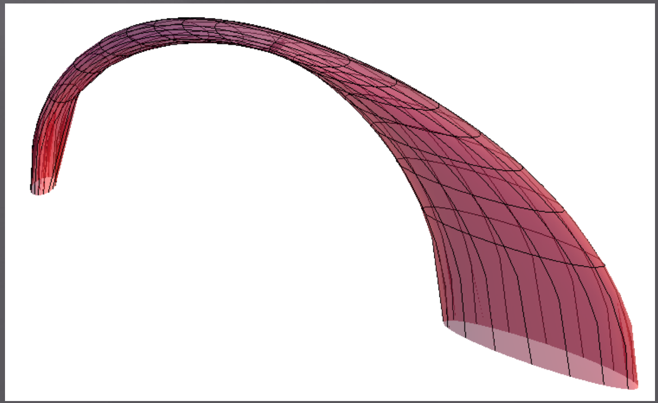


Separatrices and Null Points



QSLs

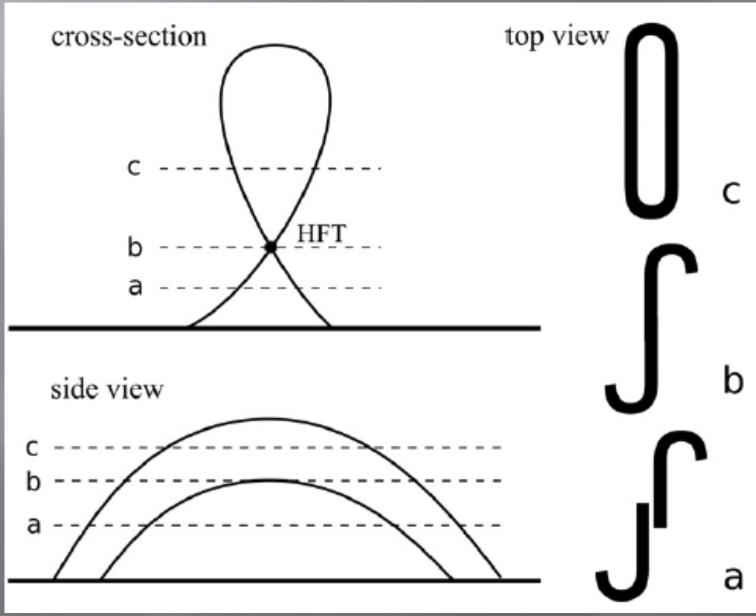




The Hyperbolic Flux Tube (HFT)

Savcheva et al. '12a,b, '15, '16

- Inverted tear-drop shape – twisted FR
- HFT (Titov eta l. '07) appears under the FR before flares/CMEs
- Found at location of flares in < 20 events with NLFFF



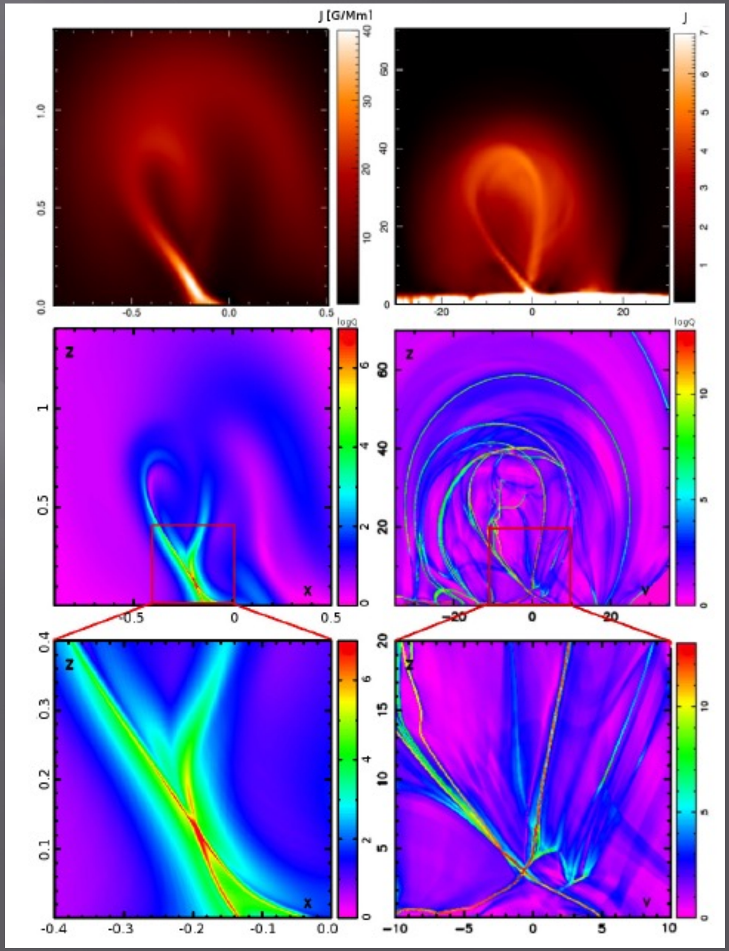
MHD simulation

NLFFF model

J Side view

QSL Side view

QSL Side View Blow up

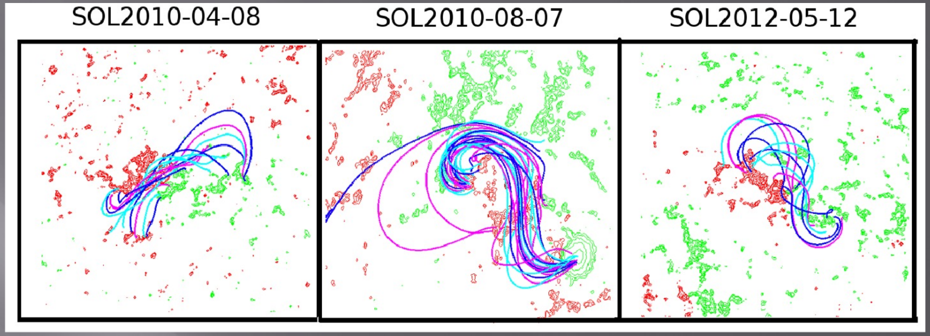


10 Mm

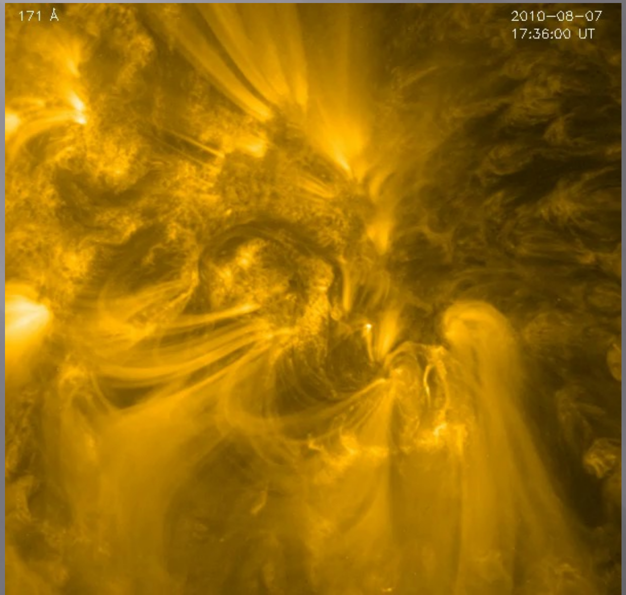
Relation between CME topologies and observed flare features

- Data-constrained NLFFF models of 8 sigmoidal ARs
- Make unstable FR models with the FR insertion method, MF evolution
- Horiz. and vertical QSL maps at different iteration

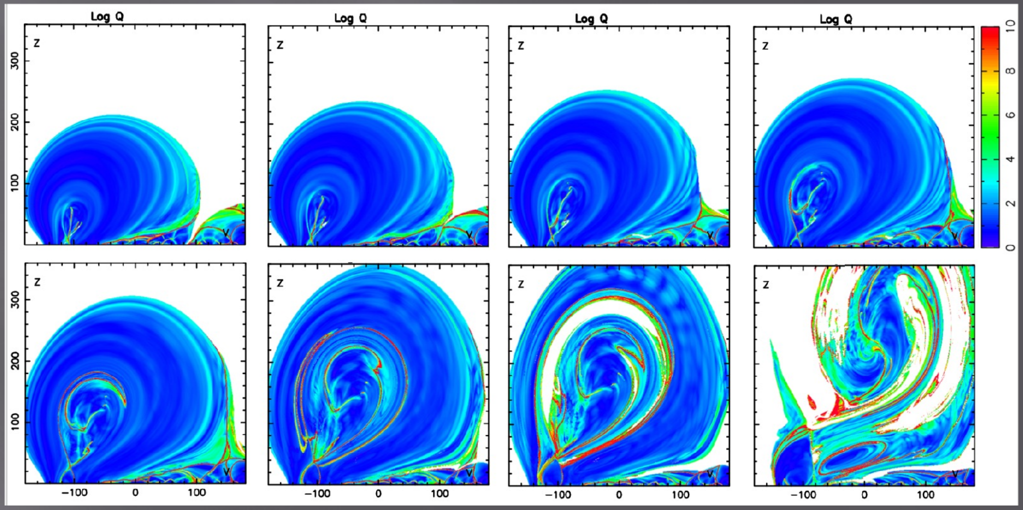
Best-fit NLFFF model for 3 erupting ARs



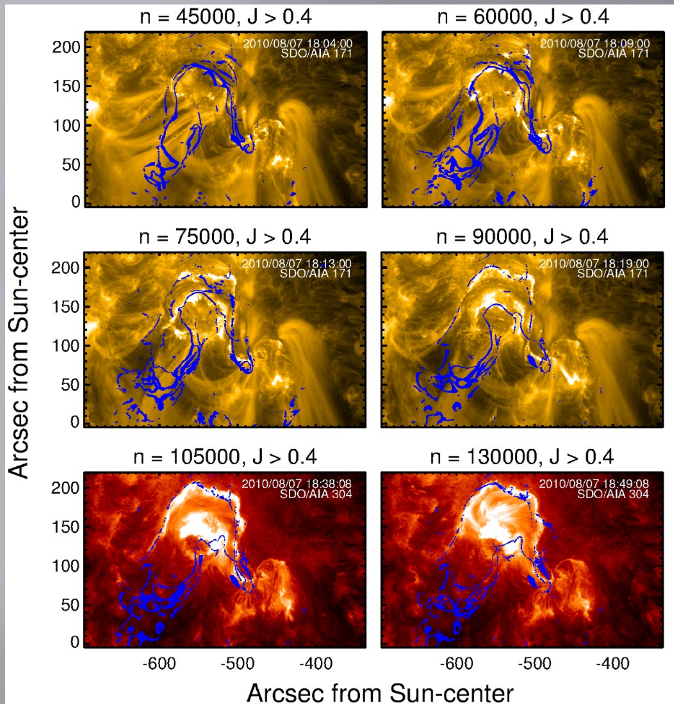
AIA 171A movie of erupting Sigmoid of 10/08/07

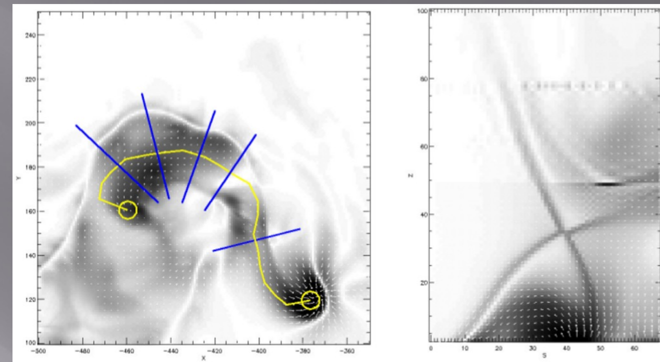


Side view of QSLs of a MF simulation of an eruption FR for 10/04/08

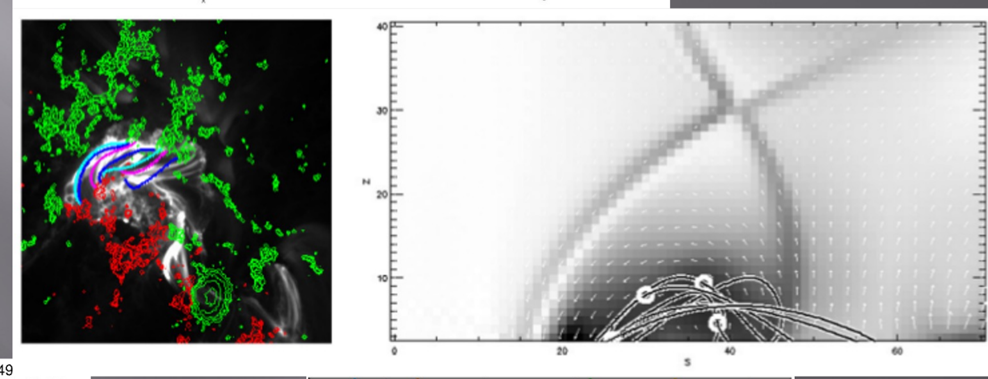


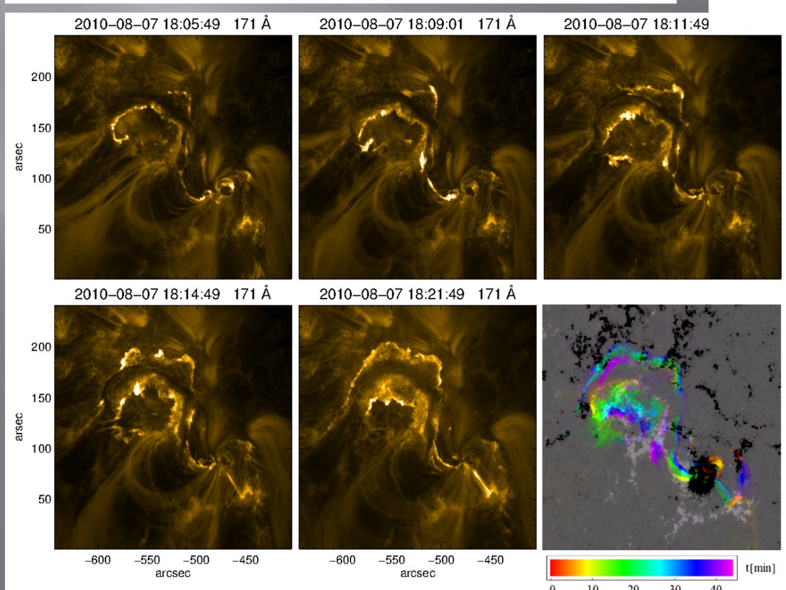
Flare ribbons and (post)-flare loops



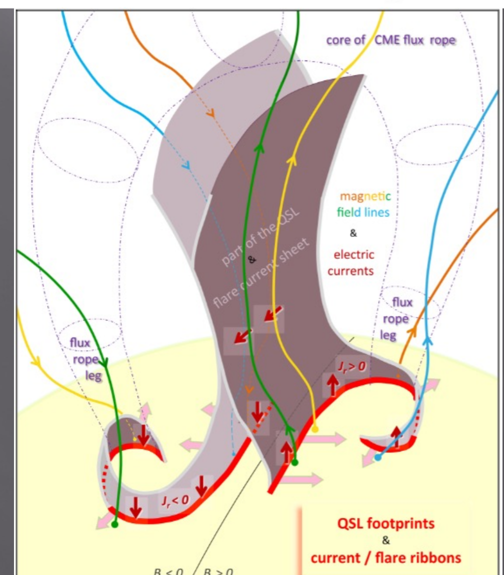


HFT and strong-to-weak shear transition in (post) flare loops





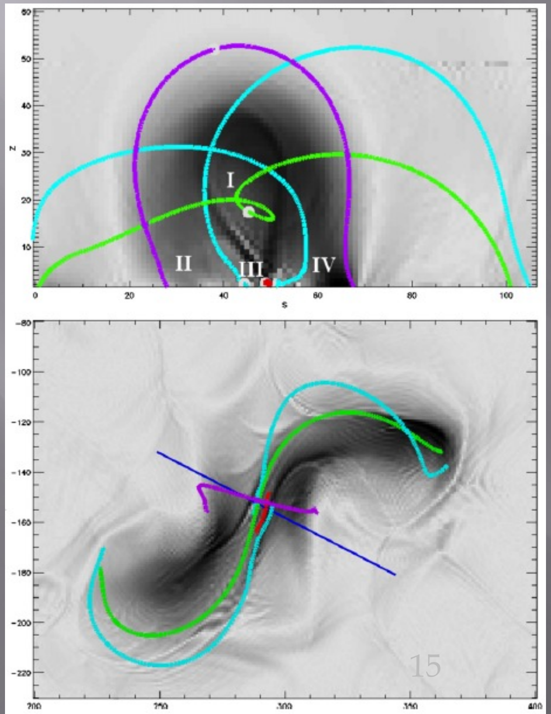
Evolution of flare rib bons In 10/08/07 sigmoid eruption



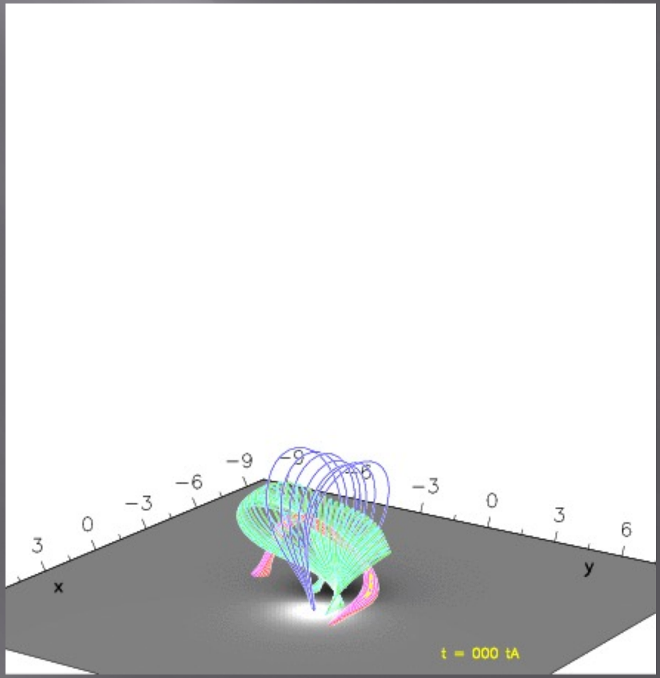
Standard 3D flare/CME model explained with current sheets and QSLs at J-shaped ribbons

Field lines at the HFT

- 2 J-shaped field lines meet at HFT – reconnect
- Flux is transferred to FR
- Weakens arcade and strengthens the flux rope
- Flux rope is elevated
- **For the 1st time we show the role of the HFT and the 2 J FLs in eruption**
- **Reconnection-torus instability feedback eruption scenario**



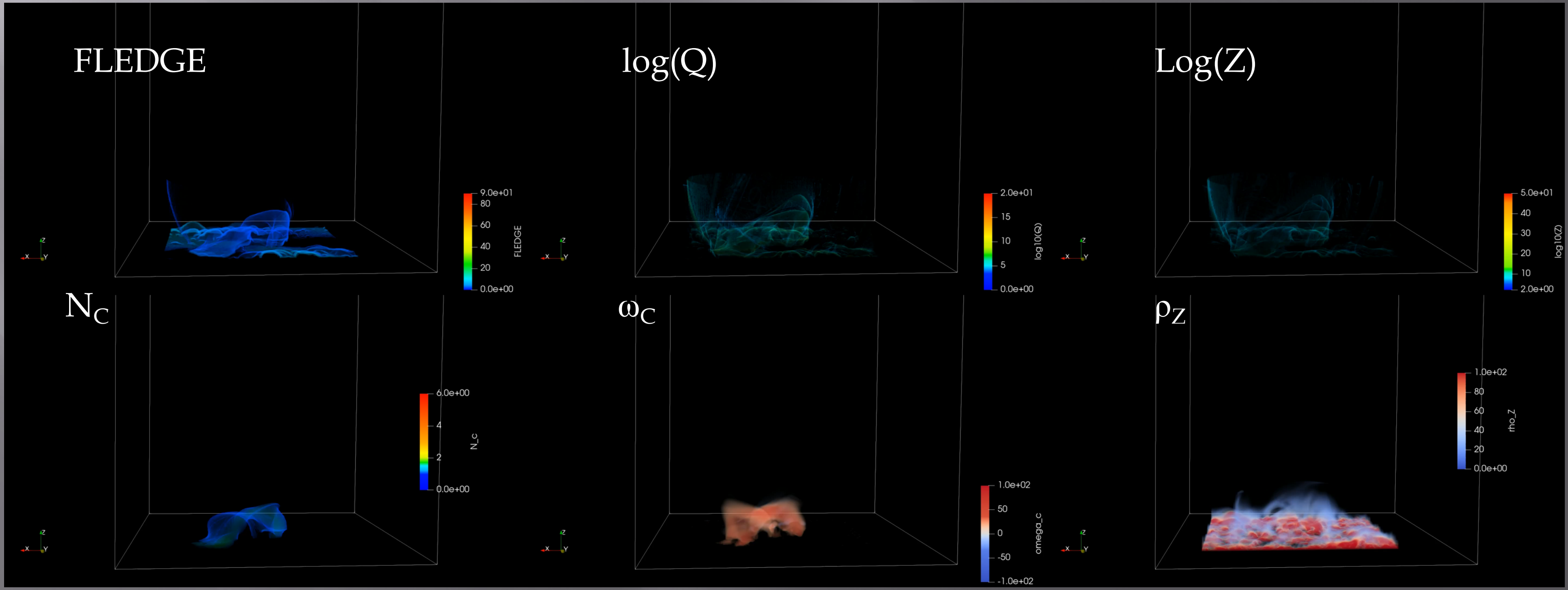
Savcheva et al. '12b2
NLFFF model/MF simulation



Aulanier et al. '12, '13
Flux cancellation
MHD simulation

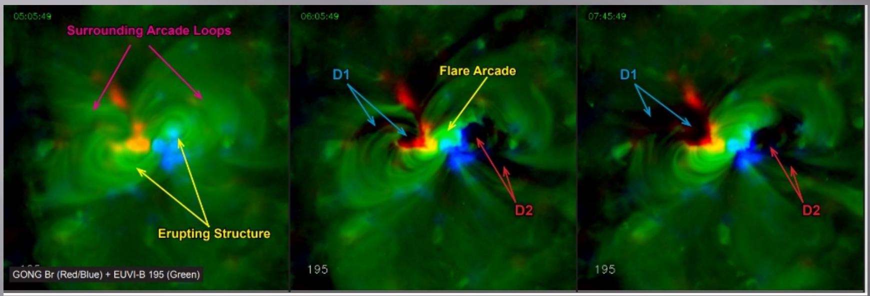
NLFFF Models as Initial Conditions to MHD Simulations

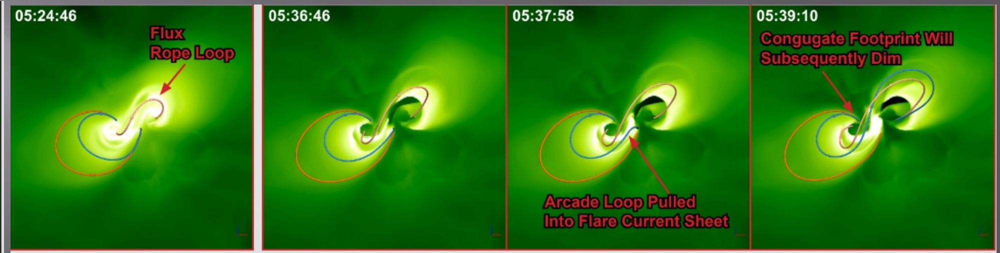
- Derive best-fit NLFFF model – realistic 3D initial condition, corona is low β
- Energize NLFFF model by adding a bit more axial flux to increase pressure in FR – system is unstable - data-constrained MHD/MF simulations
- Using MDI/HMI constantly-changing lower boundary and realistic I.C. – data-driven MHD/MF simulations
- Derive magnetic field topology and local and global properties of the transverse magnetic field for pinpointing sites of reconnection and twist using QSL_squasher 2.0 (Tassev & Savcheva 2021)



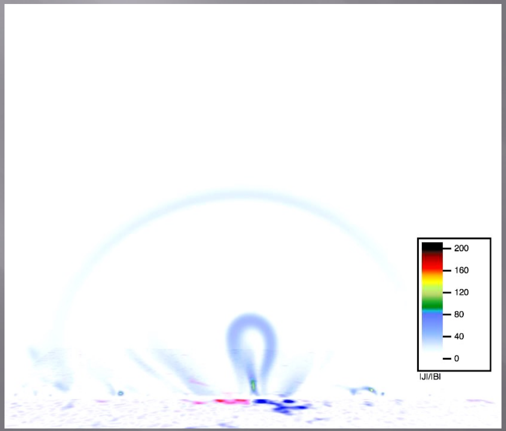
Inoue MHD simulation of 09/02/13 Sigmoid series of CMEs

- I. C. is unstable, energized best-fit magnetic field model for the pre-eruption configuration of the sigmoid on 09/02/13
- Inoue MHD simulation – 0-β simulation – study FL evolution, currents, topology, and twist evolution, match to flare ribbons and coronal dimmings from observations (Inoue & Savcheva 2021, Savcheva & Inoue 2021) Observed and simulated STEREO 195A images

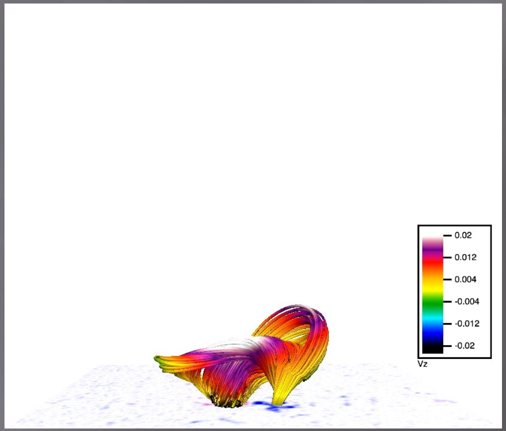




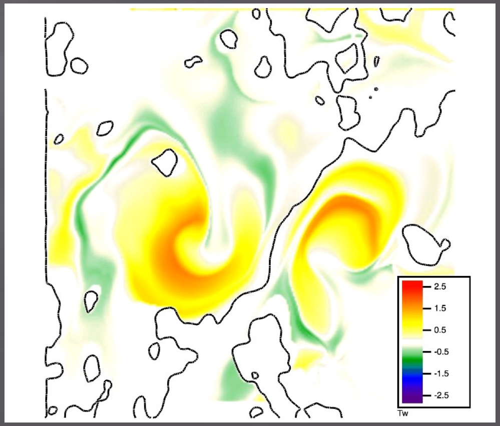
The Core Dimming Mechanism: Erupting Flux Reconnects with the Surrounding Arcade



Current cross-section evolution



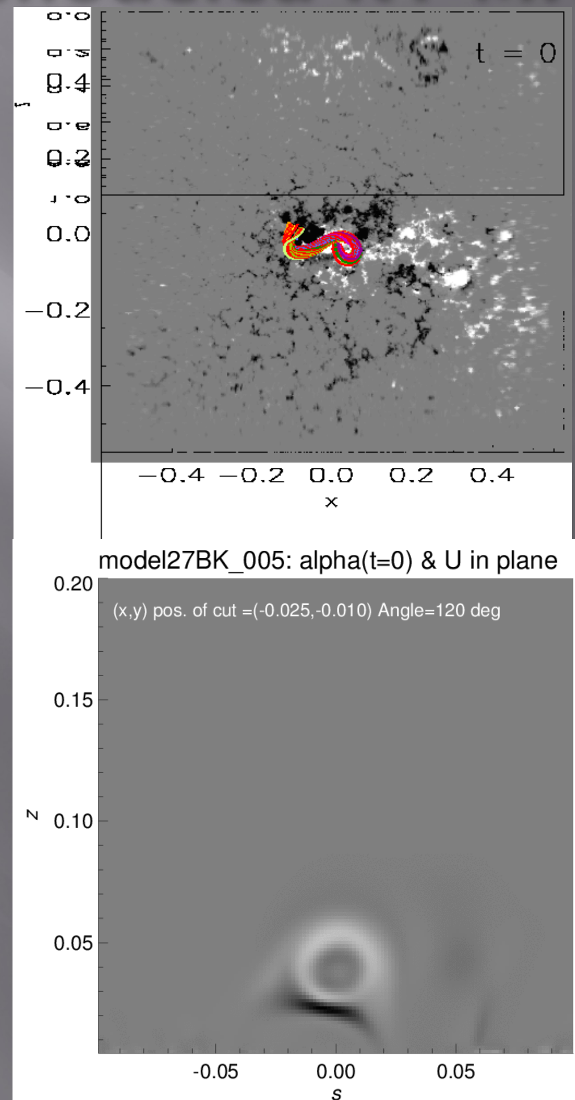
FL evolution during eruption colored by current

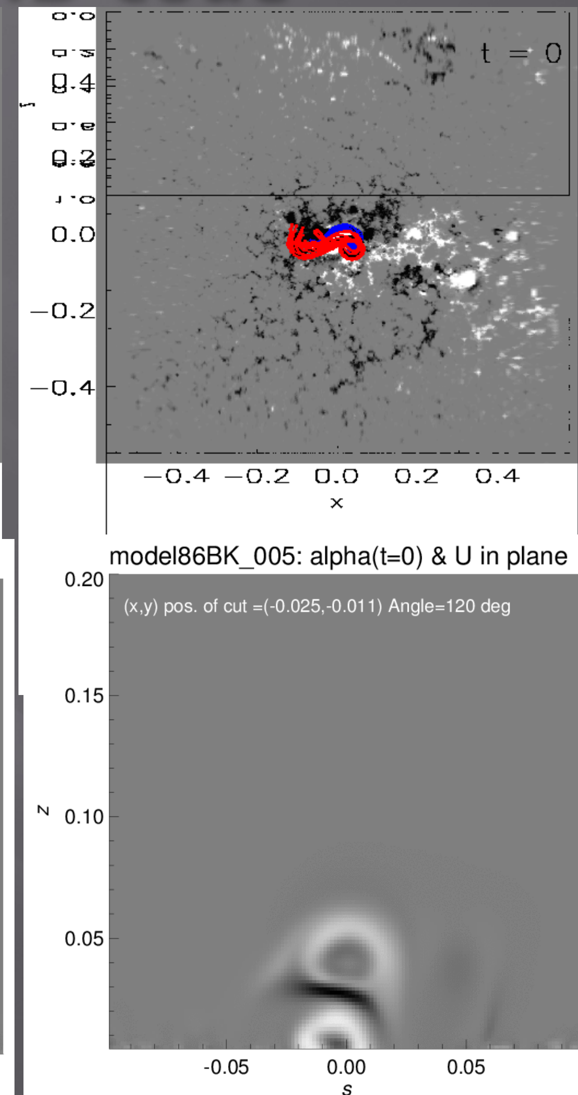


TW – twist evolution - ribbons and dimmings

Double-decker Eruption on 12/07/12 modeled KT MHD code

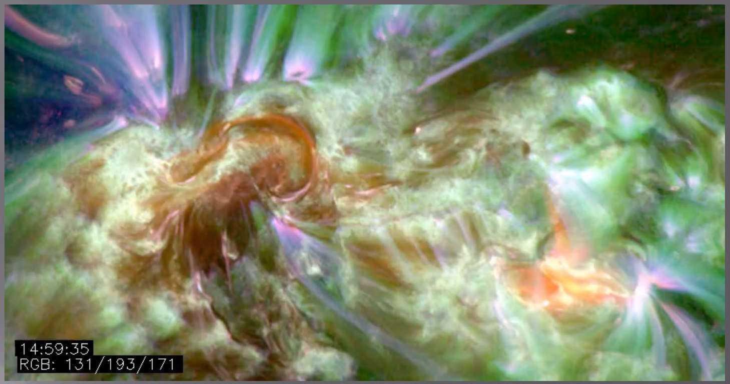
- Tried different I.C.s
  - With single FR – explored stability and eruptuion
  - Double-decker FR with 2 distinct FR paths
  - Changed FR paths and combinations of axial and poloidal flux
- Kliem-Torok 0-β MHD simulation to explore currents, FL eruption, and complex topology, overlay with flare ribbons

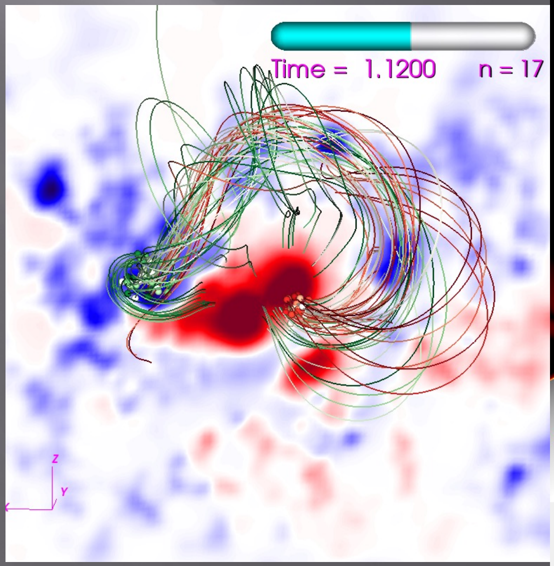


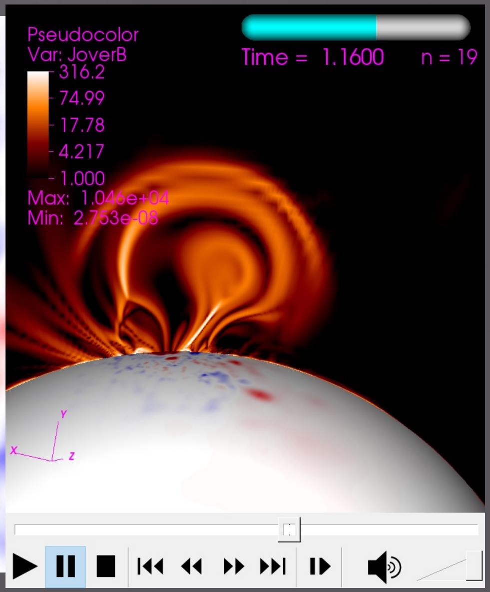


12/07/12 Event with global thermodynamic MAS simulation

- Initial condition best-fit NLFFF from flux rope insertion method – single flux rope
- Study stability state
- Energize by multiplying the force-free part of the field by a factor 1.15 to 2
- Global potential field from MAS added to (NLFFF-CMS potential field)
- Calculation performed in vector potential
- Study eruption morphology in simulated images, ribbons and topology



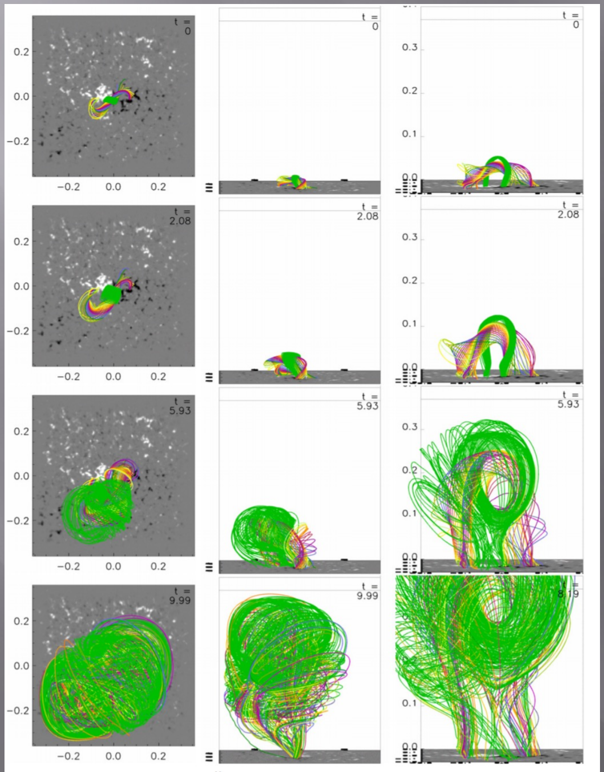




KT MHD Simulation of 10/04/08

- First data-constraint simulation by Kliem et al. (2013)
- Studied stability of NLFFF in MHD
- Energized IC of Full wedge B model made Cartesian by shrinking to center of Sun
- Good match to observations of early CME velocity

FL evolution during eruption



Current sheet and recconection

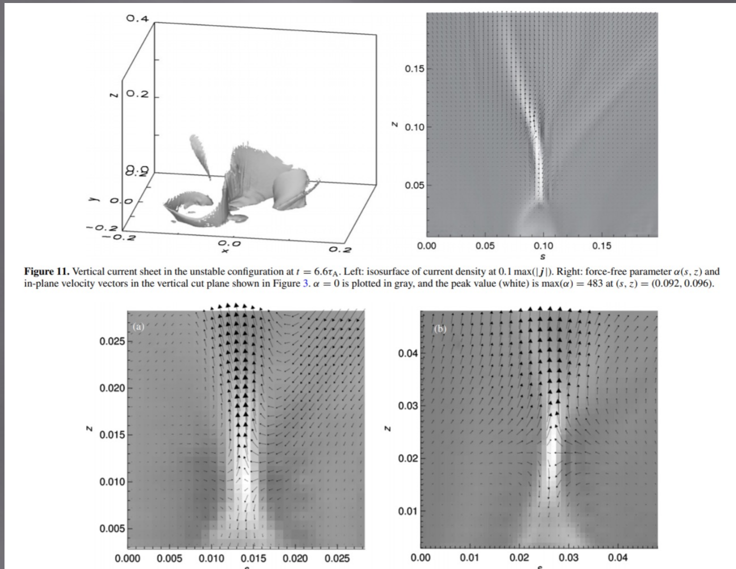
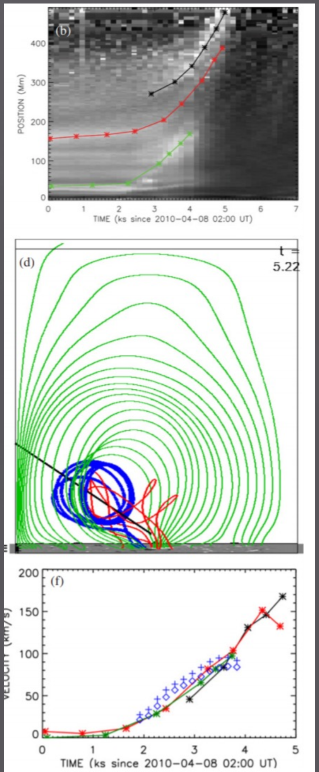


Figure 11. Vertical current sheet in the unstable configuration at $t = 6.6\tau_A$. Left: isosurface of current density at 0.1 $\max(|\boldsymbol{j}|)$. Right: force-free parameter $\alpha(s, z)$ and in-plane velocity vectors in the vertical cut plane shown in Figure 3. $\alpha = 0$ is plotted in gray, and the peak value (white) is $\max(\alpha) = 483$ at $(s, z) = (0.092, 0.096)$.

Figure 12. Reconnection flows of the models with (a) $\Phi_{axi} = 5 \times 10^{20}$ Mx and (b) $\Phi_{axi} = 6 \times 10^{20}$ Mx in the vertical cut plane shown in Figure 3 at $t = 2\tau_A$. The peak in-plane velocities are 0.0045 in (a) and 0.034 in (b).

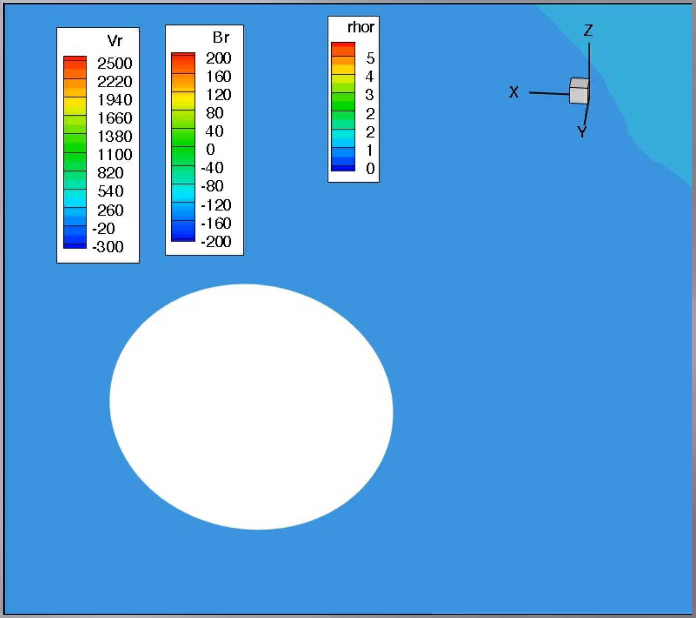
Match to observe CME velocities



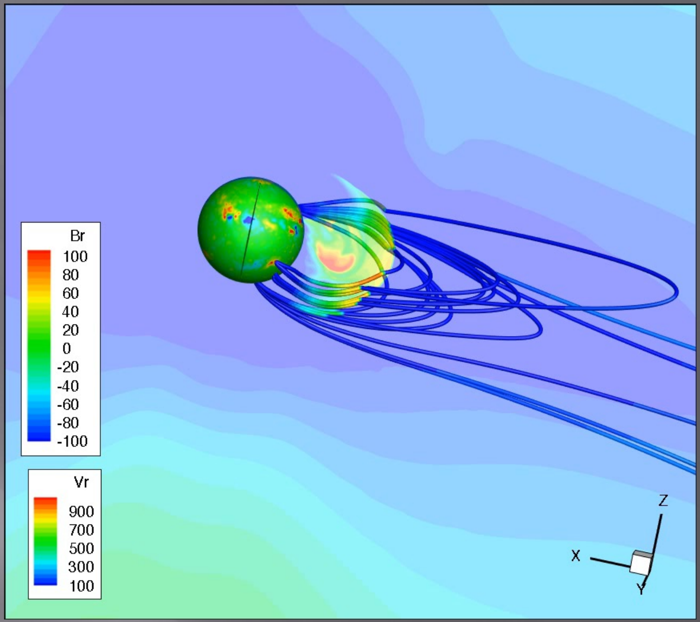
SWMF global thermodynamic MHD simulation of 10/04/08 event

- Space Weather Modeling Framework (SWMF):
  - Includes complete physics
  - Incorporate 3D cube of NLFFF-CMS potential field in B form
  - Establish AWSoM solar wind solution with SWMF global potential field: includes coronal heating by dissipation and reflection of Alfven waves
  - Add SWMF potential field to the Force-free part of the inserted 3D cube of B
  - Launch CME to 1AU
    - Try different multiplicative factors to energize the field to achieve a good fit to observations – CME deflections, shocks, velocities, panckaking
  - Can interact with magnetosphere/ionosphere of Earth and other planets
  - *Can be used in Exoplanetary systems by substituting the Sun with the parent star and interact the scaled eruptions with exoplanets*

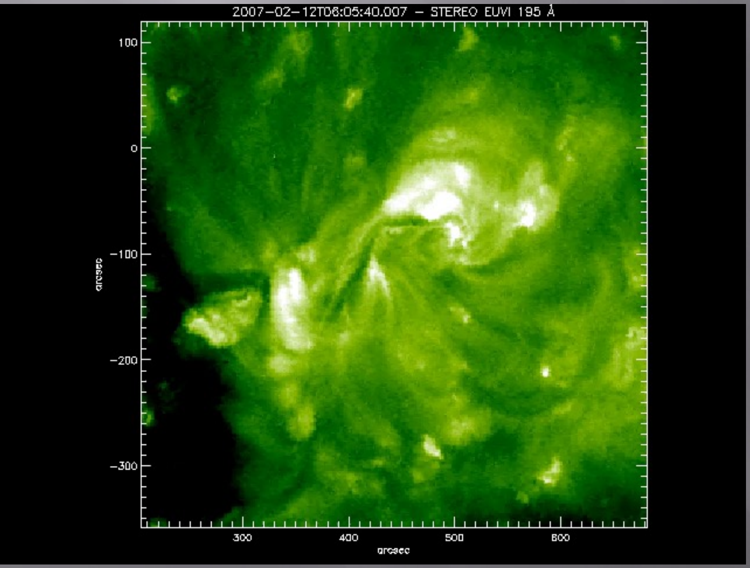
Results from SWMF simulation



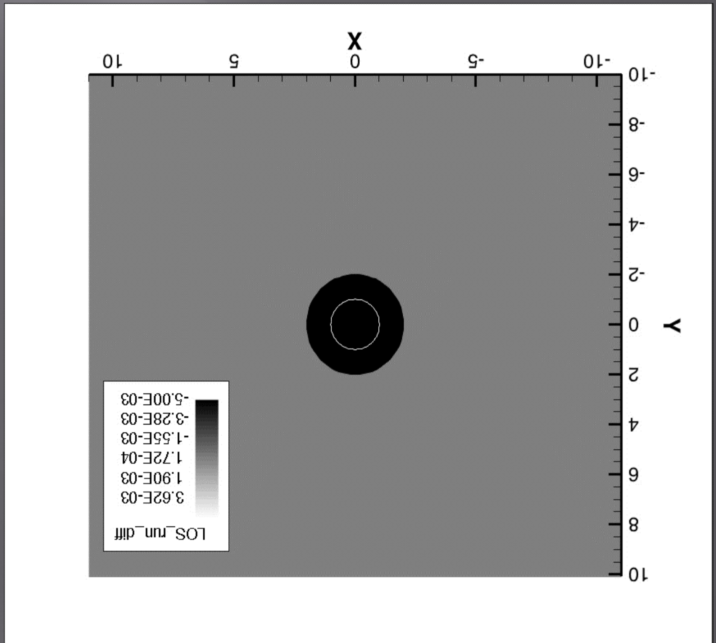
CME in velocity space



CME in Velocity space with FLs, pancaking

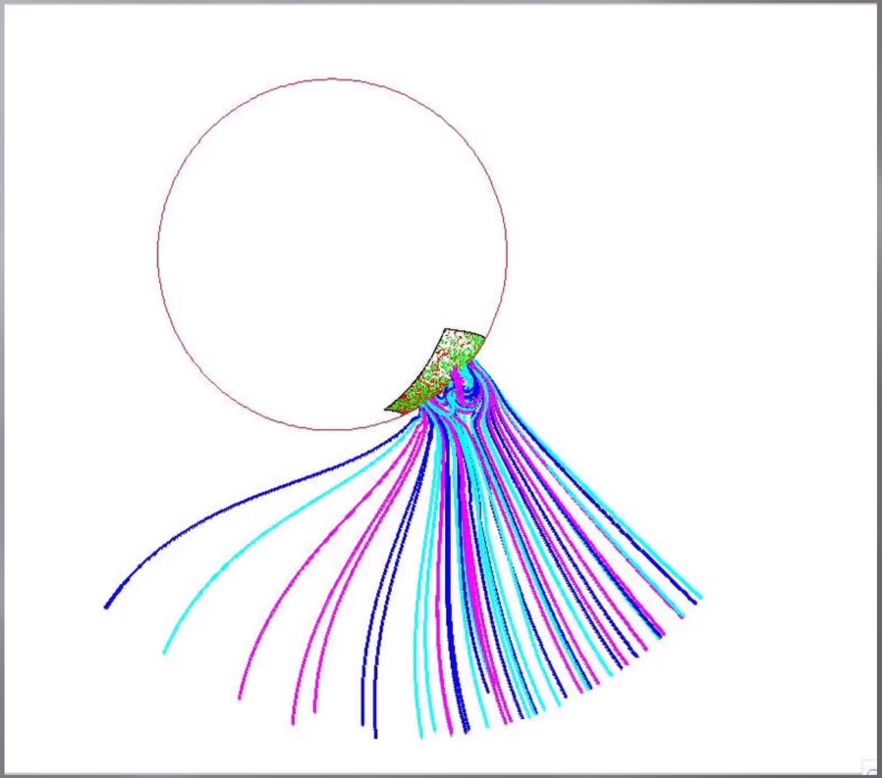


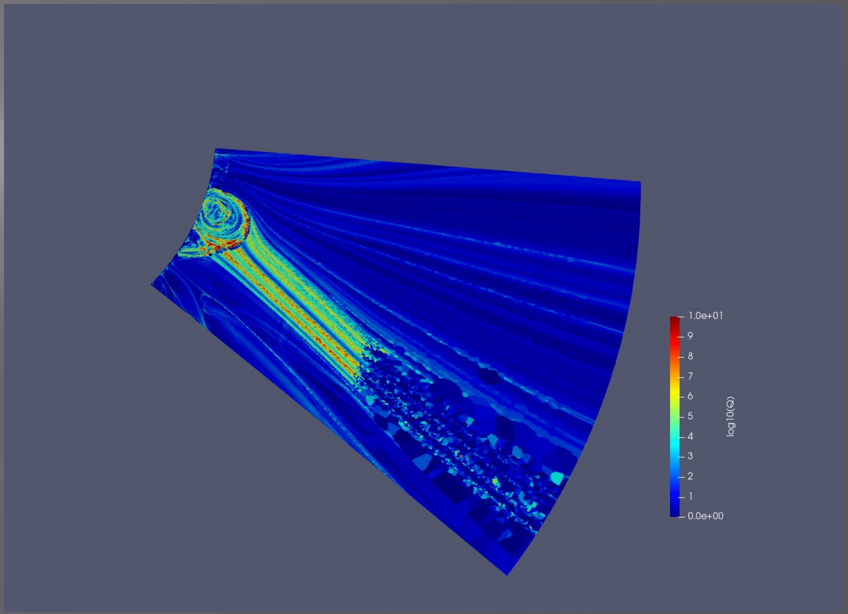
STEREO 195A movie of the eruption



Simulated STEREO running difference movie

MF simulation anmd topology analysis of erupting pseudostreamer





Summary and conclusions

- Topology is powerful tool for analyzing complex magnetic field configurations and has predictive capabilities when used in sync with observations
- We have performed the first data-constrained and data-driven partial-sun 0-β Cartesian and global full-physics MHD simulations