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Thursday 17:15-17:45

Recent Advances from Theory and 3-D Numerical Modeling in Understanding the Origin and Evolution of CMEs and Related SEP Events

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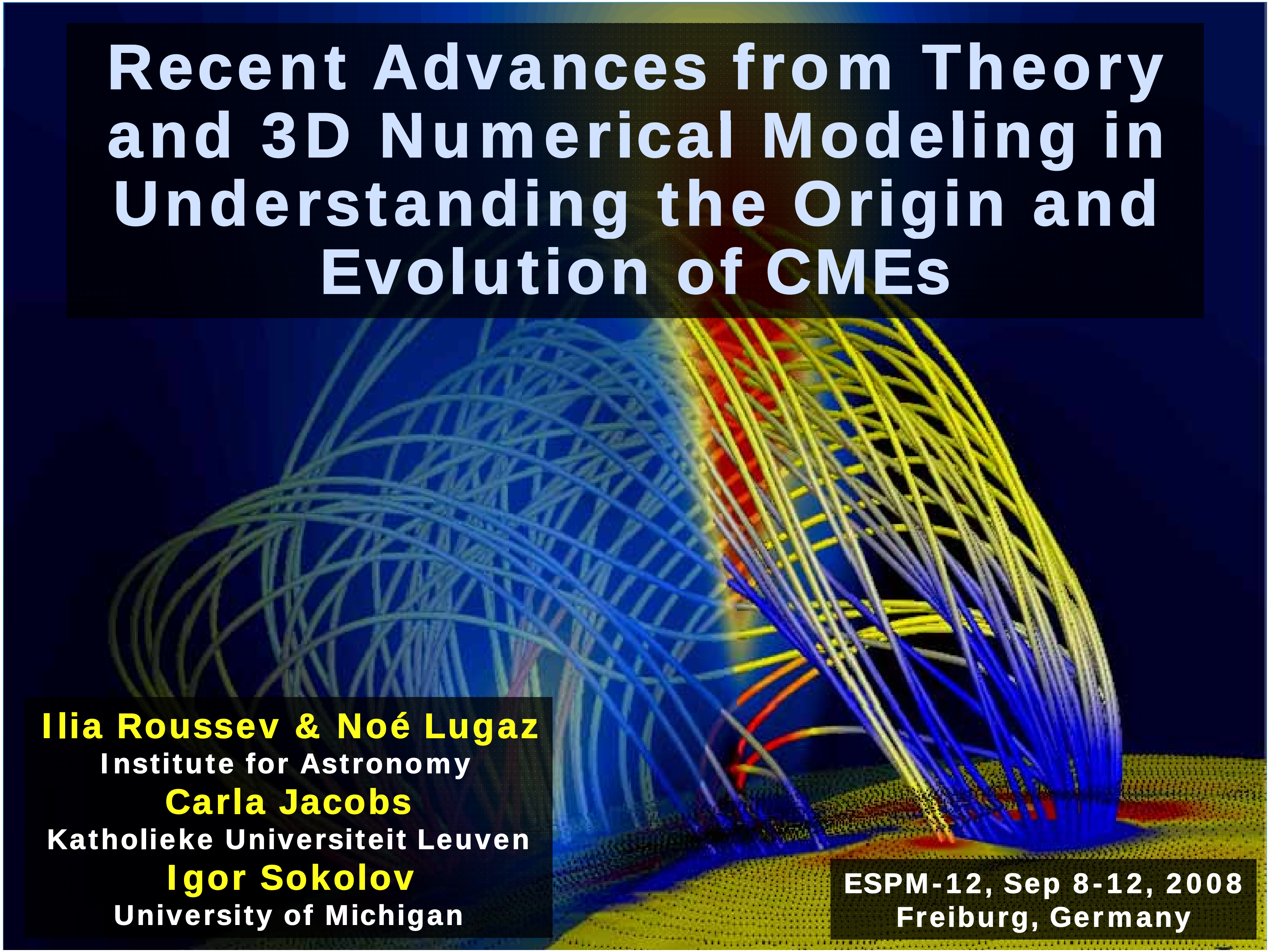
To date, it is well established that Coronal Mass Ejections (CMEs) play a leading role in the Sun-Earth connection, because of their large-scale, energetics and direct impact on the space environment near the Earth. As CMEs evolve in the solar corona and interplanetary space they drive shock waves, which act as powerful accelerators of charged particles in the heliosphere by means of Fermi acceleration processes. Some of these so-called Solar Energetic Particles (SEPs) can strike our planet, and in doing so they can disrupt satellites and knock out power systems on the ground, among other effects. The SEPs, along with the intensive X-ray radiation from solar flares, also endanger human life in outer space. That is why it is important for solar scientists to understand and predict the ever changing environmental conditions in outer space due to solar eruptive events -- the space weather. To enable the development of accurate space weather forecast, in the past 35 years solar scientists have been challenged to provide an improved understanding of the physical causes of CMEs and related phenomena, such as the production of SEPs. This talk summarizes the most recent advances from theory and 3-D numerical modeling in understanding the origin and evolution of CMEs and related SEP events.



Recent Advances from Theory and 3D Numerical Modeling in Understanding the Origin and Evolution of CMEs

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ESPM-12, Sep 8-12, 2008
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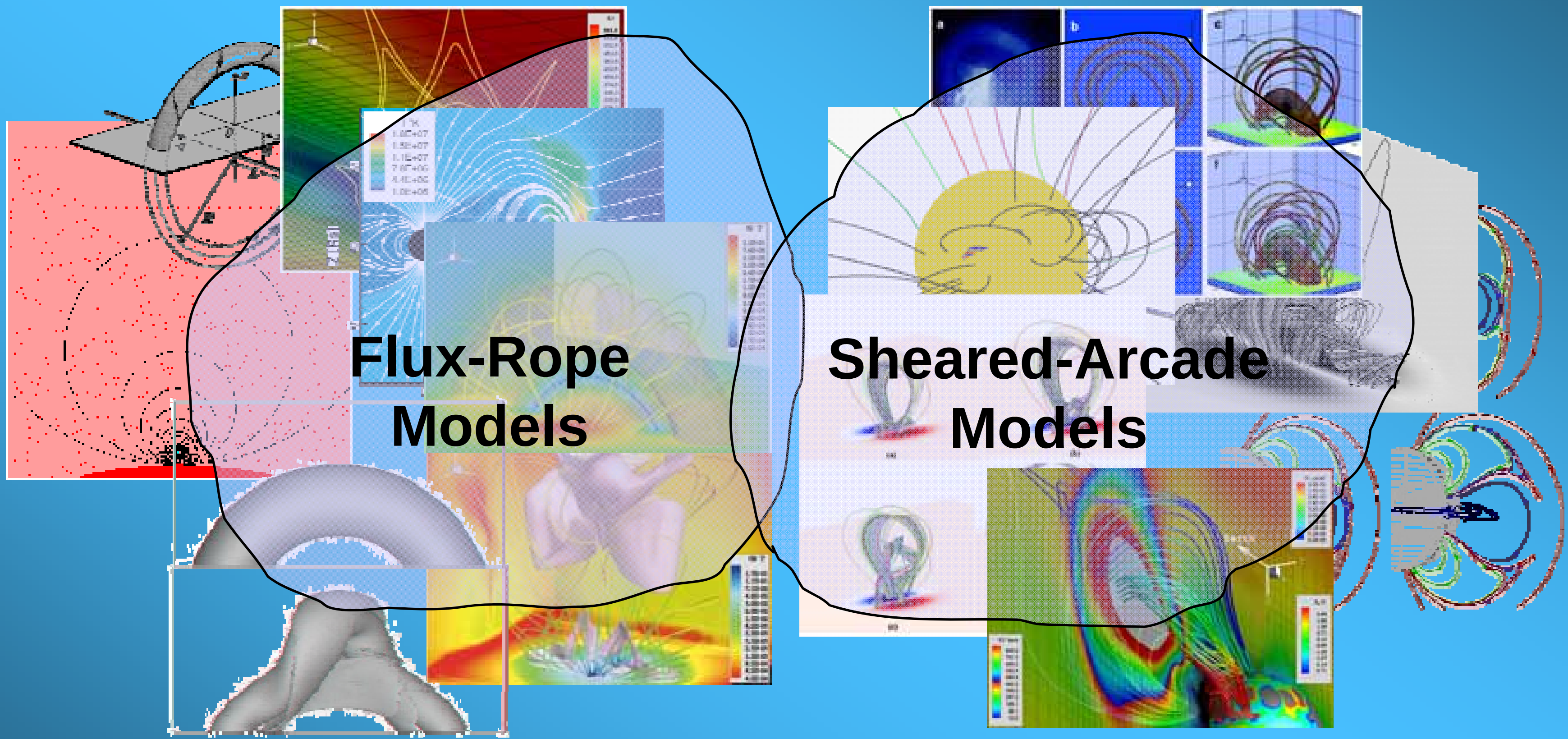
CME Models



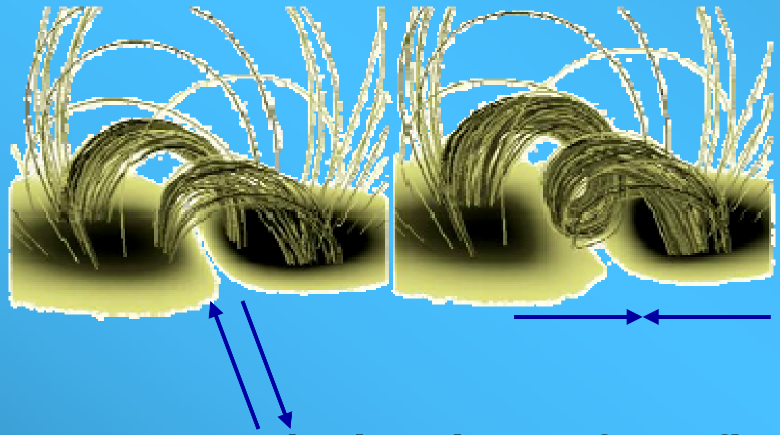
Amari *et al.* (2000, 2003, 2007); Antiochos *et al.* (1999); Forbes & Isenberg (1991); Gibson & Low (1998); Kliem *et al.* (2004); Lin *et al.* (2001); Linker *et al.* (2001); Lynch *et al.* (2005); Manchester *et al.* (2003, 2004); Moore *et al.* (2001); Sturrock *et al.* (2001); Titov & Démoulin (1999); Tokman & Bellan (2002); and Roussev *et al.* (2003, 2004, 2007).

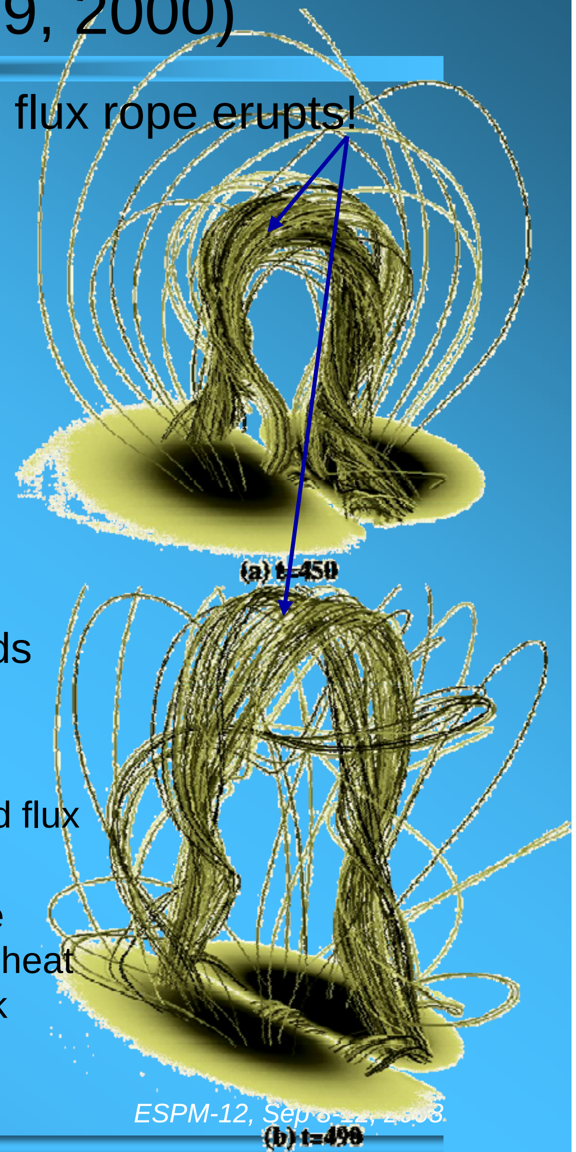
Overview

- Great progress has been made to date in understanding CME origin in idealized magnetic settings (dipolar and quadrupolar).
- Although we have general agreement on what powers CMEs, there is still ongoing debate on:
  - Actual means of energy storage in coronal magnetic field prior to CME.
  - Physical driver of eruption.
- In recent study by Ugarte-Urra *et al.* (2007), it has been found that:
  - 7 out of 26 studied CMEs could be interpreted with the "breakout" model.
  - 12 CMEs could be explained with other CME models (in dipolar geometries).
  - 7 events were *unclassifiable*.
- This talk focuses on CME events originating from complex active regions; we studied 3 events so far (1998 May 2, 2002 Apr 21, and 2002 Aug 24).
- Key points for discussion include:
  - Magnetic field evolution in CME source region, and
  - CME and related shock wave dynamics in low corona.

How to Make Use of “Toy Models” to Study Real Events? (from Amari *et al.*, 1999, 2000)

Result: flux rope erupts!





Numerical recipe to form flux rope

1. Apply shear motions along polarity inversion line
   - Evolve potential field to non-potential, force-free field.
   - Build free energy in sheared field needed to power CME.

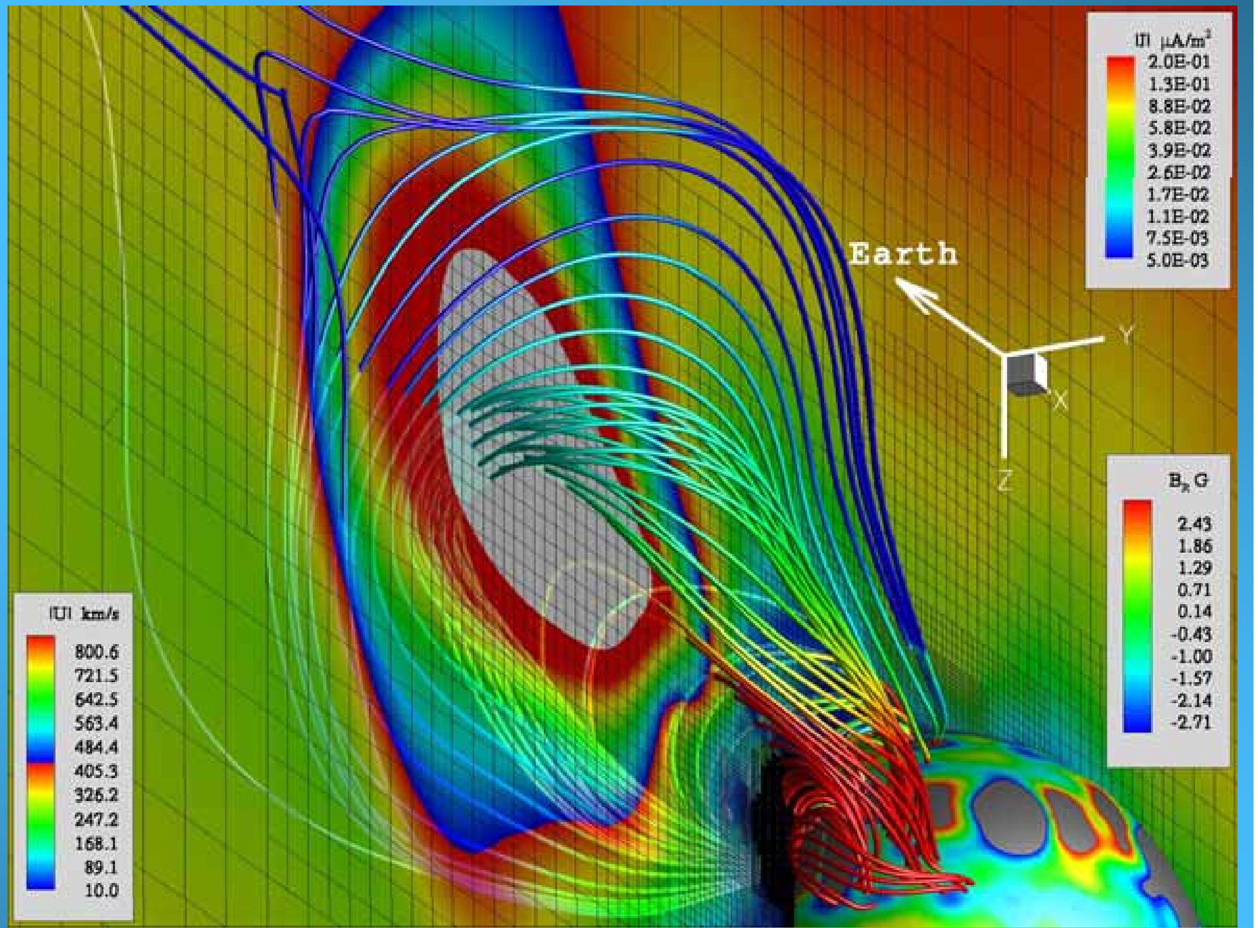
2. Apply converging motions towards polarity inversion line
   - Field lines begin to reconnect and flux rope forms.
   - ~8-17% of energy built during the shearing phase is converted into heat and kinetic energy of plasma bulk motions.

Modeling of 1998 May 2 CME & SEP Event

Model of 1998 May 2 CME
(from Roussev *et al.*, 2004)

Model Features

- Magnetogram data from Wilcox Solar Observatory incorporated in the model
- CME achieved by slowly evolving boundary conditions for magnetic field to account for:
  - **Rotation** of main sunspot of AR8210, and
  - **Flux cancellation** nearby rotating sunspot.



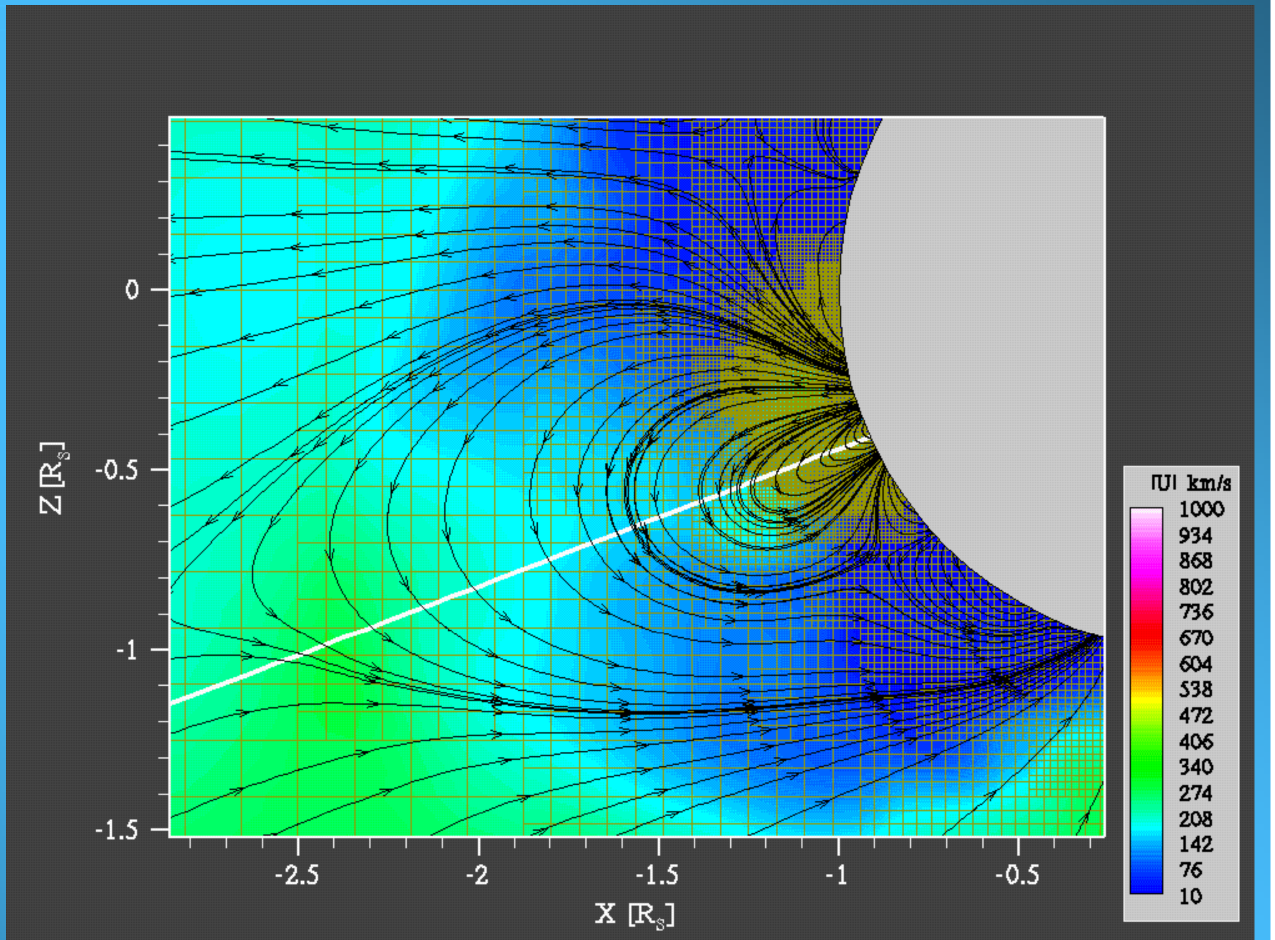
Global MHD Model

- Global model of solar corona and solar wind
  - Magnetic field extrapolated into solar corona using PFSS method (Altschuler *et al.*, 1977).
  - Magnetic data taken from WSO (or SoHO/MDI).
  - Initial density and temperature prescribed in ad-hoc manner: radial component of magnetic field used as a proxy for T and ρ.
  - Solar wind powered by energy exchange between solar plasma and MHD turbulence (variable γ model of Roussev *et al.*, 2003).
    - Energy exchange occurs on time scale much smaller than characteristic advection time in simulations.
  - Initial static (and potential) MHD solution is evolved using BATS-R-US to steady-state solution with solar wind.
  - Block-adaptive meshes are used to better resolve ARs of interest, null points, CSs, etc.
- CME model
  - Horizontal motions (2% local Alfvén speed) are introduced at inner boundary to resemble (1) sunspot rotation and (2) flux cancellation at later stage.
  - Magnetic energy increases during phase 1 (storage phase).
  - Excess magnetic energy is converted into kinetic energy and heat during phase 2.
  - Flux rope forms during phase 2 and it accelerates fast (within few Alfvén crossing times).

CME Dynamics in Solar Corona

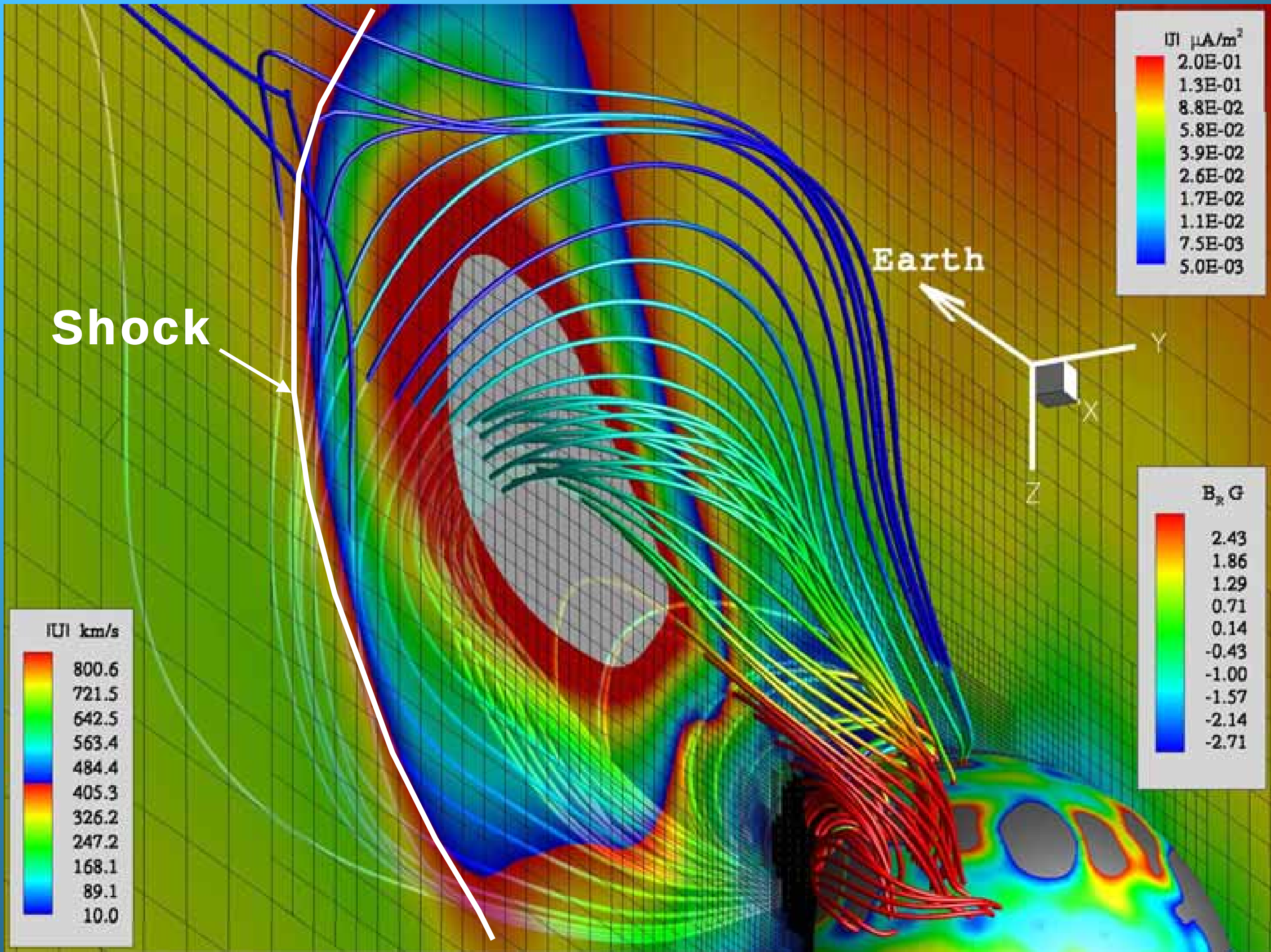
Key Results

- Excess magnetic energy in CMF prior to CME in good agreement with observations.
- Eruption takes place in a multi-polar type magnetic field configuration.
- Ejected flux rope achieves maximum speed in excess of 1,000 km/s.
- CME drives quasi-parallel shock.
  - Fast-mode Mach number > 4 and compression ratio ~ 3 at 5 R_S.
  - Shock geometry *changes* in first hour of evolution.



Color code represents flow speed in meridional plane. Black lines visualize CMF. Grid structure is shown as yellow mesh.

Shock Wave Driven by CME



Kinetic Equation Describing SEP Production

- Consider the kinetic equation (Parker, 1966) describing the DSA of charged particles:

$$\frac{\partial f}{\partial t} + (\mathbf{u}\cdot\nabla)f - \frac{1}{3}(\nabla\cdot\mathbf{u})\frac{\partial f}{\partial \ln p} = \nabla\cdot(\mathbf{D}\cdot\nabla f)$$

- Here **f** is the isotropic part of the SEP distribution function, **u** is the bulk plasma velocity, **D** is the diffusion tensor: $\mathbf{D} = D\mathbf{b}\otimes\mathbf{b}, \quad \mathbf{b} = \mathbf{B}/B$
  - Assume that diffusion only occurs along the magnetic field:
  - Assume that the magnetic field is frozen into the plasma
  - By introducing the Lagrangian coordinate along the magnetic field, **s**, the kinetic equation can be written for each field line separately:

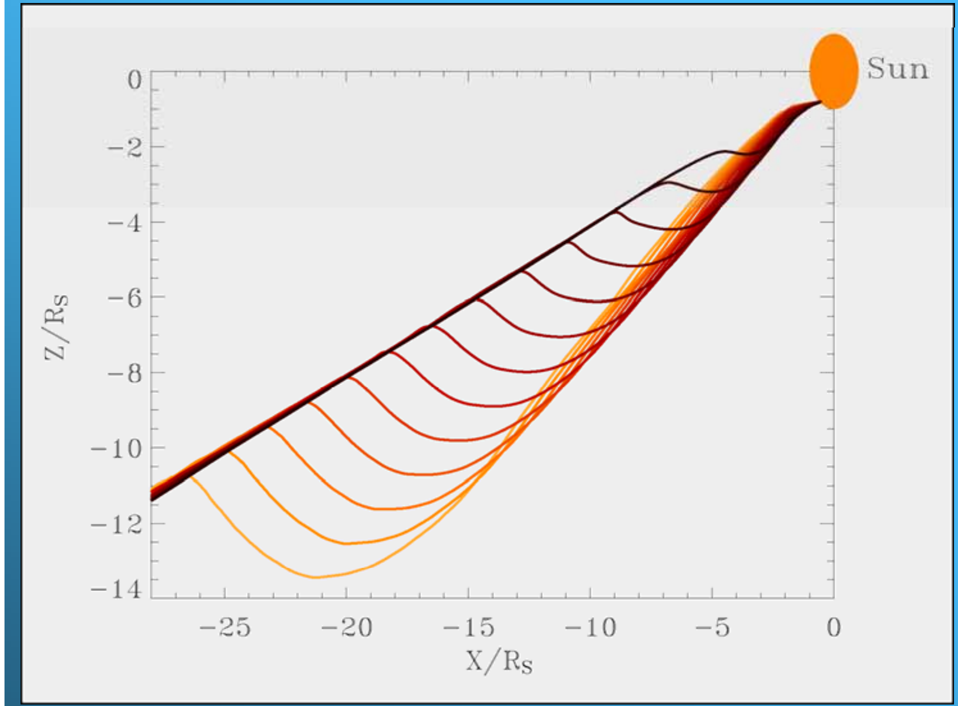
$$\frac{df}{dt} + \frac{1}{3}\frac{d\ln\rho}{dt}\frac{\partial f}{\partial \ln p} = B\frac{\partial}{\partial s}\left(\frac{D}{B}\frac{\partial f}{\partial s}\right)$$

where ρ is the plasma density.

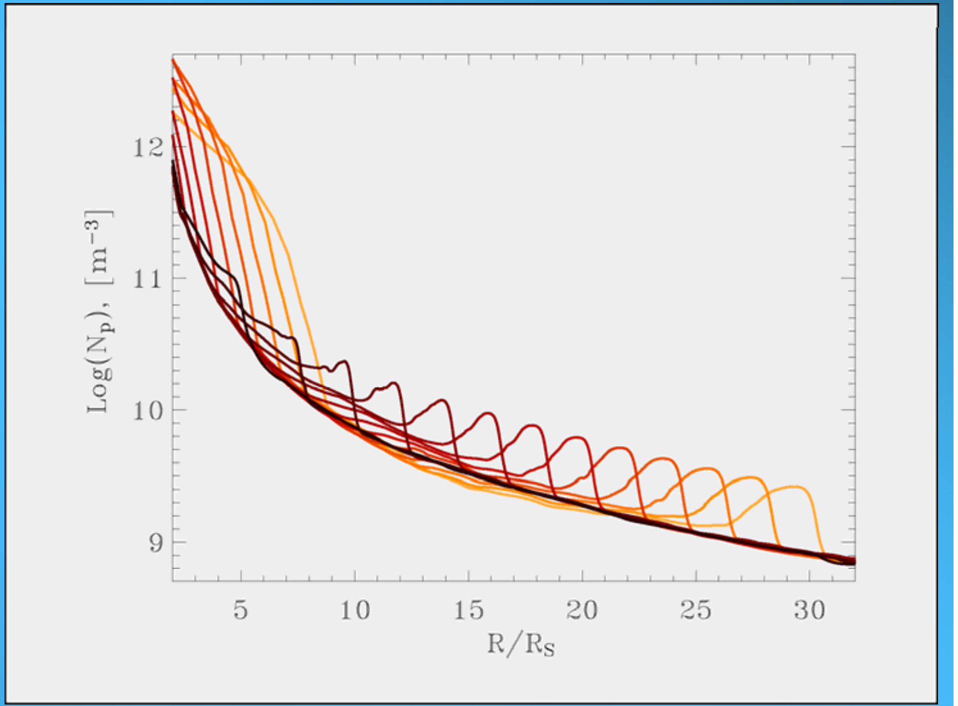
Note: Transformed equation depends on a single spatial coordinate, **s**. At the same time, the full 3D geometry of the magnetic field is preserved.

Evolution of Shock Wave Along Magnetic Field

Field line position (in XZ-plane) at 13 instants of time (30 min apart)

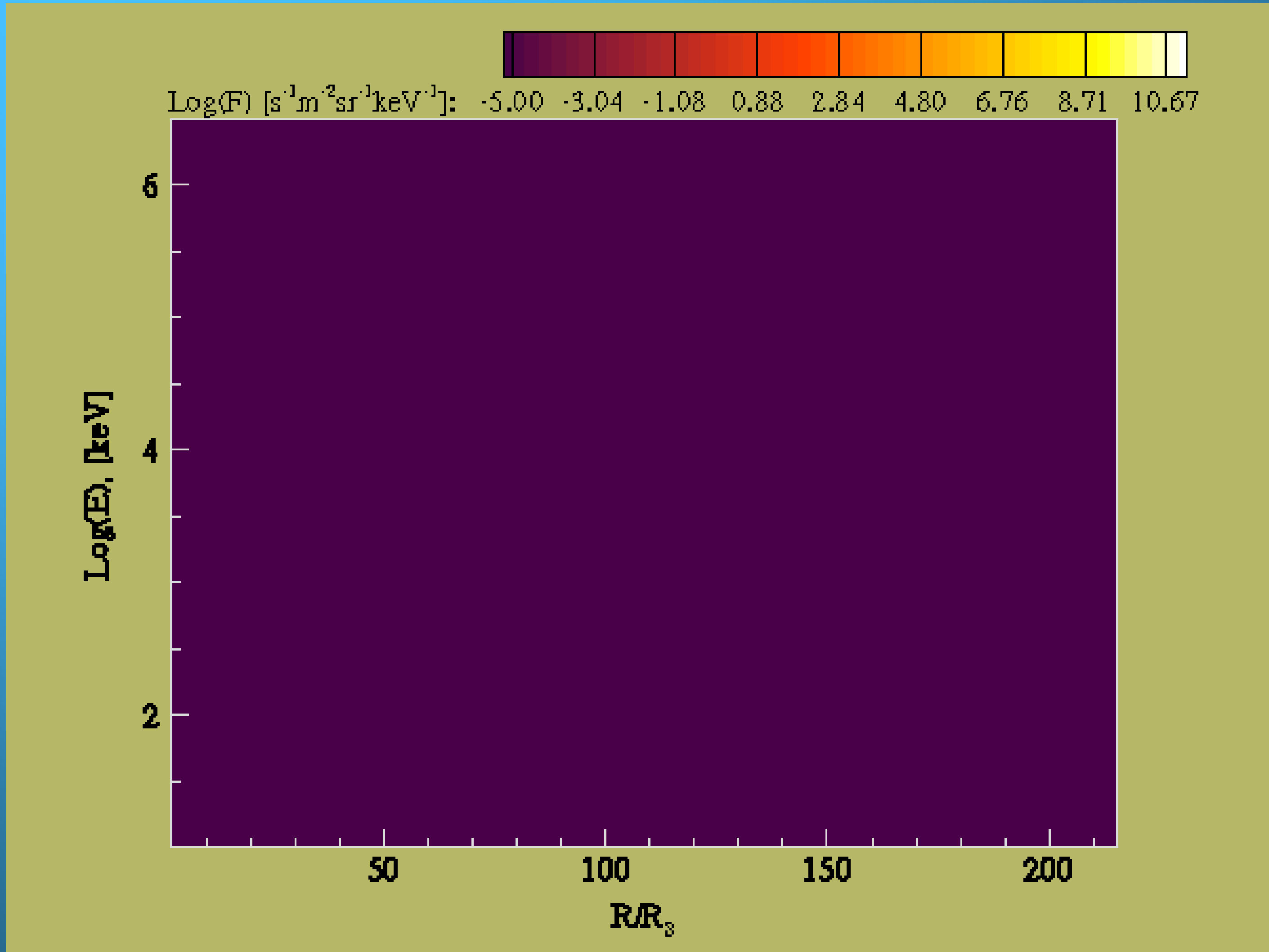


Number density distribution along the same field line at the same 13 instants



From coupled CME-SEP Simulation of Sokolov *et al.* (2004)

DSA Acceleration of Protons at CME Shock



Modeling of 2002 Apr 21 CME

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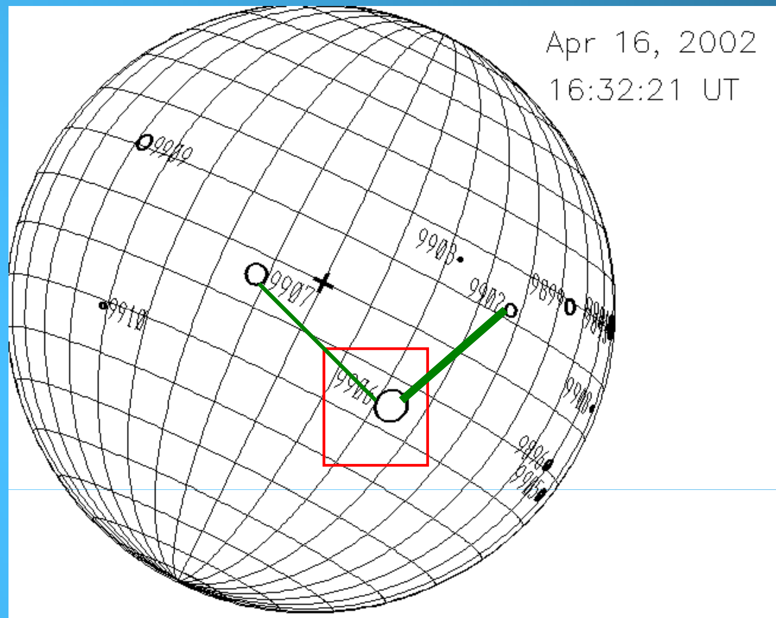
CME Event on 2002 Apr 21

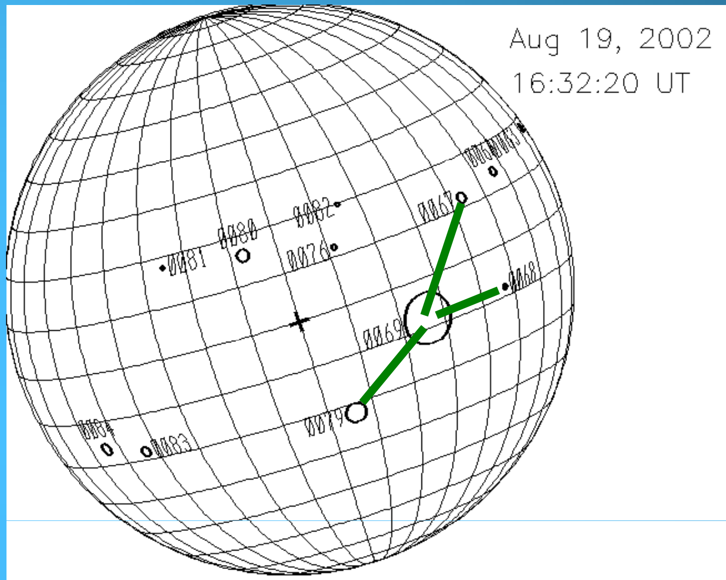
- CME took place on west limb and was associated with X-class (X1) flare.
  - HXR emission associated with closed flare loops.
- CME drove quasi-parallel shock moving at speed > 1,500 km/s.
  - Formed at ~1.6-1.7R_S (inferred from UVCS)
  - Shock arrived at 1 AU @ 51 hr.
- CME took place near open field region, which was magnetically connected to Earth.
- SEP event (Apr 21-23) was associated with CME.
  - SEP composition data showed decline in Fe/C ratio for energies above 10 MeV/nuc.



NOAA map of ARs on 2002 Apr 16. There were large-scale closed field connections of **AR 9906** to distant ARs.

CME Event on 2002 Aug 24

- CME took place on west limb and was associated with X-class (X3.1) flare.
- CME drove quasi-perpendicular shock moving at speed > 1,500 km/s.
  - This event was somewhat faster than CME on 2002 Apr 21.
  - Shock arrived at 1 AU @ 58 hr.
- SEP event (Aug 24-25) was associated with CME.
  - SEP composition data showed increase in Fe/C ratio for energies above 10 MeV/nuc.
  - This behavior is opposite to what was observed for SEP event on 2002 Apr 21-23.

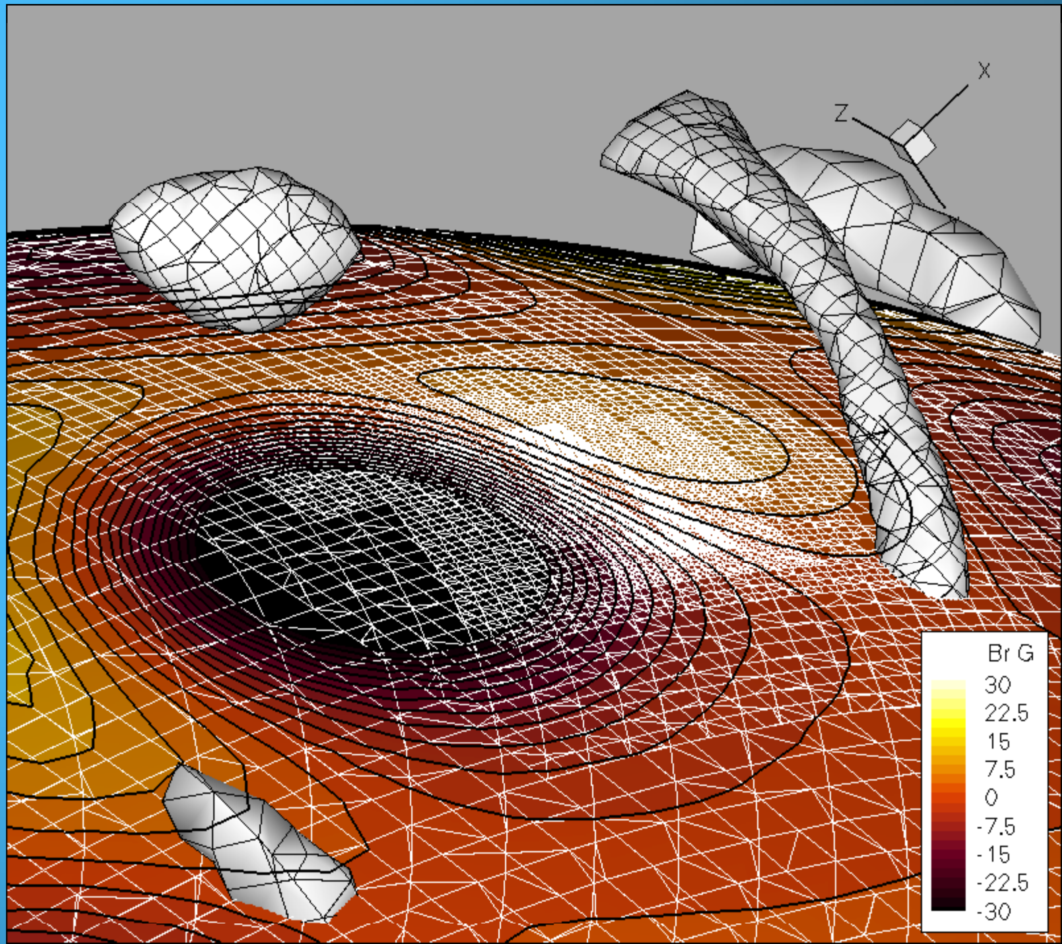


NOAA map of ARs on 2002 Aug 19. There were large-scale connections of **AR 0069** to distant ARs.

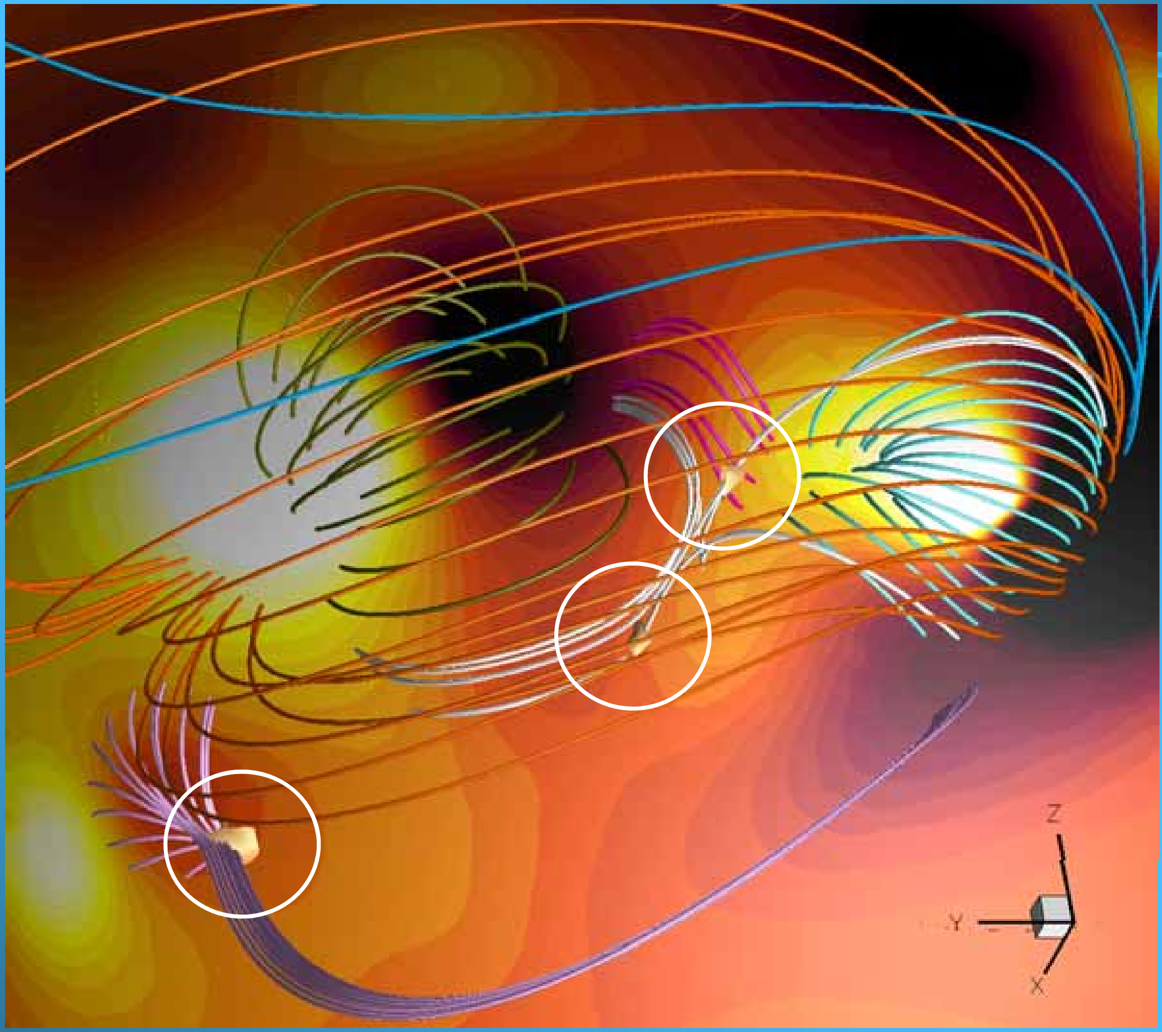
Our goal was to model both events in attempt to explain observed similarities and differences in CME and SEP dynamics.

Simulation Setup

- $[-20\ R_s, 20\ R_s]^3$ Cartesian box.
- CSEM's SWM Framework with Roe solver (least diffusive).
- ~ 1.4M cells (initially).
- Smallest cells < $1.5 \times 10^{-3}\ R_s$ near Polarity Inversion Line of CME source region (~ 1.4″).
- Average resolution on solar surface is $2 \times 10^{-2}\ R_s$.
- Image shows iso-surfaces of plasma-β of 0.5 (null points for 2002 Aug 24 event).



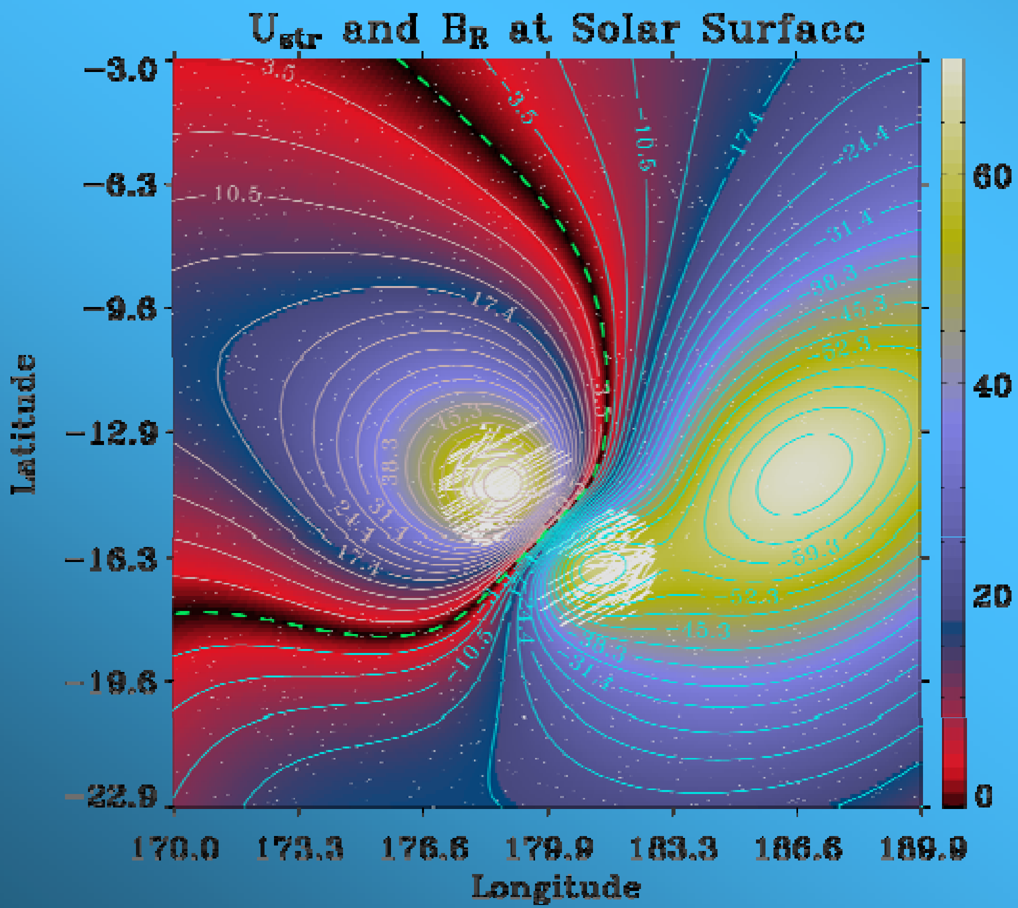
Magnetic Topology for Apr 21 CME at *t* = 0



Magnetic topology of **AR 9906**. Null points are encircled and different flux system are shown in various colors.

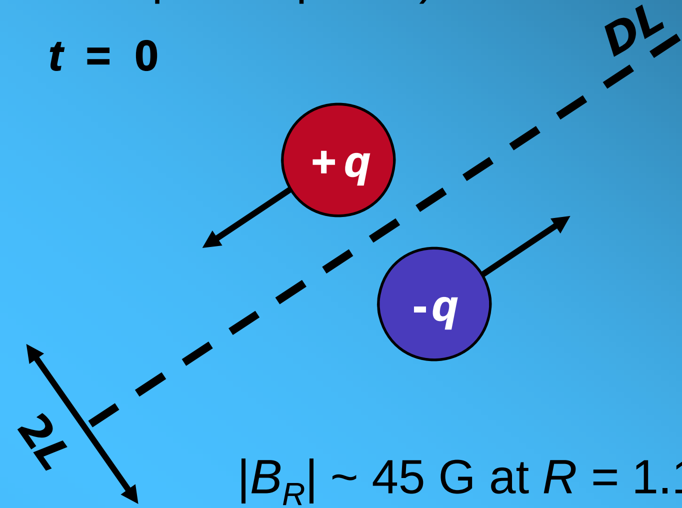
CME Model

(from Roussev *et al.*, 2007)



$|B_R| \sim qd/R^3$ (d is depth of charges below photosphere).

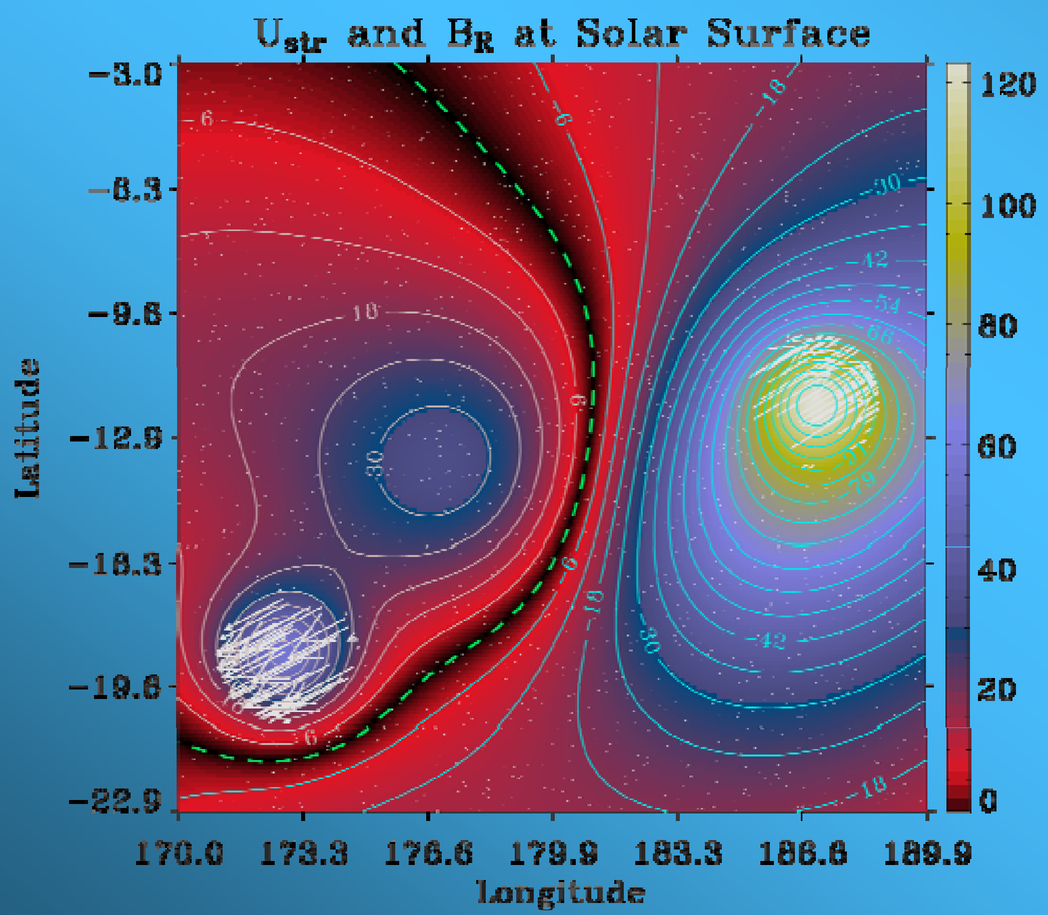
***t* = 0**



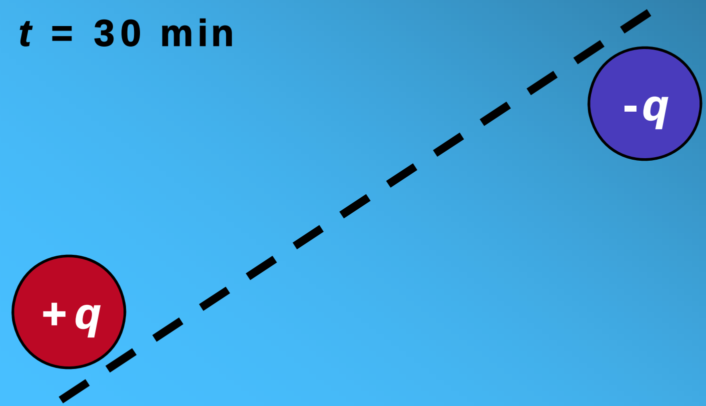
$|B_R| \sim 45$ G at $R = 1.1\ R_\odot$

Move both charges along dashed line (DL) from t = 0 to t = 30 min.

CME Model



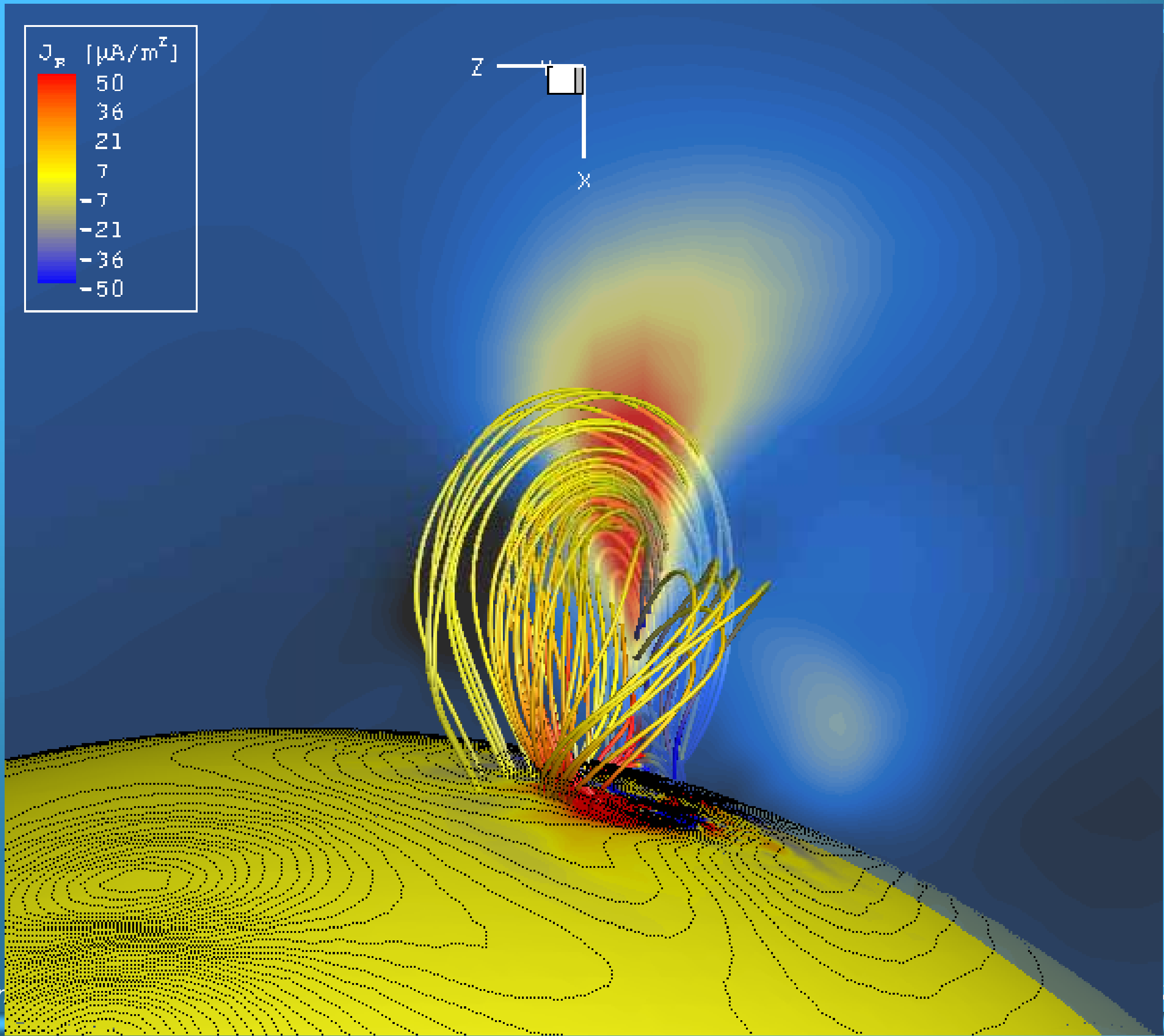
$|B_R| \sim qd/R^3$ (d is depth of charges below photosphere).



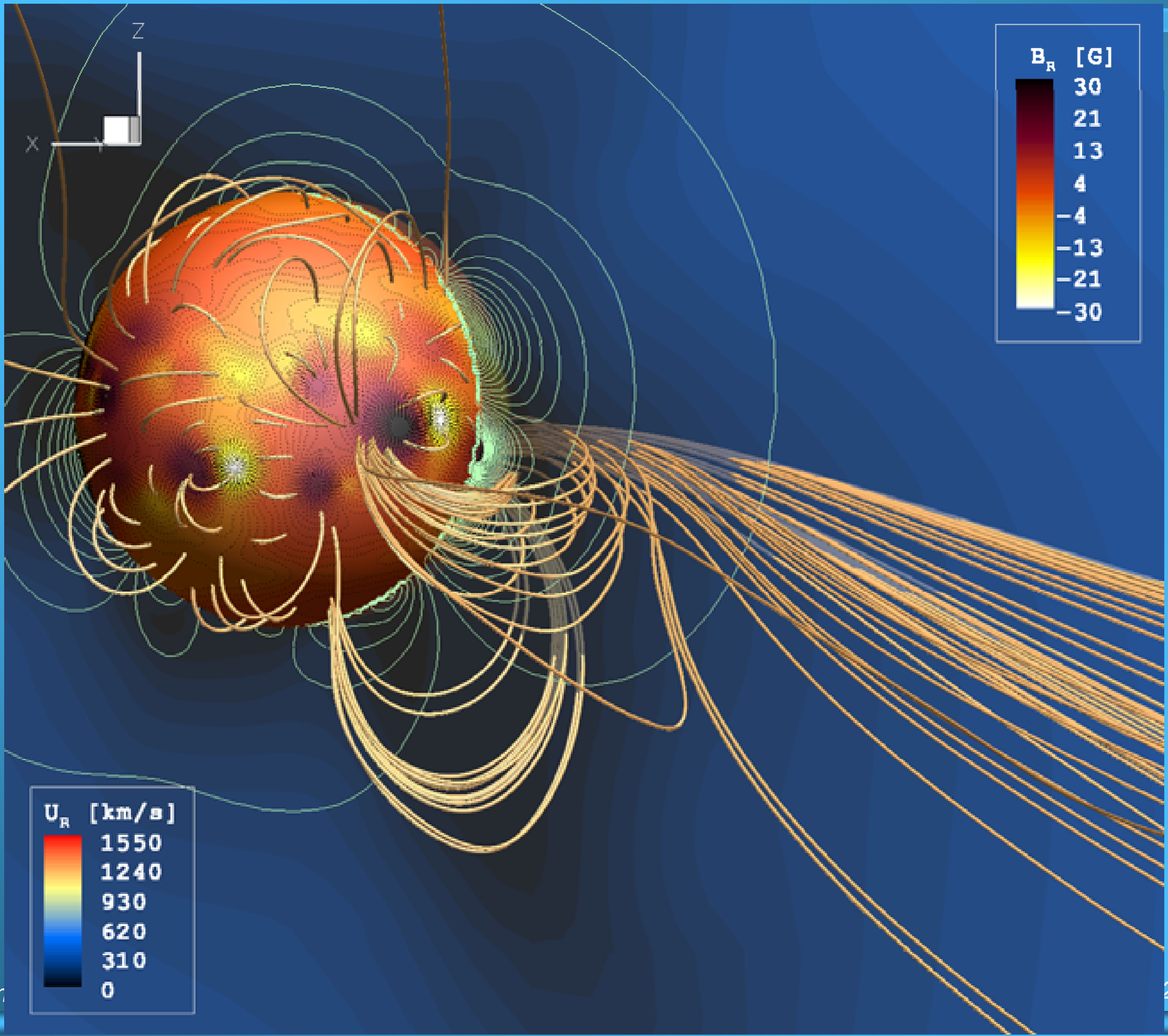
$|B_R| \sim 45$ G at $R = 1.1\ R_\odot$

- Magnetic field of dipole expands while sheared until loss of equilibrium with overlying field occurs (excess magnetic energy is ~ 2.0×10^{32} erg).
- *CME starts as result of loss of equilibrium: acceleration occurs fast!*

3D View of Erupting Magnetic Field at *t* = 30 min

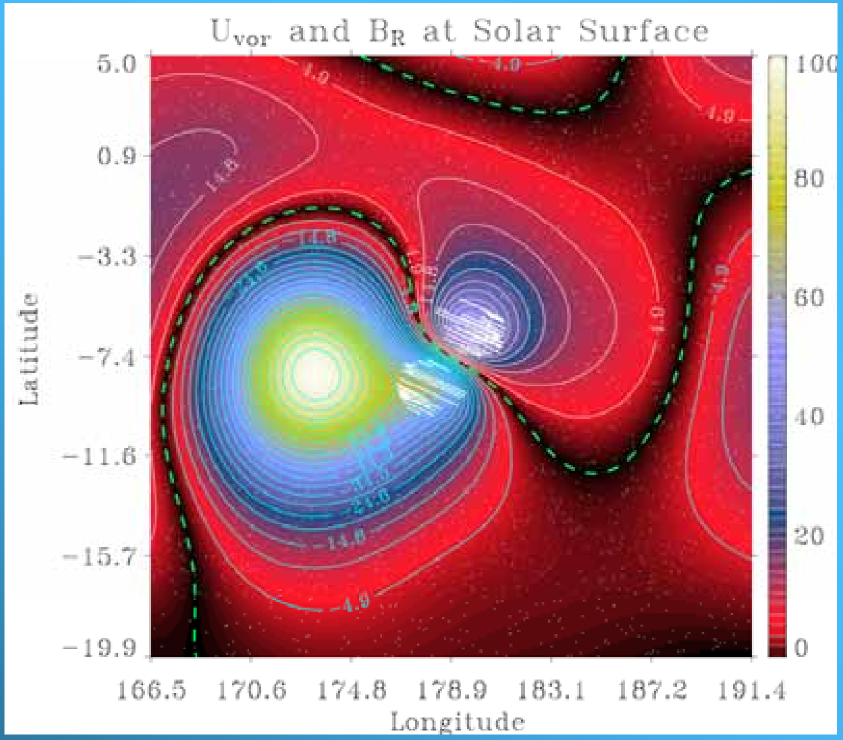


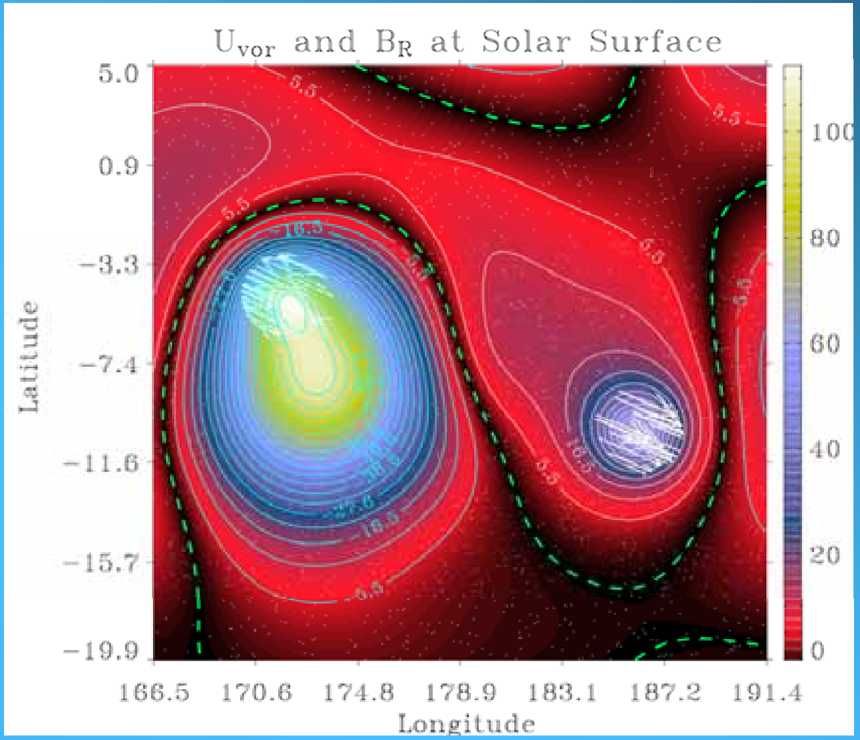
CME Dynamics in Solar Corona up to t = 50 mins



Modeling of 2002 Aug 24 CME

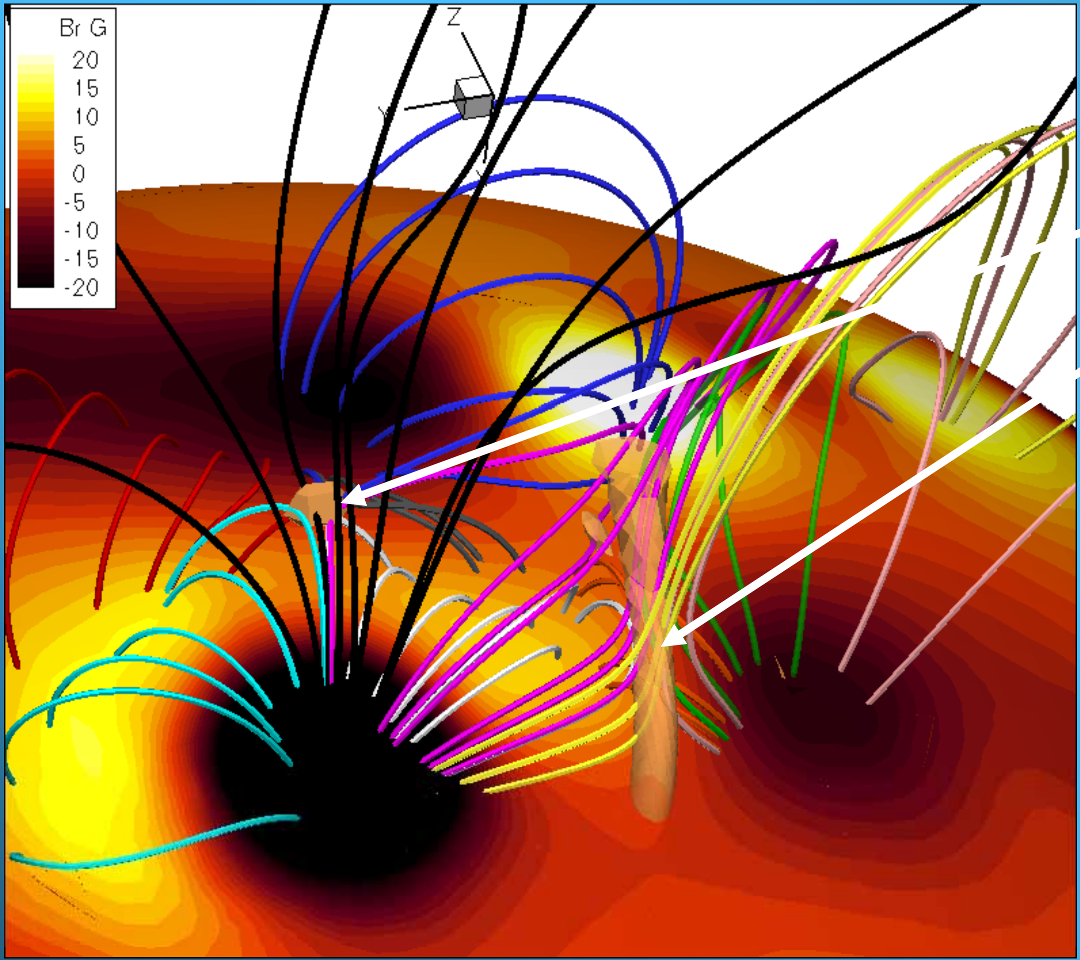
Model of CME Initiation





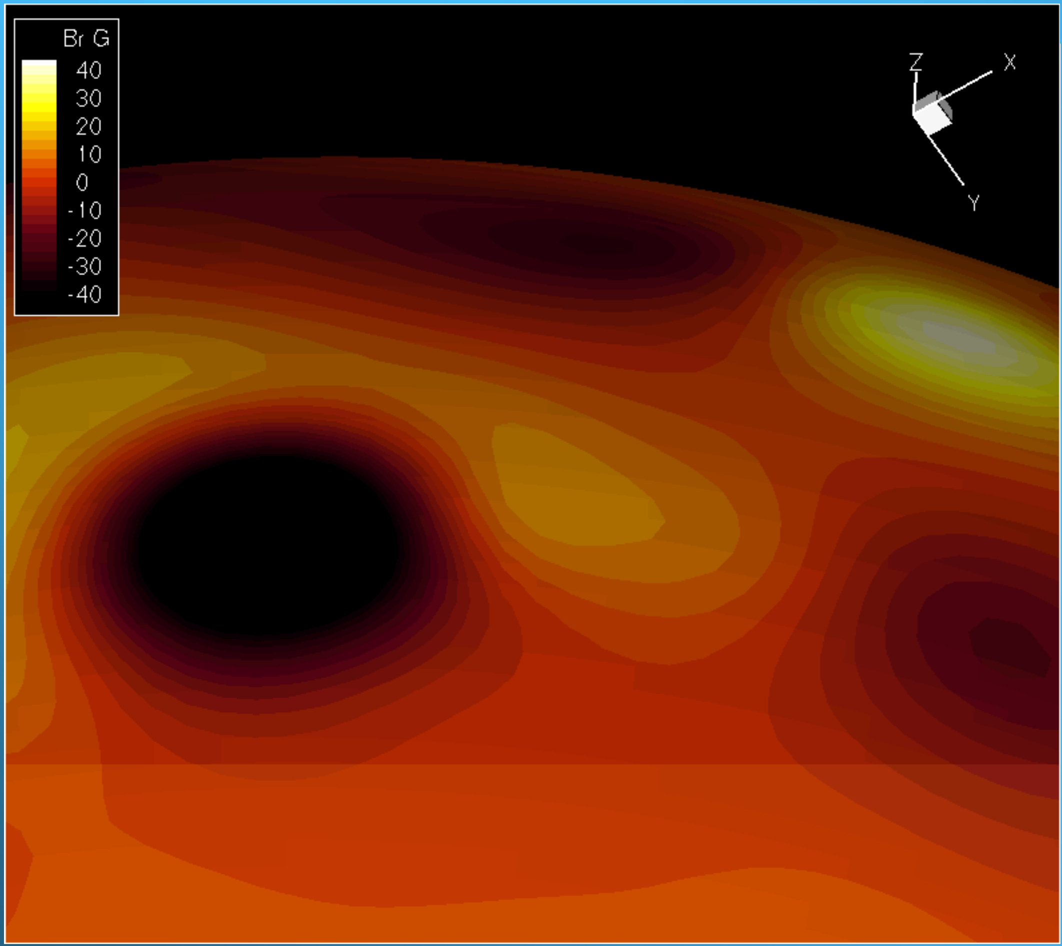
As before, magnetic charges **+/-*q*** generate small-scale dipole field ($|B_R| \sim 45$ G at $R = 1R_\odot$) superimposed onto background CMF. Charges are moved apart (as shown) over finite time (t = 30 min) to stress CMF towards loss-of-confinement state. Excess magnetic energy built in CMF prior to eruption is $\sim 2.3 \times 10^{32}$ erg.

Magnetic Topology of AR 0069 at *t* = 0



- Multiple null points (NPs) in CMF associated with AR 0069 and adjacent ARs.
  - “Northern” NP associated with AR 0067.
  - Quasi-separator (QS) associated with NPs between ARs 0067, 0068 and 0069.

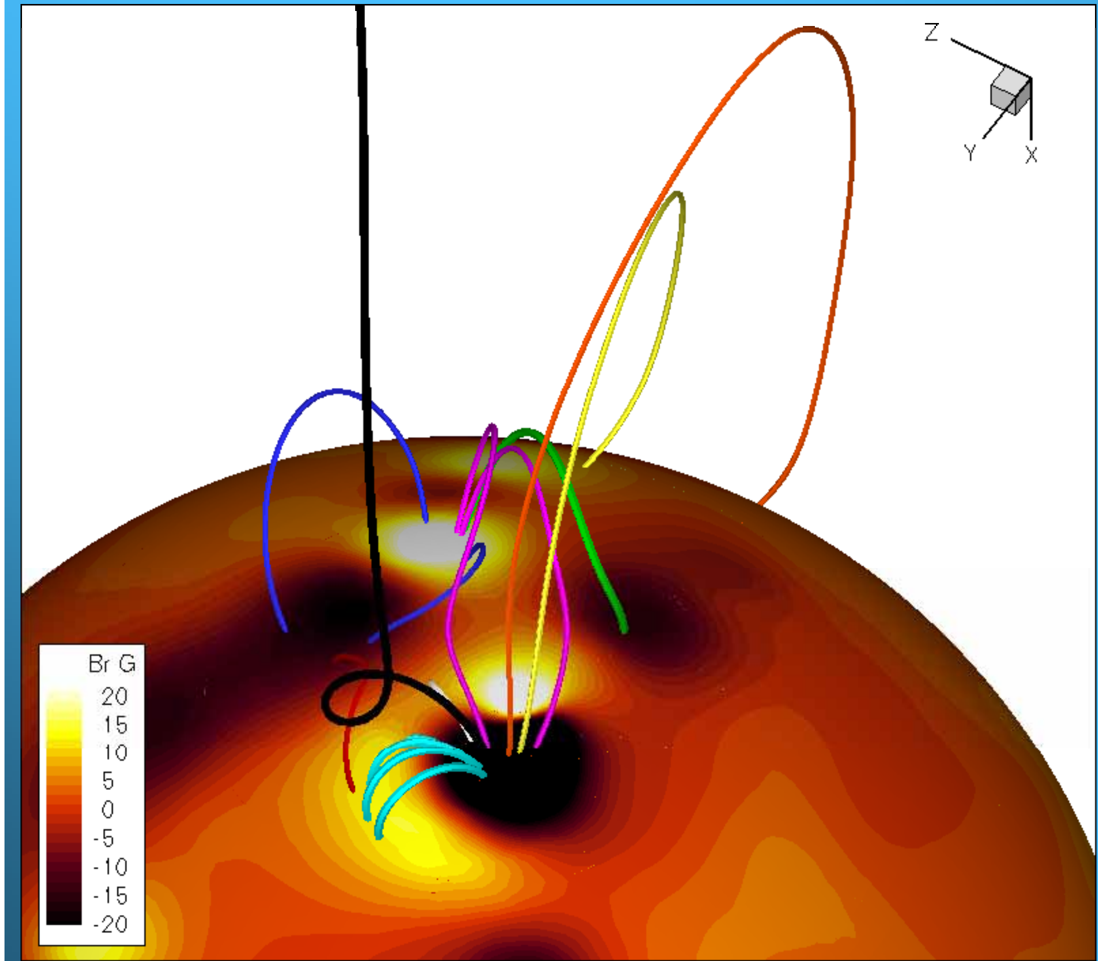
Current Buildup for $t > 0$



Current buildup during shearing phase ($t < 30$ min)

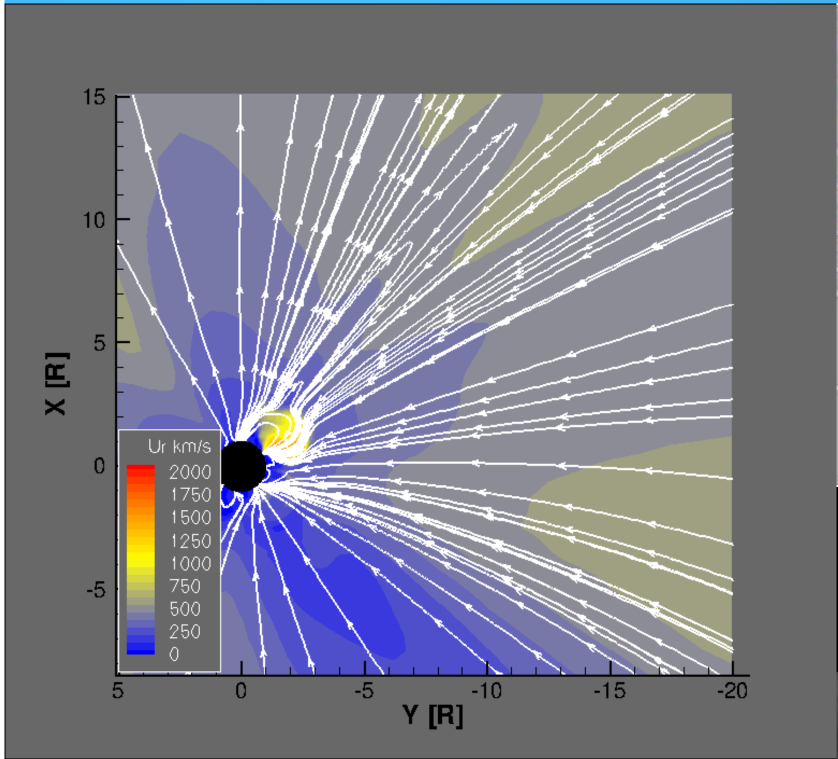
- Moving magnetic spots apart creates shear and twist in coronal magnetic field.
  - Field-aligned currents are build that energize magnetic field of moving spots.
  - Electric currents are also built at pre-existing NPs and QS: QS transforms into current sheet as expanding field from below pushes against it.
  - Subsequent loss of equilibrium leads to eruption and disruption of QS.

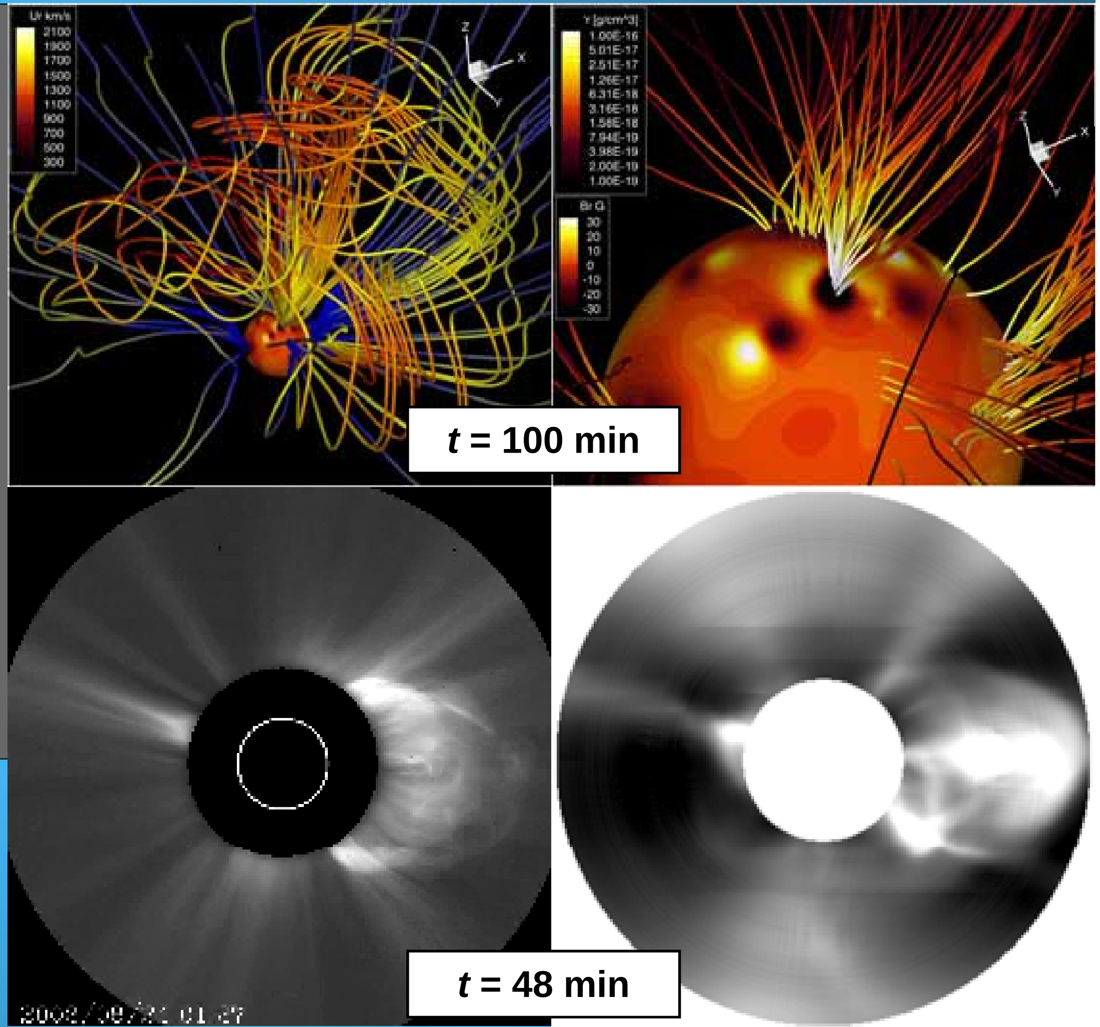
Evolution of CMF



- Reconnection at “northern” NP and through QS leads to transfer of magnetic flux and helicity between twisted dipole field and adjacent magnetic flux systems.
  - Green field line first reconnects through QS and later on through “northern” NP.
  - Light-blue field lines (originally from AR 0069) reconnect through “northern” NP and become part of flux rope.
- One footprint of flux rope remains in AR 0069, whereas other footprint moves westward (due to reconnection through NPs and QS).
  - Erupting flux rope is made out of “bits & pieces” of field lines from various magnetic flux systems!

CME Evolution in Solar Corona

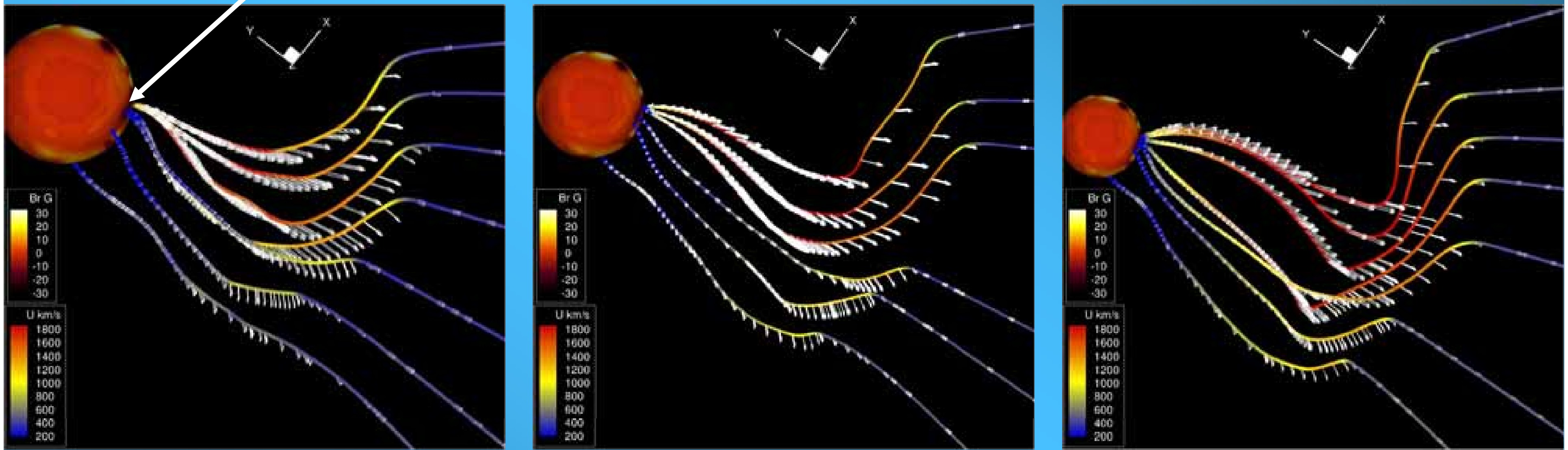




- CME accelerates up to speed of ~ 1,500 km/s in 1hr.
- Simulated CME structure agrees well with LASCO observations.

Evolution of Shock Angle

AR 10069

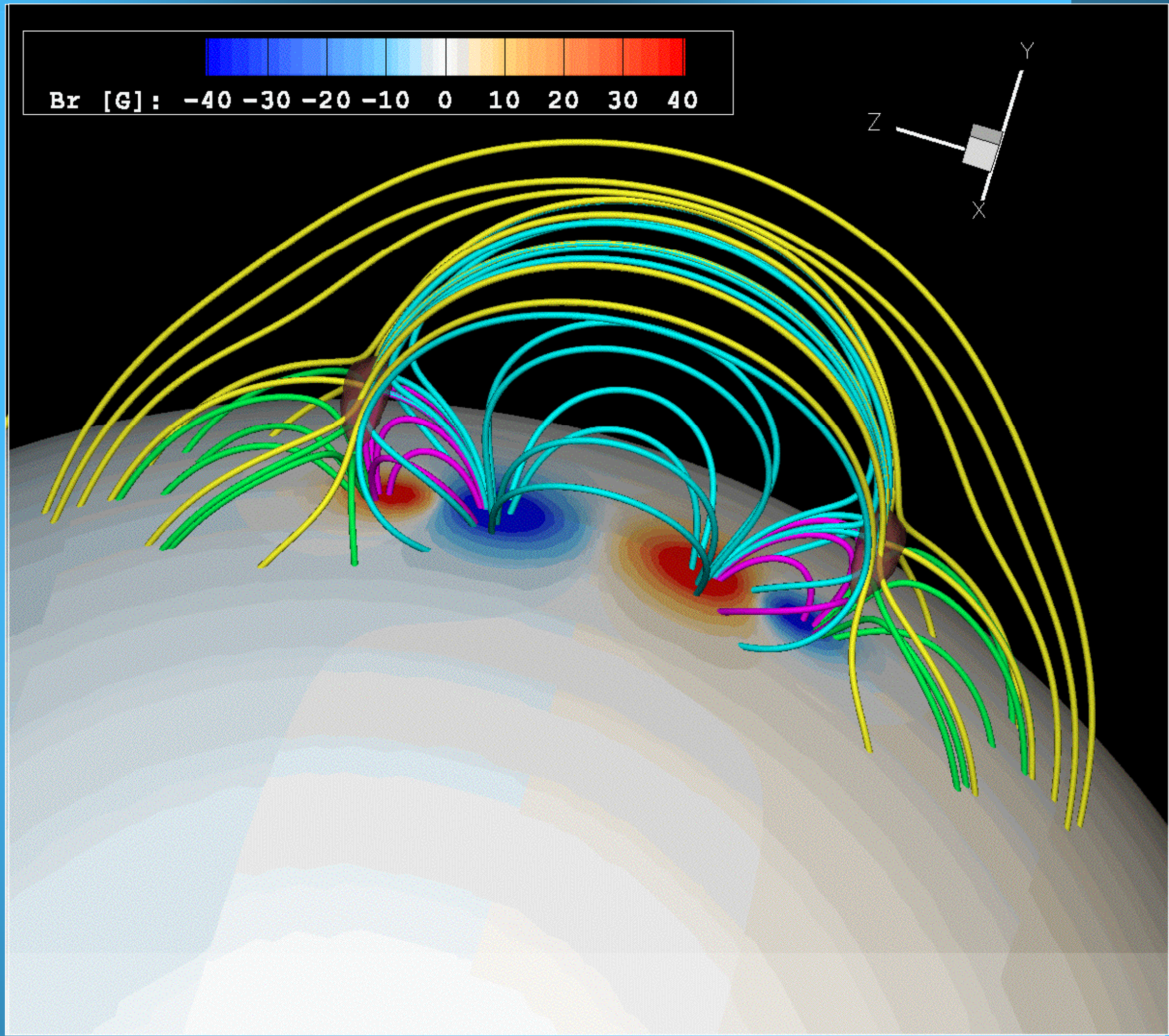


Evolution of magnetic field lines passing nearby L1.

- Shock angle along IMF in direction of L1 is 68º, 53º and 39º at a distance of 4.4, 6.2 and 8.2R_s, respectively (fast Mach is 1.9, 2.68, 3.1).
  - Shock remains quasi-perpendicular in first hour of evolution!

Do All Regular CMEs Contain Flux Ropes?

3D Model of Magnetic Breakout in Idealized Settings
(from Jacobs *et al.*, 2008)

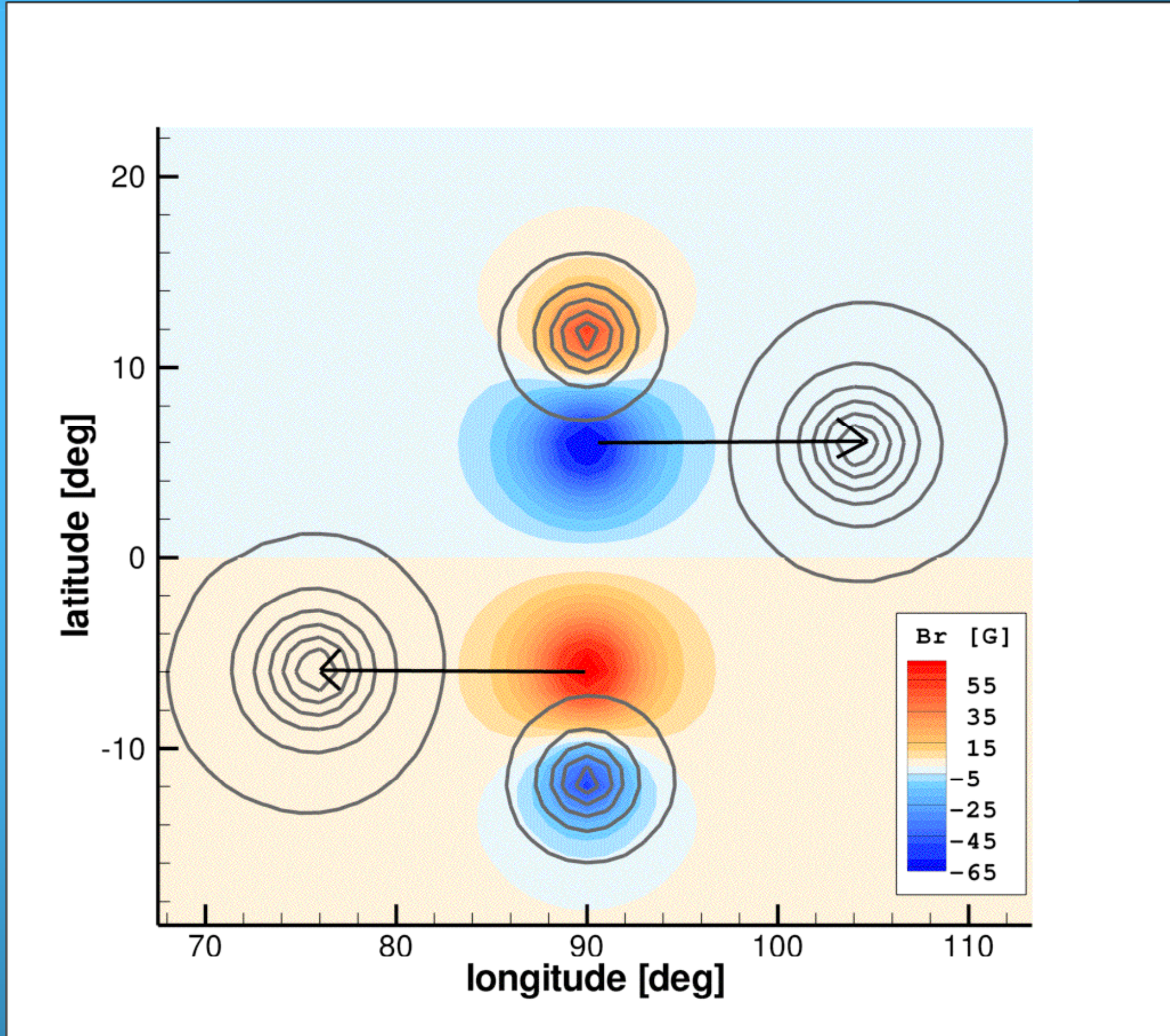


Model Features

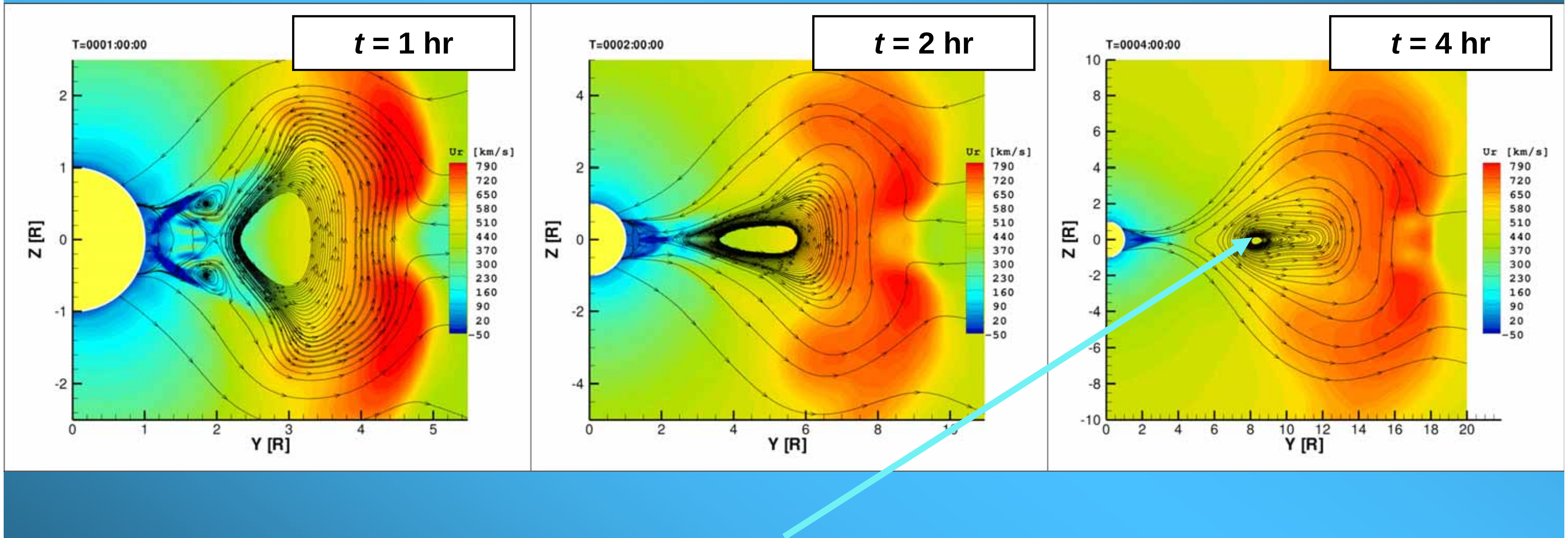
- Multi-polar magnetic field is produced by:
  - Global, dipolar-type magnetic field resembling Sun at solar minimum.
  - Pre-existing active region (outer spots with B_R ~ 50 G).
  - Newly emerged active region (inner spots with B_R ~ 70 G).
- Steady state soar wind.
  - Coronal magnetic field is open beyond 2.5 R_S.

CME Driver: Shearing Motions

- Inner spots are moved apart in finite time (30 min) with speed 160 km/s (which is 2% of local V_A).
- These shearing motions energize the magnetic field by creating field-aligned electric currents.



Radial Flow Structure in Meridional Plane



This appears to be cross-section of magnetic flux-rope, but is it really so?

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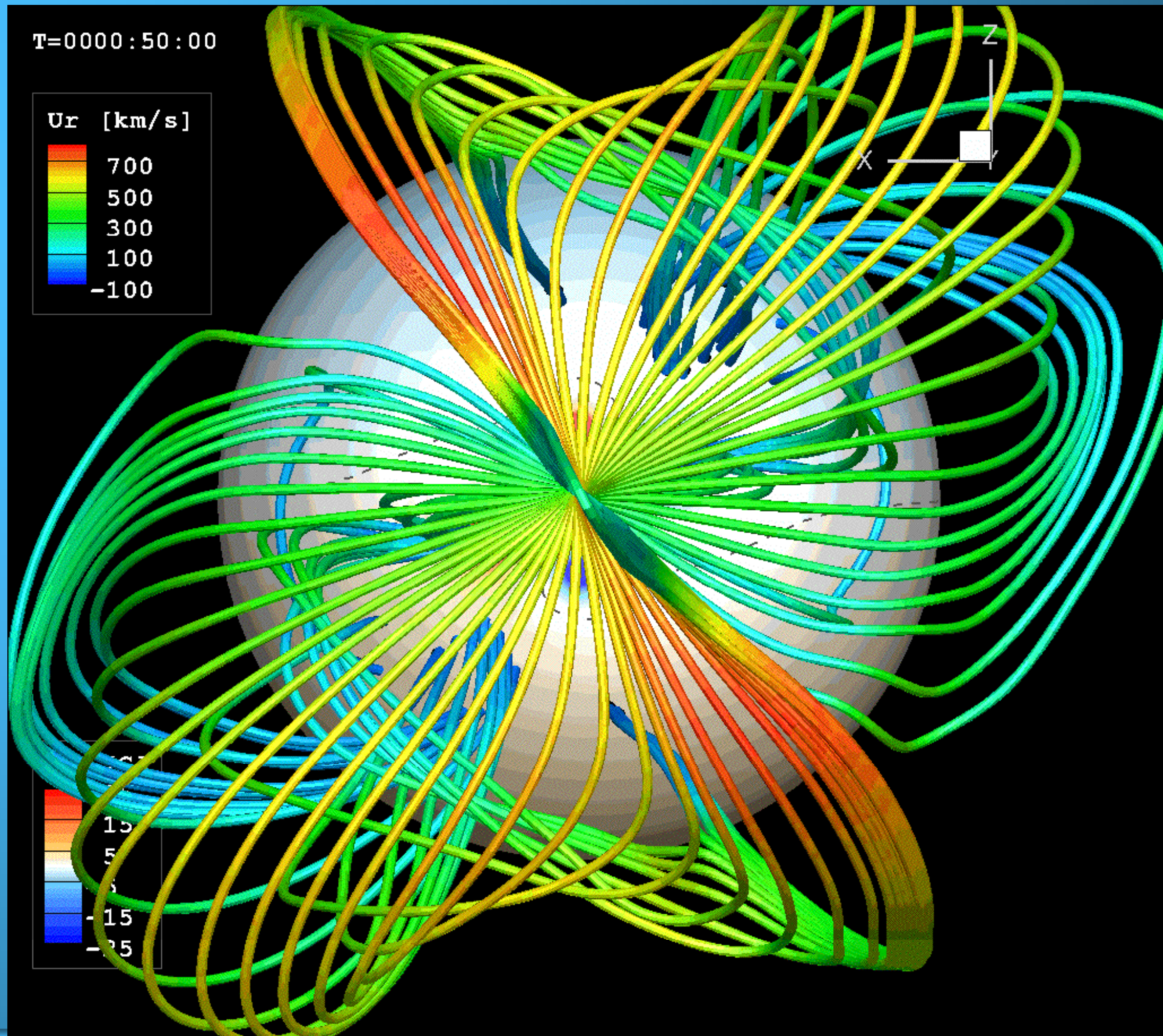
What Is New in This Idealized Simulation?

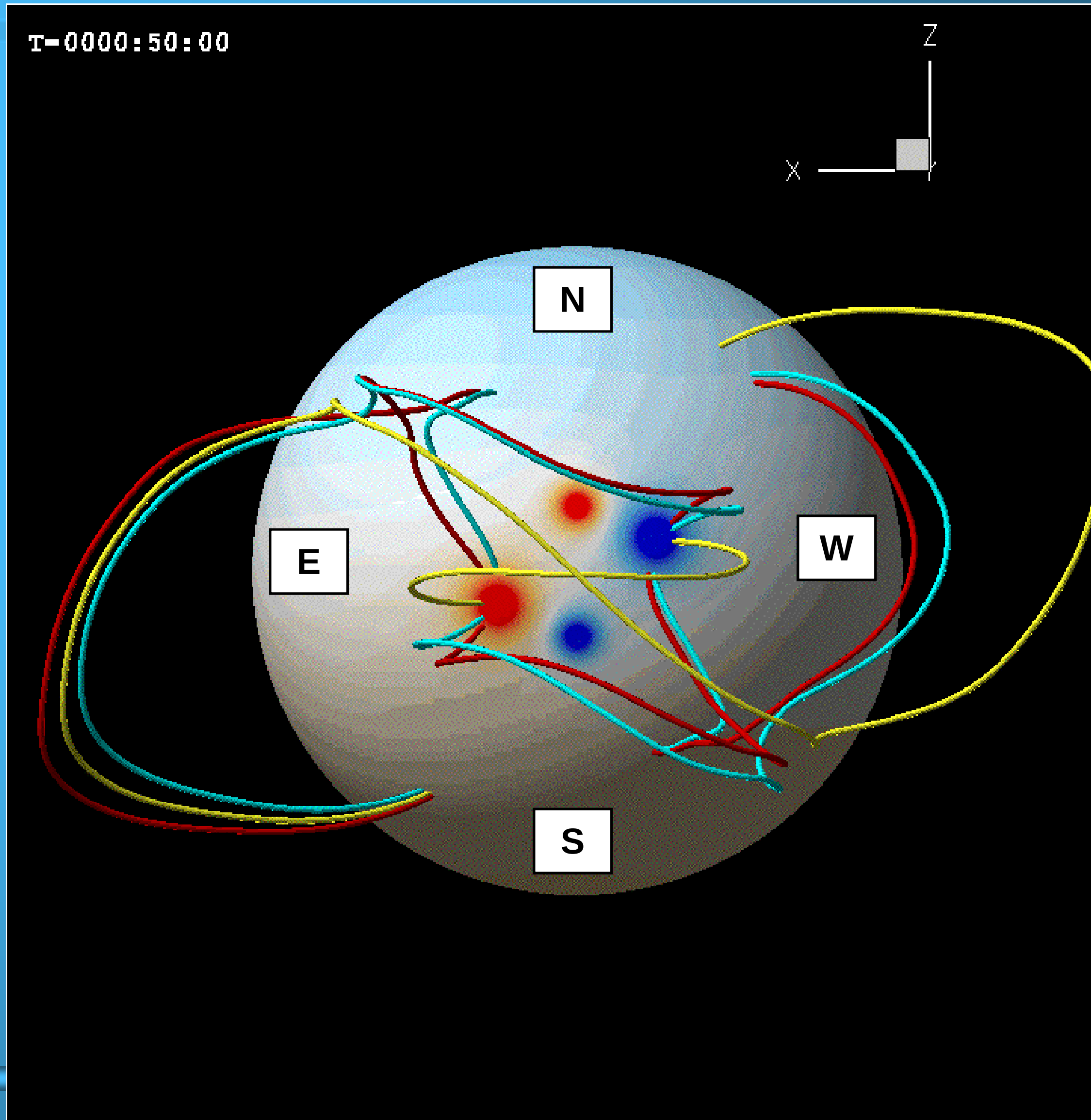
Key Results

- This is not standard flux-rope type CME.
  - Magnetic field of CME has significant writhe.
- Foot-prints of erupting magnetic field are not localized on solar surface.
  - There may be jumps in field line mapping on solar surface as satellite flies through CME.
- Passage of shock wave changes angle of overlying field in plane of shock surface.



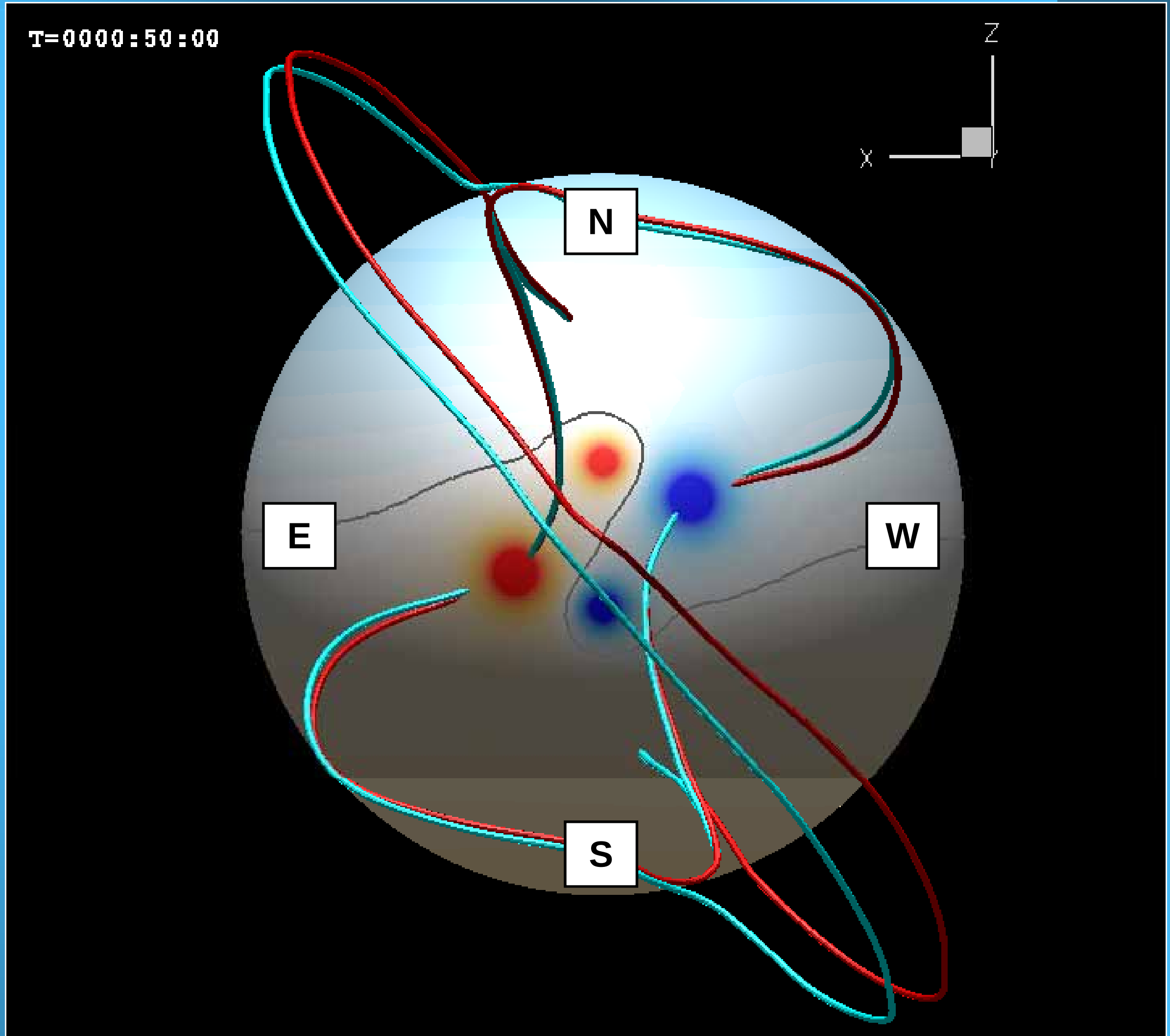
Why Is Magnetic Field So Complicated?

- Magnetic reconnection occurs at three sites:
  - Red field lines reconnect through current sheets formed at two pre-existing null points in **NE** and **SW**: result of reconnection is blue field lines.
  - Blue field lines are pushed equator-ward and reconnect to form the yellow field lines.

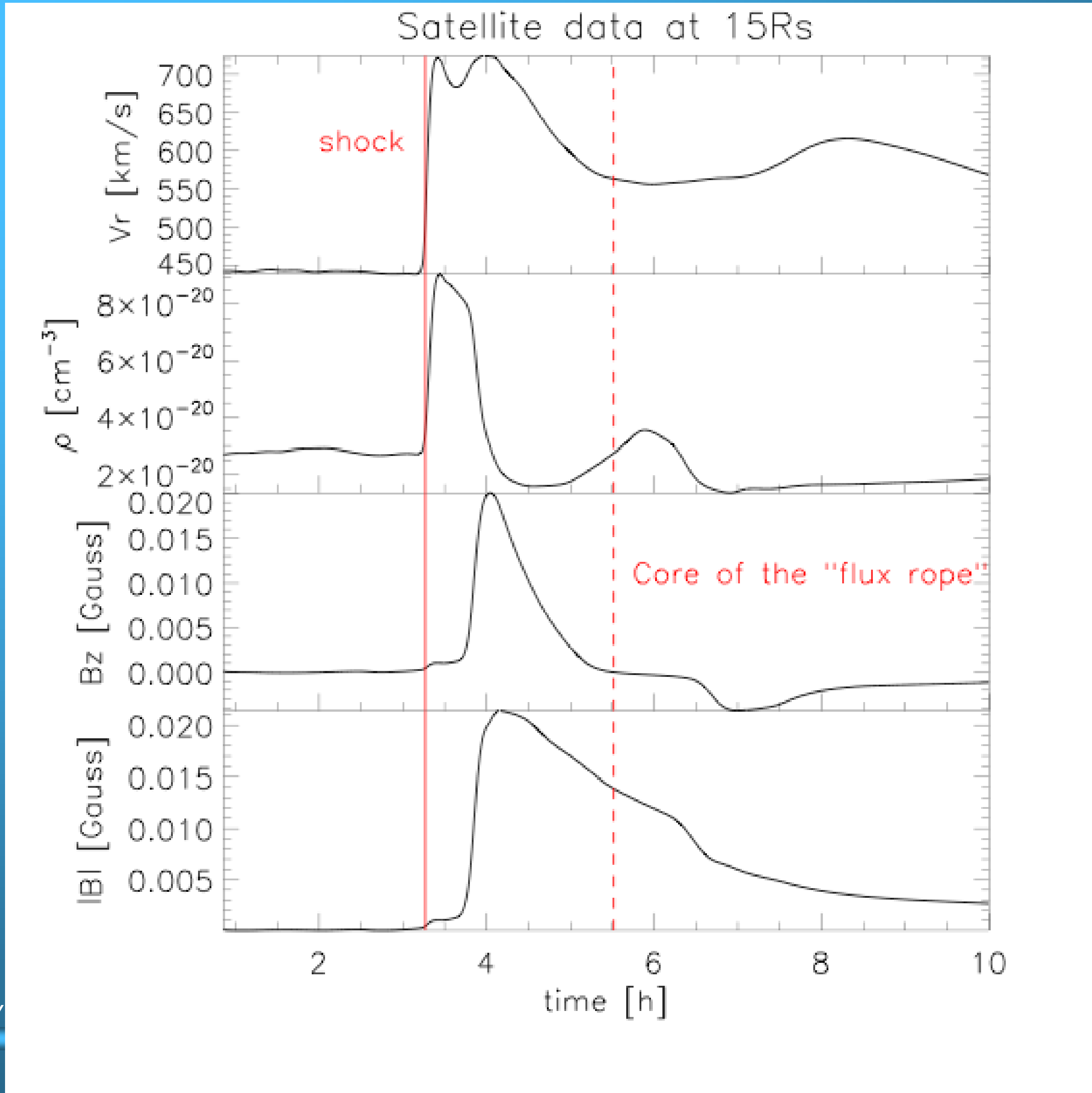


Why Is Magnetic Field So Complicated? (Cont.)

- There is also reconnection from two other flux systems through the **N** and **S** parts of the current sheets in **NE** and **SW**:
  - Red field lines reconnect to form the flue field lines (one of which is highly kinked).



In-Situ Measurements at 15 R_S

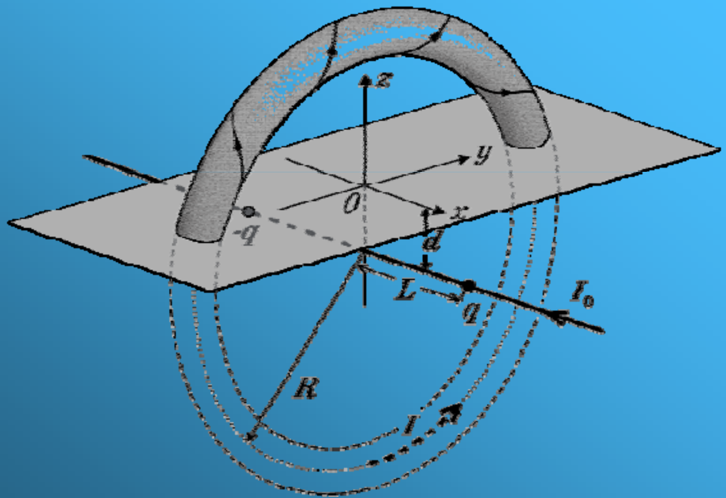


Conclusions

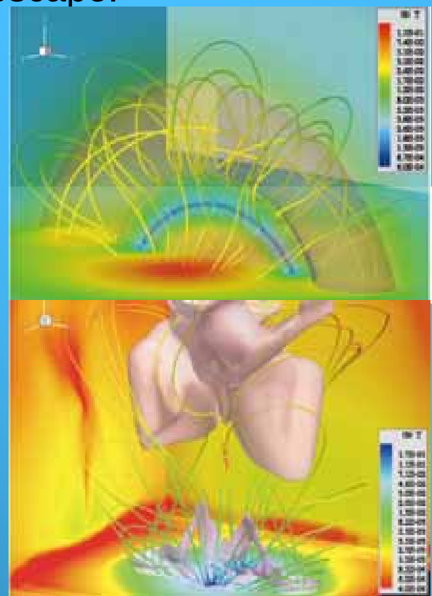
- CMEs originating from complex ARs undergo major reconstruction as they evolve on the way out.
  - Magnetic null points, quasi-separators (or separators), etc., play important role.
  - Transfer of magnetic flux and helicity takes place across number of flux systems.
  - Footprints of erupting magnetic field do *not* remain stationary as CME evolves: one or both legs of CME migrate along solar surface.
- Not all regular CMEs have the standard flux-rope structure.
  - Revision of magnetic cloud models is required.
- Shock waves driven by CMEs also undergo complex evolution.
  - Shock geometry along IMF may change from quasi-perpendicular to quasi-parallel during early stages of evolution.
- Connectivity of CMF may change from open to closed and back to open.
  - This enables suprathermal particles trapped along flare loops to undergo DSA at CME-driven shock once flare loops become open due reconnection.
- CMEs need to be studied on a case-by-case basis if we are to understand their dynamics, energetics, and IP consequences.

Flux-Rope Models

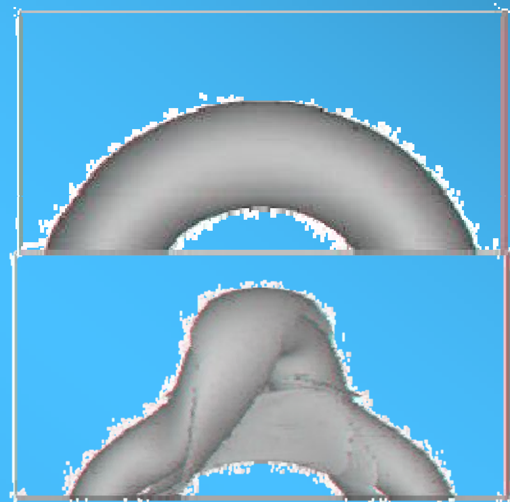
- **Magnetic topology**
  - Twisted flux rope suspended in the corona.
  - Balance between magnetic compression, hoop and tension forces.
- **Trigger for eruption**
  - Slow driving by flux emergence or foot-point motions.
  - Growth of perturbations leads to ideal instability, or lack of equilibrium, and current sheet forms.
  - Non-ideal process (magnetic reconnection) dissipates the current sheet so that the flux rope can escape.



Titov & Démoulin (1999)



Roussev *et al.* (2003)



Kliem, Titov & Török (2004)
Török, Kliem & Titov (2004)

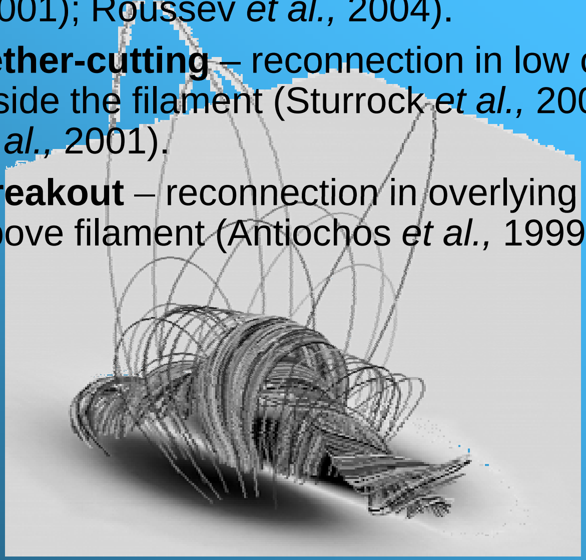
Shared-Arcade Models

Magnetic topology

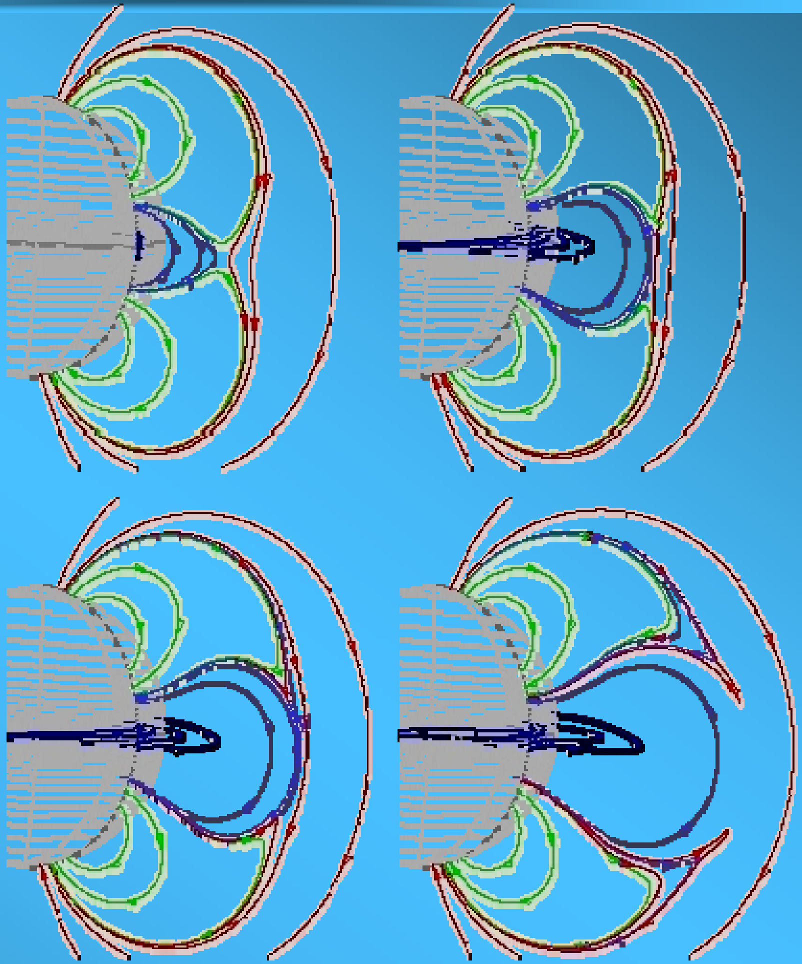
- Sheared magnetic arcades contain free energy in field-aligned electric currents.
- Non-ideal process (magnetic reconnection) required to achieve abrupt loss of equilibrium.
- Flux rope forms during the eruption process.

Trigger for eruption

- **Flux cancellation** – reconnection near photosphere (Amari *et al.,* 2000; Linker *et al.* (2001); Roussev *et al.,* 2004).
- **Tether-cutting** – reconnection in low corona inside the filament (Sturrock *et al.,* 2001; Moore *et al.,* 2001).
- **Breakout** – reconnection in overlying field, above filament (Antiochos *et al.,* 1999).



Amari *et al.* (2000)

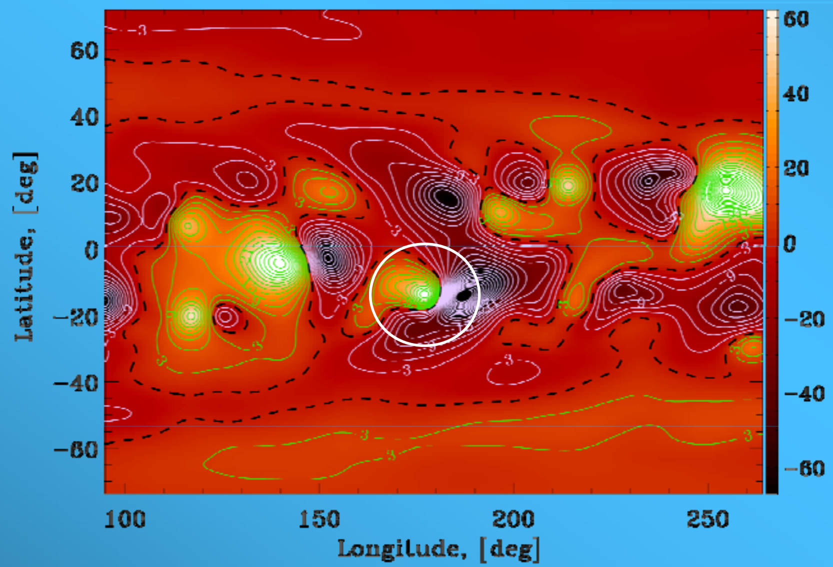


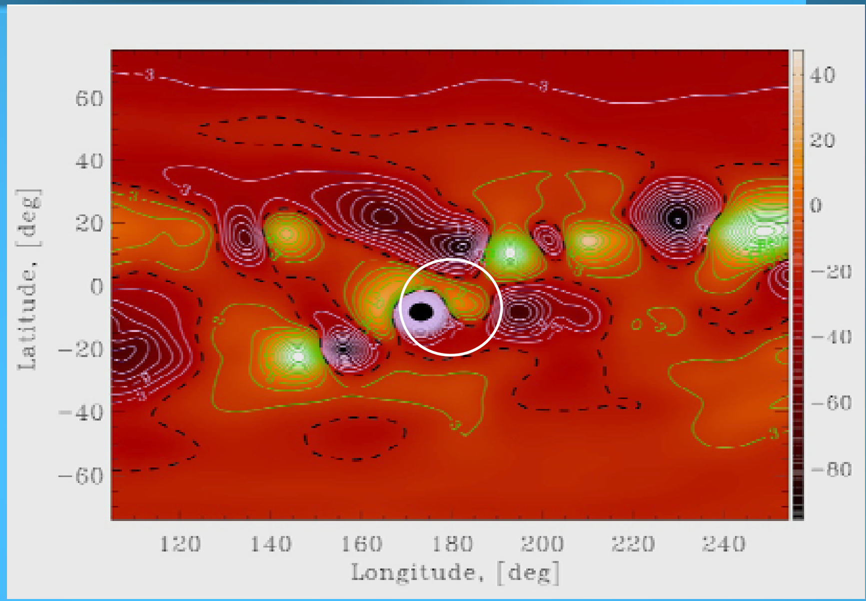
Antiochos *et al.* (1999)

Kinetic Equation Describing SEP Production II

- We adopt diffusion coefficient of the form: $D = \left(\frac{B}{\delta B}\right)^2 v\, r_B, \quad r_B = \frac{c\, p}{e\, B}$
- Boundary condition at "injection energy" is:
  (we assume E^{-1} spectrum for suprathermal particles) $f\,|_{p=p_{Inj}} = \frac{1}{4\pi} \frac{N}{(2m_p T)^{3/2}} \left(\frac{\sqrt{2m_p T}}{p_{Inj}}\right)^4$

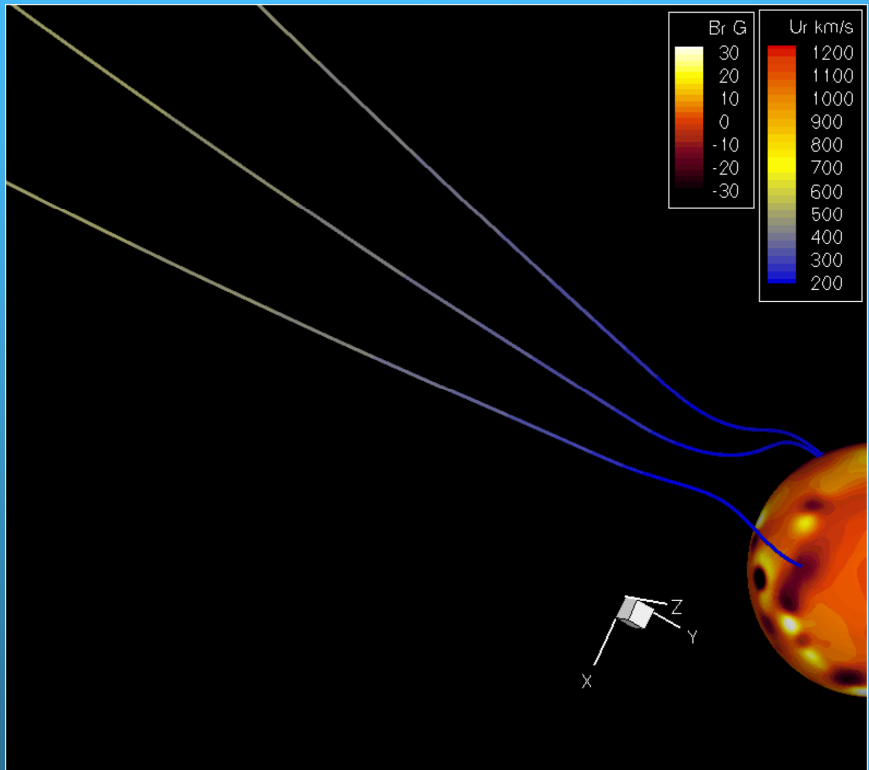
Event Comparison

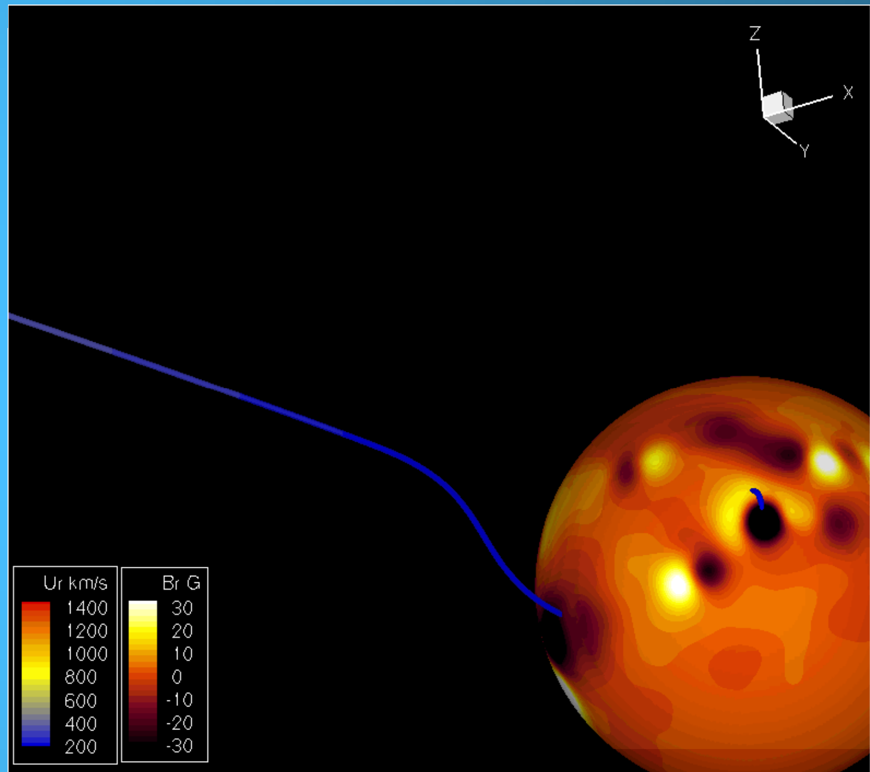




- Both events took place on west limb and were associated with X-class flares.
- Both CMEs drove shock waves which formed within 2-3 R_s and traveled at speeds > 1,500 km/s.
- Both source regions were magnetically connected to adjacent active regions.
- Both CMEs were associated with large SEP events.

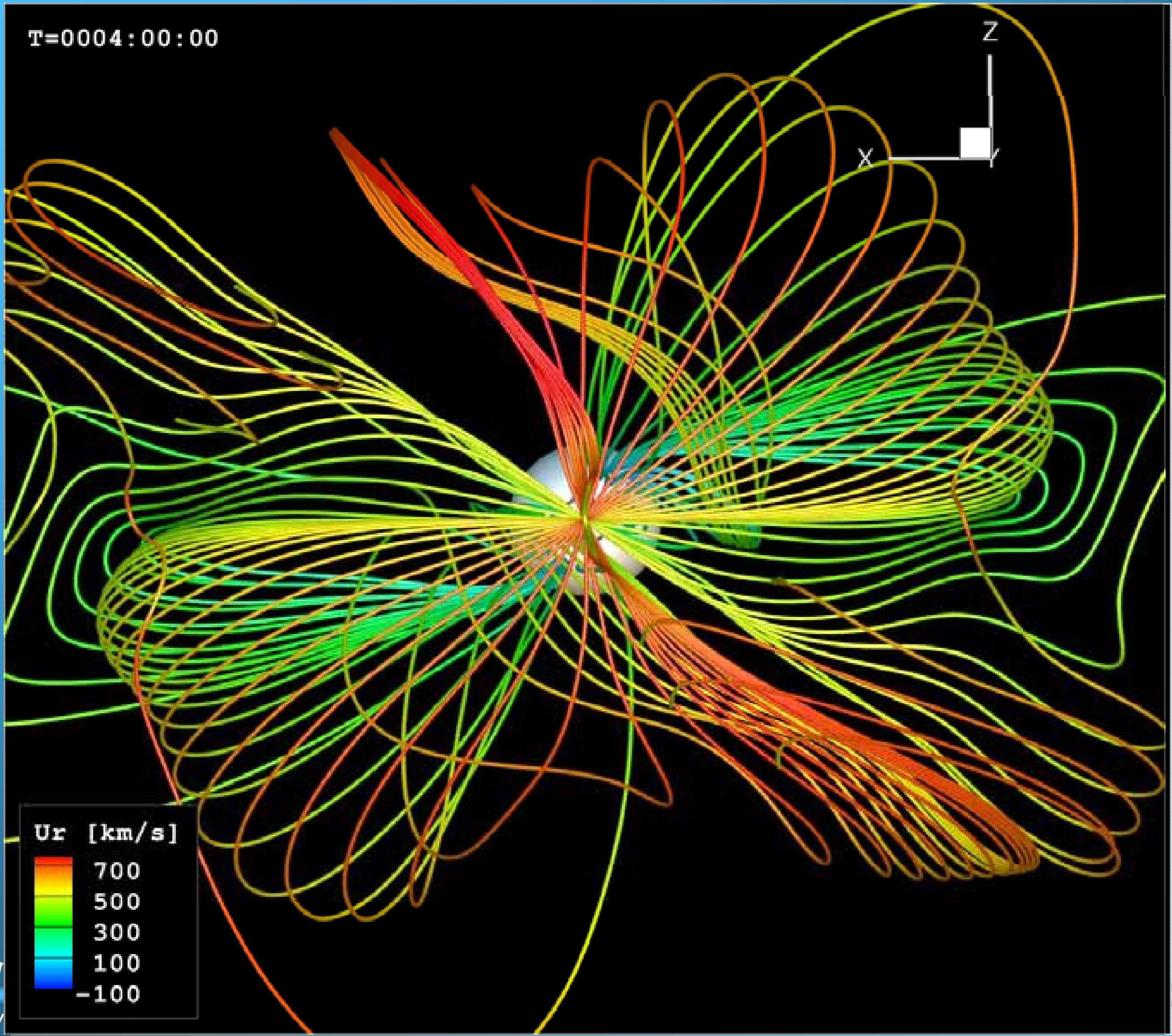
IMF Evolution





- IMF footprints at Sun change due to reconnection.
  - This may enable suprathermals (produced during flare) to undergo diffusive-shock-acceleration once closed loops become open.

3D Structure of Coronal Magnetic Field at *t* = 4 hr



Synthetic White Light Observations