Recent Advances in Understanding the Nature of CMEs by Combining Solar Observations with Numerical Simulations

Ilia Roussev[1,2], Cooper Downs[3], Noe Lugaz[4], and Klaus Galsgaard[5]

(1) Institute for Astronomy, USA

(2) Yunnan Astronomical Observatory, China

(3) Predictive Science, Inc., USA

(4) University of New Hampshire, USA

(5) Niels Bohr Institute, Denmark

Motivation/Philosophy

- "Realistic" simulation tools (*e.g.*, SWMF) can function as effective (digital) laboratory to learn about complex phenomena we observe (flares, EIT waves, CMEs, *etc.*)
  - Incorporation/assimilation of observational data (*e.g.*, full-disk magnetogram data) into relevant computational models (as initial conditions, boundary conditions, *etc*.) is crucial.
  - Capability to reproduce other relevant observations (scattered white light, EUV emission, soft X-rays, *etc*.) is also crucial for constraining the simulation tools.
- We need computational tools capable of providing ***direct*** comparison to observations.
  - Interpretation of complex observations (SoHO, SDO, STEREO, future Solar Orbiter).
  - Validation of models themselves.
  - Fill data gaps from observations.

This talk discusses recent progress in developing such tool.

DiSEL Digital Sun-Earth Laboratory

Global Model of Solar Corona Constrained by Solar Observations

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(Tóth *et al.*, 2005).

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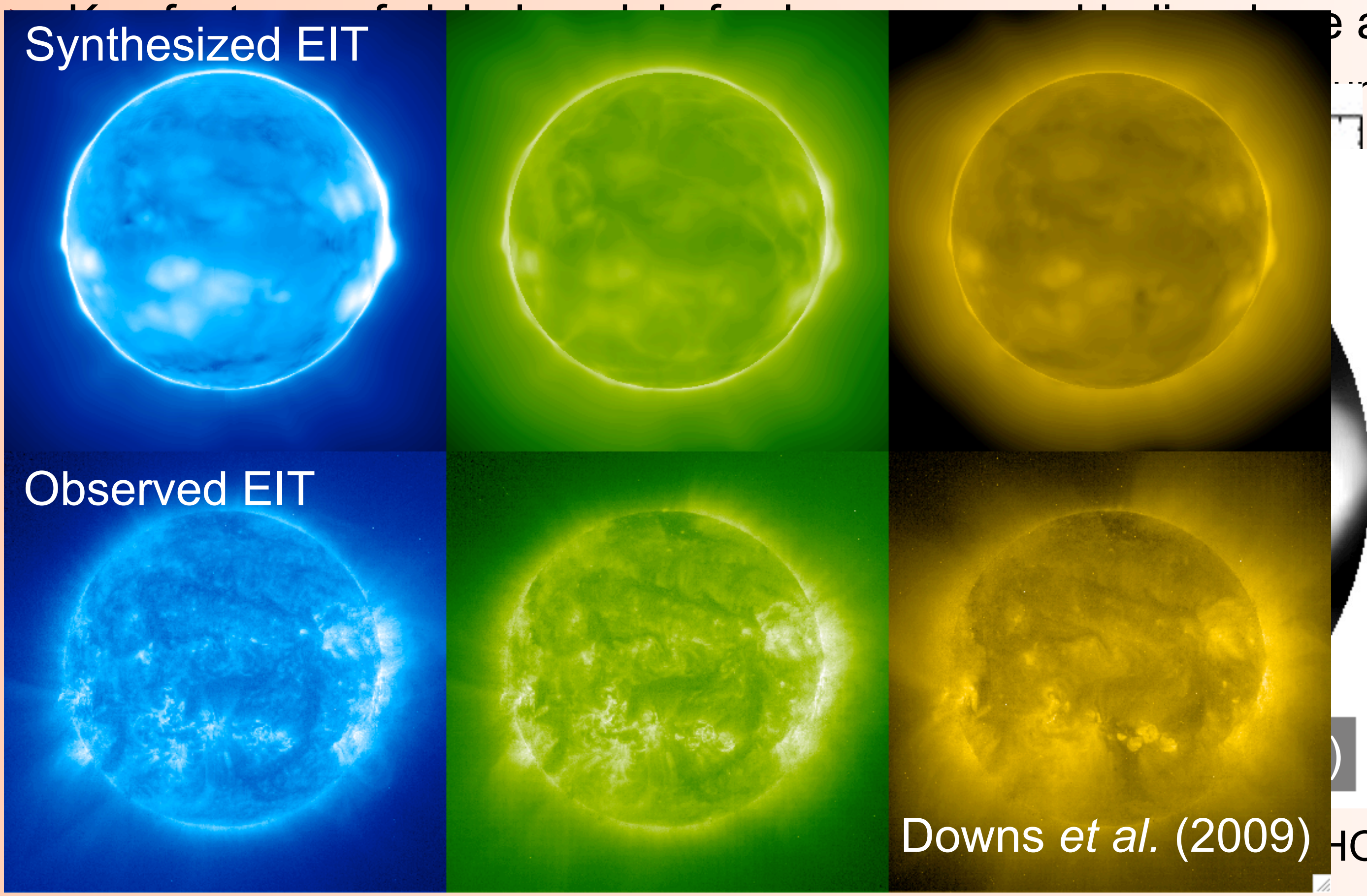

HO/LASCO).

- Solar observation in Extreme UV (SoHO, STEREO, and SDO).

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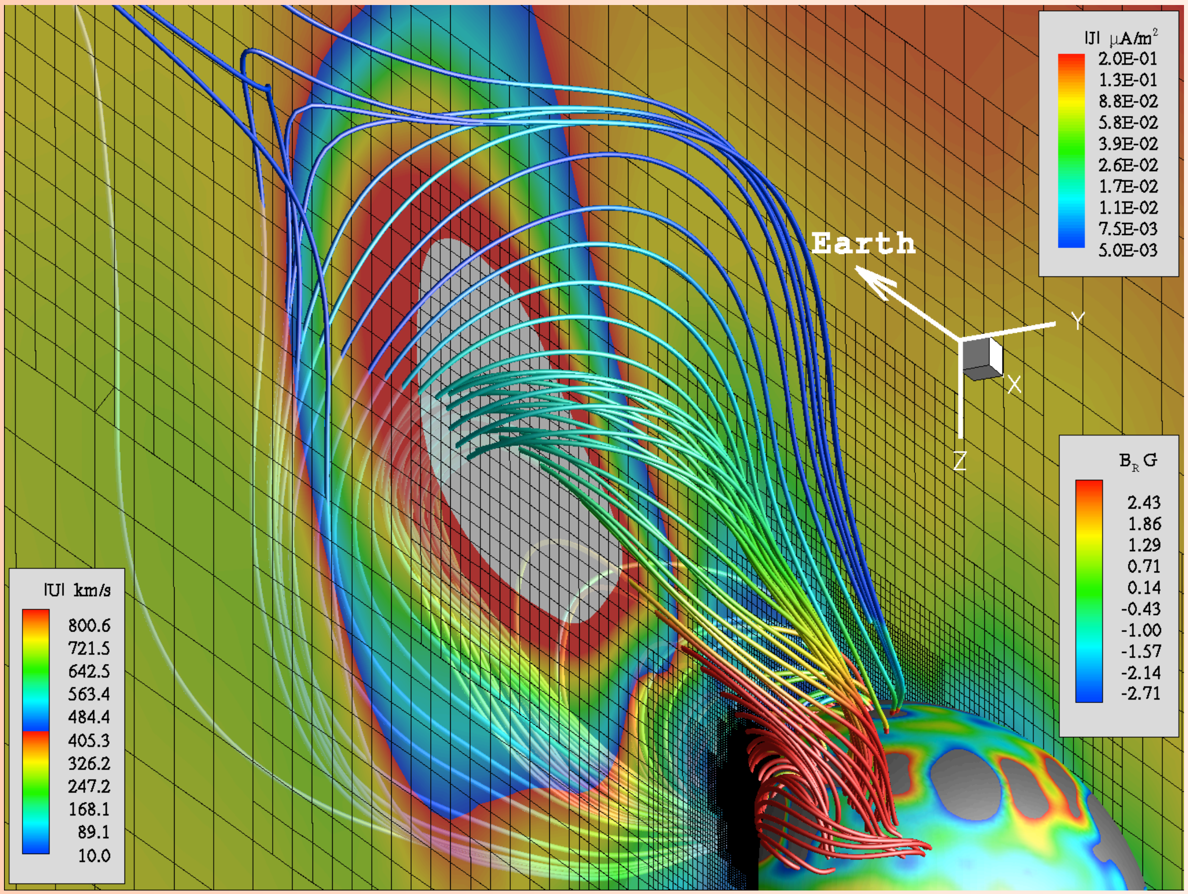
Data-Driven Models of CMEs

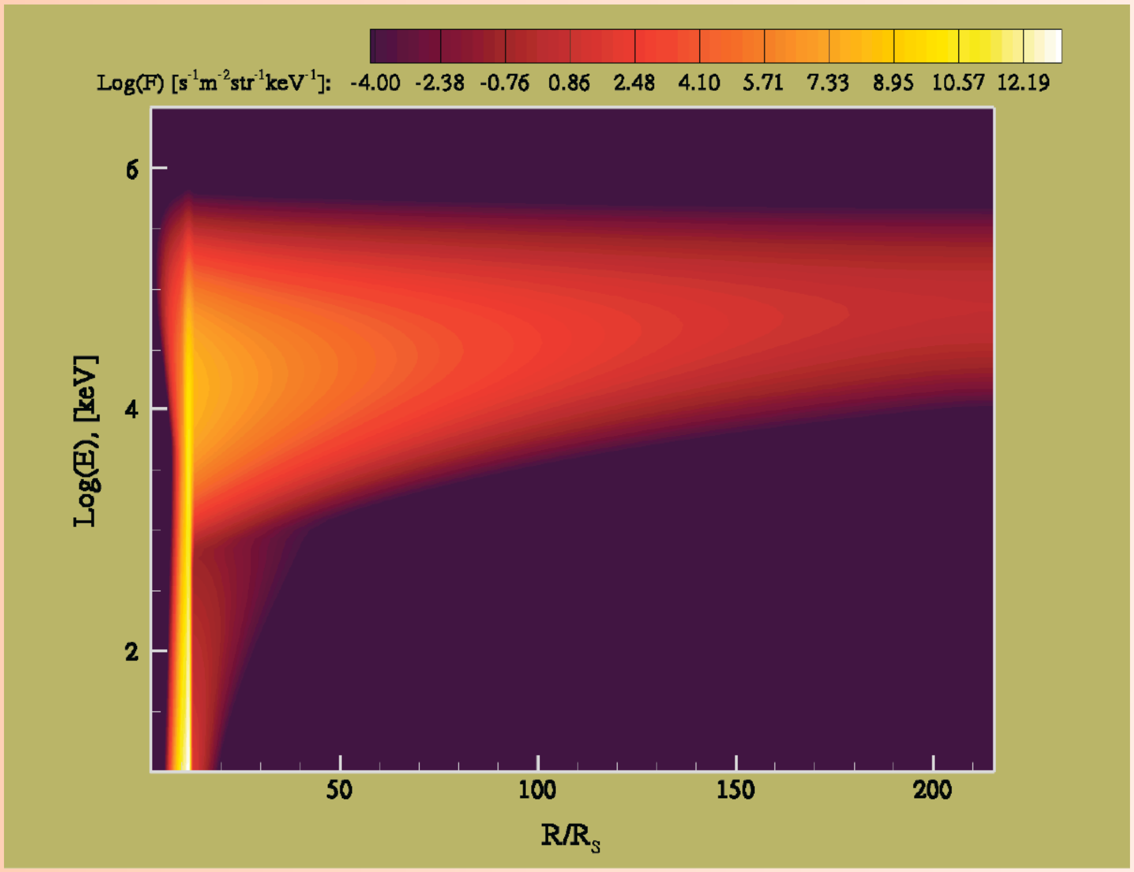
Model of 1998 May 2 CME Event



- Physical mechanisms leading to occurrence of CMEs have been debated by solar community for 40 years now.
- Answering fundamental questions concerning energy build-up, CME trigger, evolution of background magnetic field & coronal plasma, shock formation & evolution, *etc*., requires event studies.
- By studying 1998 May 2 event, we have demonstrated that strong CME-driven shock can develop relatively close to Sun (Roussev *et al.*, *ApJ Lett.*, ***605***, *L73*, 2004).

Data-Driven Modeling of SEPs

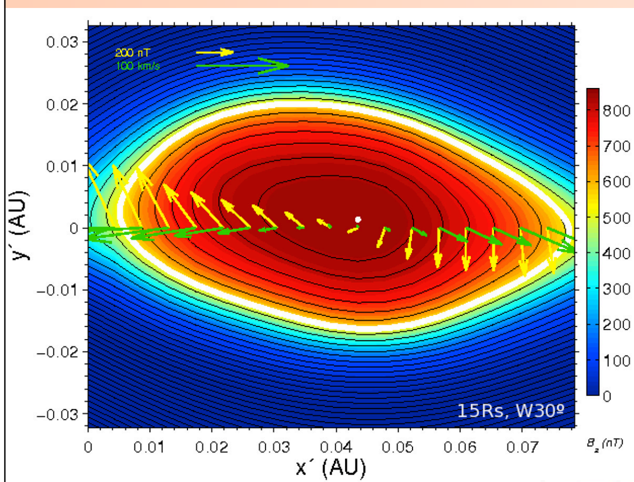
Model of 1998 May 2 SEP Event

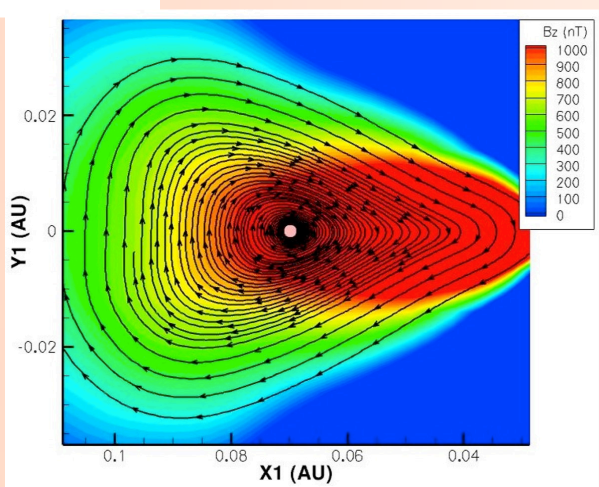


- Production of SEPs at CME-driven shocks is long-standing problem, because little is known from observations about properties of shock waves, level of IP turbulence, strength & geometry of IP magnetic field, *etc*.
- By having “realistic” model of CME-shock evolution, as for 1998 May 2 CME event, we can address the issue of SEP production at CME shocks more self-consistently.
- Simulated proton fluxes for 1998 May 2 SEP event are found to be in good agreement with *GOES-8* data (Sokolov *et al*., *ApJ Lett.,* ***616***, *L171*, 2004).

Model of ICMEs and Magnetic Clouds

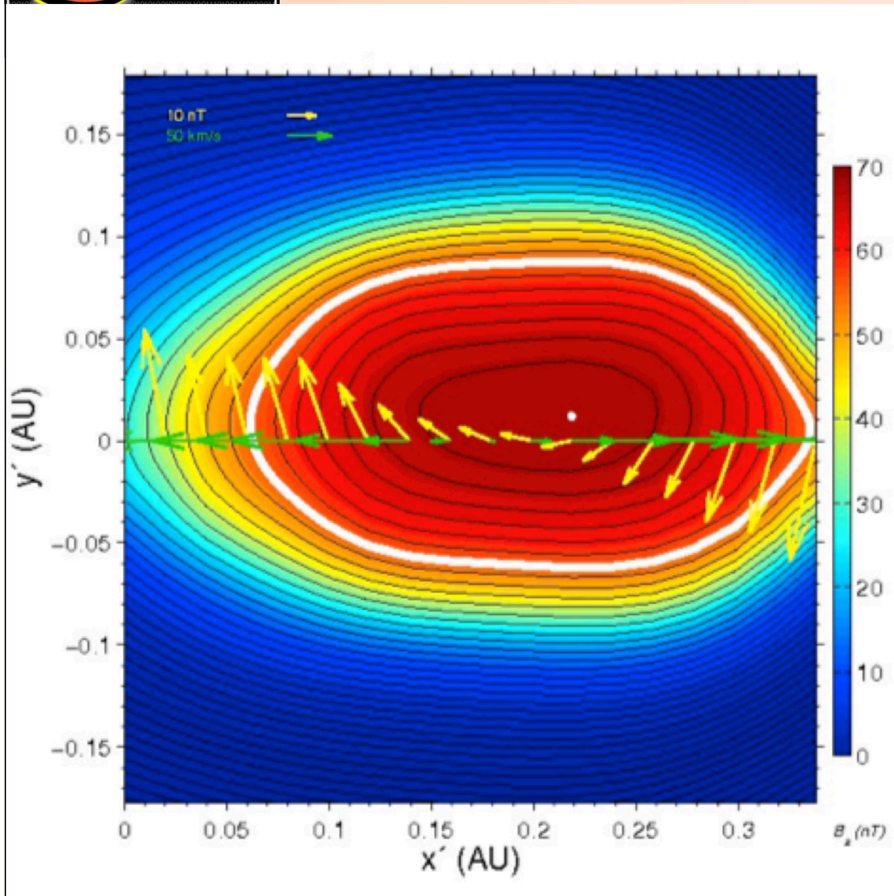
Comparison of 3-D ICME Model with MC Reconstruction



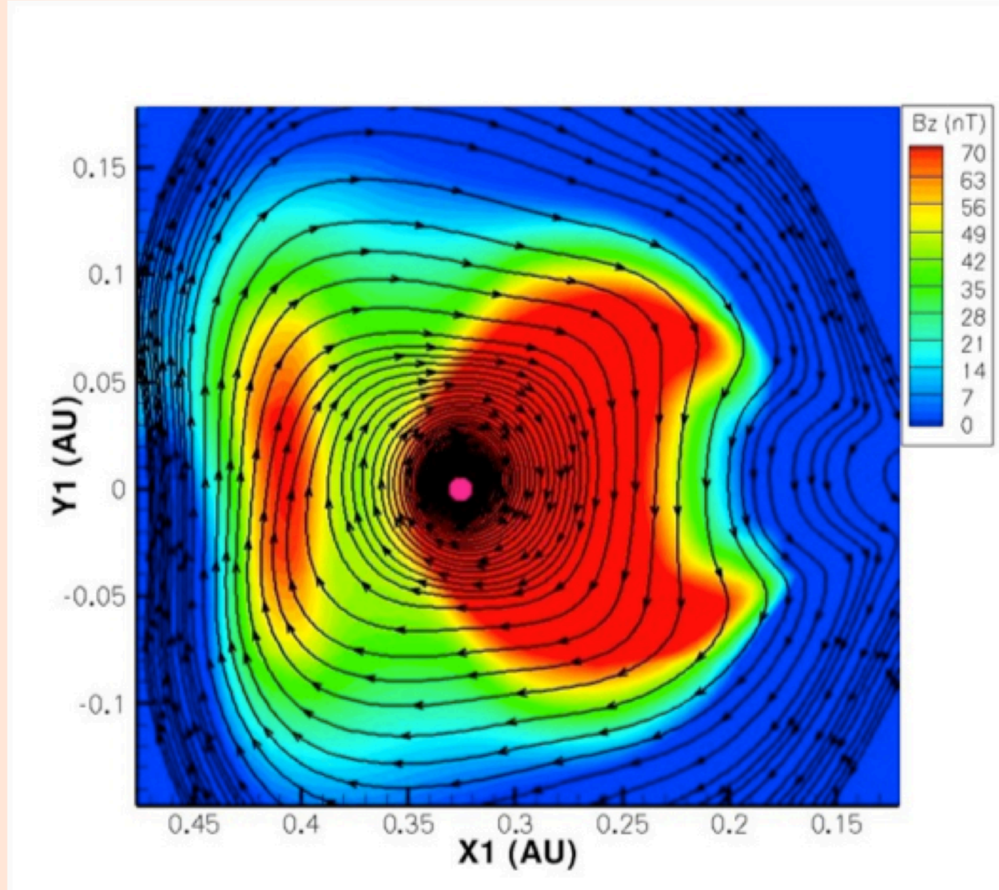


- Magnetic fields inside ICMEs are most often modeled as twisted flux ropes.
- Different interpretation of magnetic field structure of MCs is possible if writhe is considered.
- We created a simulated ICME with limited twist but strong writhe.
- We were able to reconstruct MC structure (left) and to compare with 3-D simulation (right) in a way that would be interpreted as typical twisted flux rope.
- This result challenges accepted paradigm that ICMEs are always twisted magnetic flux ropes (Al-Haddad *et al*., *ApJ Lett.*, ***738***, *L18*, 2011).

Comparison at $70R_S$

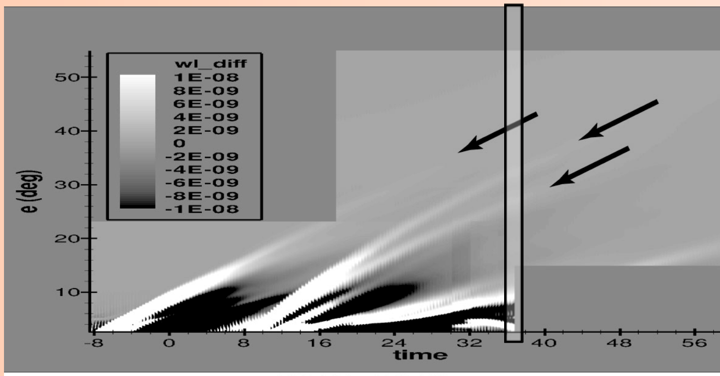


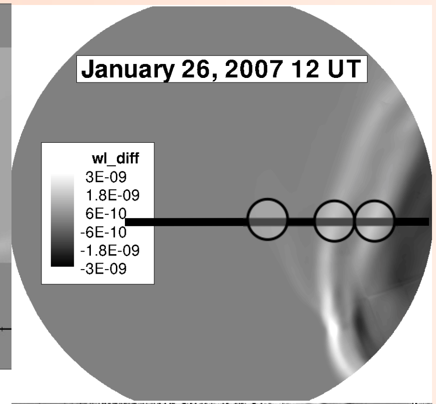
GS Reconstruction of MC

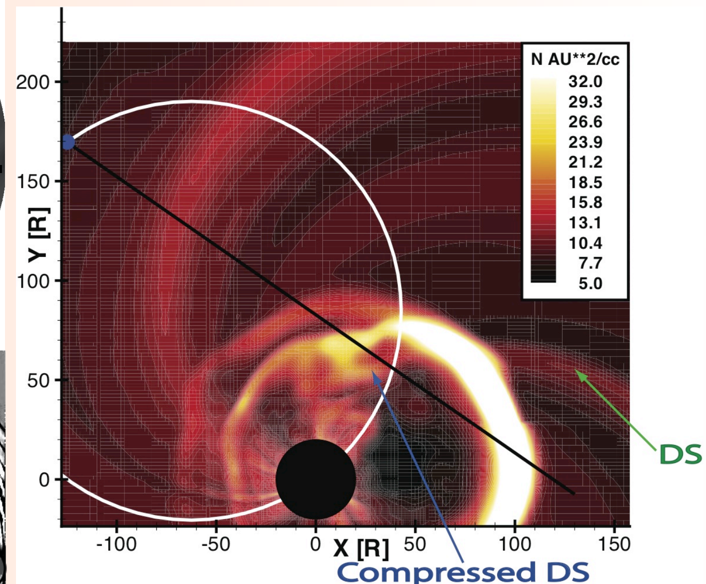


MHD Simulation of CME

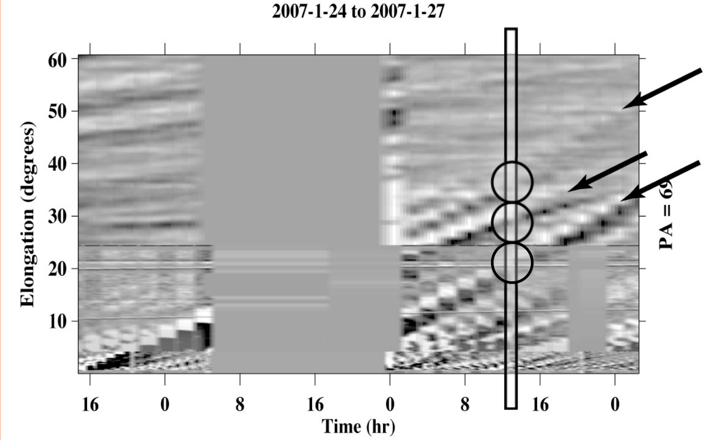
Filling Data Gaps in STEREO Observations

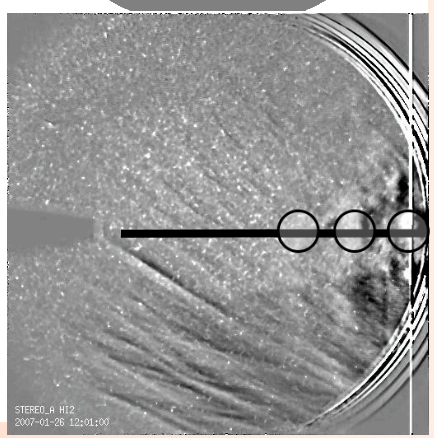






Lugaz *et al.*, *ApJL* (2008)



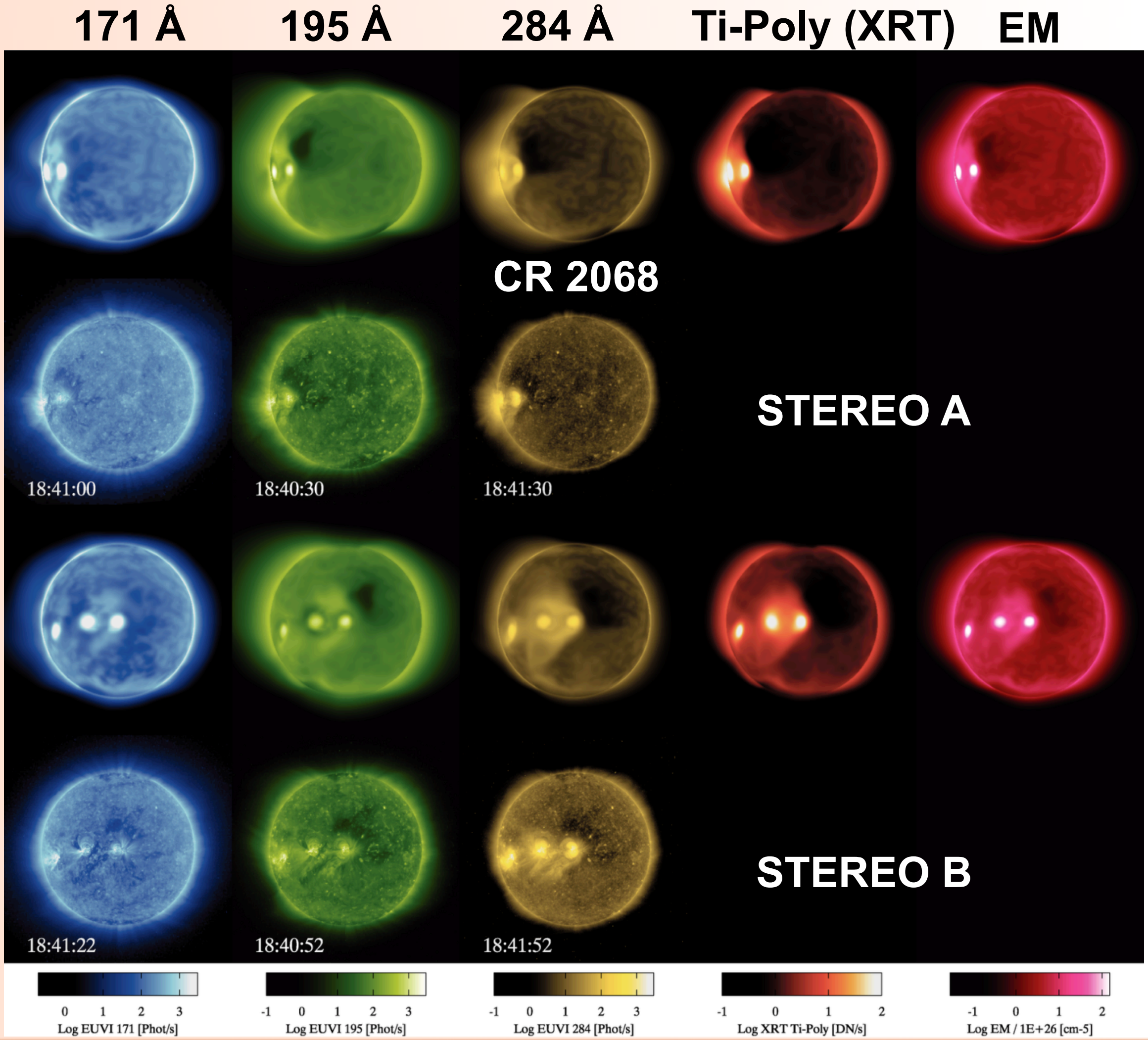


Time (from 01/25) - elongation plots for PA 69.

J-maps: see Sheeley *et al.* (1999) and Davies *et al.* (2009).

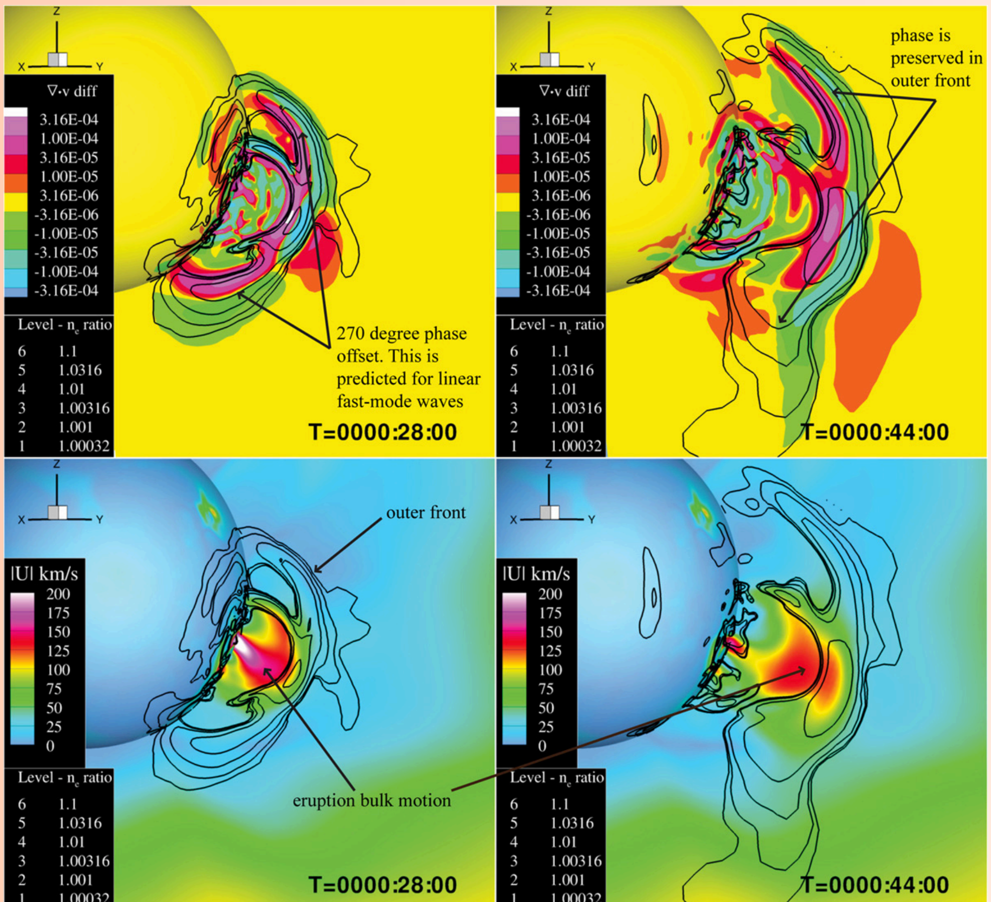
“Realistic” Modeling of “Steady-State” Solar Corona

- We have developed advanced thermodynamic model of low solar corona by including physical effects of:
  - Electron heat conduction.
  - Radiative losses.
  - Coronal heating (due to waves, reconnection, resistive dissipation).
- Use magnetic BCs from MDI observations (CR 2068).
- Synthesize EUVI instruments onboard STEREO A and B.
- Include XRT soft X-ray for high temperatures and LOS EM for just density (Downs *et al.*, *ApJ*, ***728***, 2, 2011).



Realistic Modeling of EUV Waves

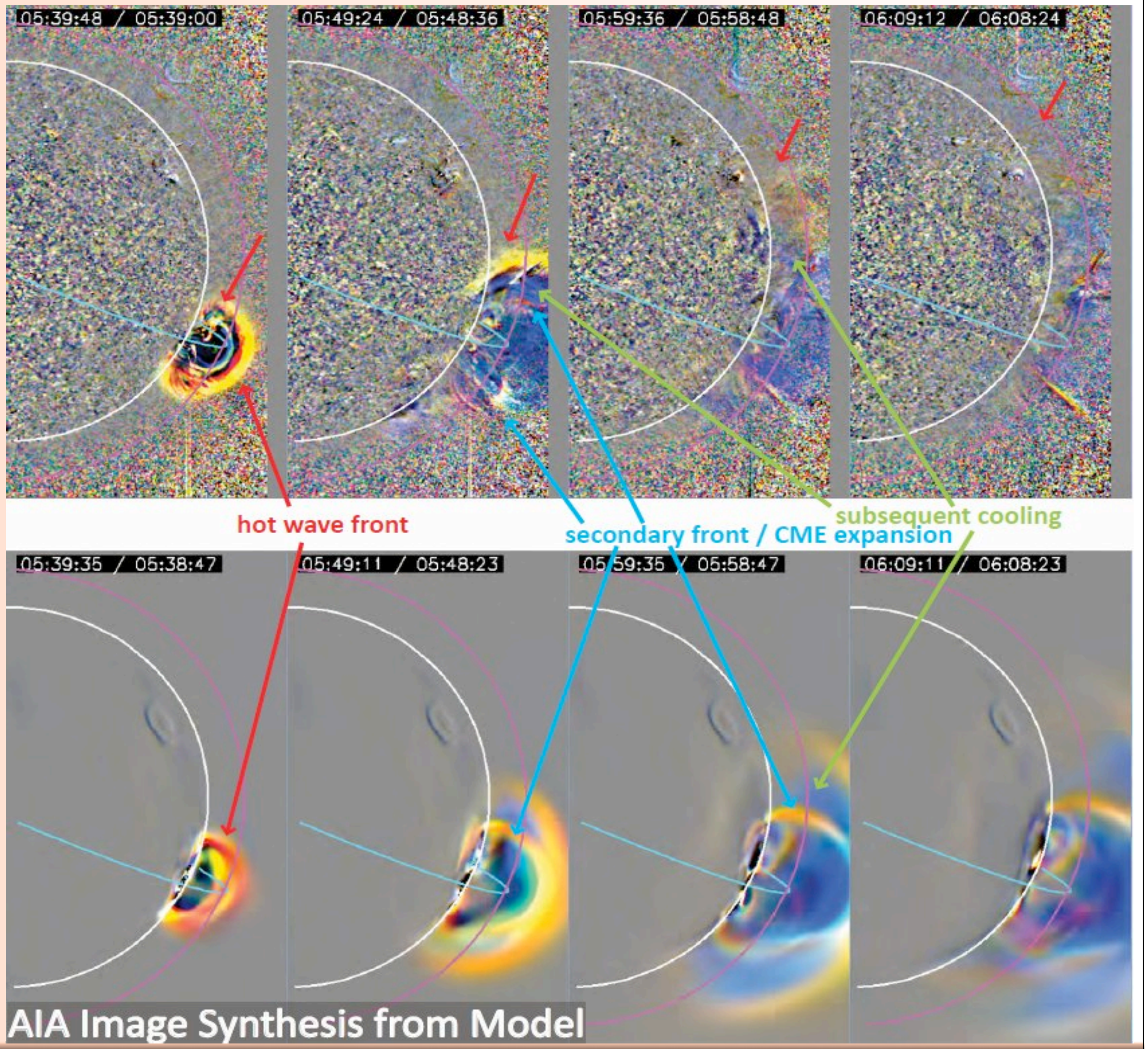
Model of 2008 Mar 25 EUV Wave



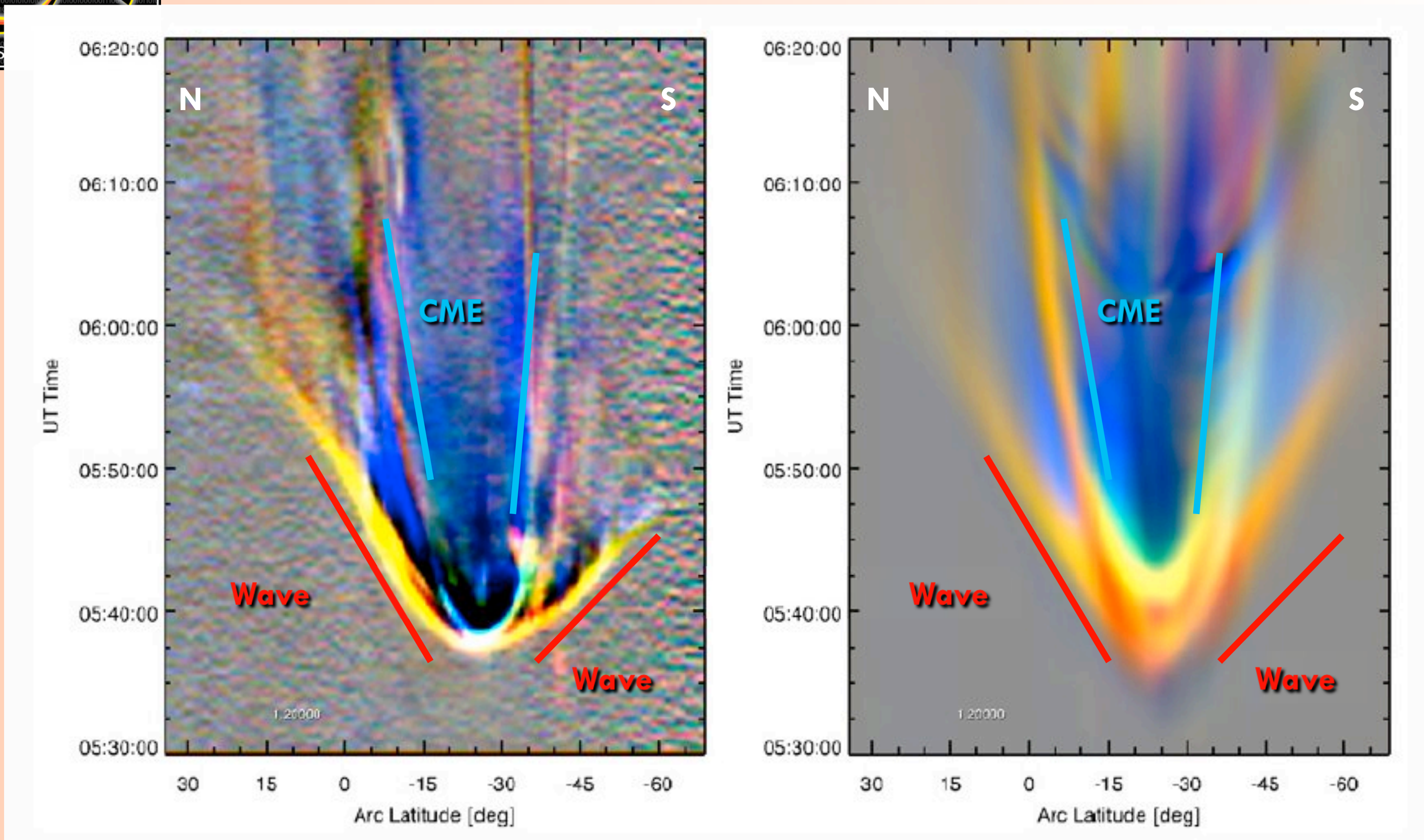
- Physical mechanism behind coronal waves generated during CMEs has been controversial topic.
- We simulated recent EUV wave event in order to investigate this controversy.
- Outer wave front, which exhibits observed properties of an EUV wave, resembles that predicted for fast-mode waves (top).
- In comparison, CME itself (bottom) does not match compression contours of EUV wave.
- This important result provides strong support for fast-mode wave explanation of EUV waves and is robust test of non-wave theories (Downs *et al*., *ApJ*, ***728***, 2, 2011).

Tri-Color Running Ratio Analysis for 2010 Jun 13 EUV Wave

- 3-D MHD simulation of 2010 Jun 13 EUV wave produces similar thermodynamic perturbation as reflected in relevant EUV observations (Downs *et al*., *ApJ*, ***750***, *134*, 2012).
  - Here three tri-color channels are SDO/AIA 171 Å (blue), 193 Å (green), and 211 Å (red), with 48 s running ratios.
- Wave heats up plasma as it passes through (red).
- CME depletes coronal material and it cools solar plasma near source region (blue).



Tri-Color Time-Distance Diagram for 2010 Jun 13 EUV Wave



Downs *et al.*, *ApJ*, ***750***, *134*, 2012)

Flux Emergence as CME Driver

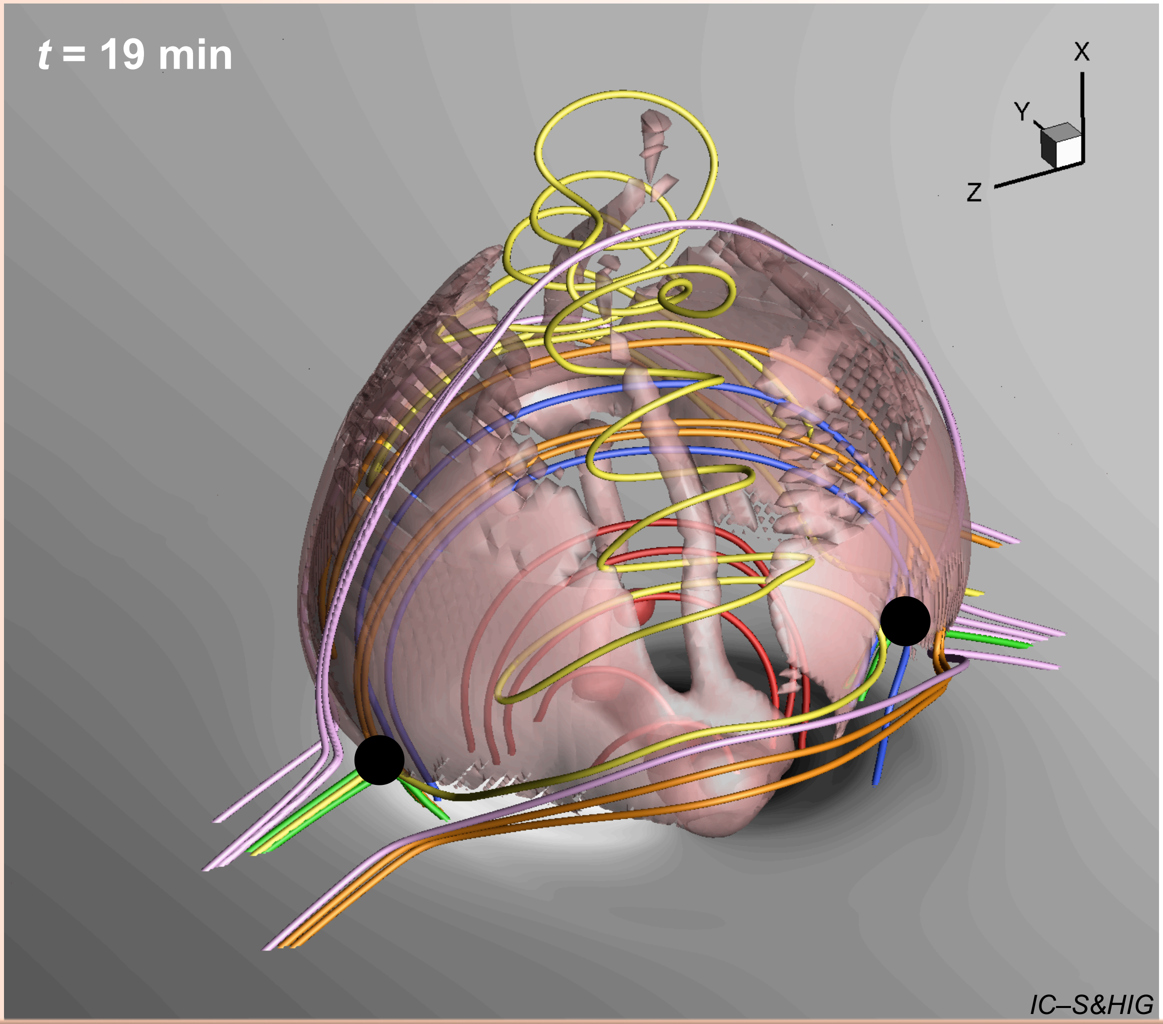
Modeling FE from Convection Zone (CZ) to Solar Corona (SC)

- None of existing CME models to date invokes self-consistent evolution of motional electric field, ***E*** = – ***V*** x ***B***, at the solar boundary (photosphere).
  - Defining such boundary conditions from observations is extremely difficult even today (Leka *et al*., 2009; Fisher *et al*., 2012).
- Self-consistent evolution of ***E*** at the photosphere from single numerical model would require flux emergence process be modeled continuously from CZ to SC taking into account pre-existing coronal field.
  - This represents enormous technical and computational challenge; it requires model to resolve 10-12 (8-10) orders of magnitude change in plasma density (pressure) (Abbett *et al*., 2000, 2003; Archontis *et al*., 2004; Fan 2008; Manchester *et al*., 2004, 2007).
- Even if achieved, this is not a practical solution as far as space weather forecasting is concerned.
  - It requires vast computational resources to resolve small-scale structures present in CZ that are miniscule in comparison to large-scale structures in SC.

Global 3-D Model of Magnetic Flux Emergence

Model Features

- ➢ Local flux-emergence model of Archontis *et al.* (2004) coupled with global 3-D MHD model of solar corona and solar wind using SWMF.
- ➢ Multi-polar magnetic field is produced by:
  - Global, dipolar-type magnetic field resembling Sun at solar minimum.
  - Emerging twisted flux rope along solar equator (y-axis).
- ➢ Flux-emergence model provides *self-consistent* time-dependent evolution of electric field, ***E***, at solar boundary!



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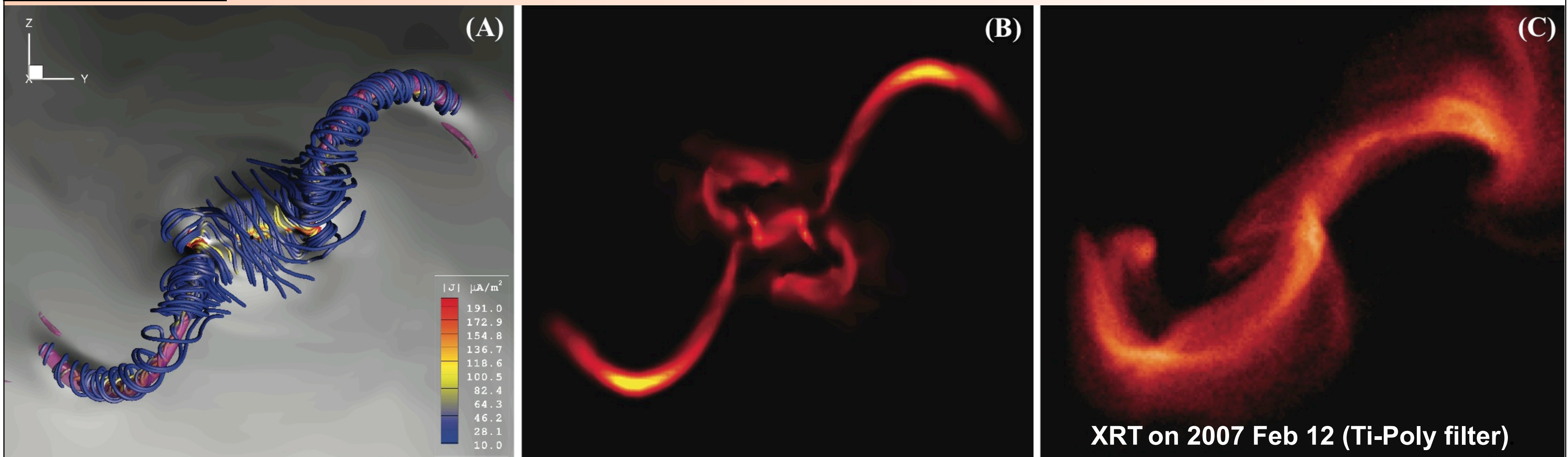
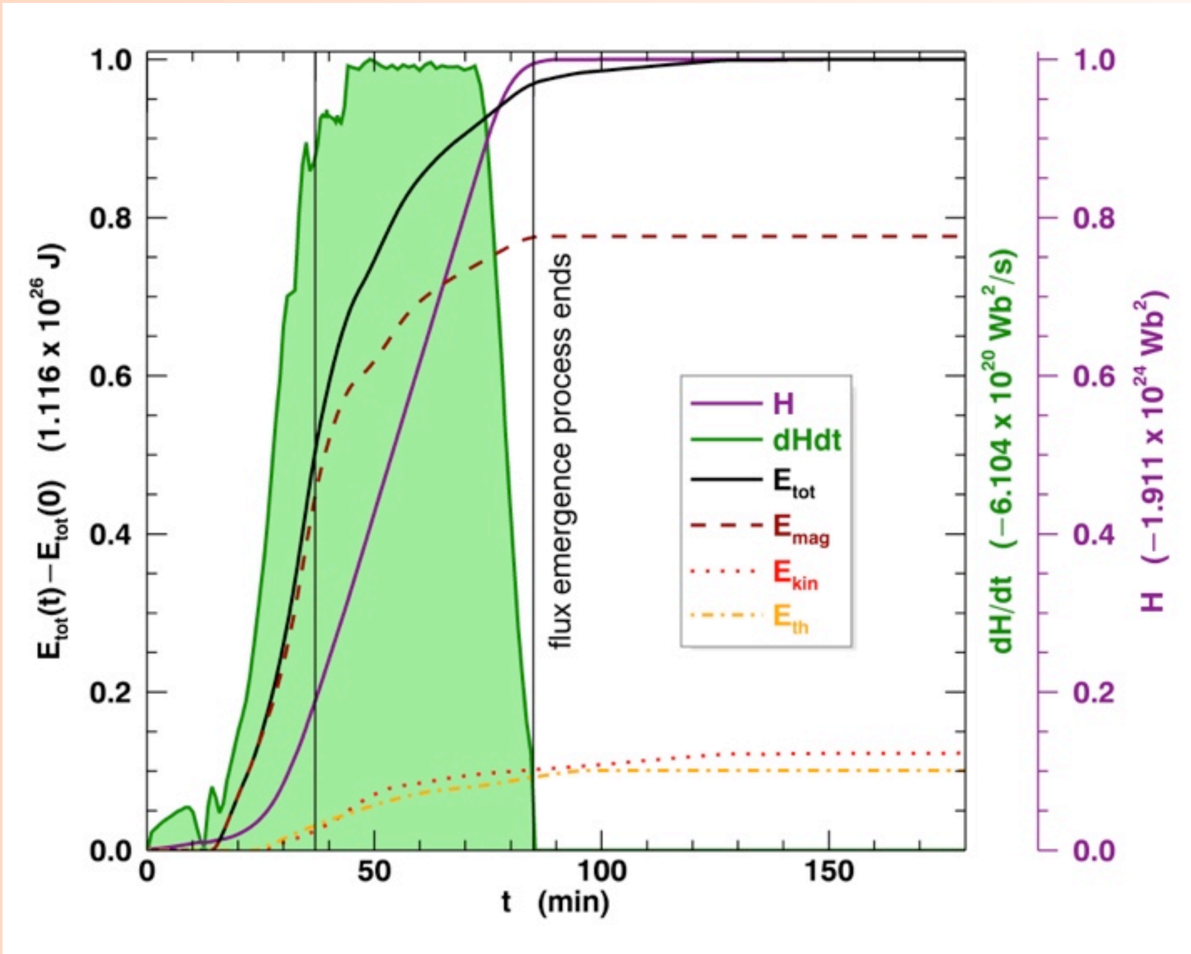
Realistic Modeling of X-ray Sigmoids



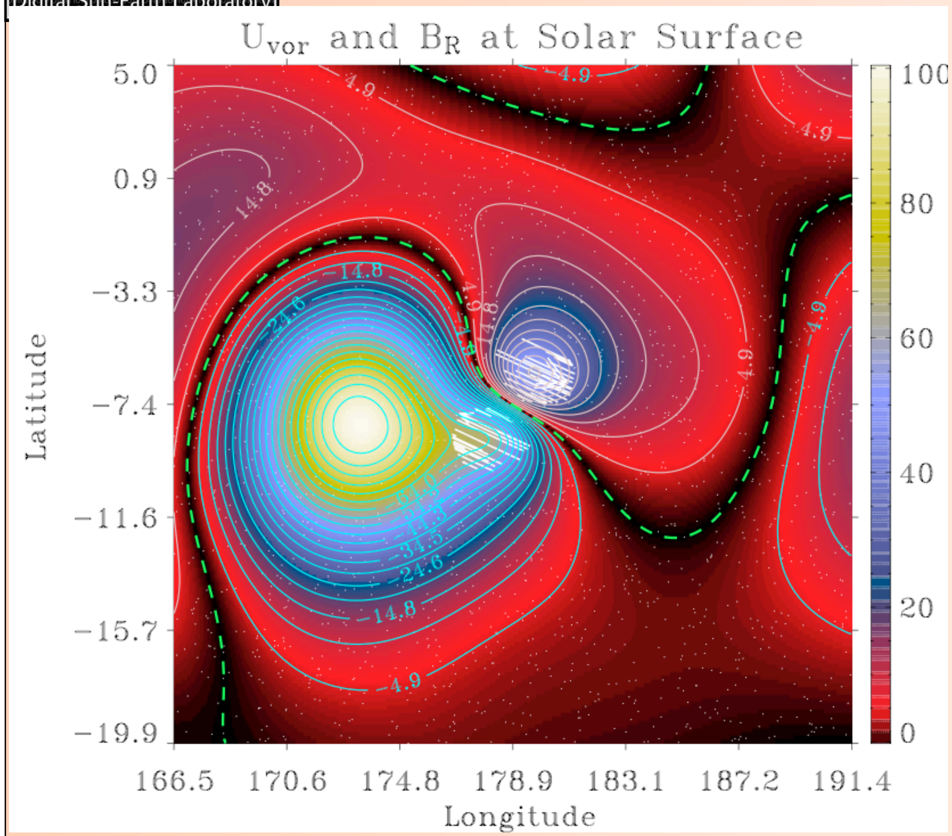
- With this improved low-solar-corona model, we have performed 3-D MHD computer simulation that captures fundamental connection between emergence of magnetic flux into solar atmosphere and origin of CMEs.
- Simulation provides evidence for formation of: (i) fast CME that is independent of emerging flux tube, (ii) two confined flux ropes in low corona (left image), and (ii) hot X-ray sigmoid (middle image).
- With realistic treatment of electric field at photosphere, we gain new insight on how magnetic flux and helicity injection lead to reorganization of solar corona.

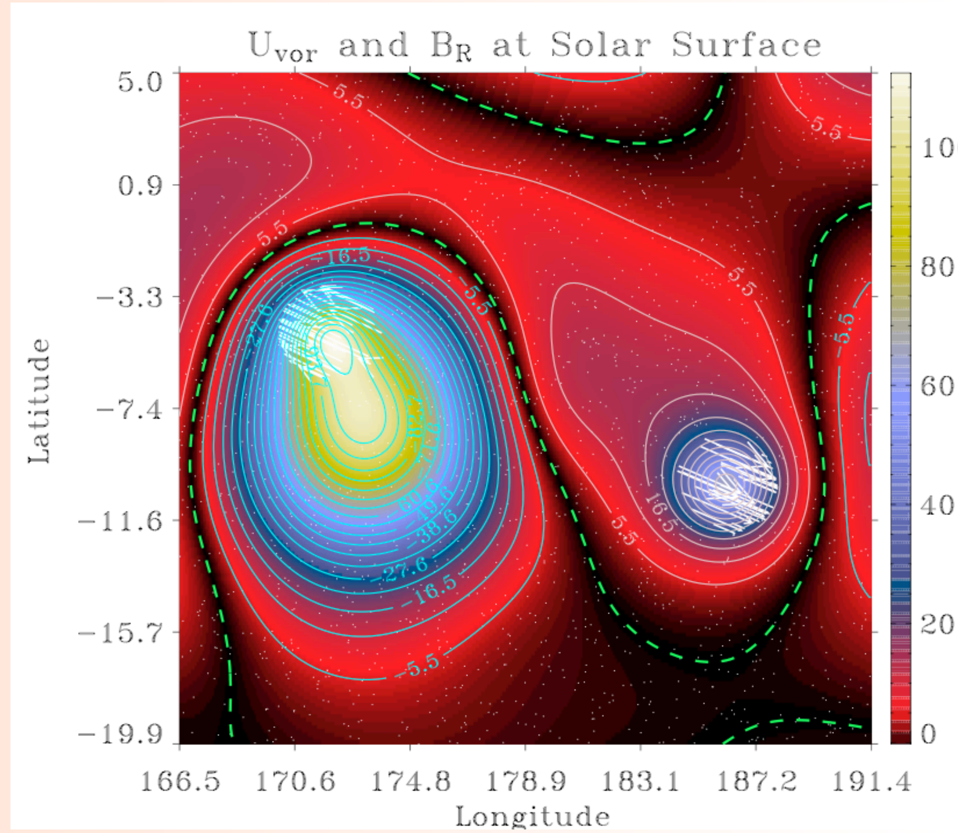
Evolution of Helicity and Various Forms of Energy



Modeling of Complex CMEs in “Realistic” Magnetic Settings

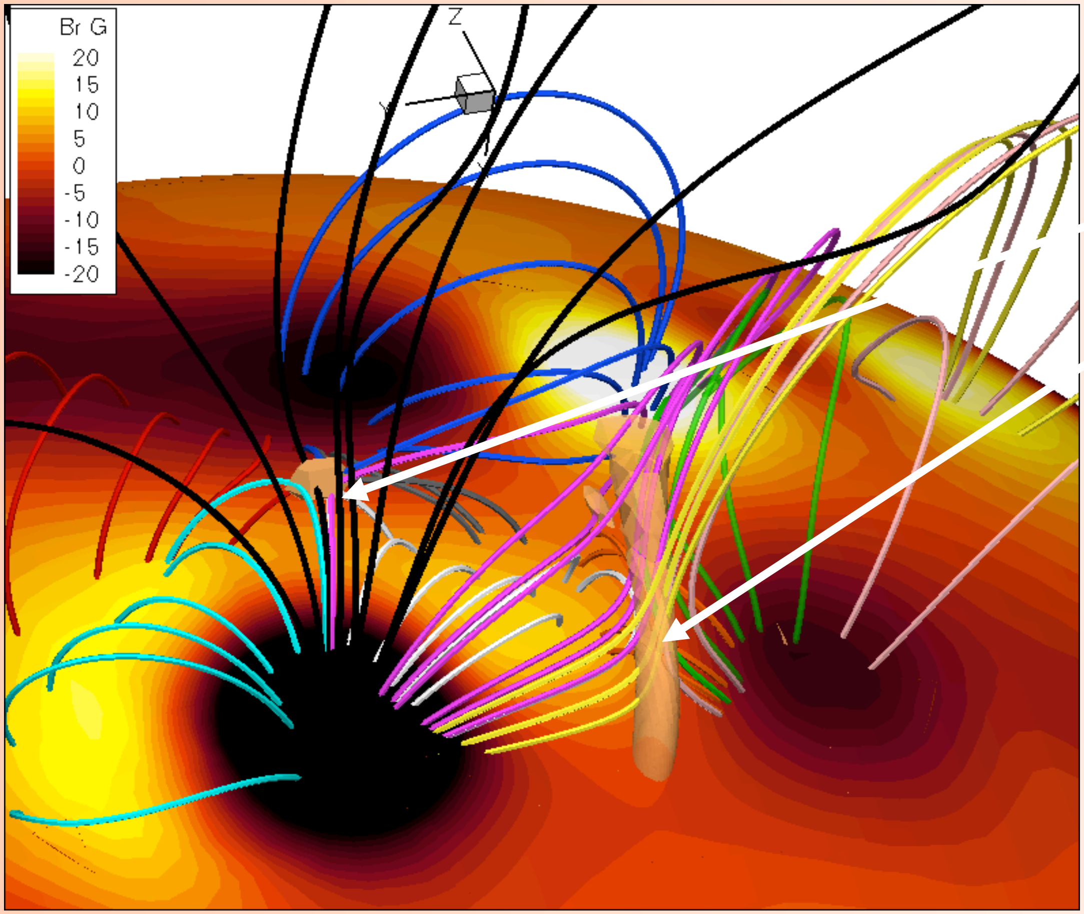
Model of 2002 Aug 24 CME





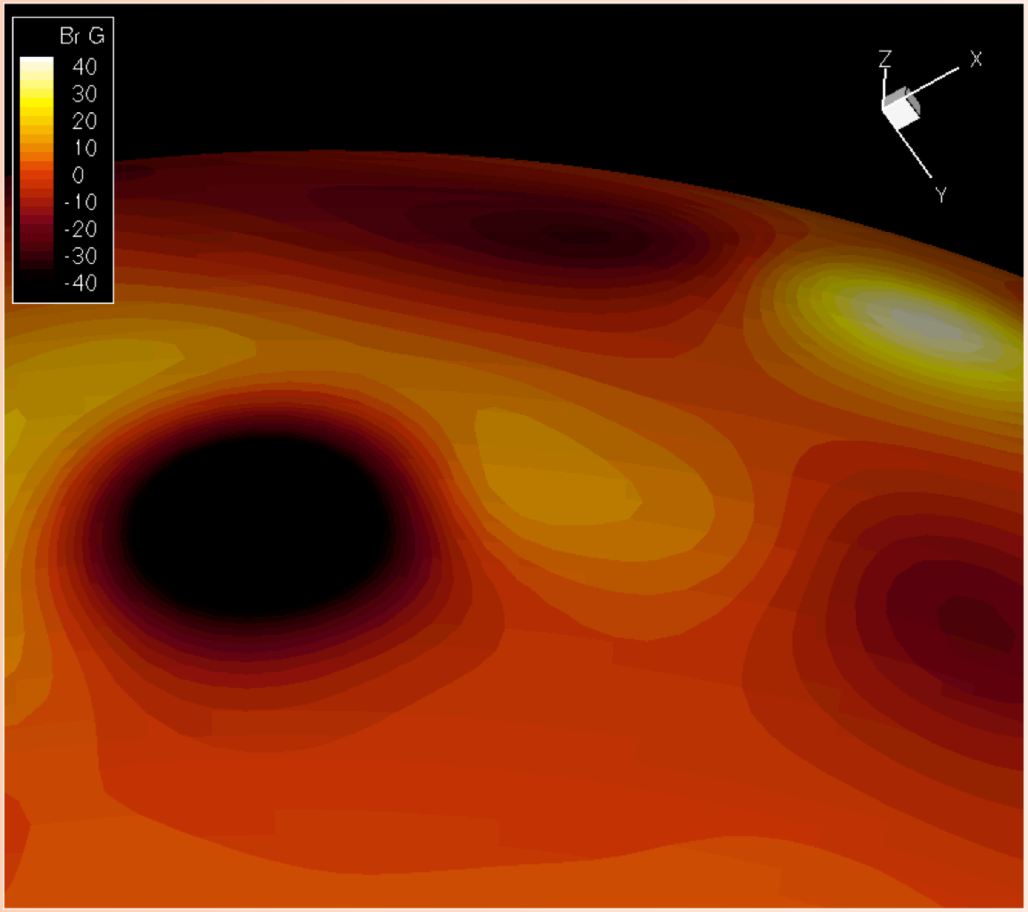
Magnetic charges ***+/-q*** generate small-scale dipole field ($|B_R|$ ~ 45 G at $R = 1R_\odot$) superimposed onto background coronal magnetic field (CMF). Charges are moved apart over finite time (t = 30 min) to stress CMF towards state of loss of confinement.

Magnetic Topology of AR 0069



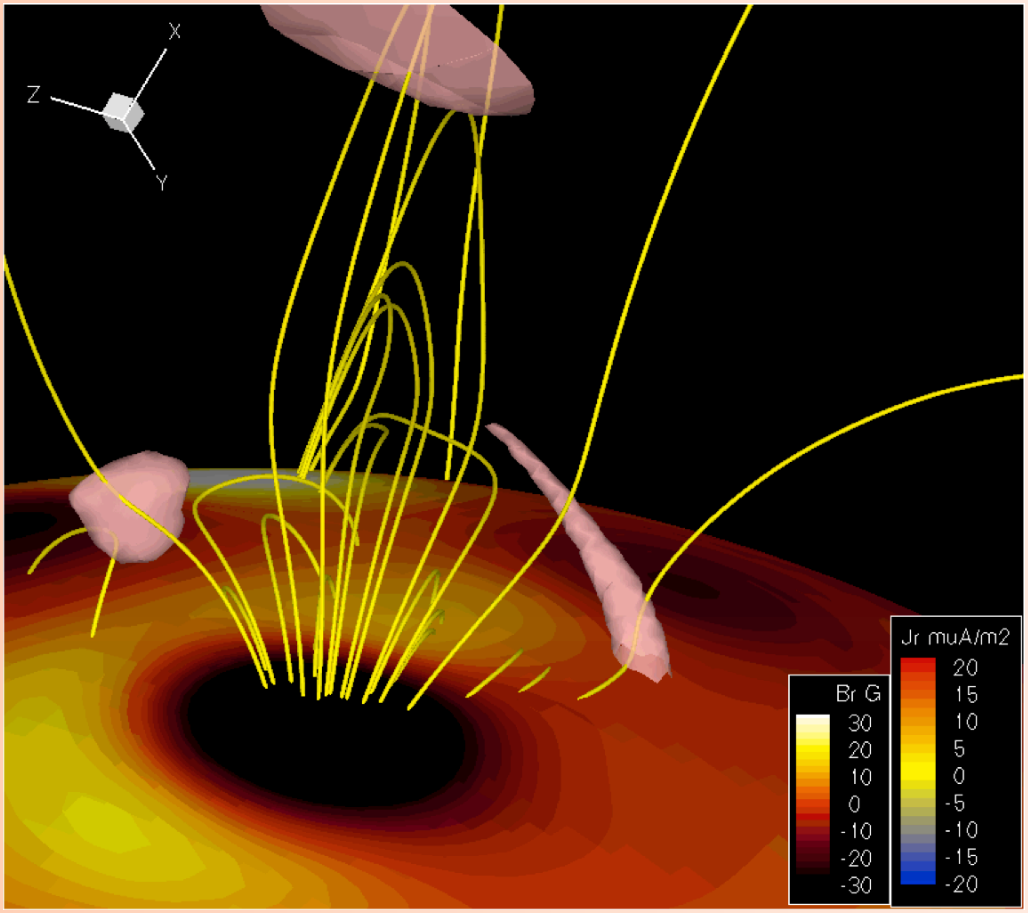
- Multiple null points (NPs) in CMF associated with AR 0069 and adjacent ARs.
  - “Northern” NP associated with AR 0067.
  - Quasi-separator (QS) associated with NPs between ARs 0067, 0068 and 0069.

Current Buildup for *t* < 30 min



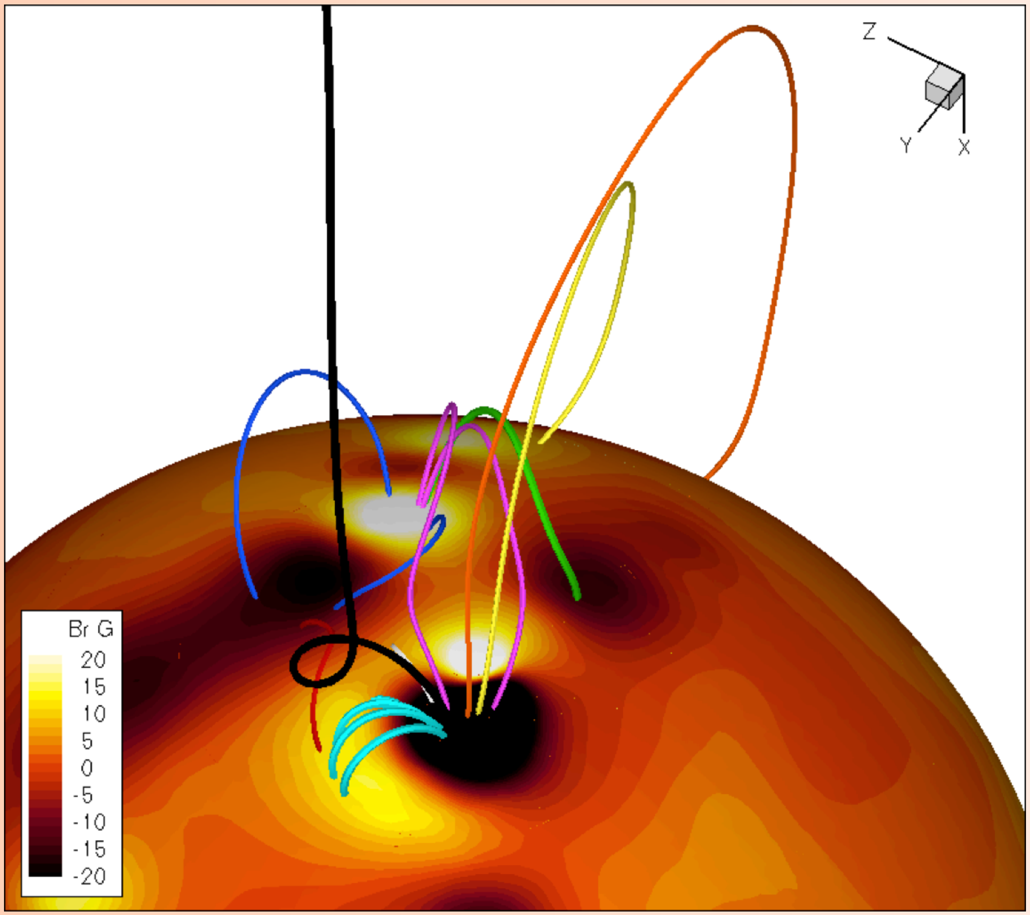
- Moving magnetic spots apart creates shear and twist in coronal magnetic field.
  - Field-aligned currents are build that energize magnetic field of moving spots.

Current Buildup for t < 30 min



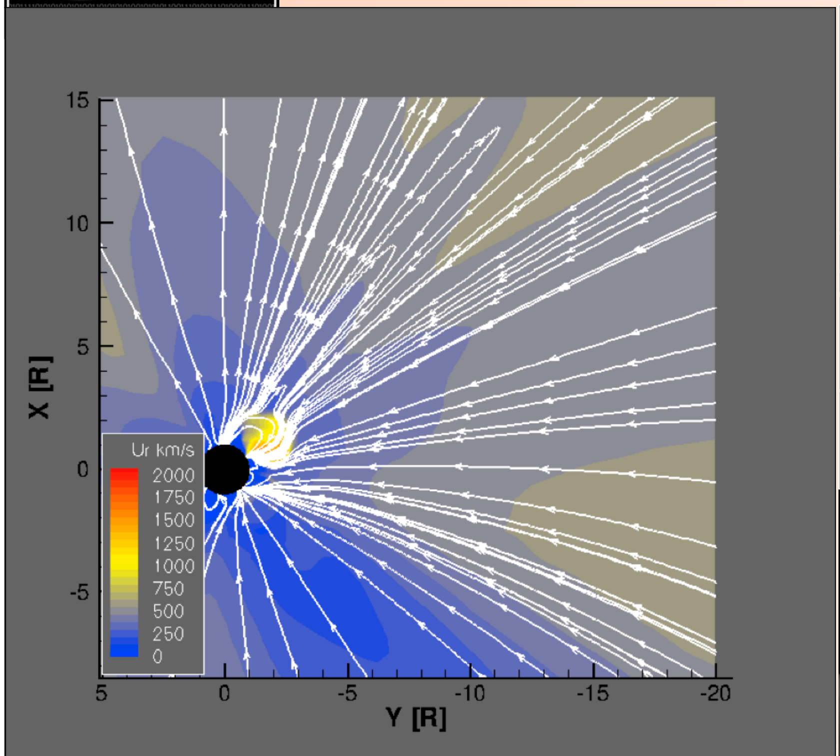
- Moving magnetic spots apart creates shear and twist in coronal magnetic field.
  - Field-aligned currents are build that energize magnetic field of moving spots.
  - Electric currents are also built at pre-existing NPs and QS: QS transforms into current sheet as expanding field from below pushes against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

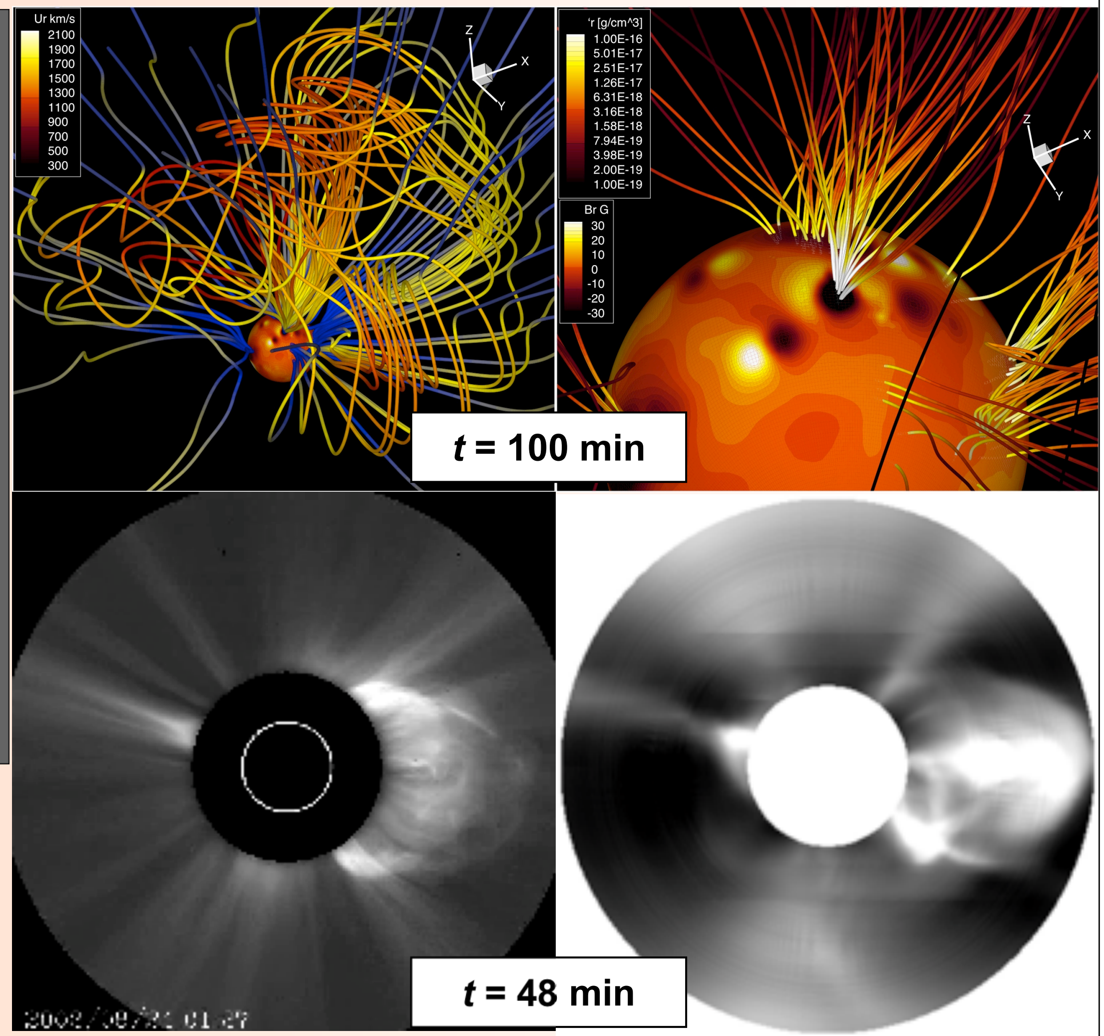
Evolution of CMF



- 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 CME field lines.
- One CME footprint remains in AR 0069, but other footprint moves westward (due to reconnection through NPs and QS).

CME Evolution in Solar Corona





- ➢ CME accelerates to speed of ~ 1,500 km/s in 1st hour of evolution.
- ➢ Simulated CME structure agrees well with LASCO observations.

Conclusions

- "Realistic" 3-D MHD simulation tools can function as an effective lab to learn about complex solar phenomena (CMEs, EUV waves, SEPs, *etc.*) observed by SoHO, STEREO, SDO, and future Solar Orbiter.
  - Incorporation/assimilation of observational data (*e.g.*, full-disk magnetogram data) into relevant computational models (as ICs, BCs, *etc.*) is of crucial importance.
  - So is capability to reproduce other relevant observations (scattered white light, EUV emission, soft X-rays, *etc.*).
- With such computational tools capable of providing ***direct*** comparison to observations, we achieve:
  - Improved physical interpretation of complex observations.
  - Validation of computational models themselves.
  - Filling data gaps from those solar observations.

Conclusions (Cont.)

- With “realistic” modeling of CMEs, we have learned that they undergo a major reconstruction as they evolve on the way out from the Sun.
  - 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 ICMEs have the standard (highly twisted) flux-rope structure.
  - Writhe instead of twist can explain *in-situ* characteristics of regular MCs too.
  - Revision of MC models is required.
- “Realistic” modeling of CMEs enables us to investigate in a self-consistent manner other related phenomena, including:
  - Production of SEPs at shock waves driven by CMEs.
  - Generation and evolution of EUV waves observed by SoHO, STEREO and SDO.

Conclusions (Cont.)

- With “realistic” modeling of EUV waves, we have been able to determine that:
  - Extended EUV enhancement and temperature changes can be well explained with fast-mode wave.
  - CME itself, however, also drives a non-linear EUV perturbation, which complicates the EUV signal; that is why it is difficult to tell the two parts.
  - Inherently 3-D nature of EUV waves greatly complicates interpretation of solar observations directly; there is no single speed or location at which EUV wave propagates.
  - Last, but not least, no two events will ever be “the same”.

This is why case-by-case studies of these phenomena are important!

Thank you!

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