The Coronal Global Evolutionary Model (CGEM): Current Status, Future Applications

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Overview of the two talks on CGEM

- **George Fisher (UCB)** will discuss the overall goal and current status of the CGEM project and discussion of its future applications, followed by 10 minutes for questions and discussion.
- **Maria Kazachenko (UCB)** will discuss the importance of vector magnetic fields in quantitative studies of solar evolution. This will be followed by 10 minutes for questions and discussion.

The Goal of CGEM

The goal of CGEM is to develop a model of the evolving magnetic field in the solar corona, driven by SDO/HMI photospheric magnetic field and Doppler velocity data. Magnetic evolution is computed using the magnetofrictional (MF) approximation, driven by electric fields determined from the SDO/HMI data at the photosphere. The CGEM model assumes spherical geometry, and can employ either high-resolution active-region scale domains, or lower-resolution fully global models. Output from MF models can then be used to drive MHD models of the corona or heliosphere if desired.

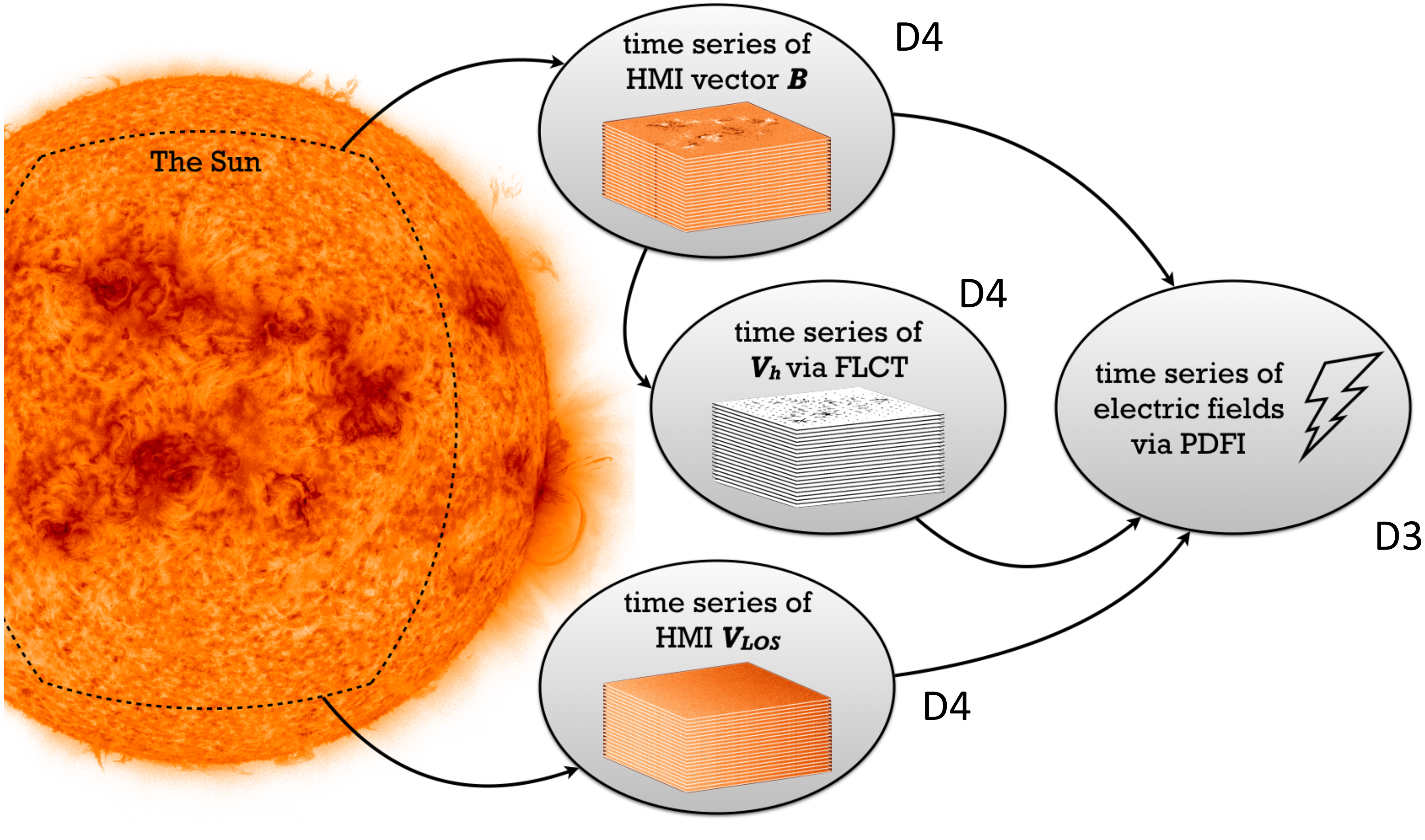
An Overview of CGEM: Fisher et al., Space Weather Vol. 13, (6), pp. 369-373, 2015.

CGEM URL: http://cgem.ssl.berkeley.edu

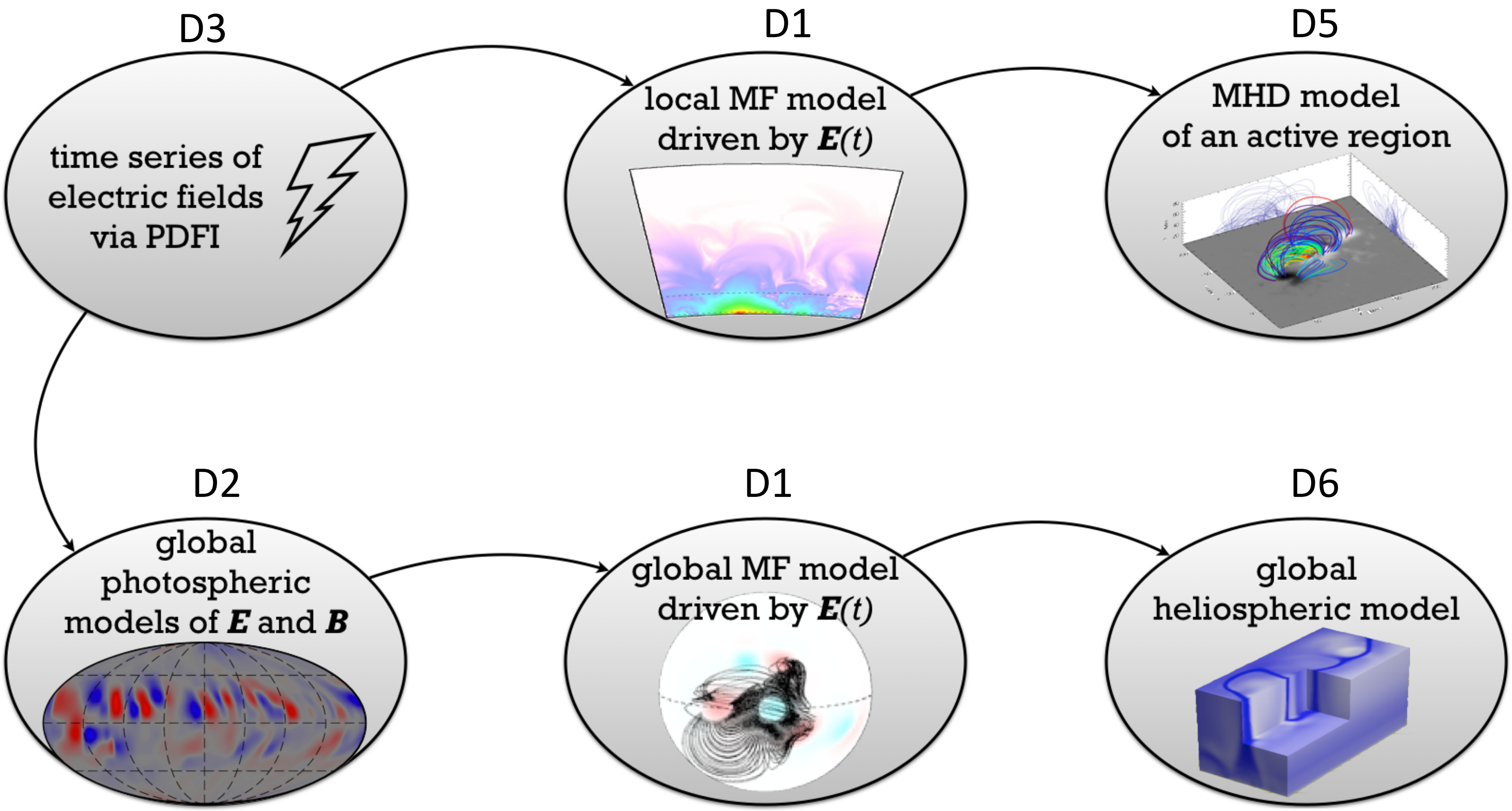
Six Deliverables Are Needed to Achieve the CGEM Goal

- D1: A Magnetofrictional (MF) Model of the Sun’s coronal magnetic field
- D2: A Global Flux Transport (FT) Model used for unobserved parts of the Sun’s photosphere
- D3: Electric Fields at the Photosphere derived from HMI magnetic field and Doppler data
- D4: Enhanced data products (for input to D3) and for other scientific and space-weather purposes
- D5: An MHD model of the corona in active regions, initialized by the MF model, to study erupting magnetic geometries
- D6: A Global Coronal MHD model driven by the global MF or active-region MHD models

CGEM Workflow Diagram 1



CGEM Workflow Diagram 2



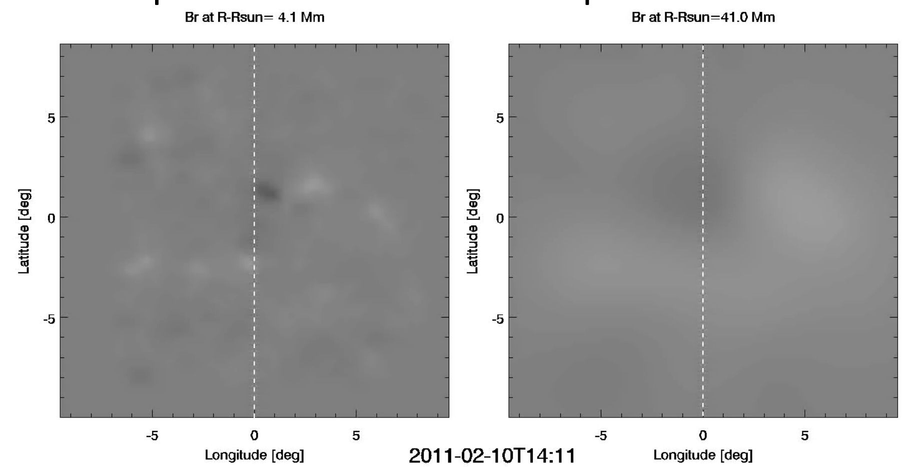
Executive Summary of CGEM Progress Years 1-4:

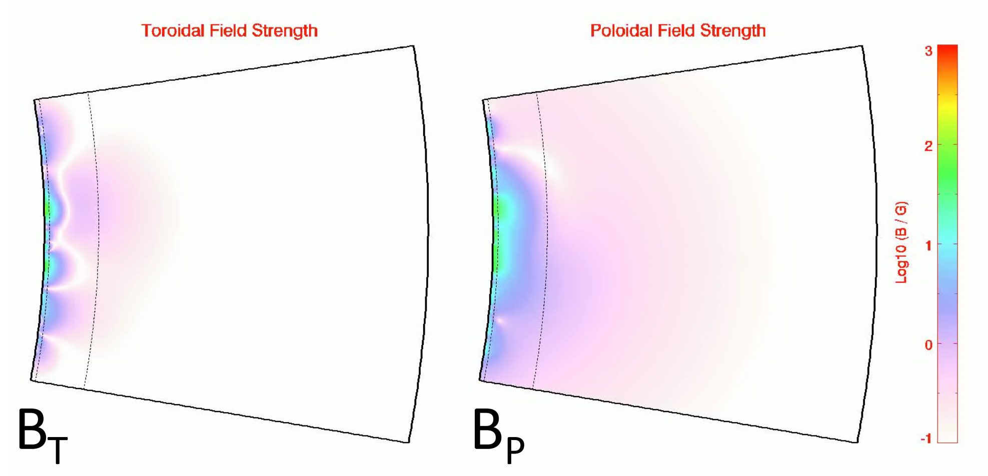
- D1 (MF Model): Code written, working in both localized and global geometries. CCMC delivery discussions started.
- D2 (FT Model): Code written, working, starting CCMC delivery discussions in conjunction with MF model.
- D3 (Electric Field Inversions): Code written, working, delivered to JSOC. Code is an open-source fortran library, written for a broad spectrum of uses, including data analysis and for use in MHD codes.
- D4 (Enhanced Data Products) Codes written, working, most delivered to JSOC. One piece of IDL code still needs to be ported to the JSOC.
- D5 (Active Region Models) Code written, working, source code released to public
- D6 (Heliospheric Models) Code written, working, delivered to JSOC

D1: MF model of AR 11158 (spherical wedge run, 6 days, 720 HMI vector magnetograms)

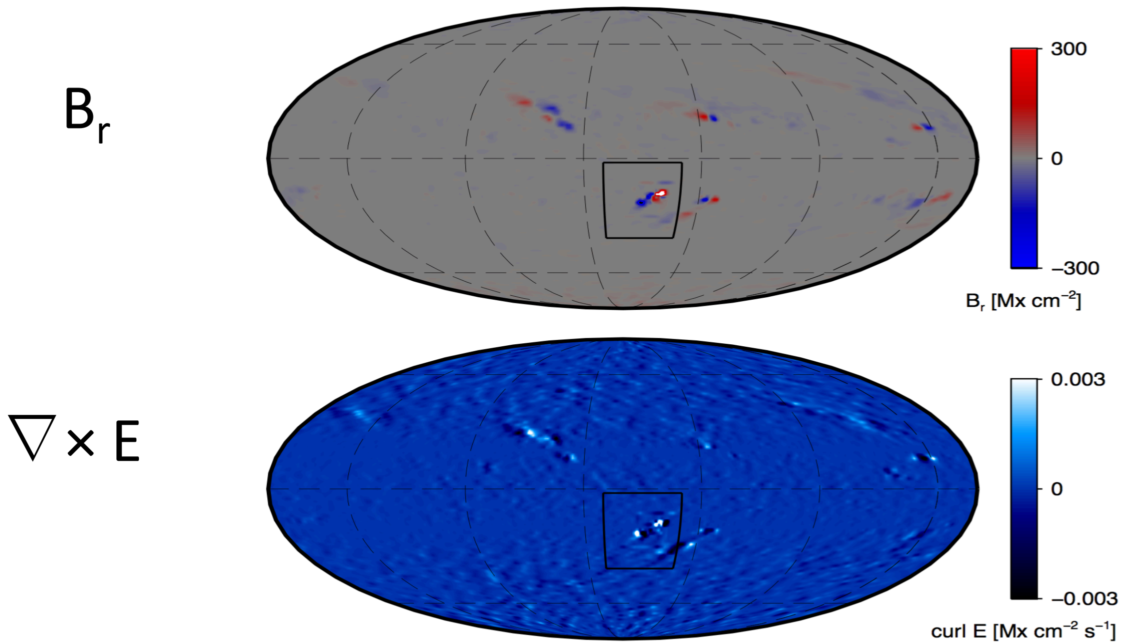
- MF model balances the Lorentz force against a fictitious frictional force
- MF model evolves vector potential $\boldsymbol{A}$ to compute magnetic field $\boldsymbol{B}$.
- MF model uses staggered, Yee grid in spherical coordinates.
- MF model is driven from the photosphere by values of the electric field $\boldsymbol{E}$.
- MF model now working in both spherical wedge and global spherical configurations.
- At 512 processors on Pleides cluster, compute time about equal to elapsed solar time

B_r at 4 Mm $\qquad$ B_r at 40 Mm



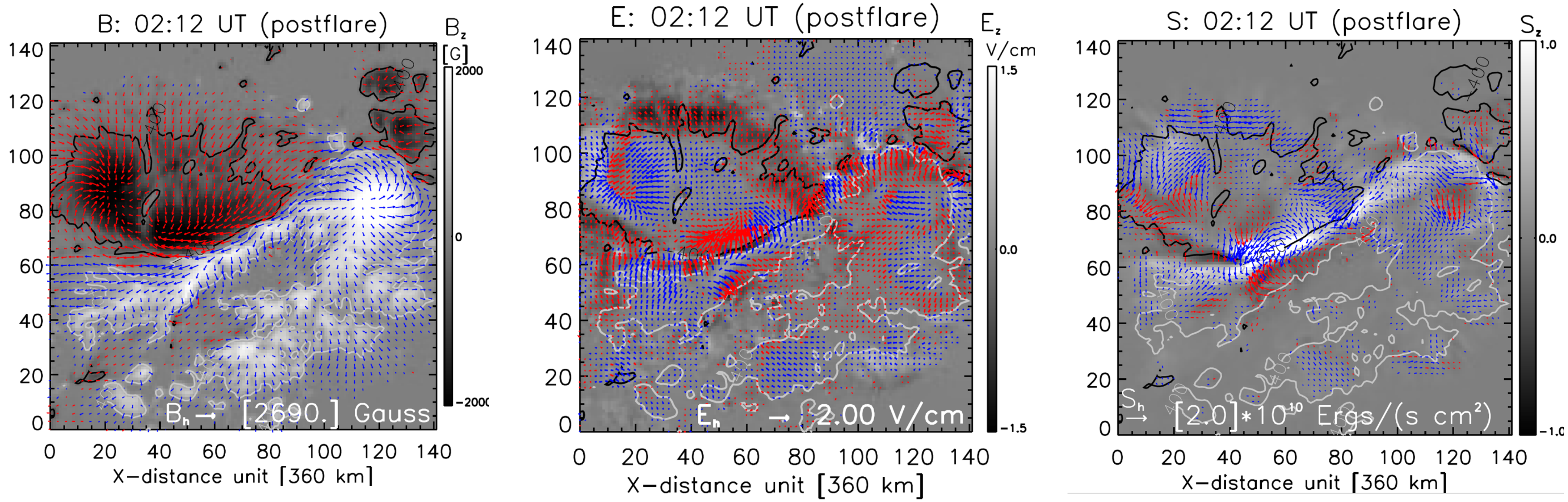


D2: Surface Flux Transport Model



- Global model for B_r
- Electric field-based formalism, using staggered Yee grid, consistent with MF model (D1) and Electric Field Inversion software (D3). The electric field formalism provides more physical information than previous flux transport models
- Can imbed electric field inversions (D3) from SHARP regions into global solutions

D3: Electric Fields at photosphere from HMI magnetic and velocity data using PDFI method



Magnetic field, Electric field and Poynting flux vectors in core of AR 11158 (see Kazachenko et al. 2015).

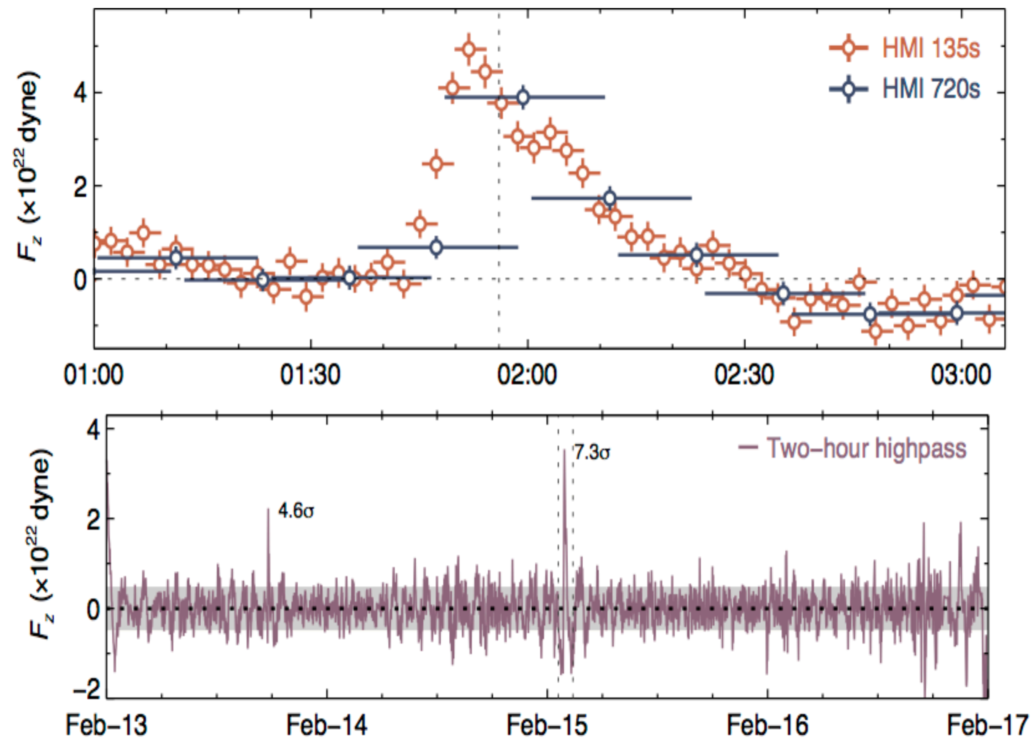
- The PDFI method is described and validated in Kazachenko et al (2014) for a centered, Cartesian grid.
- We have since re-written the software in spherical coordinates, using the staggered Yee grid (compatible with D1, D2 deliverables)
- PDFI Software now written entirely in Fortran, delivered to JSOC for spherical wedge geometry. 6 days of SHARP data processed in ~2 hr on a macbook pro
- Electric fields can be used for independent science investigations as well as for the CGEM model-driving goals.

General Uses of the D3 deliverable software (PDFI_SS) beyond CGEM:

- Electric field inversion software is now written as a general purpose, open-source fortran library. URL: http://cgem.ssl.berkeley.edu/cgi-bin/cgem/PDFI_SS/index
- Scientific Studies involving Poynting flux and helicity injection
- Data assimilation: Subroutines for “nudging” MHD or SMF solutions to use observed magnetic field data at photosphere.

D4: Enhanced Data Products

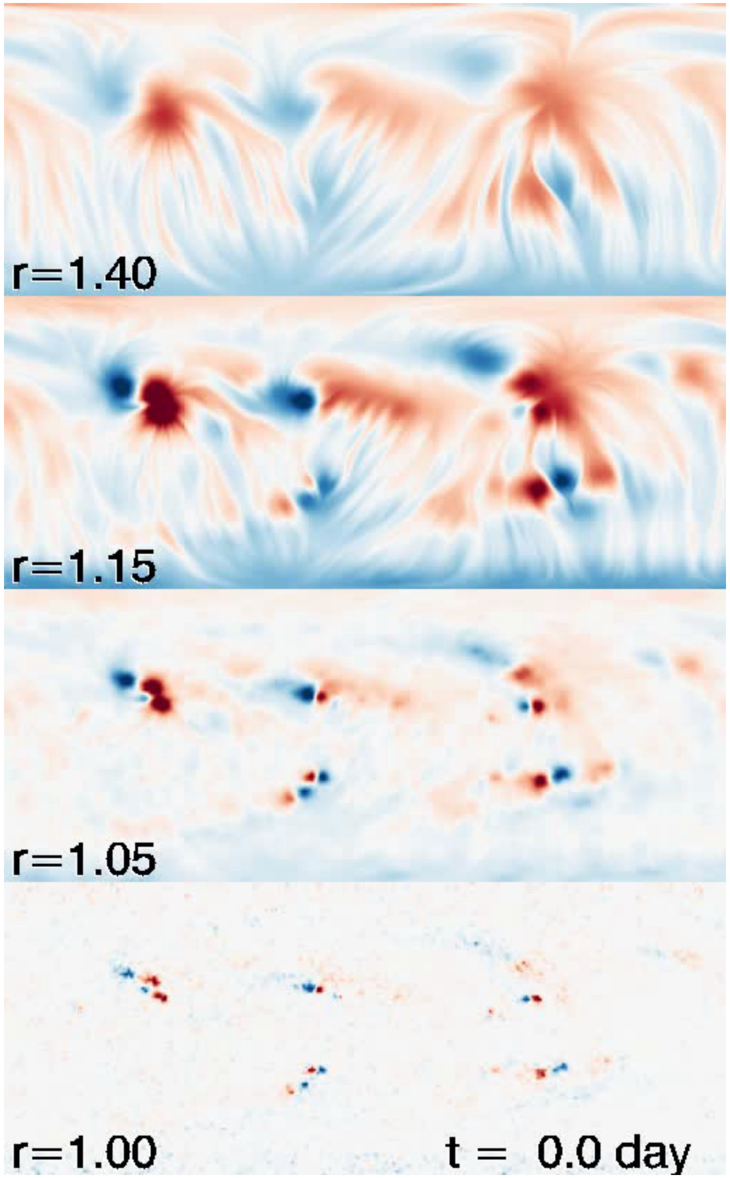
- Sub-pixel co-registration of magnetic field and Doppler data from HMI
- Corrected magnetic azimuth values using observed time evolution
- FLCT derived horizontal velocities
- PIL values of Doppler velocity, corrected for convective blue-shift
- Lorentz forces in flaring active regions
- High-cadence (135s) vector magnetic field data (see Sun et al. 2017, ApJ 839, 67.)



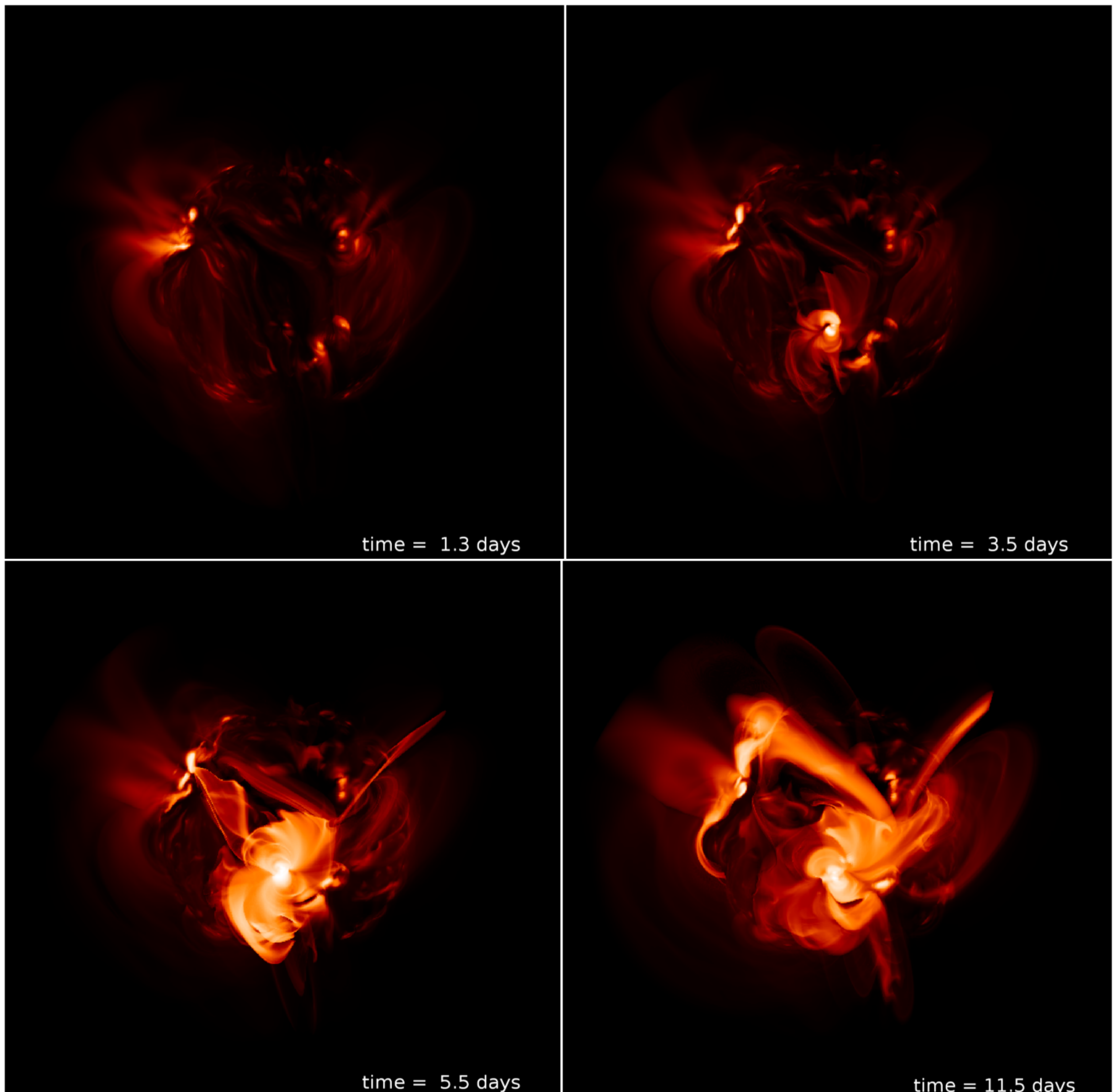
This Figure shows the vertical Lorentz force transient derived from high cadence vector magnetic field data for AR 11158.

Global CGEM model: An early result illustrating the workflow between D4, D3, D2 and D1:

- 33-day run of GMF using PDFI electric field solutions for AR11158 for days 1-6, SFT model for E everywhere else and globally after the 6 days of data ingestion
- Low resolution mode 256x104 in lon,lat and 128 in r between 1.0 and 2.28 R_S.
- Simulation runs on 4 16-processor nodes (Sandy Bridge) on Pleides (NASA Ames) at roughly 130x faster than solar time
- Note “seam” artifacts in magnetic field where PDFI_SS results are imbedded into FTM at photosphere. This is due to inconsistencies in boundary conditions between FTM and PDFI_SS; can be fixed by adding curl-free solution to PDFI_SS that matches FTM at boundary.

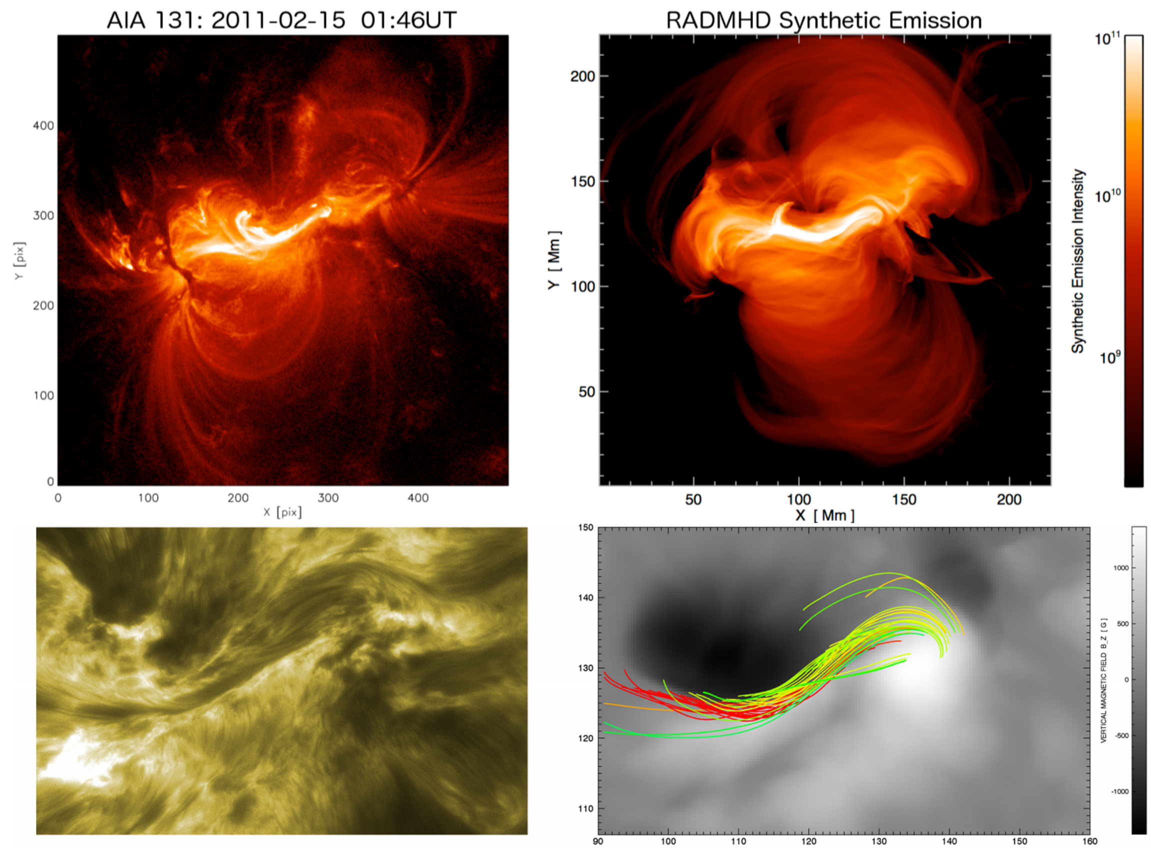


Global CGEM model: coronal field appearance using Cheung-DeRosa J^2 emissivity at 4 simulation times:



D5: MHD models of unstable AR configurations, starting from MF model output

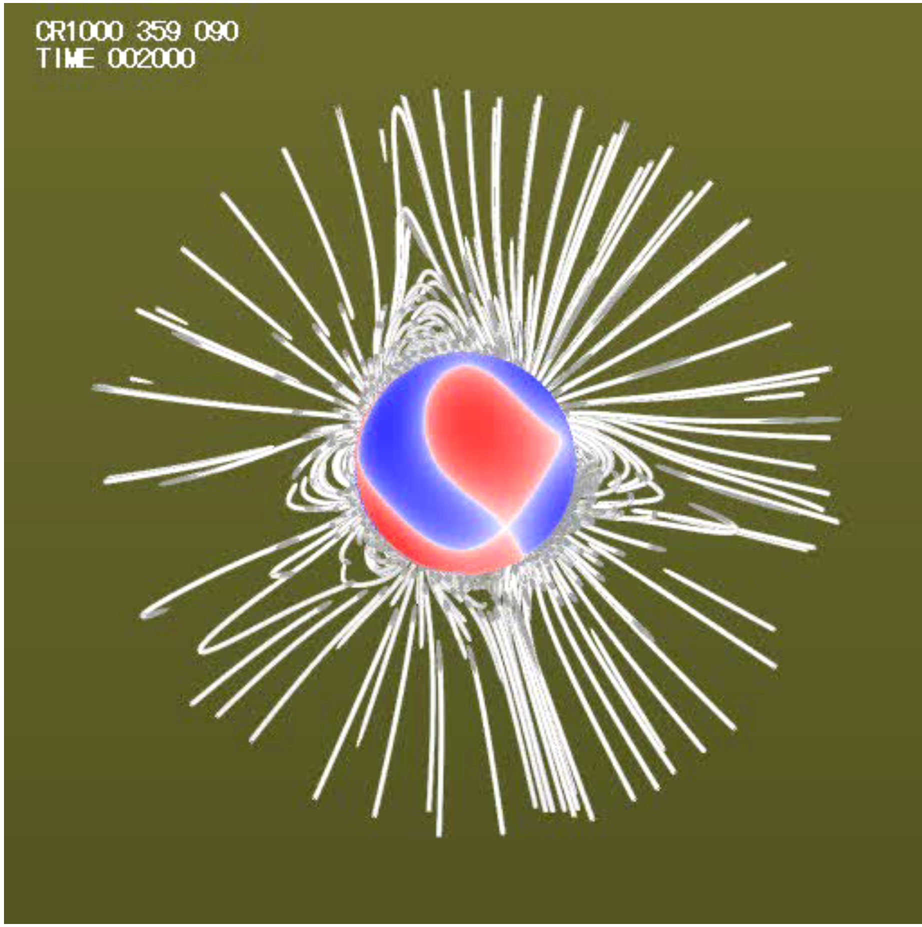
- We use a simplified zero-beta version of the RADMHD code to evolve unstable magnetic configurations found with the MF model.
- RADMHD Source code available to the public with an open-source license.
- Output from CGEM MHD runs will be posted on the JSOC or CGEM websites.
- RADMHD simulations will also be used to explore the effects of additional physics beyond the MF or zero-beta MHD approximations.



Comparison of synthetic emission (Cheung & DeRosa 2012) computed with RADMHD code with observations of the corona in AR 11158

D6: Large-scale Global Coronal MHD

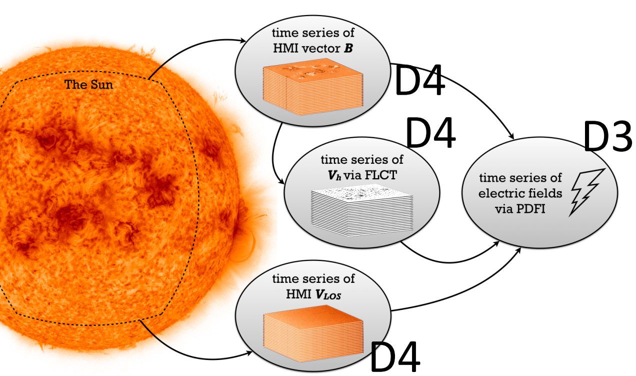
- Low-resolution global MHD models of the corona are now made available daily on the JSOC website.
- The global MHD model will be extended to 1 AU in the intermediate future.
- The interface between the MF and active-region scale MHD models and the global MHD model is now being defined.



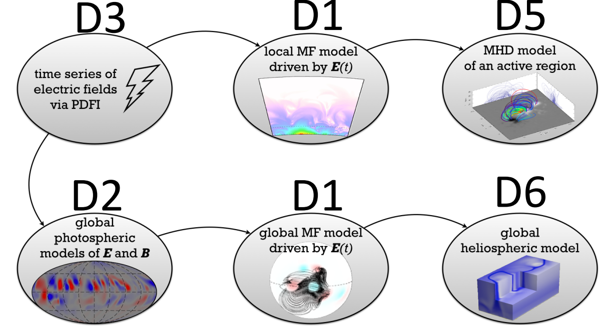
A few frames from a simulation from 1.2 R_S to 50 R_S over a period of 10 hours. Domain shown from 1.2 to 5 R_S.

Publications and Presentations funded by CGEM

- 16 publications during Years 1-4 were funded by the NASA and NSF CGEM awards.
- Over 45 public presentations on the CGEM project were made during Years 1-4
- Links to the publications, and the descriptions of the presentations can be found on the CGEM website, http://cgem.ssl.berkeley.edu . The website also has links to all of the progress reports for CGEM.



Delivery, Documentation, and Validation



- Discussions have begun with Peter MacNeice regarding delivery of the D1 and D2 models to the CCMC. Working versions of D3 and D6 have been delivered to the JSOC. Most components of D4 are now running at the JSOC. D5 source code released to community as open-source software; simulation results to be posted on JSOC or CGEM websites.
- Documentation for D1, D2 deliverables is in progress. D3 source code includes an overview plus details of programming interface with each subroutine. Documentation for Lorentz-force diagnostic (part of D4) has been published. Documentation for D5, D6 in progress.
- Validation of D1, D2 have been done for simple known test cases (D1) and comparison with other flux transport codes (D2). Validation of D3 is performed by comparing electric field inversions from known electric fields in MHD simulations. D4 validation is done by cross-checks and self-consistency checks with the HMI data. D5, D6 validation done with known MHD test cases.
- End-to-end validation of CGEM model will entail a comparison between emissivity proxies and known coronal emission diagnostics, plus checks between the predicted versus observed times and locations of magnetic eruptions.

Work planned for Year 5

- Complete transition of all D4 software to a form which can be run automatically at the JSOC
- More "campaign" studies using more active regions observed by SDO
- CGEM simulations using large-scale FOV regions of the Sun (some early results shown in this presentation)
- Begin studies integrating global MF model with global coronal/heliospheric MHD model
- Improved techniques for visualizing spherical MF and MHD data (some early results shown in this presentation)
- More documentation of the deliverable models
- Complete and validate the deliverables for JSOC and CCMC

Summary: Significant results and key outcomes

- Key outcome: We have successfully achieved our goal of building a temporally evolving model of the Sun's coronal magnetic field in spherical geometry, driven by electric fields at the photosphere. While much remains to be done to complete the project, we now know that our model goal is possible, practical, and is well on its way to successful completion.
- Major accomplishments were made for all 6 of our deliverables.
- We welcome collaborations with the other strategic capability efforts.