SWMF Solar/Heliosphere

Bart van der Holst

Center for Space Environment Modeling
University of Michigan

http://csem.engin.umich.edu

Outline

- Data-driven two-temperature solar wind model with Alfvén waves
- Validation of solar wind models
- Coupled evolution of electrons and ions in CME-driven shocks
- Chromosphere to corona model
- Magnetic flux emergence model
- Summary

Two-temperature Solar Wind Model

Physics in this model:

- MHD with separate electron and proton temperatures, coupled by collisions (close to the Sun), but single fluid velocity.
- Collisional electron heat conduction close to the Sun
- Heating by Kolmogorov wave dissipation (Hollweg, 1986); Optionally electrons are also heated by Alfven waves
- Alfvén wave pressure provides extra solar wind acceleration

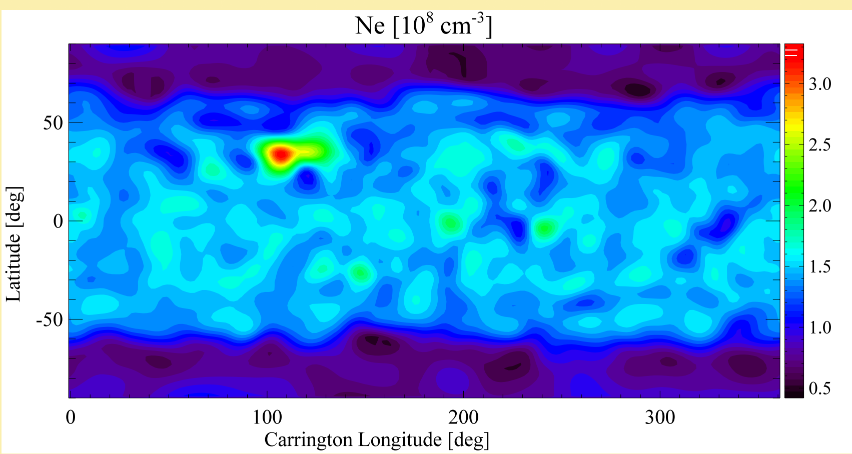
Observational inputs:

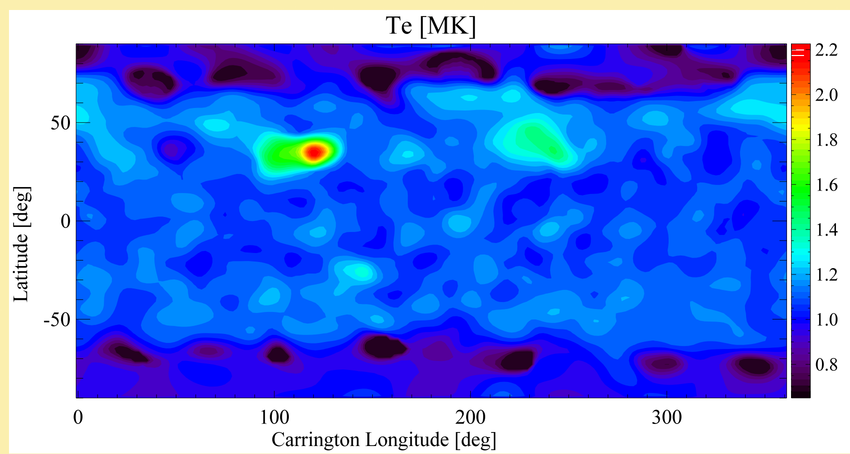
- Synoptic magnetogram for inner boundary
- Electron temperature and density obtained from solar rotational tomography applied to STEREO EUVI images
- WSA model sets total Alfvén wave pressure

- For details see van der Holst et al., Ap.J. 2010

Data-driven Inner Boundary

- Apply solar rotational tomography (SRT) to a time series of EUVI Fe (171, 195, 284 Å) band images to obtain the 3D emissivities
- In each volume element determine the local DEM (LDEM) from these 3D emissivities
- First two moments of the LDEM provide 3D electron density and temperature in the range 1.035-1.225 R_{Sun}.
- We use r=1.035 R_{Sun} data for the inner boundary of the model.

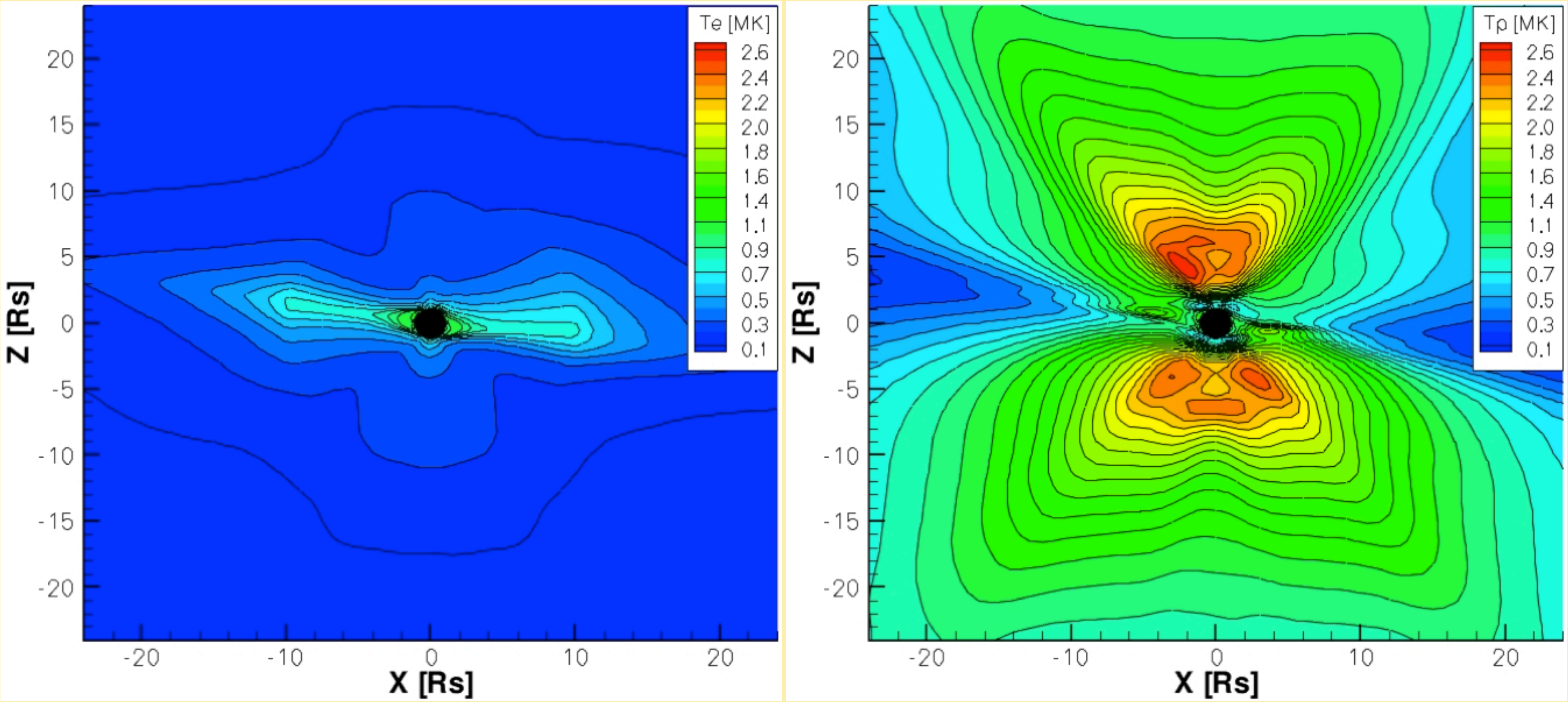




DEMT: Differential Emission Measure Tomography (Frazin et al. 2009; Vasquez et al. 2010)

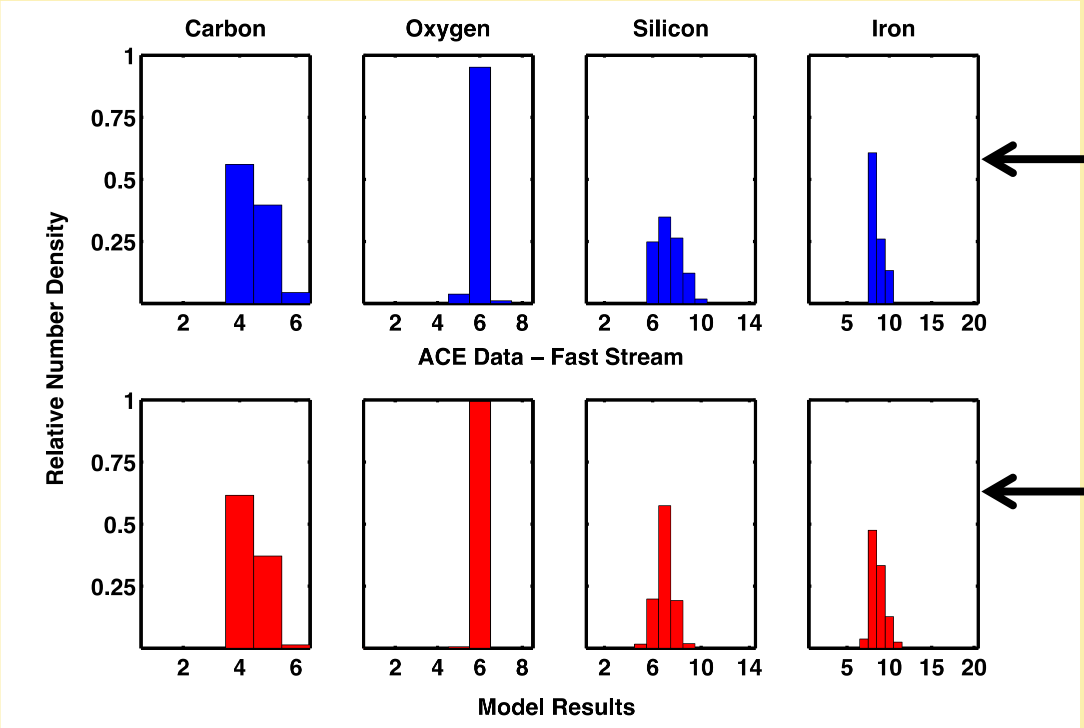
Two-temperature Model

- **Protons are hotter in fast wind due to Alfvén wave dissipation**
- **High electron temperature above streamer due to heat conduction, cooler electrons in fast wind by adiabatic expansion.**



In-situ Charge States

- Ion charge states are frozen-in within a few solar radii, thus can be used to validate the electron temperature/density near the Sun.
- Charge state composition is determined via a 1D model (Gruesbeck et al., 2011) along selected field.
- Here, we compare field line in fast wind region of the 2T solar wind model with ACE/SWICS observations in the fast wind.

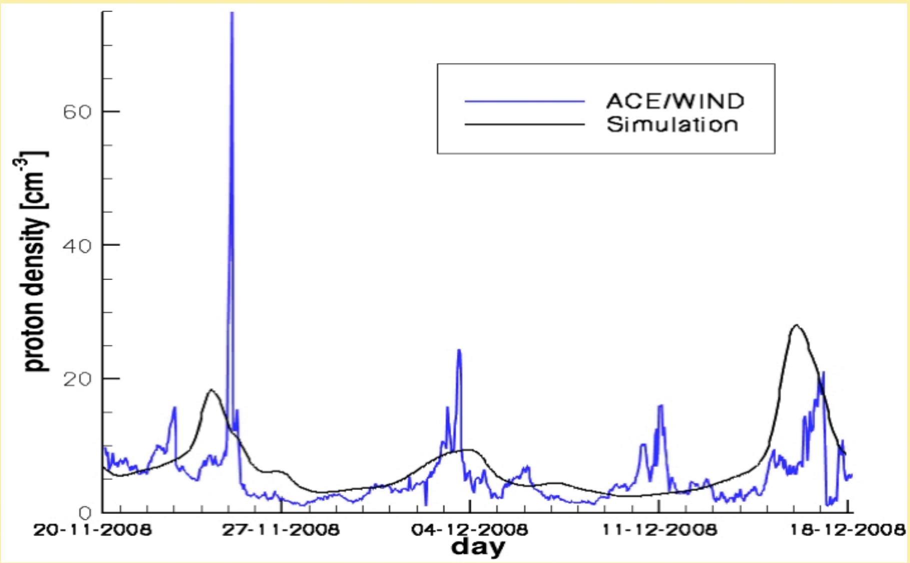


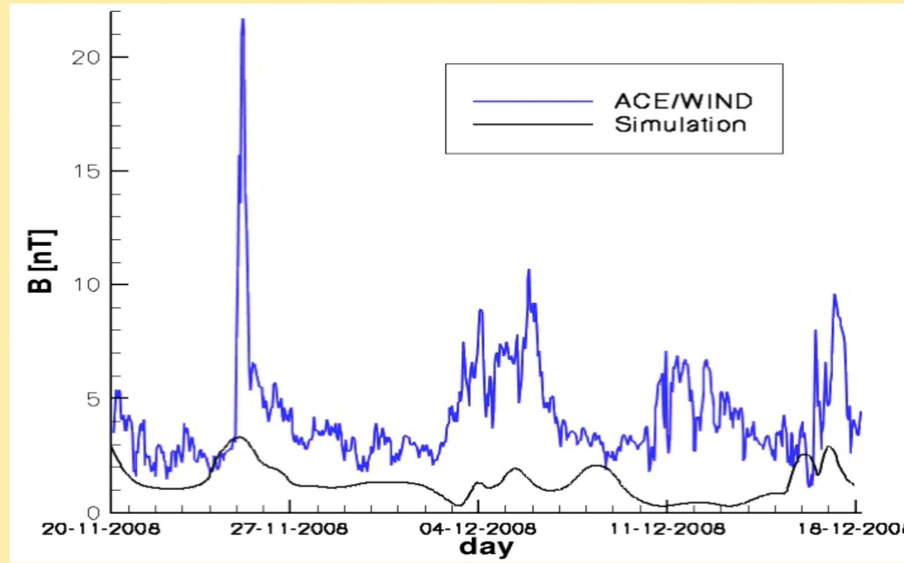
ACE Data – Fast Stream

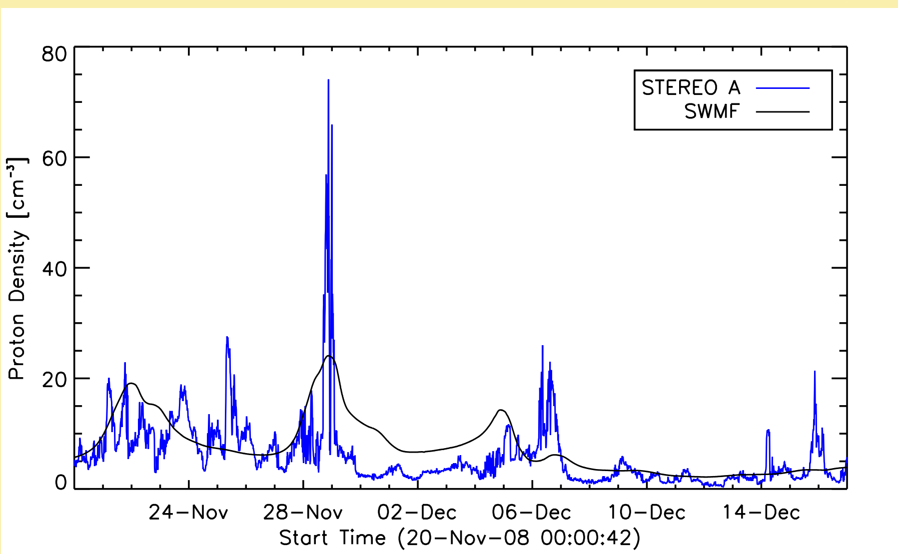
Model Results

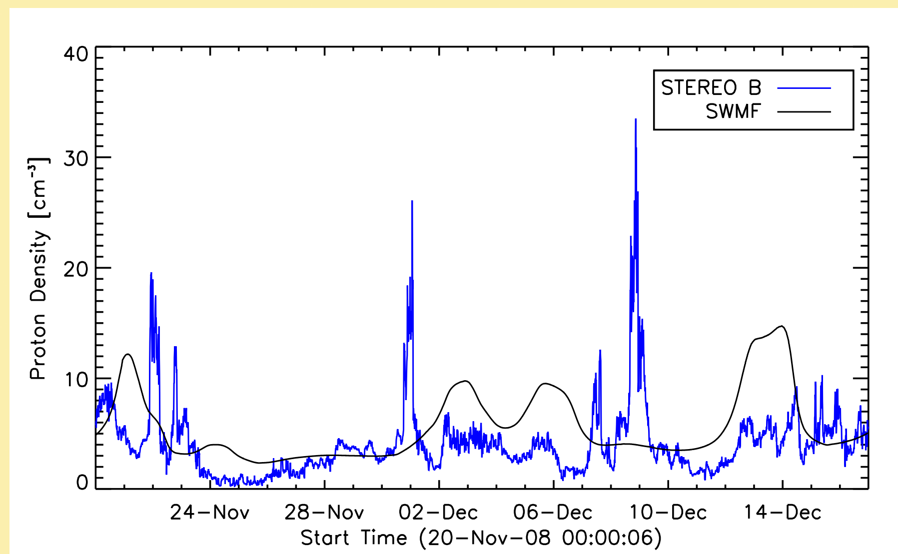
M. Jin et al., Ap.J. 2012

In-situ Validation





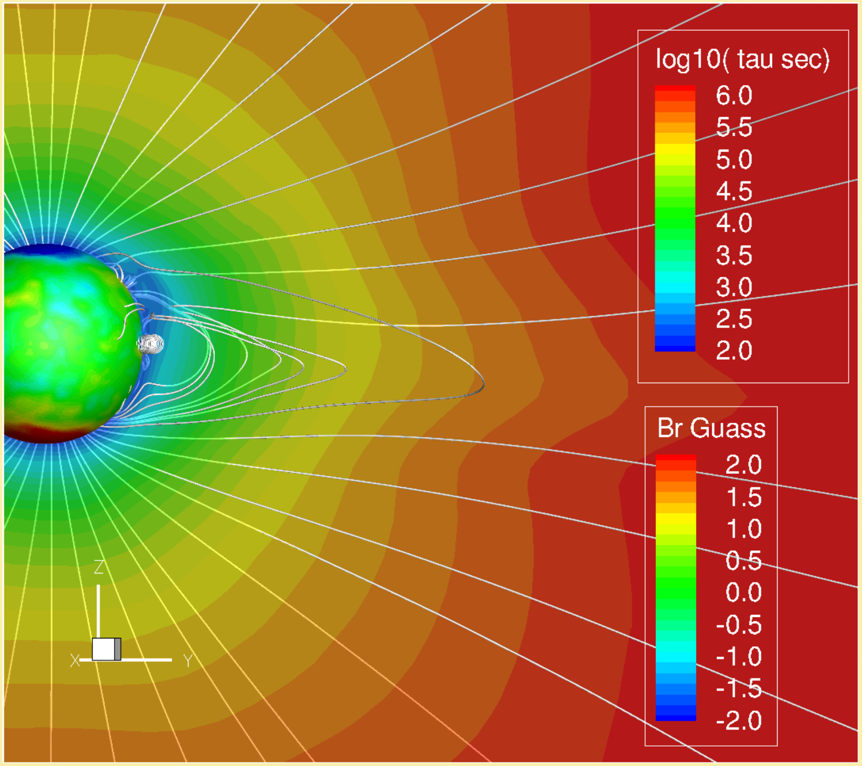


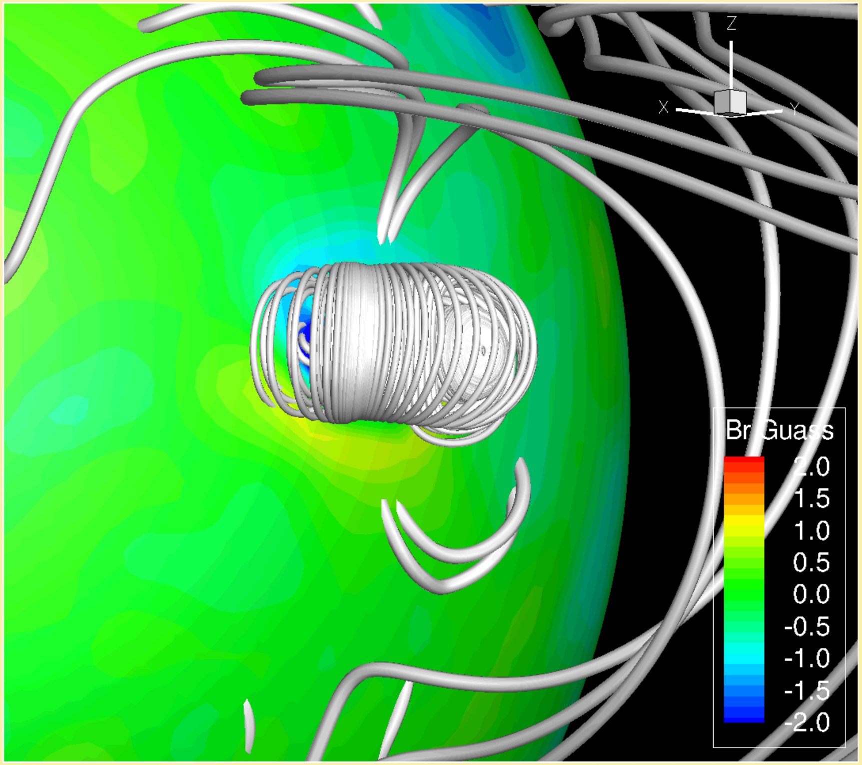


Two-temperature CMEs

W. Manchester et al., in preparation

Electron-proton thermal relaxation time: This shows that 2T is important for the thermodynamic analysis of CMEs

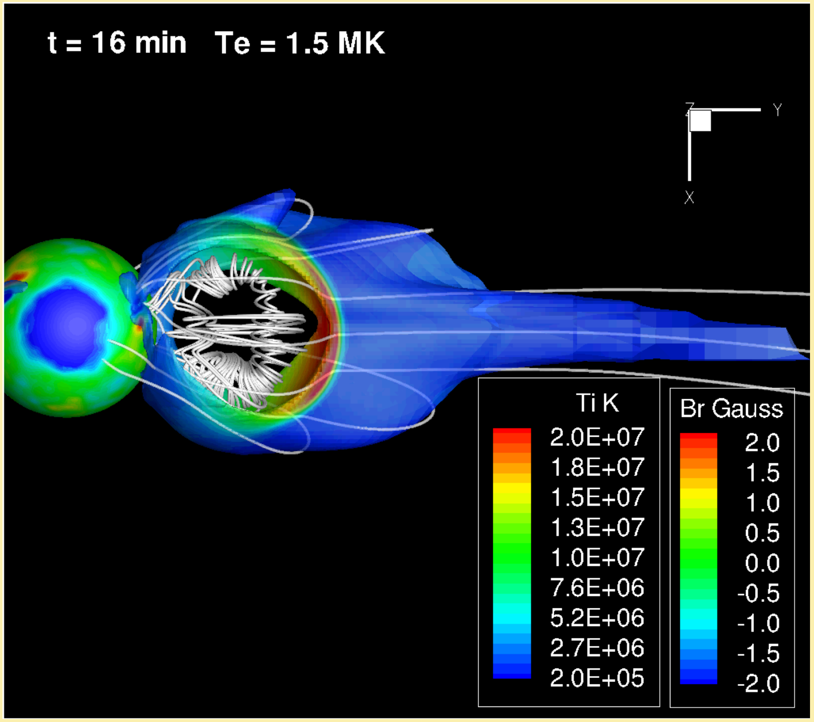




CME initialized as the flux rope model of Titov-Demoulin, but without the strapping field.

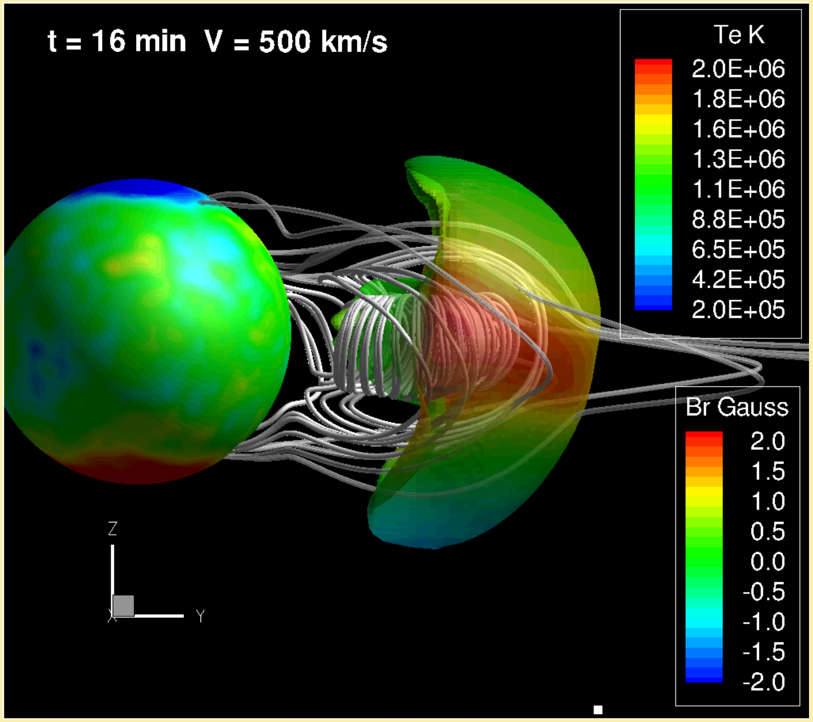
Two-temperature CMEs

Equatorial perspective



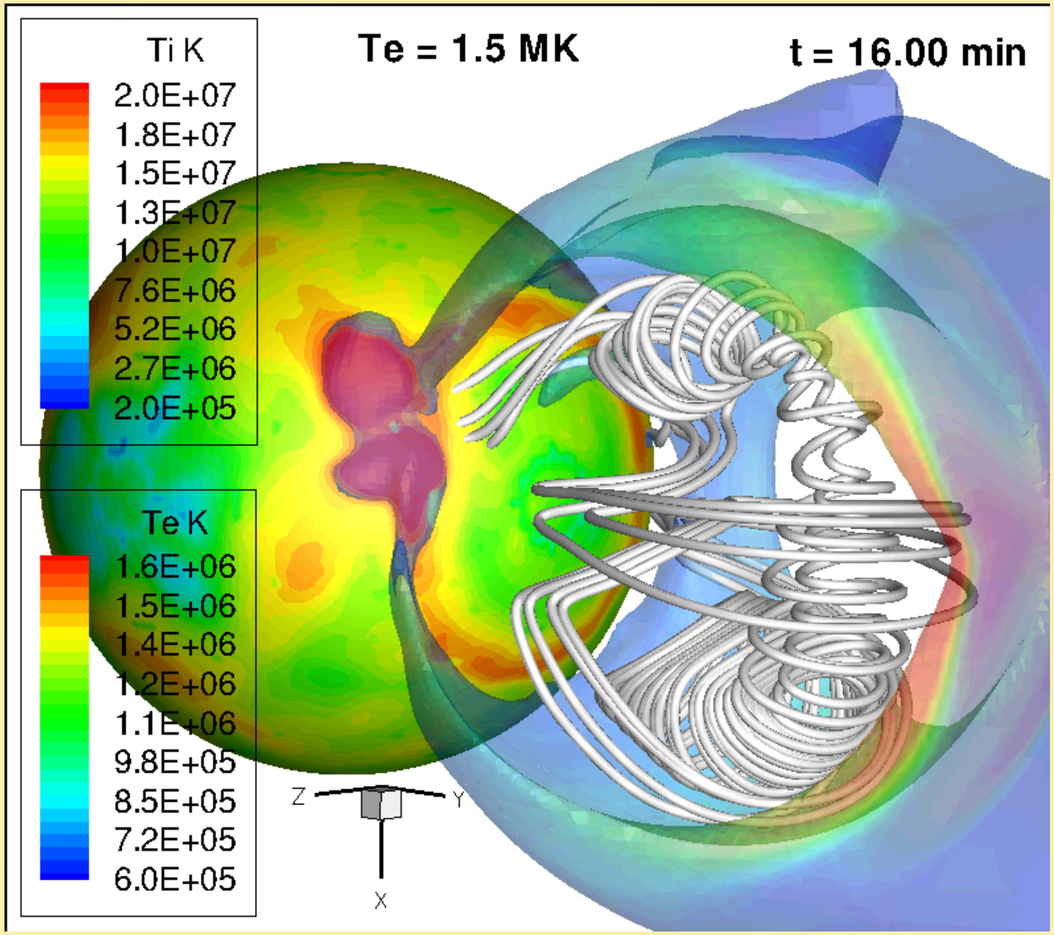
- Cool electron cavity due to adiabatic expansion
- Shock heating for protons
- Electron thermal precursor

Meridional perspective



- Electrons on open field lines cool rapidly due to heat conduction.

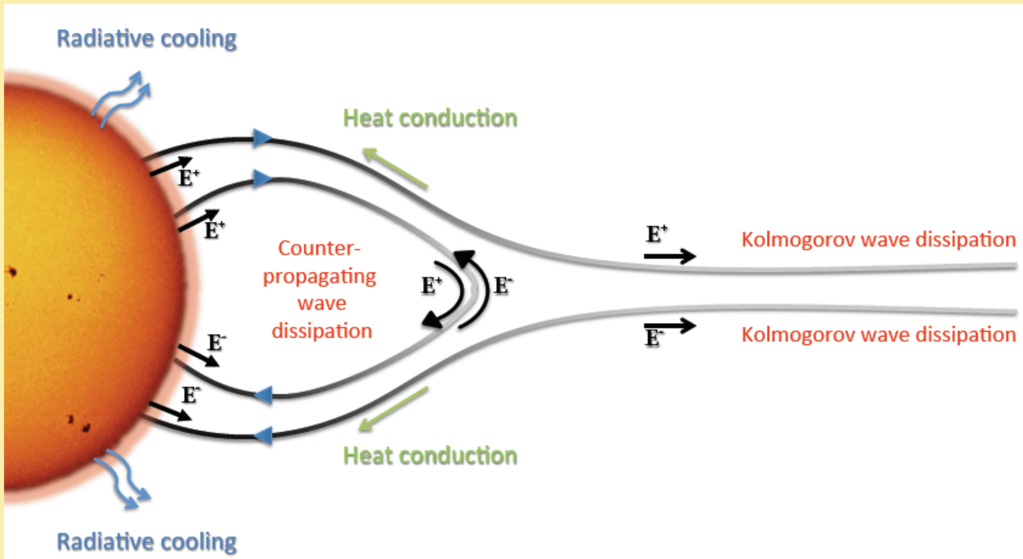
Two-temperature CMEs



- **Compressional wave in the lower corona, peaked at about 1.5-1.6 MK (EIT wave)**

Chromosphere to Corona Model

R. Oran et al., in preparation



- Unlike our previous solar wind models, the open-closed magnetic field topology is now self-consistently created with the Kolmogorov (Hollweg, 1986) wave-dissipation and counter-propagating Alfven waves.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \quad (1)$$

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = -\rho \frac{GM}{r^3}\vec{r} - \nabla(p + p_w) + \frac{1}{\mu_0}(\nabla \times \vec{B}) \times \vec{B} \quad (2)$$

$$\frac{\partial p}{\partial t} + \nabla \cdot (p\vec{u}) = (\gamma - 1)(-p\nabla \cdot \vec{u} + Q_w - \nabla \cdot \vec{q}_e + Q_{rad}) \quad (3)$$

$$\frac{\partial E_w^\pm}{\partial t} + \nabla \cdot [(\vec{u} \pm \vec{V}_A)E_w^\pm] = -\frac{1}{2}(\nabla \cdot \vec{u})E_w^\pm - Q_w^\pm \quad (4)$$

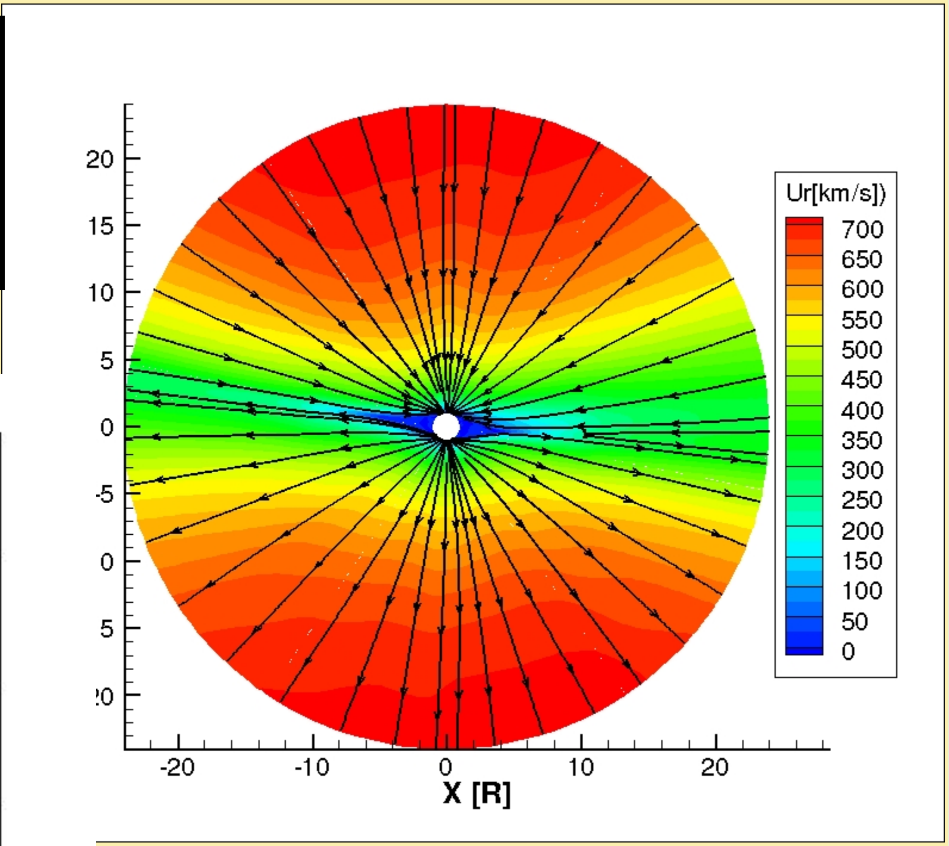
Kolmogorov dissipation

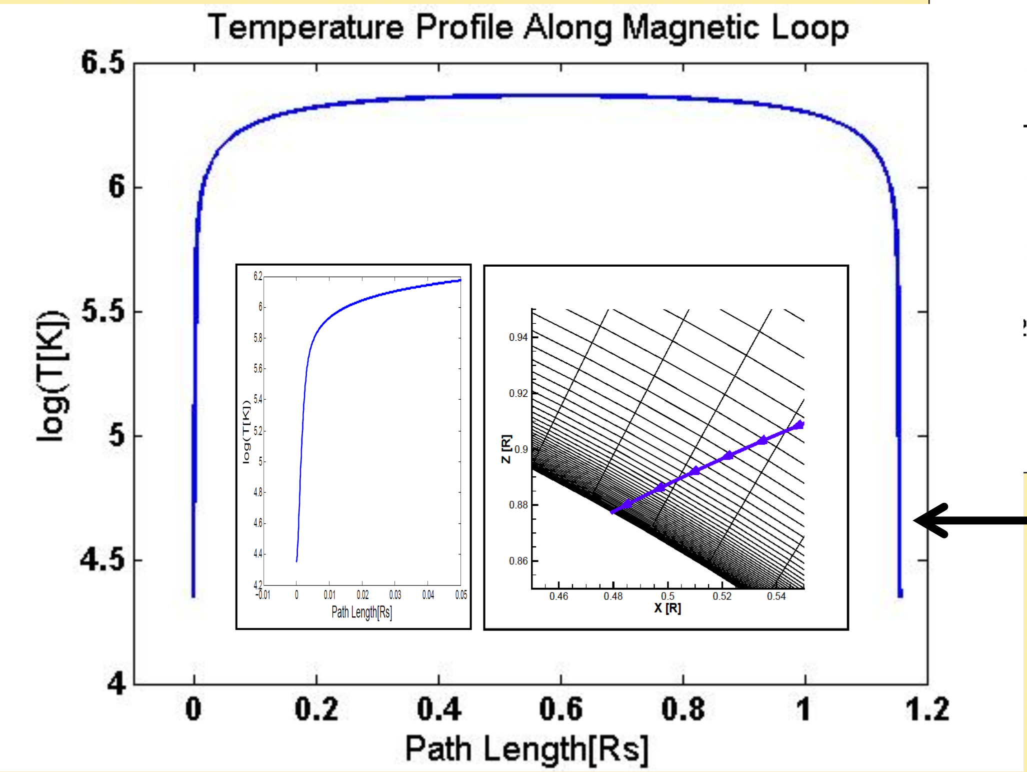
Counter propagating wave dissipation

$$Q_w^\pm = \sqrt{\frac{B}{\rho}}\left(\frac{1}{L_{Kol}}\sqrt{E_w^\pm} + \frac{1}{L_{CP}}\sqrt{\frac{2E_w^+E_w^-}{E_w^+ + E_w^-}}\right)E_w^\pm$$

Solar Minimum CR2077

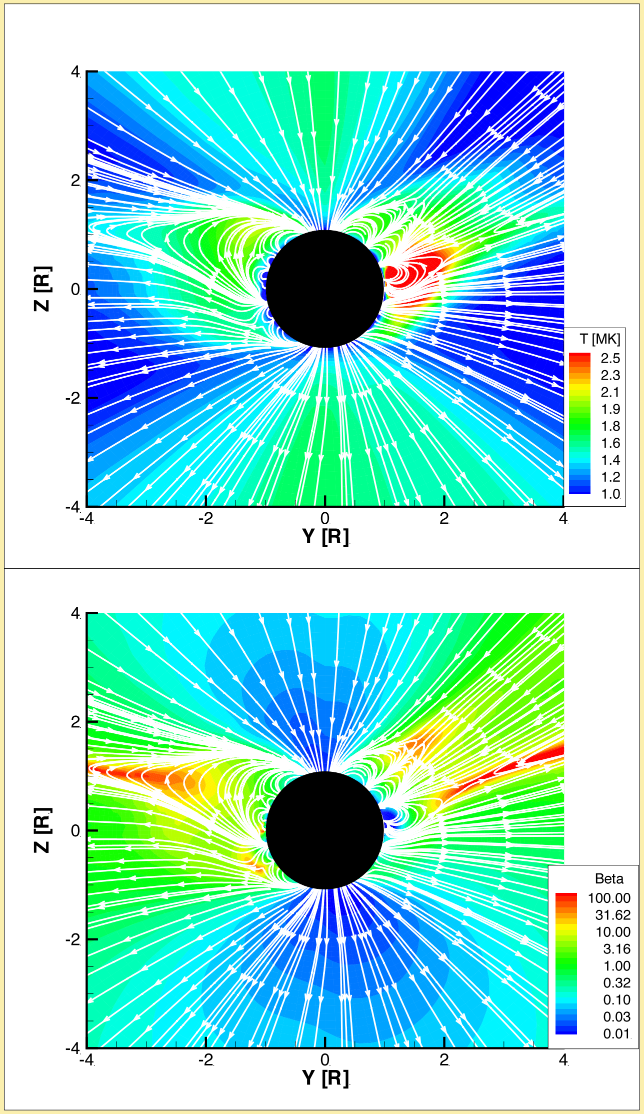
- Density, temperature at top chromosphere: $N=2x10^{16}$ [1/m^3], T = 20,000[K]
- Bimodal solar wind recovered

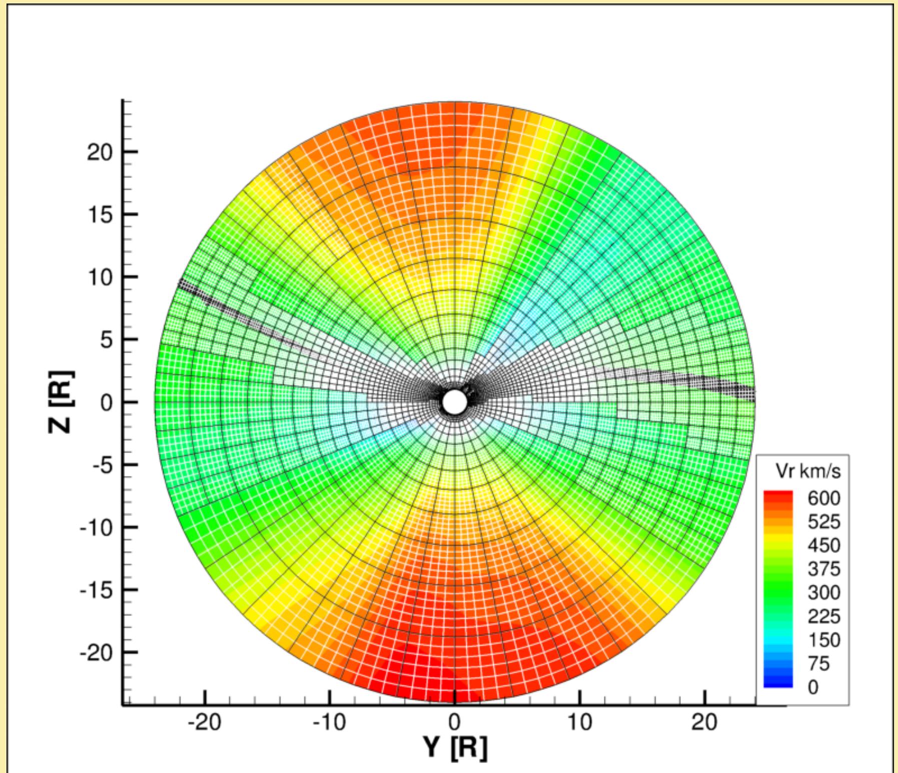




- Spherical grid with grid stretching towards the Sun
- Temperature profile is grid resolved

CR2107

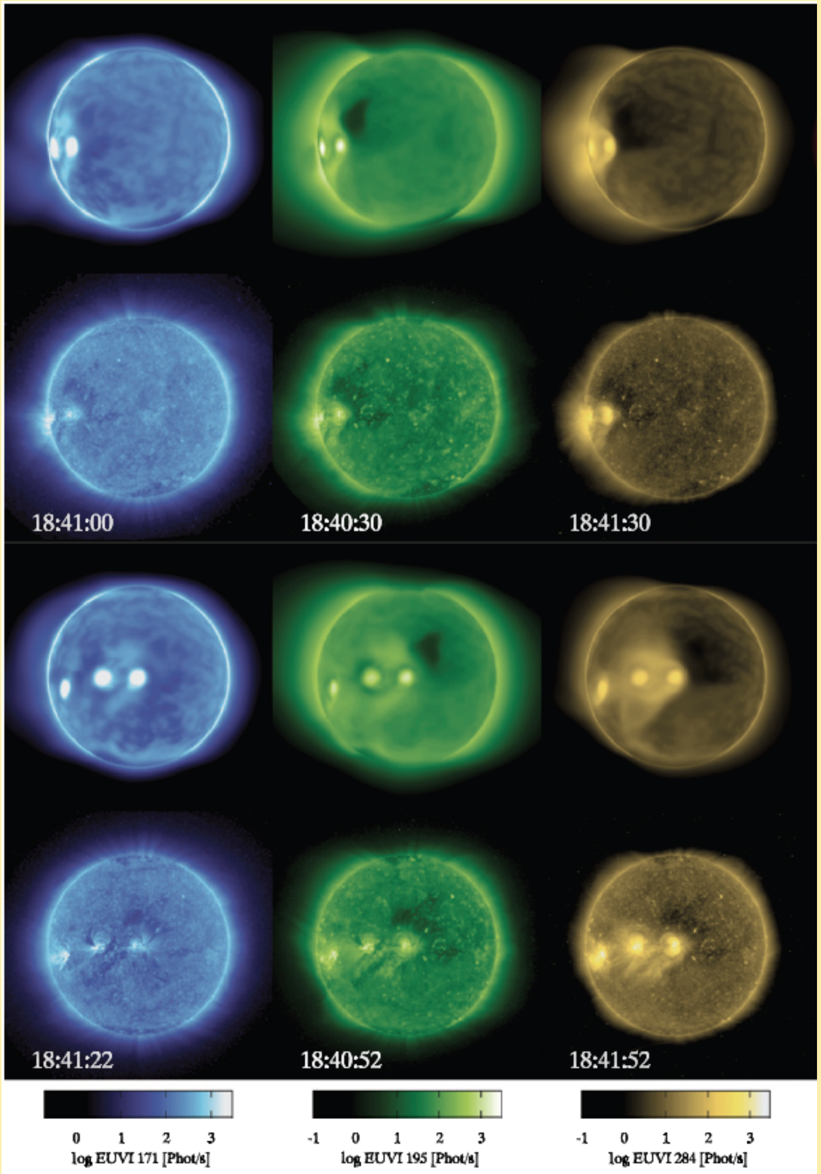




- **Adaptive mesh refinement for the heliospheric current sheet**
- **Smallest cell size = 10^{-3} Rs, largest cell size = 0.8Rs**
- **Validation studies in progress**

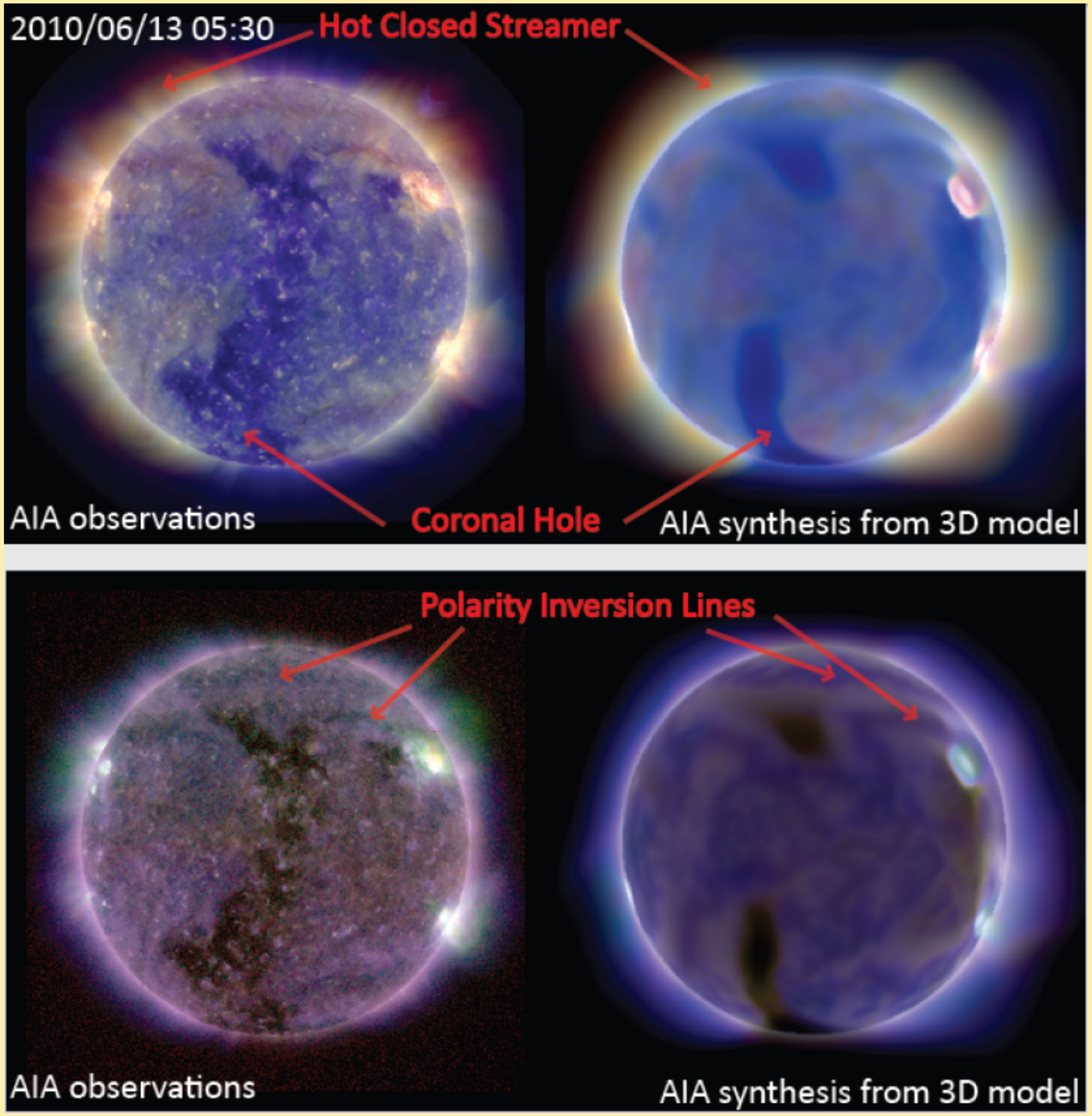
EIT, EUVI, AIA Images

- Capability for the EIT, STEREO A&B EUVI, AIA line-of-sight images as well as AIA tricolor composite (See C. Downs et al., 2010, 2011, 2012)
- On the right: model versus observational EUVI-A (upper half) and EUVI-B (lower half) for CR2068 using the previous chromosphere to corona model.



AIA Tri-color Intensity

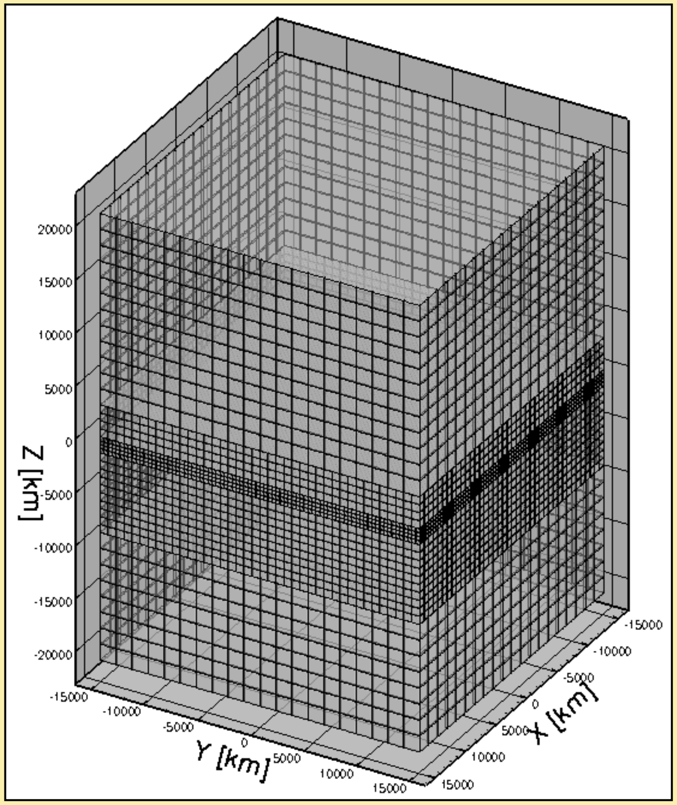
- **Tri-color intensity images (left) versus emission synthesis from coronal model (right)**
- **Top row: AIA 171 (B), 193 (G), and 211 (R) showing the contrast for 0.8 to 2 MK**
- **Bottom row: AIA 193 (B), 335 (G), and 94 (R) emphasizing 1.0 to 1.4 MK (red, blue) and above 2 MK (green)**
- **C. Downs et al., submitted**



Magnetic Flux Emergence

F. Fang et al., 2010, 2012

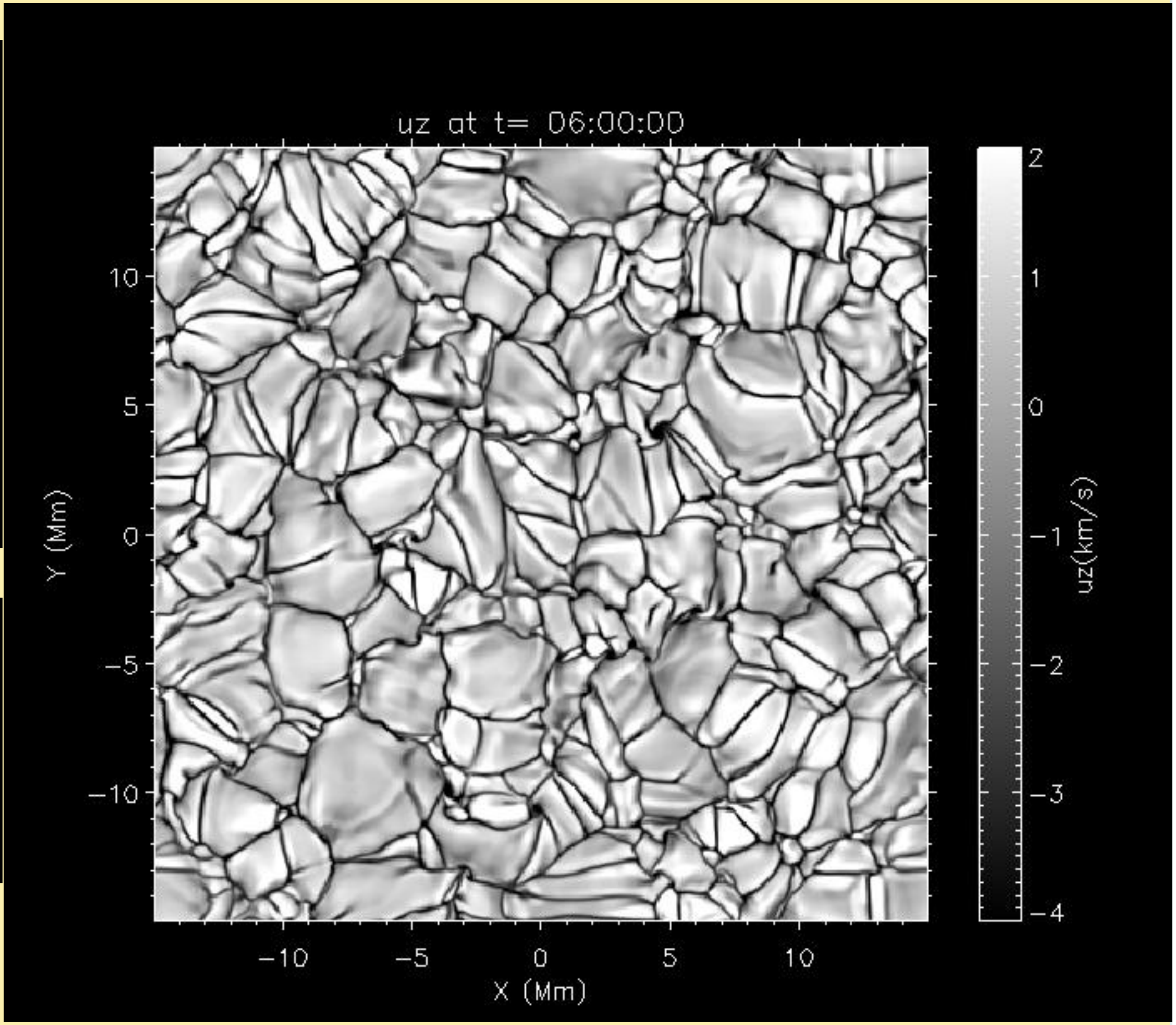
- **Electron heating source term (Abbett, 2007)**
- **Tabular equation of State (Rogers, 2000)**
- **Lower boundary is impenetrable, periodic side boundaries, top boundary prevents mass inflow.**
- **Simulation domain: near active region scale 30x30x42 Mm^3 (Photosphere in midplane)**
- **Mesh refinement towards photosphere**
- **56 million cells**



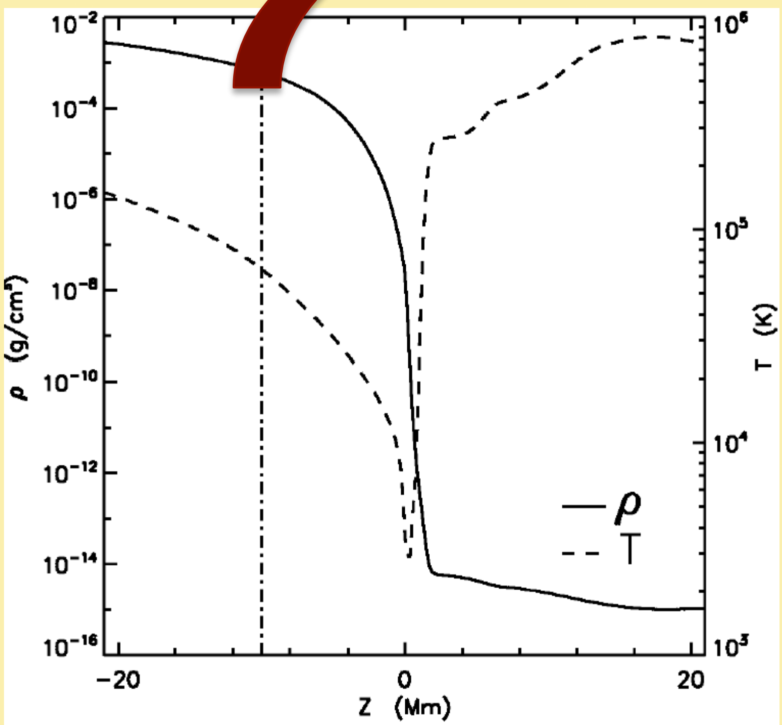
Convection Pattern

- **Convective granules with dimension ~1Mm, upflow speed of ~1km/s**
- **Surrounded by intergranular lanes with downflow speed of ~2km/s**

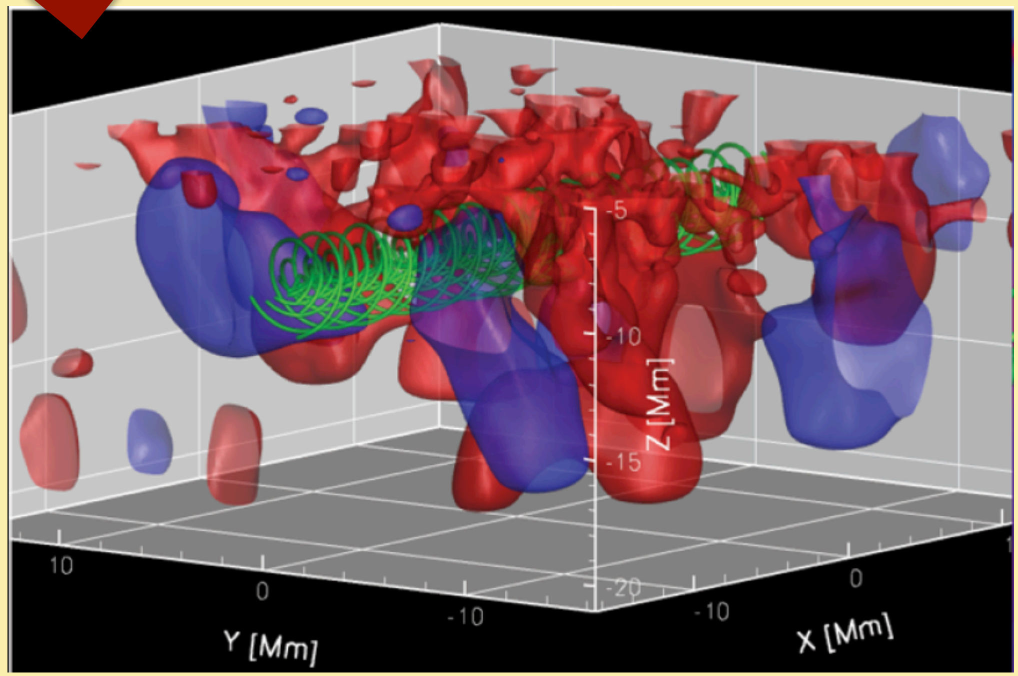
1-hour evolution of the photospheric Uz field with bright color representing upflows and dark downflows.



Initial Magnetic Flux in Convection Zone

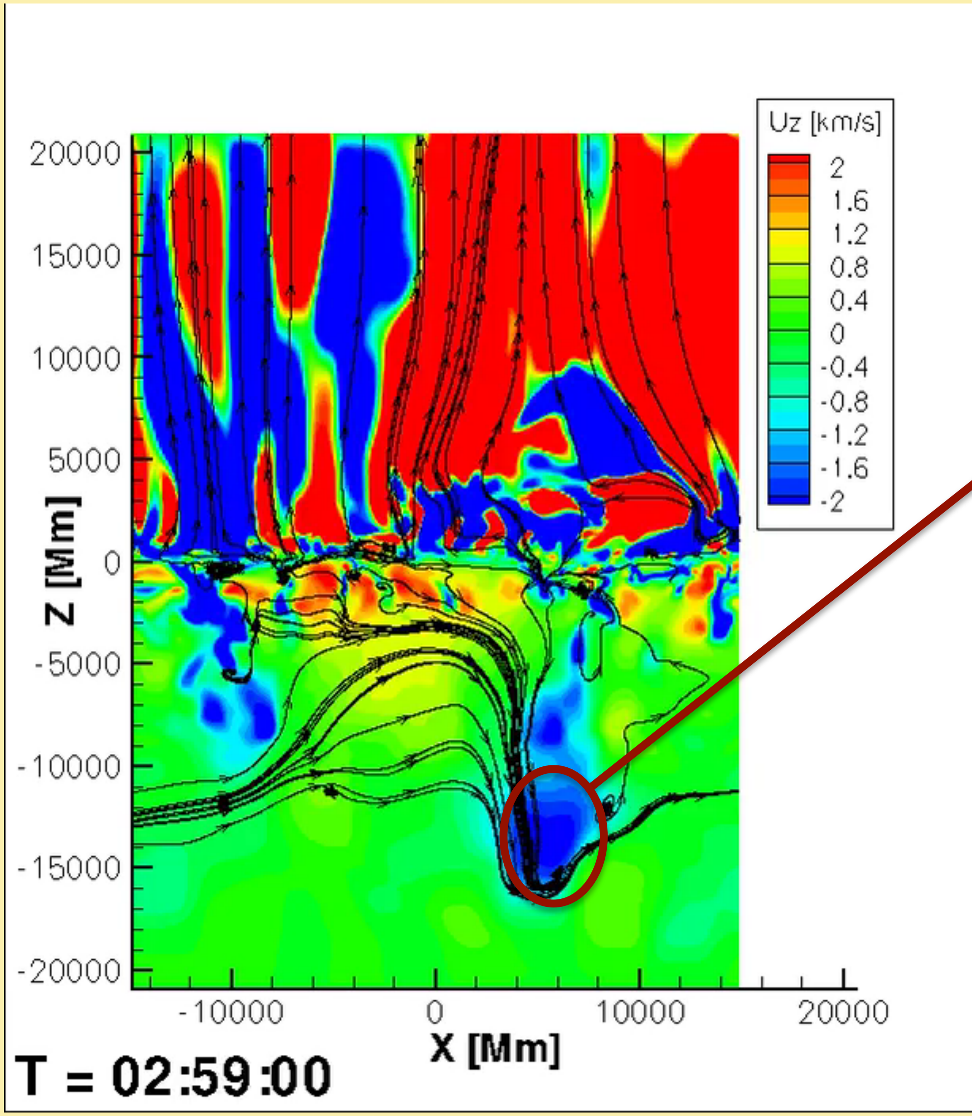


Vertical stratification of density and temperature



Initial flux rope (green rods) at Z = -10 Mm, surrounded by convective downflows (blue) and upflows (red)

Formation of Sunspots



The large-scale downflows in the deep convection zone forms and maintains the bipoles.

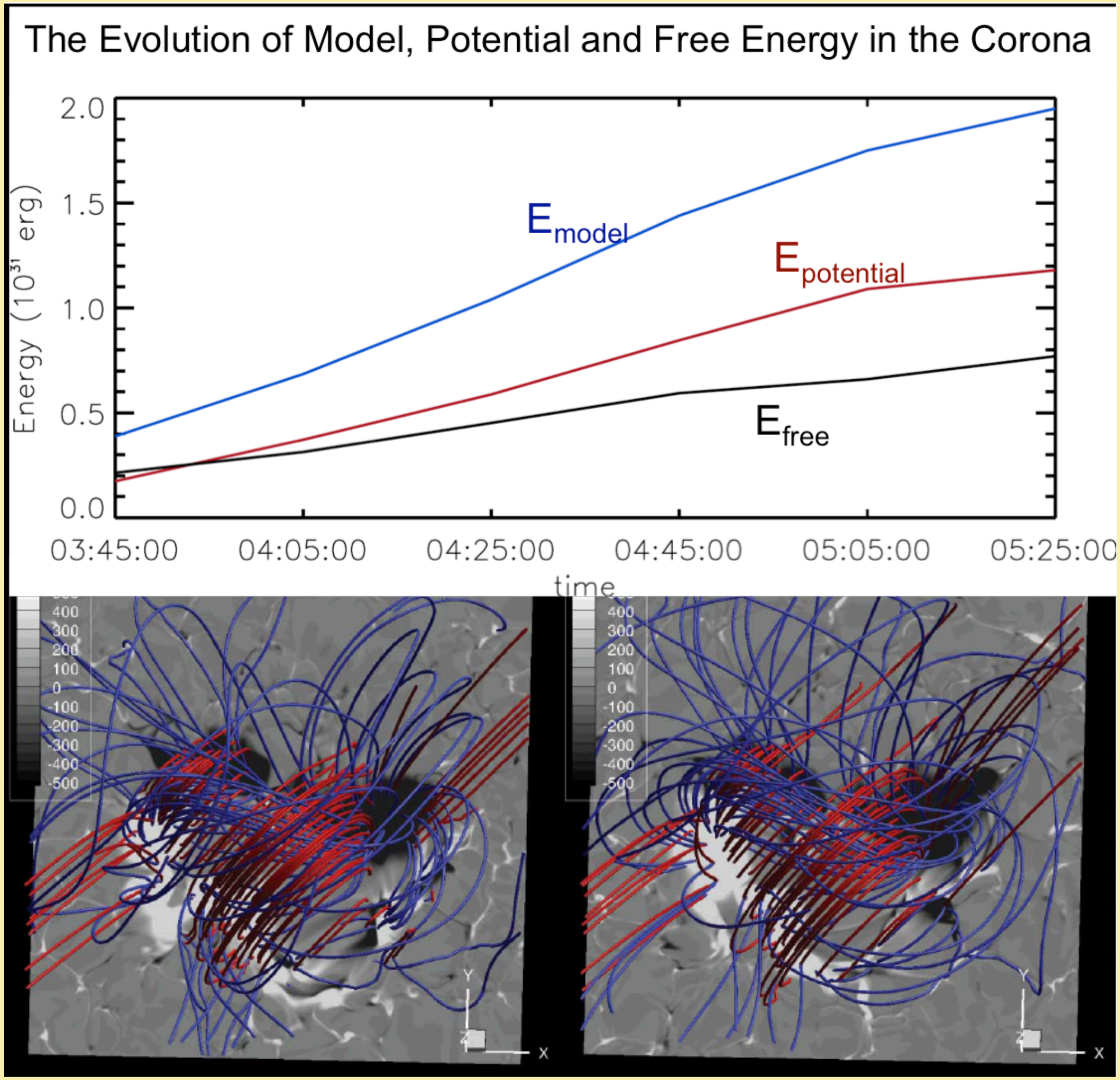
The movie shows the evolution of Uz on the Y=0 plane with streamlines showing the projected magnetic field lines

Build-up of Free Energy during Emergence

Plane: Photospheric Bz field

Blue rods: model field

Red rods: potential field



Summary

- **New more advanced solar models were added to the SWMF:**
  - Data-driven two-temperature solar wind with demonstration of the effect on the thermodynamics of CMEs
  - Single-temperature chromosphere to corona model
  - Magnetic flux emergence model
- **Validation efforts have been undertaken, but more needs to be done.**
- **These models are available in SWMF for registered users. However, none of these new models have yet been transitioned to CCMC.**