Numerical Study of Interplanetary Solar Storms: Present and Future

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This talk first reviews the main features of Current Physics-based 3D MHD Models (CorHel , BATS-R-US, CESE-MHD) and their recent results,

Then presents our data-driven study for solar wind and active region by using SIP-CESE MHD model,

Finally, outlooks the important numerical issues in numerical space weather modeling from the Sun to Earth for future research.

Outline:

- Solar storm and effects
- Current Physics-based 3D MHD Models
- Data-driven models for solar wind & active region
- Brief summary and Future Avenue

1. Solar storms and effects

Solar Storms can be solar flares, coronal mass ejections (CMEs), and solar proton events. They can lead to extreme space weather conditions on the Sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that can affect human life and health .

The movie schematically illustrates solar storms from the Sun to the Earth's space.

Solar storms and effects

Examples: The effects of space weather amy include:

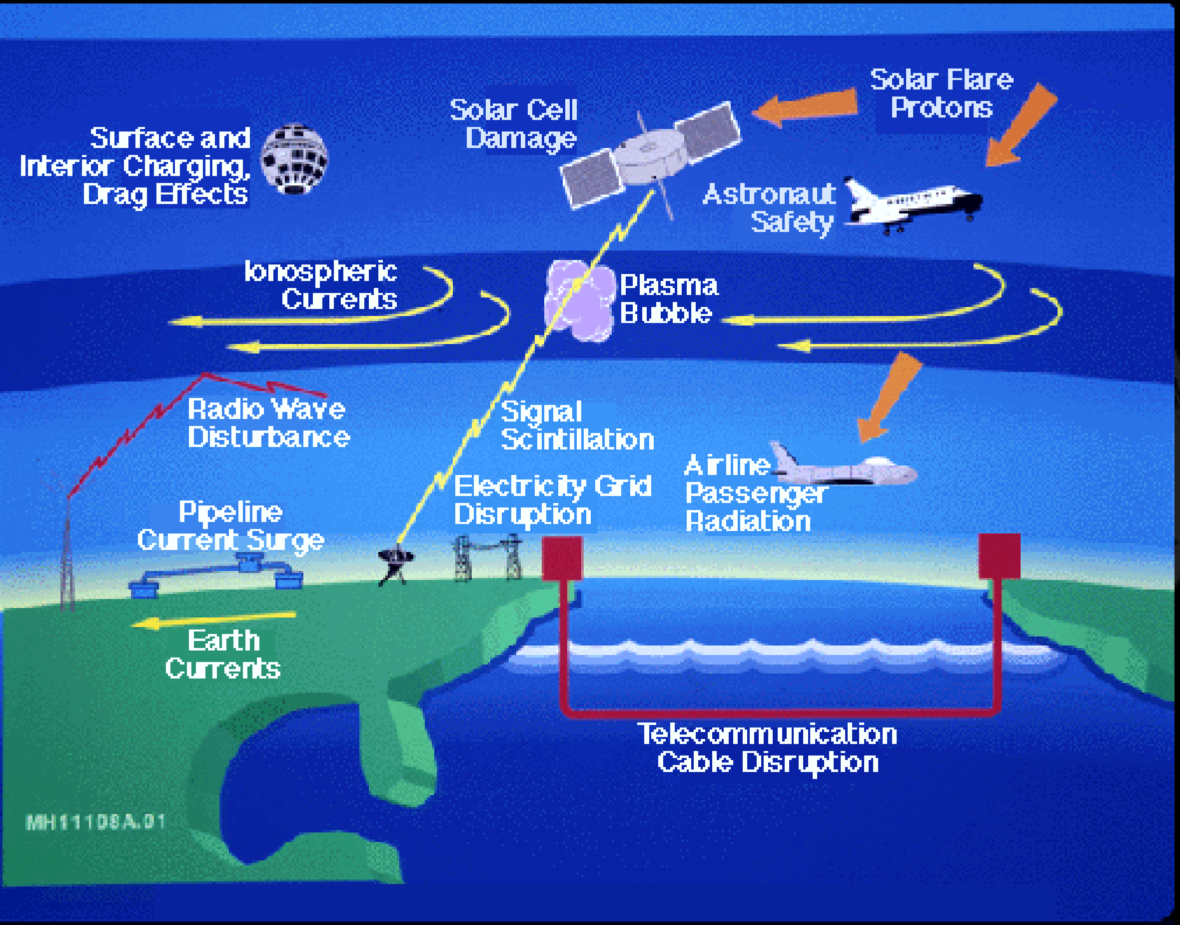

Image Credit: L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.

- **Satellite anormalies**
- **Astronauts may suffer from energetic radiation**
- **Disruption in GPS navigation systems**
- **Massive disruptions in electric power distributed systems**

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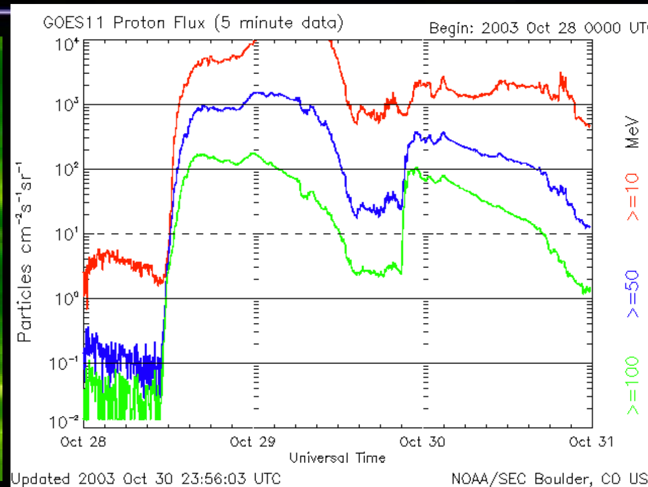
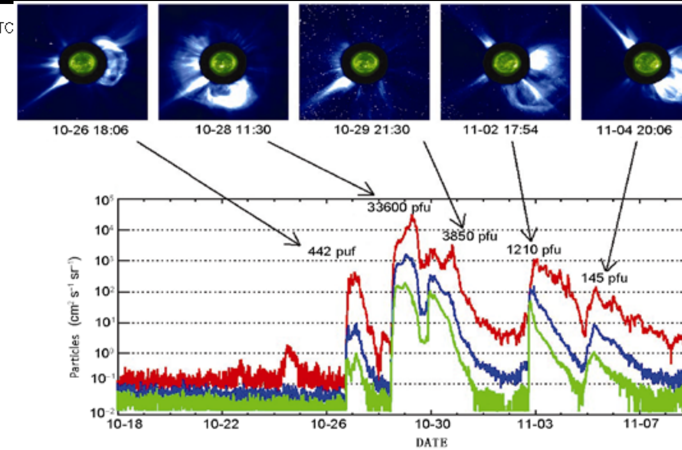
Halloween (*the 2003 October-November event*) solar storm events

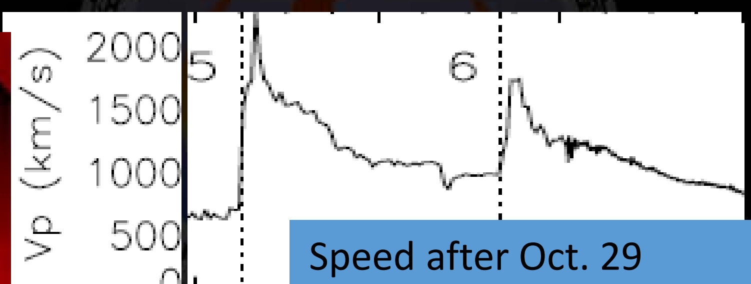
Movie of EIT 195Å observation from Oct. 17 to Nov. 5 2003

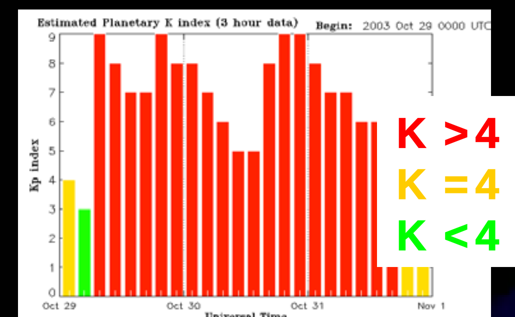


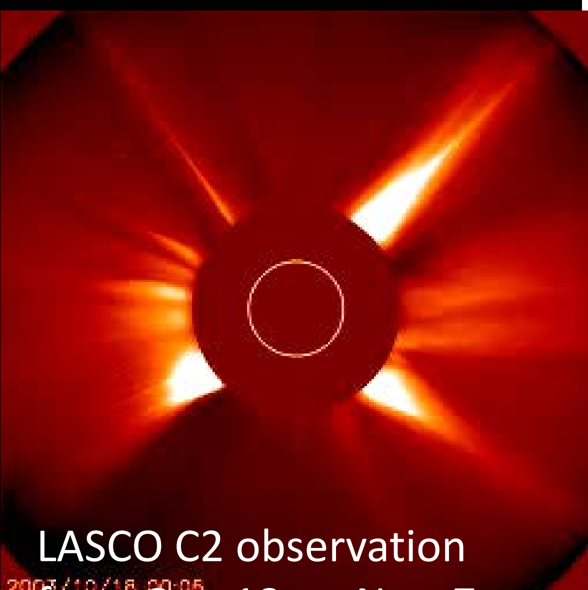
Gopalswamy N. Highlights of the October-November 2003 Events 2006



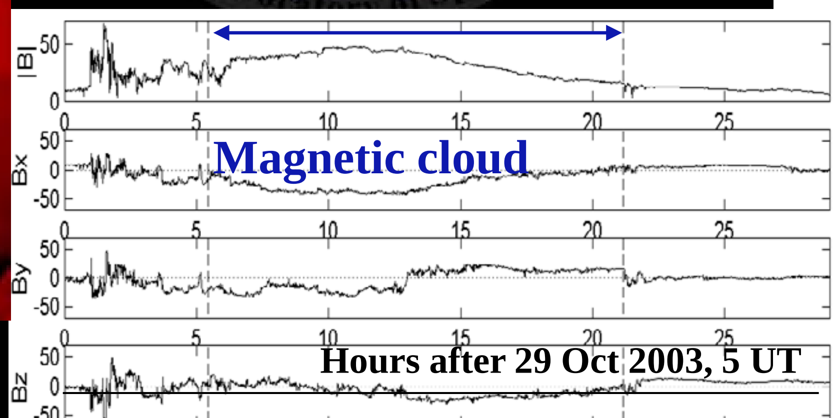
Major SEP events and the associated LASCO CMEs within the period

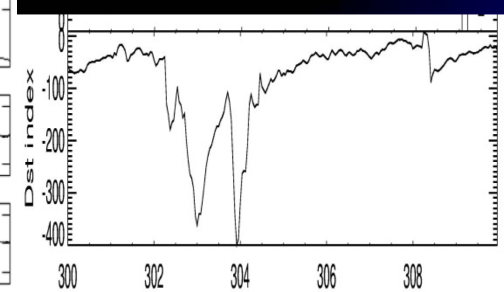






LASCO C2 observation from Oct. 18 to Nov. 7





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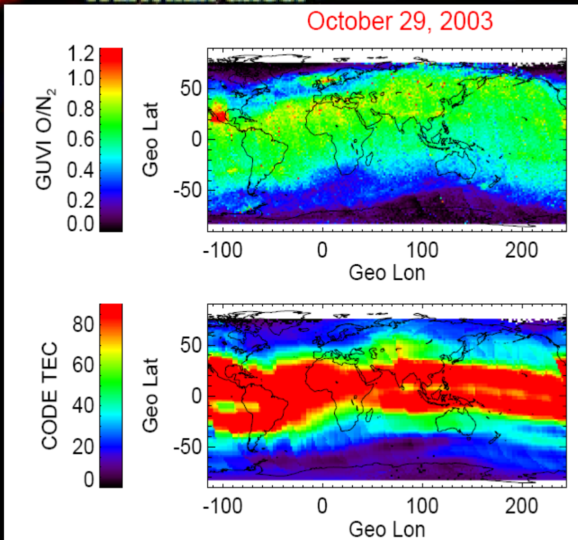
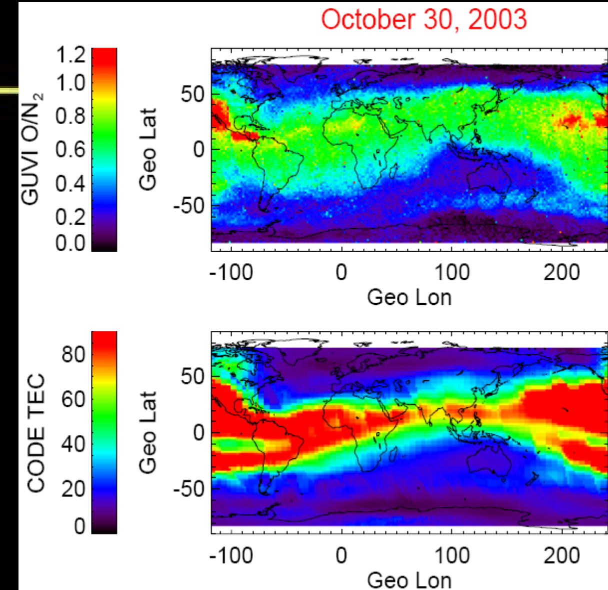
Major losses



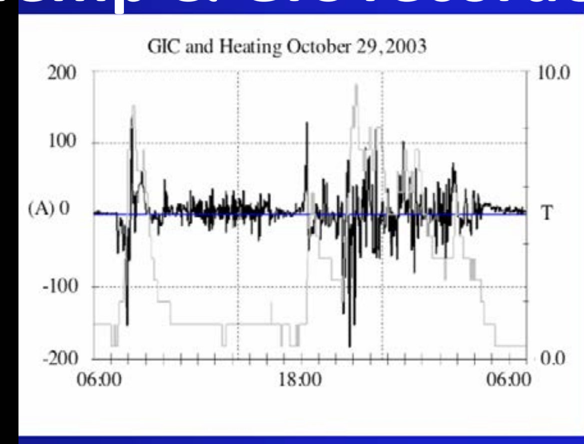
- Extra shielding required for ISS (International Space Station)
- Permanent destroy of MARIE instrument on Mars Odyssey
- Interrupted WAAS service (*Wide Area Augmentation System*)
- Failure of a power system in Sweden



Courtesy Sydsvenskan Bild.

Power Outage in Southern Sweden, October 30, 2003

Temp & GIC recorded



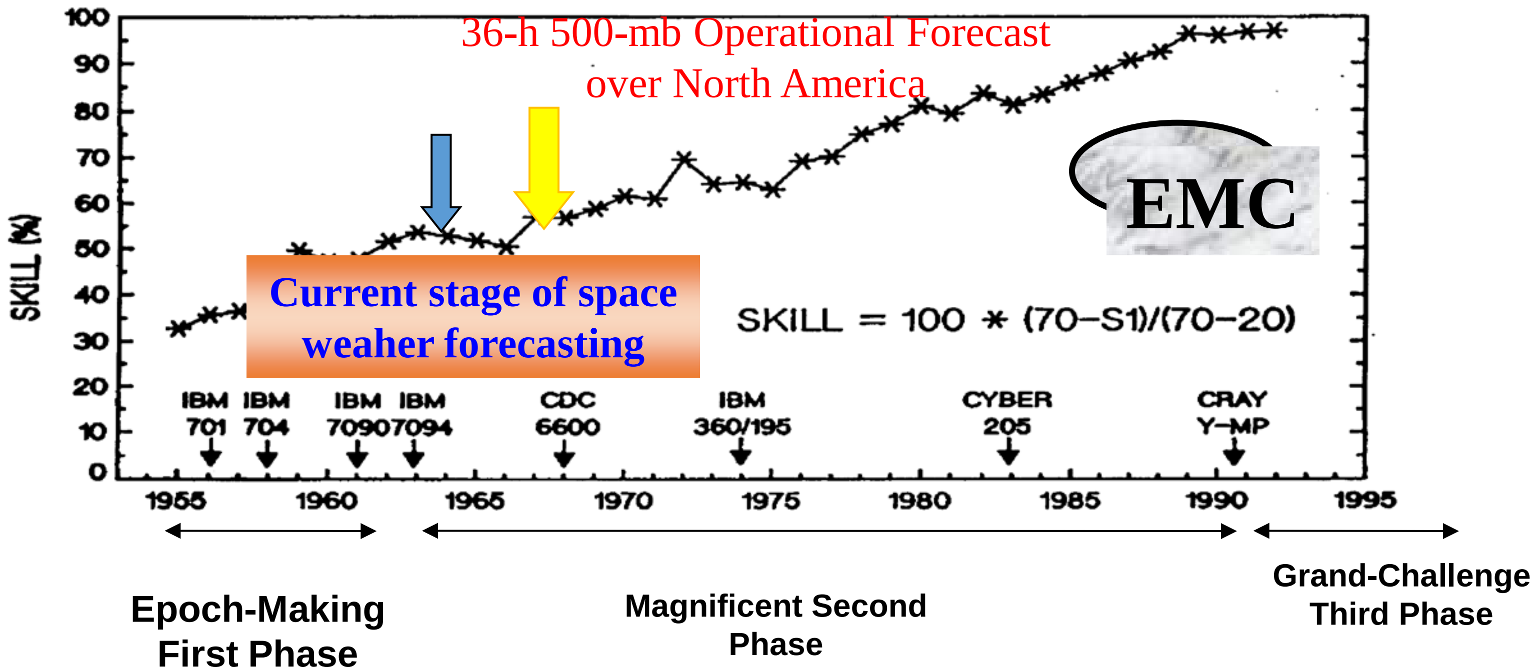
(Courtesy H. Swahn, 2003)

Transformer oil heated 10 degrees! GIC ≈ 173A

Doherty P, Coster A J, Murtagh W. Space weather effects of October–November 2003. GPS Solutions, 2004, 8: 267–271

Stages of Space weather development viewed through the lens of meteorology

1) Social impacts
2) visual observations
3) and 4) instrument observations and synoptic images
5) and 6) real-time predictions based on advection of static structures
7) subjective analysis
8) objective space weather forecasting
9) numerical space weather prediction
10) **Storm tracking** (STEREO etc)



Monitoring ability + Physics process + Numerical modeling

Siscoe G. Space weather forecasting historically viewed through the lens of meteorology. In: Space Weather Physics and Effects. Berlin Heidelberg: Springer, 2007

Numerical modeling of solar storms plays a crucial role in reducing or avoiding loss caused by space weather.

Here we focus our attention on the recent developments of the 3D physics-based solar storm modeling from the Sun to 1 AU.

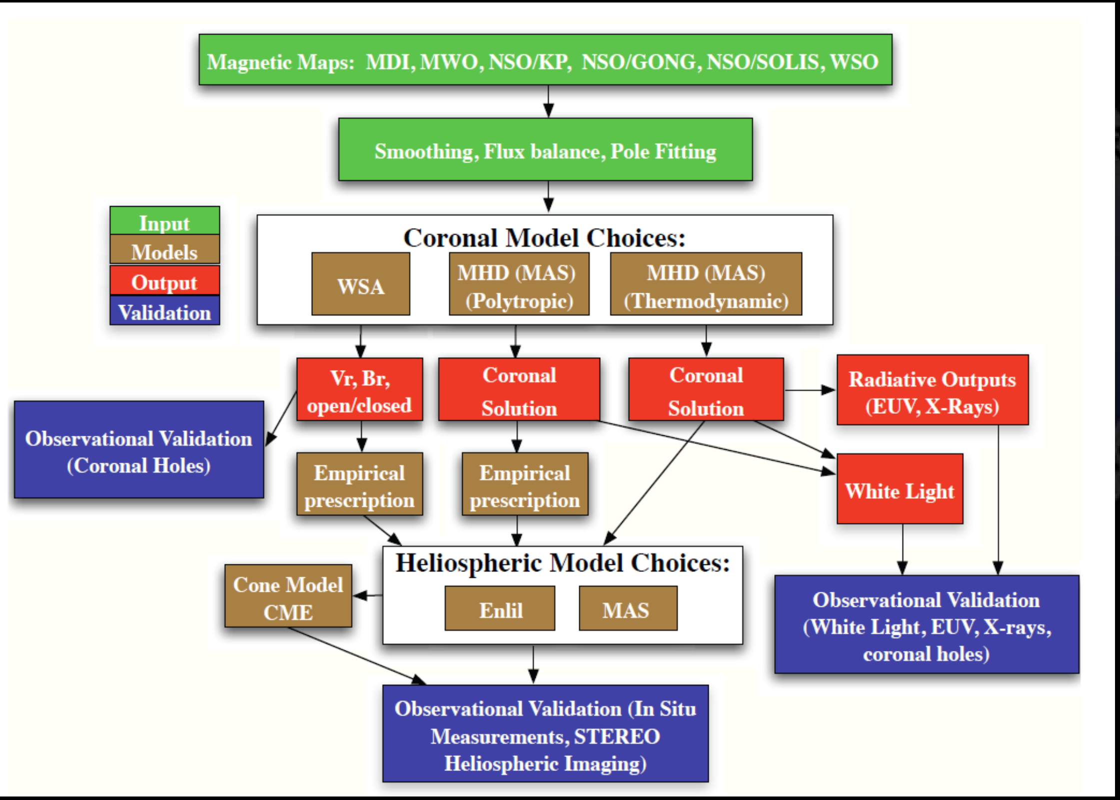
2. Current Physics-Based MHD models

2.1 **CORHEL in CISM**
2.2 **BATS-R-US** in SWMF
2.3 SIP-CESE in SWIM
2.4 etc

Our focus is on the MHD modeling from the Sun to the Earth, excluding geospace models such as magnetosphere, Ionosphere, mesosphere, atmosphere, etc

2.1 CORHEL in CISM

The Center for Integrated Space Weather Modeling (CISM), led by Boston University, developed a loosely coupled frameworks for space weather prediction. In this general framework, the coronal and heliospheric model is described as "CORHEL" for Corona-Heliosphere.



A flow chart of the key components of CORHEL.

- CORHEL consists of coronal models (MAS) + Heliospheric model (ENLIL/MAS-H)
- Now, CORHEL has been transitioned from research into operation and provided forecasters with 1-4 days' lead time.

Linker, J.A.: 2011, A next-generation model of the corona and solar wind. Technical Report 2009 AFRL-OSR-VA-TR-2012-0199

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2.1 CORHEL in CISM: coronal models

Coronal code : MAS (Magnetohydrodynamics around a sphere)

Domain: [1 Rs, 30 Rs] $\times$[- π/2, π/2] $\times$[0, 2π]

Equations: resistive MHD equations in spherical coordinates with volumetric heating

- Input: synoptic map of photospheric magnetic field+Parker solar wind solution
- Gird: staggered meshes, so that Div(B)=0 is satisfied to within round-off error.
- Scheme: an upwind scheme in *r* and *θ* directions + a pseudospectral method in ϕ direction.
- Outputs: flow and mag parameters at ~30Rs to provide some input to helioshperic models: ENLIL or MAS-H.

$$\nabla\times\mathbf{B}=\frac{4\pi}{c}\mathbf{J}, \tag{1}$$

$$\mathbf{B}=\nabla\times\mathbf{A}$$

$$\nabla\times\mathbf{E}=-\frac{1}{c}\frac{\partial\mathbf{B}}{\partial t}, \tag{2}$$

$$\nabla\cdot\mathbf{A}=\nabla\cdot\mathbf{B}=0$$

$$\mathbf{E}+\frac{1}{c}\mathbf{v}\times\mathbf{B}=\eta\mathbf{J}, \tag{3}$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{v})=0, \tag{4}$$

$$\rho\left(\frac{\partial\mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=\frac{1}{c}\mathbf{J}\times\mathbf{B}-\nabla p-\nabla p_w+\rho\mathbf{g}+\nabla\cdot(\nu\rho\nabla\mathbf{v}), \tag{5}$$

$$\frac{\partial p}{\partial t}+\nabla\cdot(p\mathbf{v})=(\gamma-1)(-p\nabla\cdot\mathbf{v}+S), \tag{6}$$

Lionello R, et al. J Comput Phys, 1998,140: 172
Mikić Z, et al. Phys of Plasma, 1999, 6: 2217

2.1 CORHEL in CISM: heliospheric models (ENLIL)

◆**Input : use the output of coronal model MAS and some ad hoc specifications**

◆**Equations: Time-dependent conservative MHD equations in a spherical geometry**

◆**Scheme: flux-corrected transport (FCT) or TVD schemes.**

◆**Domain: [20-30Rs, >1AU]×[-60°,60°]×[0°,360°].**

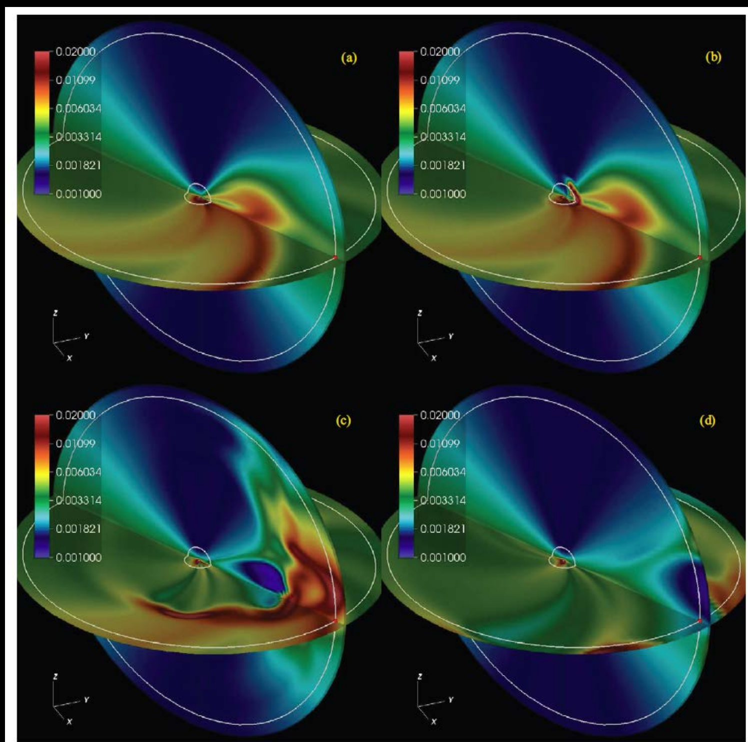
◆**Output : solar wind or CME's solution from the Sun to Earth**

http://www.bu.edu/cism/

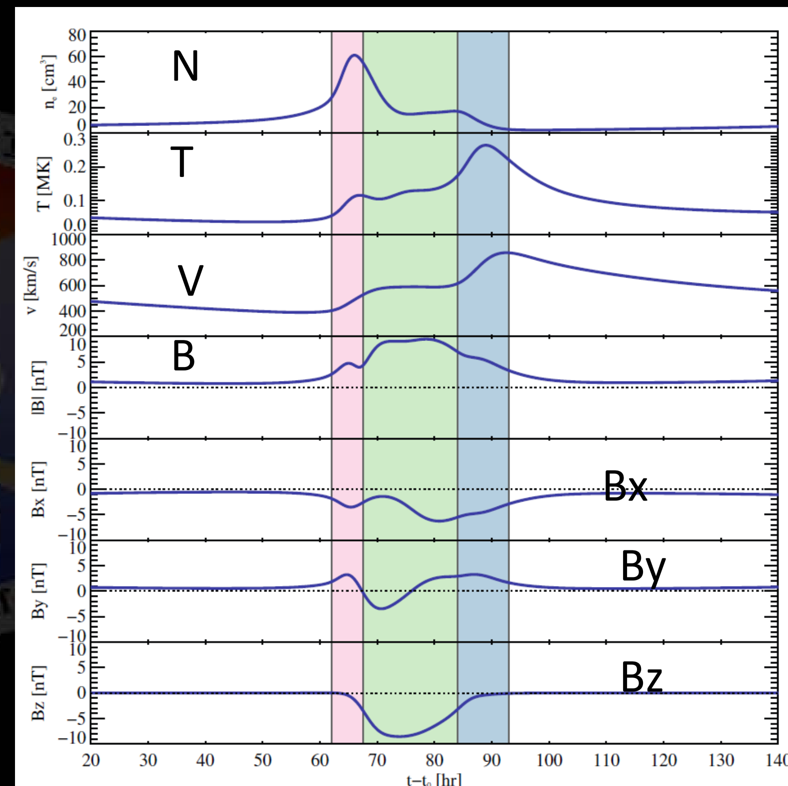
Odstrcil, D.: 2003, Adv. Space Res. 32, 497-506.
Odstrcil, D.: 1994, JGR 99, 17653.
Odstrcil, D., Pizzo, V.J.: 1999a, JGR. 104, 28225
Odstrcil, Riley & Zhao， JGR, 2004, 109, A02116
Odstrcil, Riley & Zhao， JGR, 2005, 110, A02106

2.1 Application to studying CMEs

Lionello et al. (2013) studied the propagation of an ICME from 18 Rs to 1.1 AU, with the CME modeled by a flux rope.



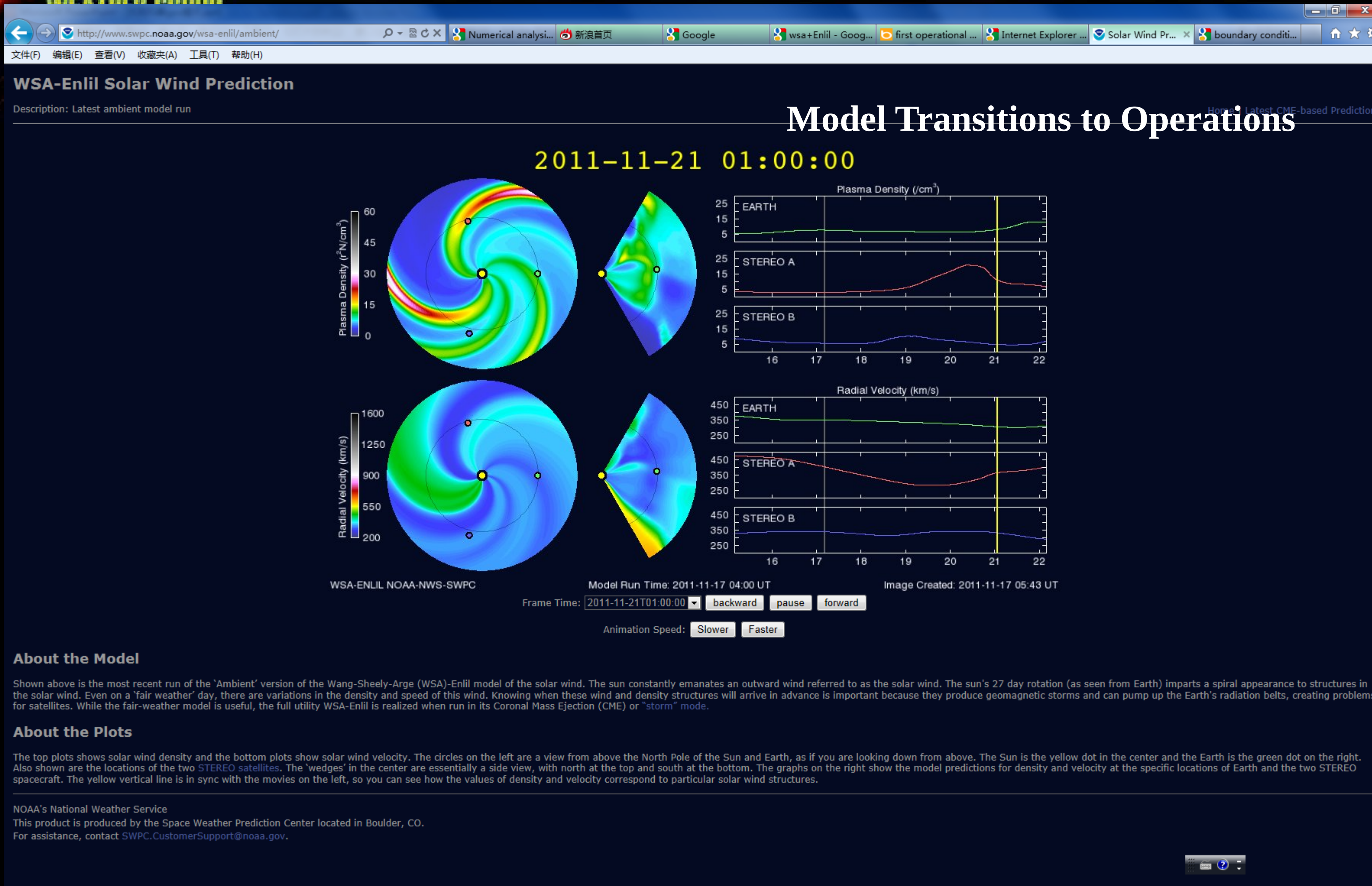
Evolution of the scaled density (ρr^2)



Time history of local plasma variables at 1 AU

Lionello,R. et al., 2013 ApJ 777(1), 76.

Wang-Sheeley-Arge–Enlil Cone Model Transitions to Operations



Pizzo, V., G. Millward, A. Parsons, D. Biesecker, S. Hill, and D. Odstrcil (2011), Wang-Sheeley-Arge–Enlil Cone Model Transitions to Operations, *Space Weather, 9*, S03004

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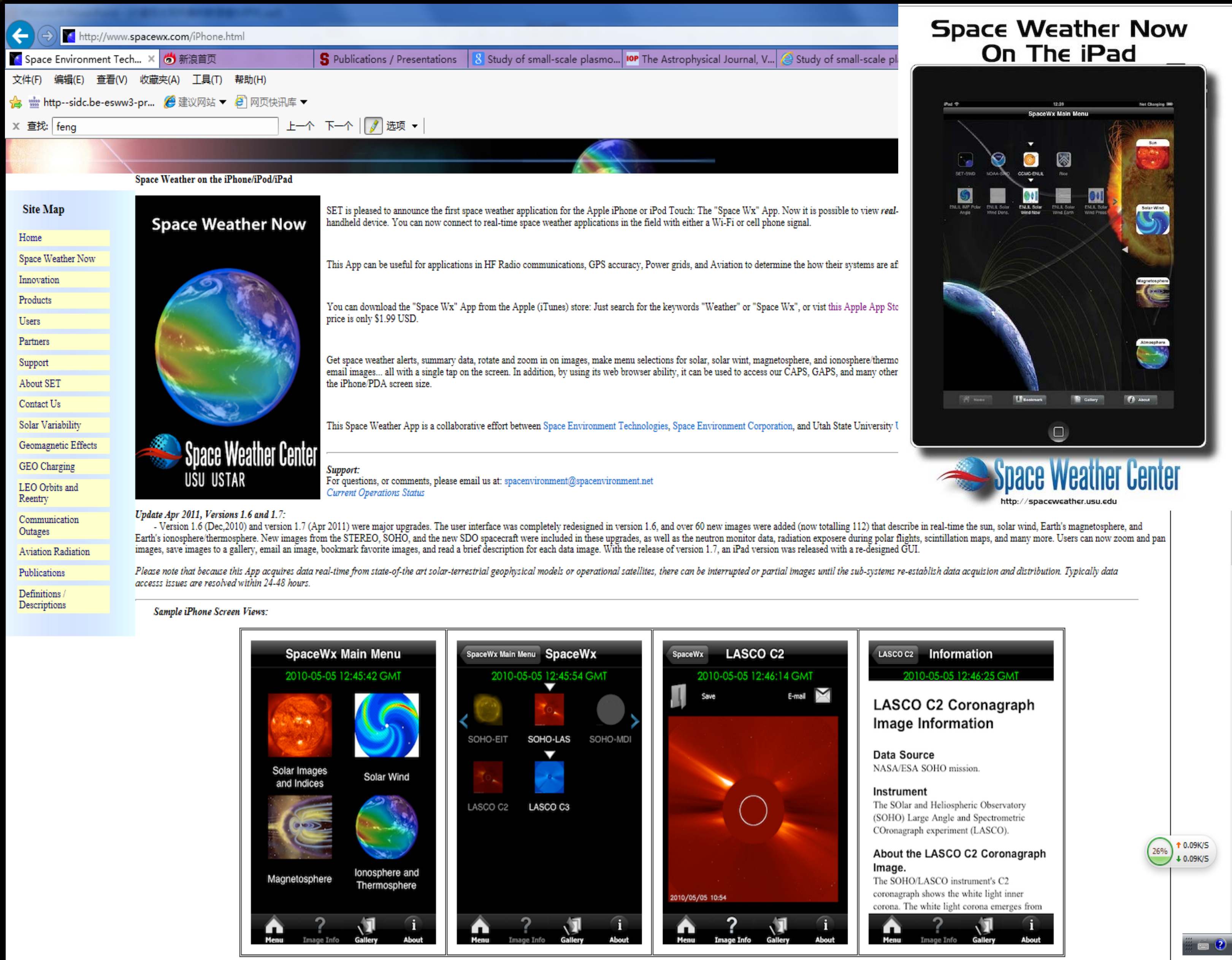
Now We can see space weather on IPAD

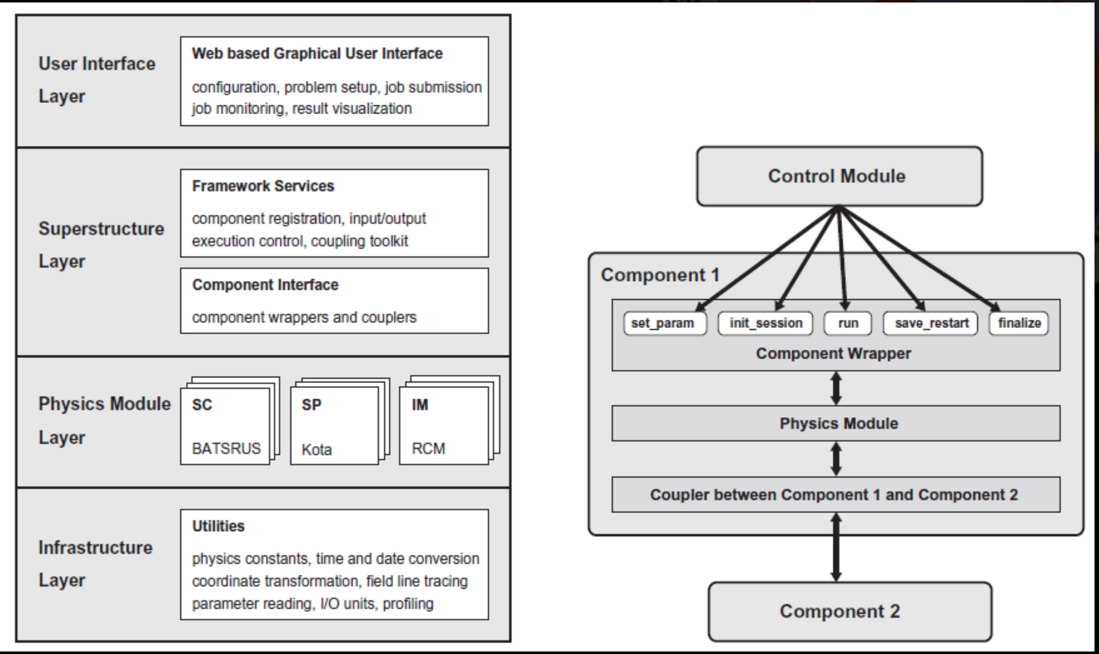


2.2 BATS-R-US in SWMF

Space Weather Modeling Framework (SWMF) at the Univ of Mich

http://csem.engin.umich.edu/tools/index.php

The SWMF integrates numerical models of Solar Corona (SC), Inner Heliosphere (IH), and other components into a high-performance coupled model, based on **T**he **B**lock-**A**daptive **T**ree **S**olarwind **R**oe-type **U**pwind **S**cheme (BATS-R-US) code



layered architecture (left) & components' structure (right)

Toth, G., et al. (2005), Space Weather Modeling Framework, JGR, 110, A12226

Toth, G., et al.: 2012, Adaptive numerical algorithms in space weather modeling, JCP, 231, 870

2.2 BATS-R-US in SWMF

■MHD in Cartesian coordinates with various volumetric heating terms

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$
$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left[\rho \mathbf{u}\mathbf{u} + I\left(p + \frac{1}{2}B^2\right) - \mathbf{B}\mathbf{B}\right] = -\mathbf{B}\nabla \cdot \mathbf{B},$$
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = -\mathbf{u}\nabla \cdot \mathbf{B},$$
$$\frac{\partial e}{\partial t} + \nabla \cdot \left[\mathbf{u}\left(e + p + \frac{1}{2}B^2\right) - \mathbf{u} \cdot \mathbf{B}\mathbf{B}\right] = -\mathbf{u} \cdot \mathbf{B}\nabla \cdot \mathbf{B},$$

$$e = \frac{p}{\gamma - 1} + \frac{\rho u^2}{2} + \frac{B^2}{2},$$

■SC Domain : [1,25]Rs ; IH domain: [20 , >1AU]

■Numerical Scheme: BATS-R-US

A TVD-Roe type numerical scheme with slope limiters of second and third order accuracy

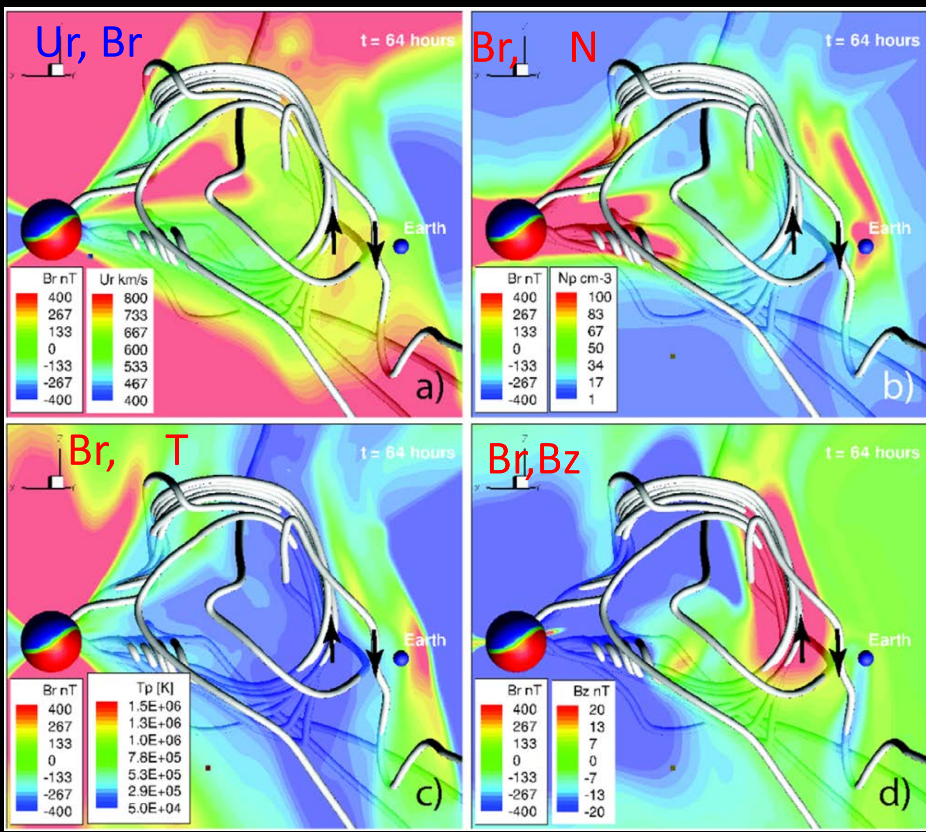
■Grid system: 3D block-adaptive grid + “supercell” approach to avoid singularity near polar region.

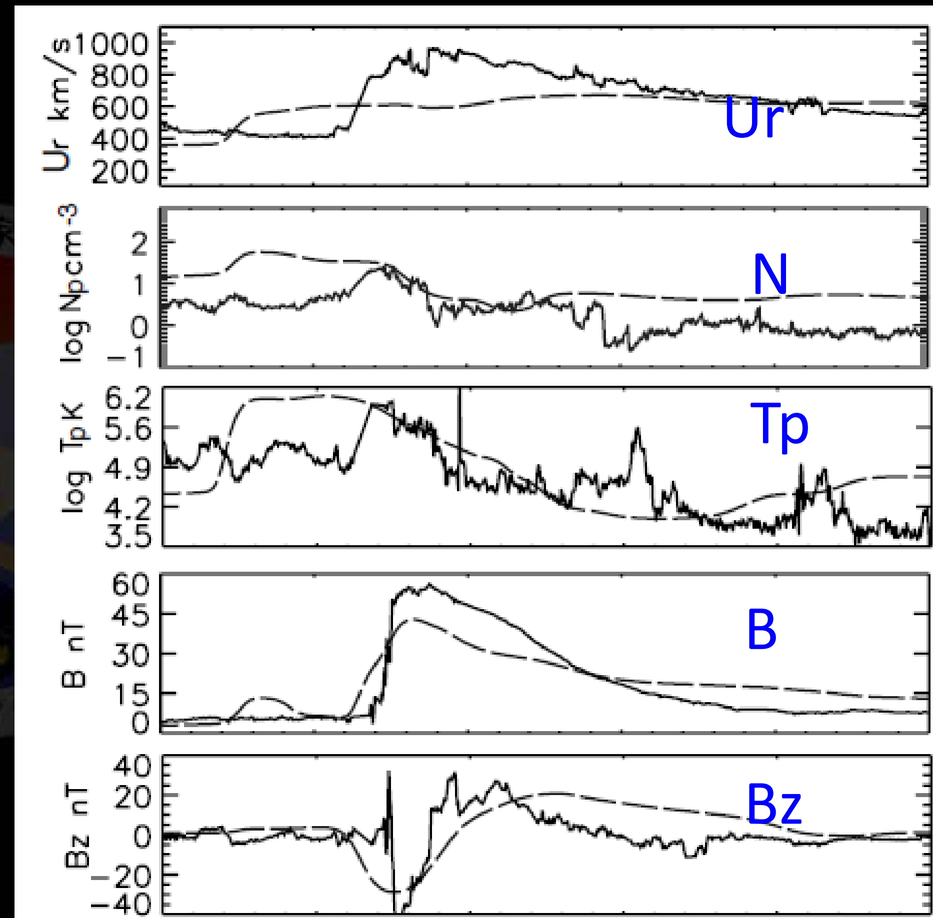
■Input: Synoptic map of photospheric magnetic field

■output: the solution from the Sun to 1AU or beyond

2.2 Applications to modeling CME

Manchester IV et al.(2014, PPCF) simulated the 13 May 2005 CME by initiating the CME with superimposing a magnetic flux rope in the streamer belt.





The structure of the CME 64 h later

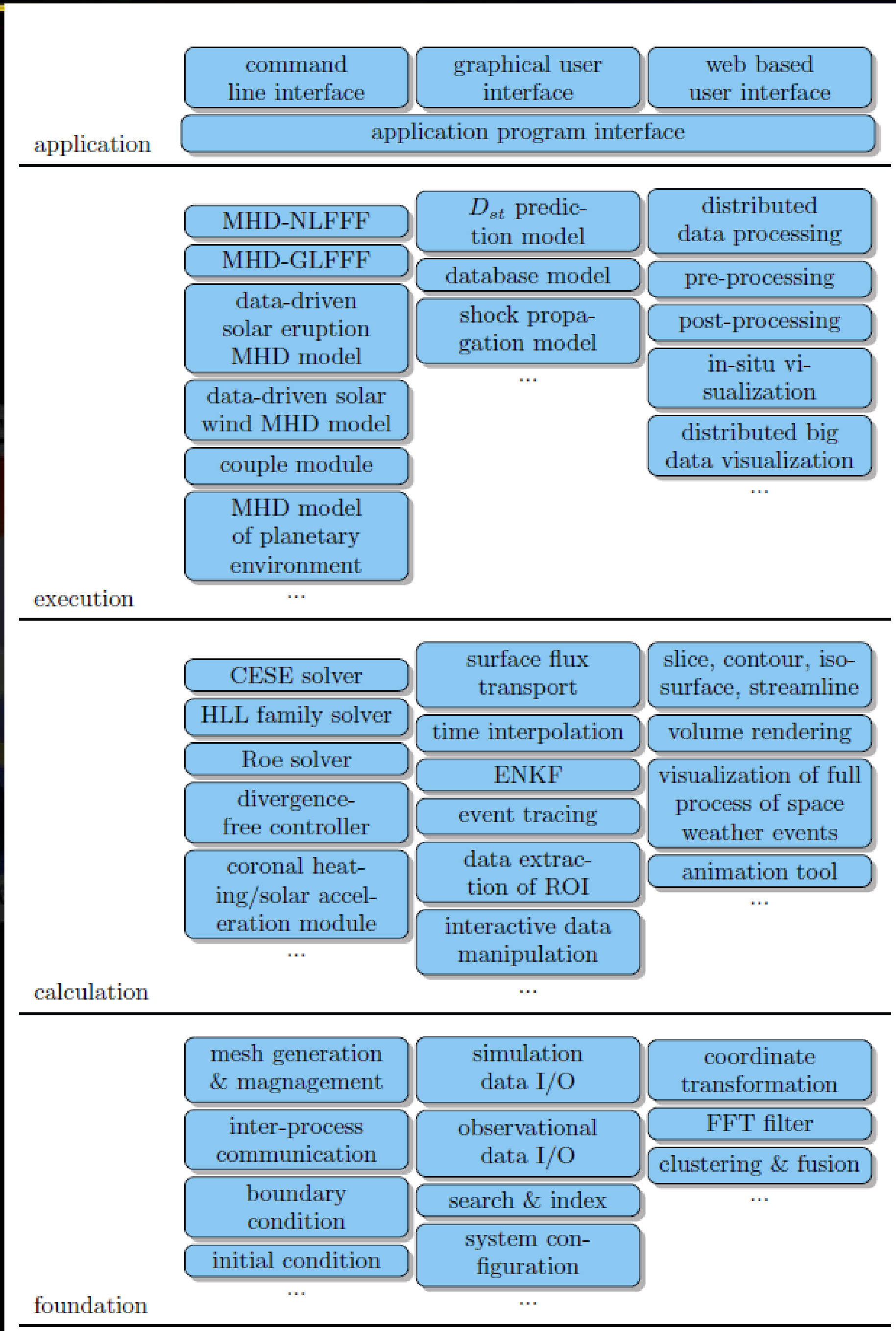
Time history of the CME as it passes the Earth

Manchester IV, W. B., et al. Plasma Phys. Control. Fusion 56 (2014) 064006

2.3 SIP-CESE in SWIM

The SIGMA weather group at the Key Laboratory for Space Weather of the CAS has developed a Space Weather Integrated Modeling (SWIM) system with layered structures

The numerical Schme is based on the space time Conservation Element and Solution Element (CESE) method

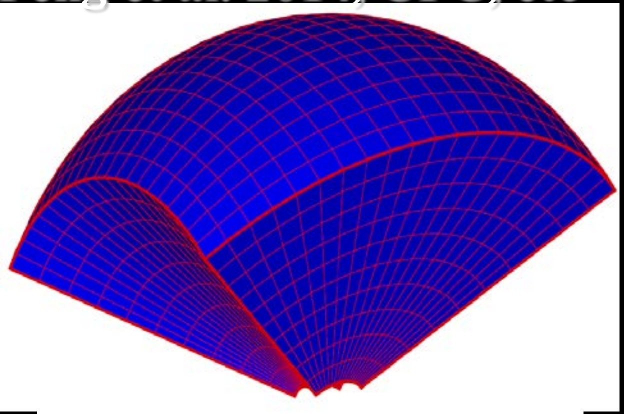


2.3.1 SIP-CESE in SWIM

*I. S*olar-*Inter**P*lanetary AMR *CESE M*odel (SIP-CESE MHD Model)

Feng et al., ApJ, 2007， JGR， 2009; Hu et al., 2008, JGR; Feng et al., APJ, 2010, 2011; Sol. Phys. 2012; Zhou and Feng, JGR, 2012, Feng et al. 2014, CPC, etc

► Grid in the solar corona



► **Scheme: Space-Time conservation**

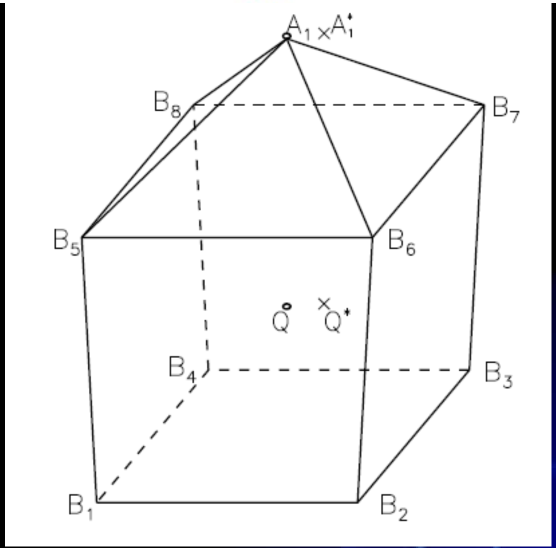
$$\frac{\partial u_m}{\partial t}+\frac{\partial f_m}{\partial x}+\frac{\partial g_m}{\partial y}+\frac{\partial h_m}{\partial z}=\eta_m$$

By Gauss's divergence theorem on space-time conservation cell Vxyzt we have

$$\oint_{S(V)} \vec{q}_m \cdot d\vec{S} = \int_V \eta_m dV$$

***S*(*V*) is the boundary of a space-time region Vxyzt**

which leads to the implicit solver of nonlinear equations.



Projection of space-time cell onto space domain

2.3.2 CESE is diff. from routine FVM/FD method

DI: According to Reynolds transport theorem

$$\frac{\partial}{\partial t}\int_{V_{ijk}} u_m dv + \oint_{S(V_{ijk})} (f_m n_x + g_m n_y + h_m n_z) ds = \int_{V_{ijk}} \eta_m dv$$

$$\int_{V_{ijk}} u_m dv \,\Big|_{t_1}^{t_2} = \int_{t_1}^{t_2} \left(-\oint_{S(V_{ijk})} (f_m n_x + g_m n_y + h_m n_z) ds + \int_{V_{ijk}} \eta_m dv \right)$$

The rate of change for the total amount of a substance in a fixed spatial cell V equals to the combination of : (i) the flux of that substance across the boundary S(V) of the cell, and (ii) the integration of the source term over the fixed cell.

$$\frac{d\mathbf{U}_{i,j,k}}{dt} = -\frac{1}{V_{i,j,k}} \sum_{m=1}^{N_f} \left(\vec{\mathbf{F}} \cdot \vec{n}\, \Delta A \right)_{i,j,k,m} + \bar{\mathbf{S}}_{i,j,k} + \bar{\mathbf{Q}}_{i,j,k} = \mathbf{R}_{i,j,k}(\mathbf{U})$$

The conventional finite volume methods concentrate on the evaluation of the right side. Some time integration solves the ODE above!

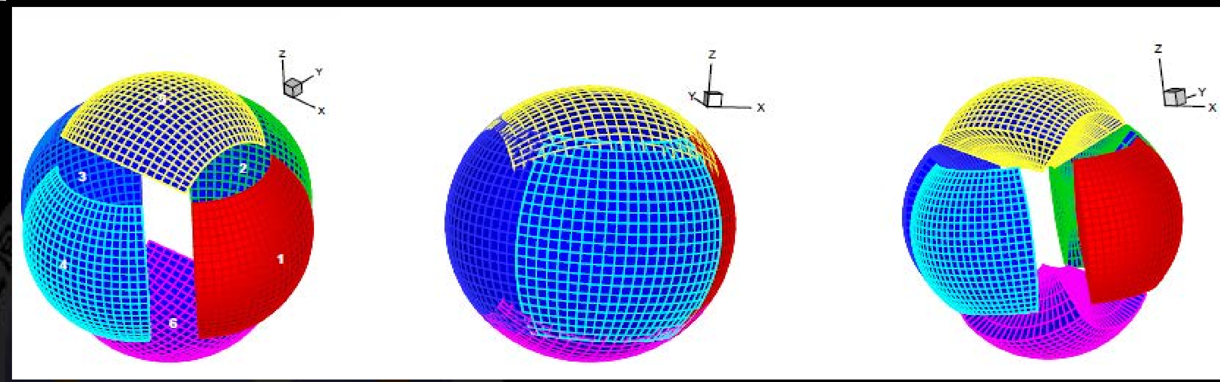
OURS is the space-time 4D volume integration →

$$\oint_{S(V)} \vec{q}_m \cdot d\vec{S} = \int_V \eta_m dV$$

DII: Grid System from the Sun to Earth space (Feng et al., APJ, 2010; 2011， Solar Physics， 2012)

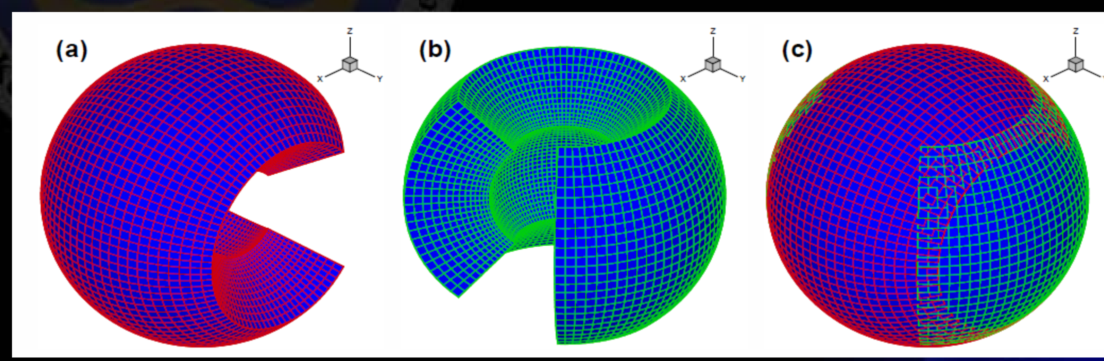
The advantages of this grid system are removal of polar singularities and easy parallel of the (theta,phi) directions

Overlapping Grids



Six-component Grid

Feng et al., ApJ, 2010

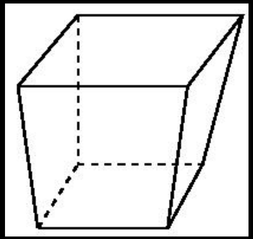


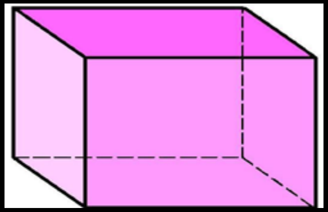
Two-component: Yin-Yang Grid by: Kageyama, J. Earth Simulator, 2005

Feng et al., ApJ, 2007， JGR， 2009; Hu et al., 2008, JGR; Feng et al., APJ, 2010, 2011; Sol. Phys. 2012; Zhou and Feng, JGR, 2012

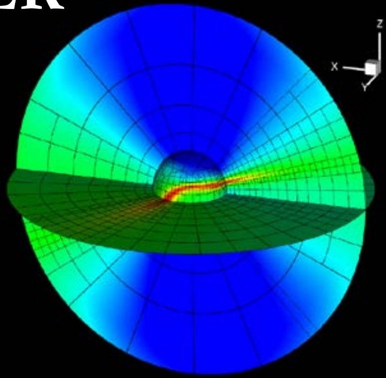
GPU accelerated with CPU/GPU CLUSTER

A) Coordinate transform (Feng et al., Solar Physics, 2012)

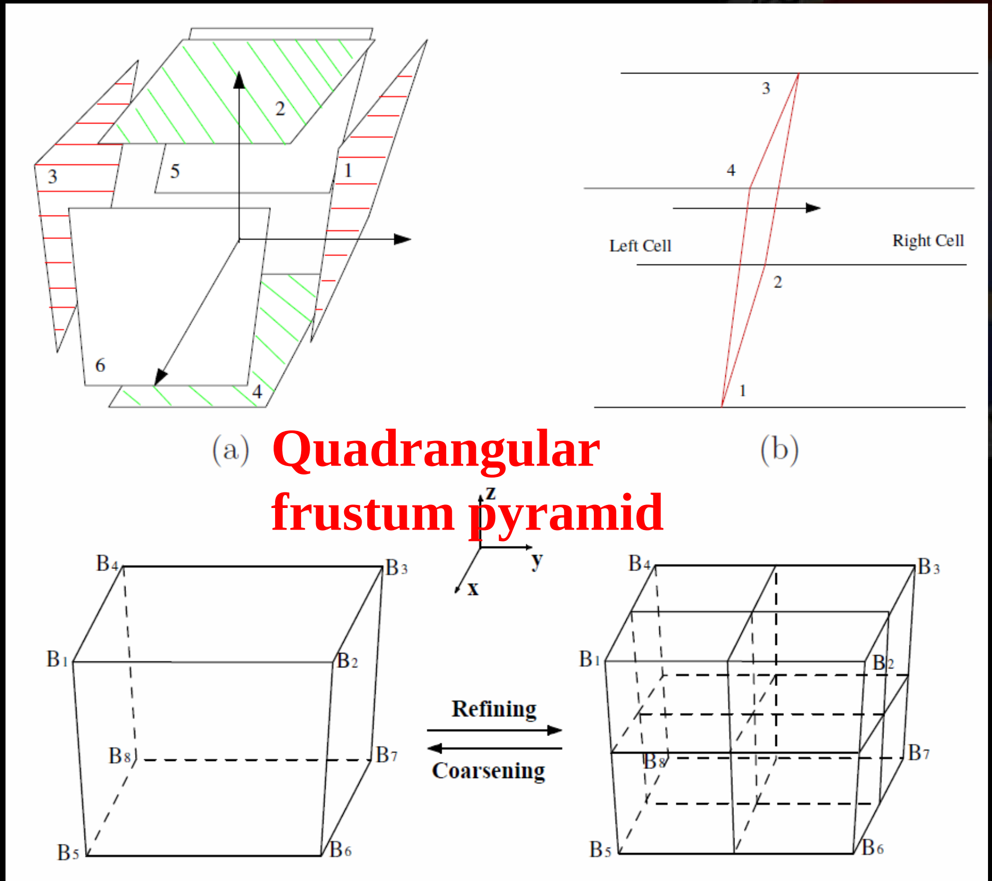




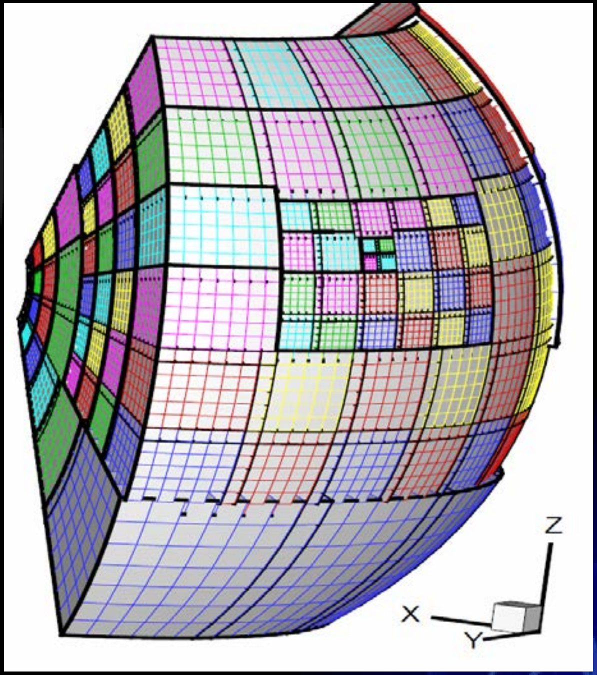
Refinement criterion of the curl of magnetic field



B) Direct AMR for such Polyhedron (Feng et al., CPC, 2014)



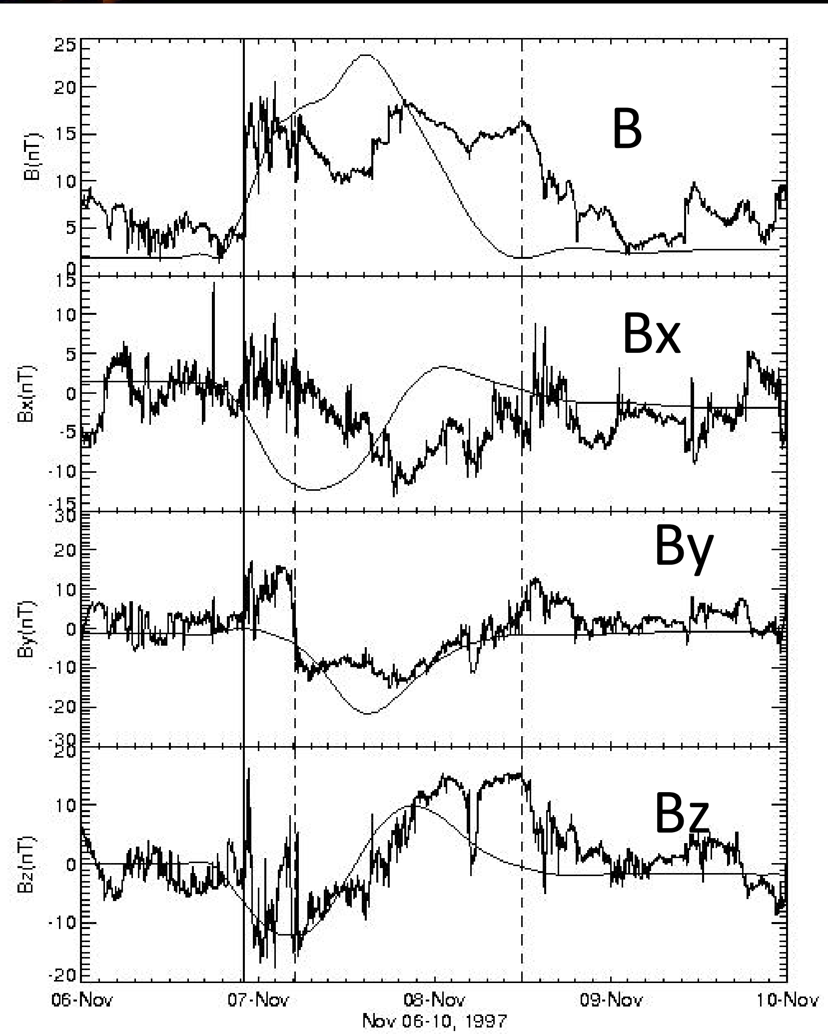
Quadrangular frustum pyramid



Berger–Oliger algorithm can be applied directly

2.3.3 Simulating Nov 4 1997 CME event

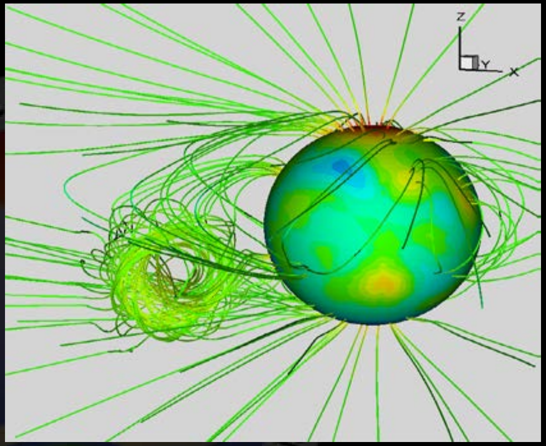
Numerical results at 1AU



Comparison with WIND

3D view of the initial coronal magnetic field. Field lines of the CME are shown in color to illustrate the magnetic field strength. The color contours are the radial magnetic field strength on the solar surface.

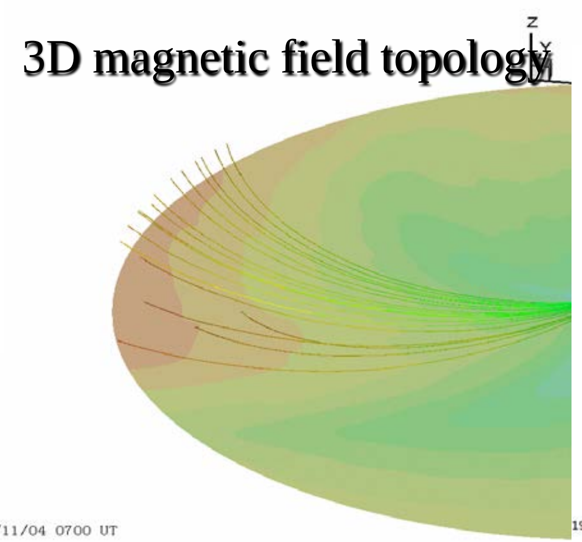
Zhou, Feng, JGR, 2012

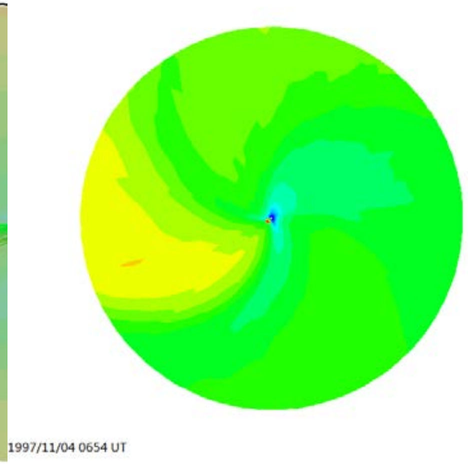


Use flux rope to mimick the CME

Evolution of radial velocity

3D magnetic field topology





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Brief Summary

◆Now 3D MHD modeling can reproduce the large-scale solar wind structures by using synoptic map of line-of-side photospheric magnetic field and can basically describe the variation trends of CMEs' propagation with mimicked CME model such as flux rope since there is no sound mechanism or available module for eruption process.

◆The physics-based MHD models are transitioning from research-oriented study to operational use.

◆It is difficult to capture the transitions for solar wind at solar maximum and CMEs' evolution with reasonable accuracy

◆There is a promising but long way to quantitatively match the observed IMF and to make forecasting with a lead time of one to three days.

3. Data-driven modeling for solar-interplanetary process

By data-driven modeling, we mean to use continuously time-varying solar observations as input to drive models to produce solar wind background and reproduce eruptive process of solar active region, instead of using one instanteous cadence of observation as input!

The idea is to Let data & MHD tell us what is going on ?

REF: Feng et al., ApJ(2012), SolPhy(2012); Yang et al., JGR(2012);
Jiang,Feng et al., 2012, ApJ(749, 759), SolPhy; 2013 ApJ(769);
Jiang & Feng, 2013, ApJL(771); Feng et al., CPC, 2014

3.1 Data-driven Solar Wind Model: From 1Rs to 1AU

Solar wind is rather than of steady state, but physically dynamic corresponding to the solar rotation, solar mass flow and solar magnetic field evolution. In fact, solar wind is constantly time varying.

Currently, we use the global photospheric mag field maps generated by the solar surface flux Transport (SFT) model for long-term synoptic data or Time Interpolation for short-term synoptic data as input to drive our CESE-MHD solar wind model.

Result: Improved, high quality "snapshots" of the Sun's global magnetic field as the input to drive our 3D numerical global coronal AMR-CESE-MHD model

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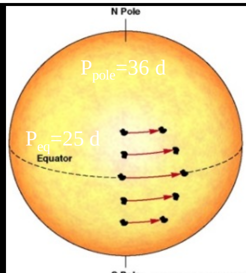
Surface flux transport (SFT) Model

Combine long-term synoptic data such 1 Carrington rotation (27 days' data from WSO, MDI/SOHO), with SFT model to get the snapshot of magnetic by considering differential rotation $\Omega(\theta)$ & meridian flow $v(\theta)$

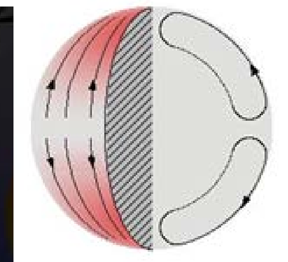
(1) Differential rotation

$$\Omega(\theta) = 0.18 - 2.3\cos^2\theta - 1.62\cos^4\theta \text{ deg day}^{-1}$$

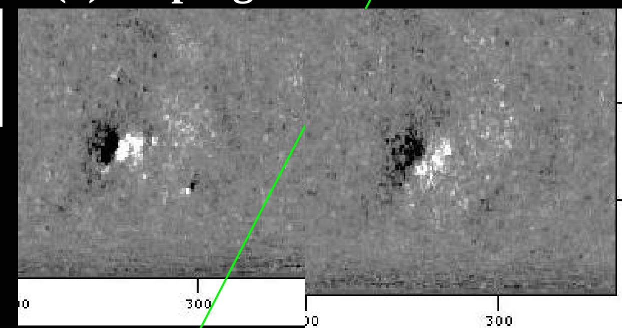


(2) Meridional flow

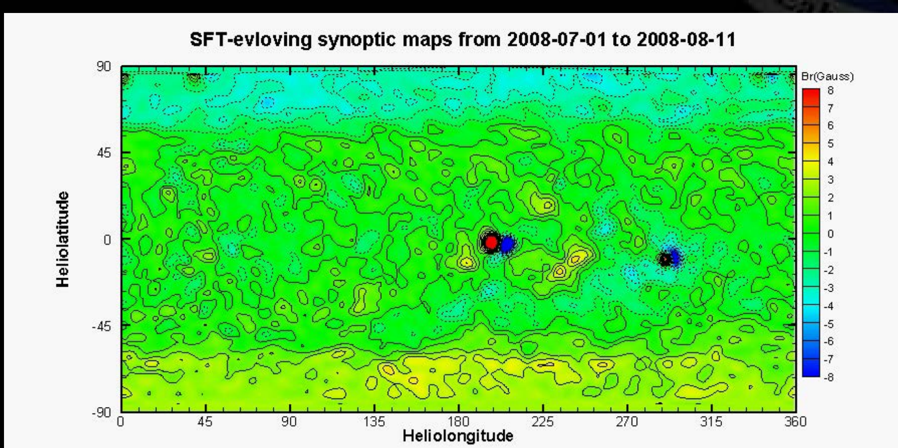
$$v_\theta(\theta) = C\cos\left[\frac{\pi(\theta_{\max}+\theta_{\min}-2\theta)}{2(\theta_{\max}-\theta_{\min})}\right]\cos\theta$$



(3) Supergranular diffusion



$$\frac{\partial B_r}{\partial t} = -\Omega(\theta)\frac{\partial B_r}{\partial \phi} - \frac{1}{R_S\sin\theta}\frac{\partial}{\partial\theta}\left[v(\theta)B_r\sin\theta\right] + \frac{D}{R_S^2}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial B_r}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2 B_r}{\partial\phi^2}\right] + S(\theta,\phi,t)$$

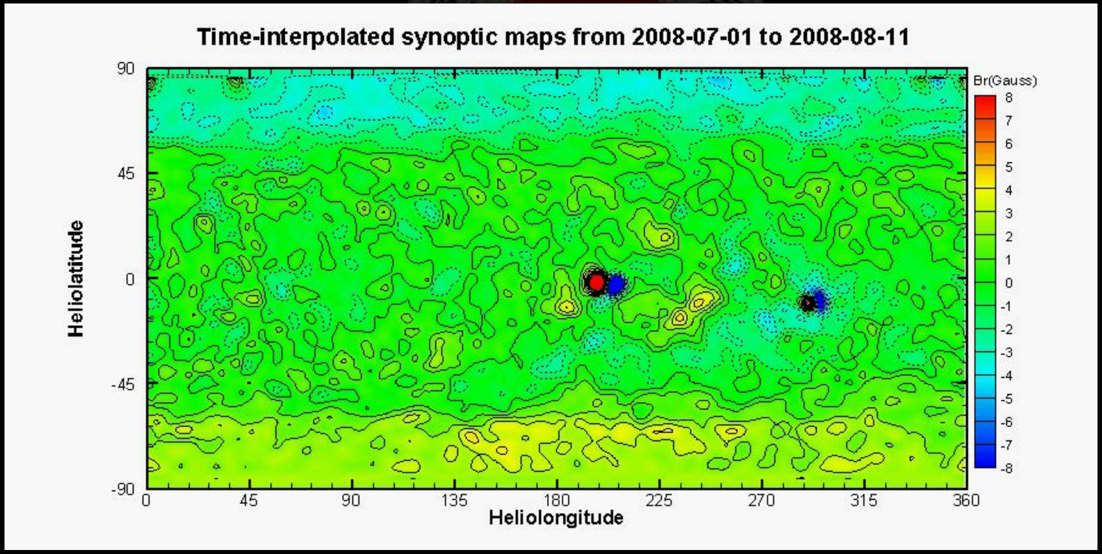


The SFT model (Yeates, ApJ, 2010) describes the time evolution of radial component of large-scale photospheric magnetic field, which accounts for known flows in the solar photosphere with differential rotation & meridian flow.

Time Interpolation

Use consecutive synoptic maps of GONG (6-hour), HMI/SDO (1-day) to achieve the snapshot of magnetic field

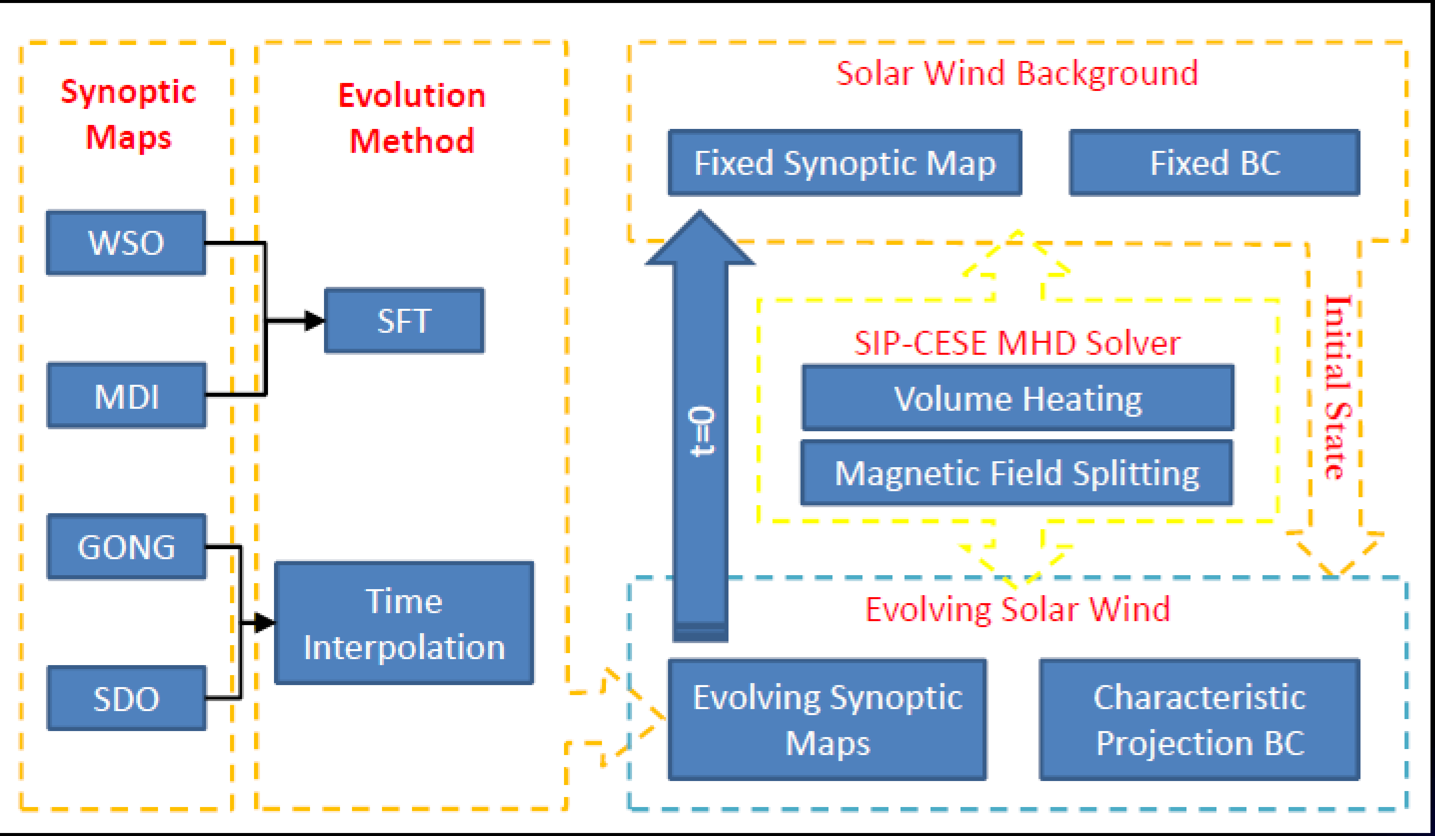
$$B_r(t) = \frac{(t-t_2)(t-t_3)}{(t_1-t_2)(t_1-t_3)} B_{r,1} + \frac{(t-t_1)(t-t_3)}{(t_2-t_1)(t_2-t_3)} B_{r,2} + \frac{(t-t_1)(t-t_2)}{(t_3-t_1)(t_3-t_2)} B_{r,3}$$



This kind of data processing method is aimed to provide snapshot of global magnetic maps

Data-driven Procedure

As usual, obtain 3D solar wind background before the period investigated. Based on this steady-state, our data-driven procedure starts!

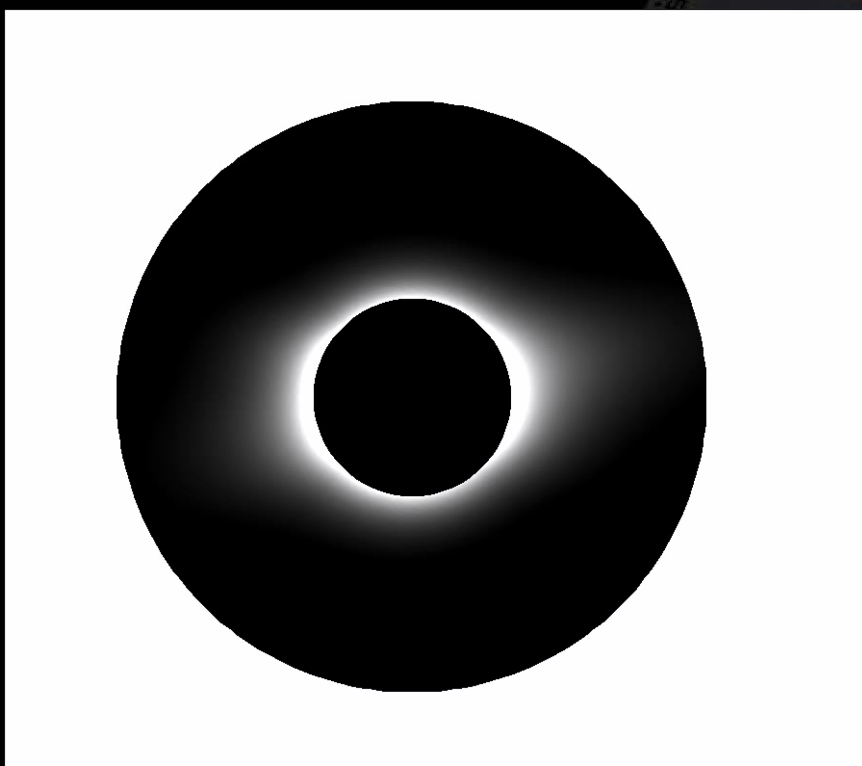


Initialize 3D code with background solar wind obtained , Evolve synoptic maps (SFT or time interpolation) for specified period with time-dependent boundary conditions at 1Rs

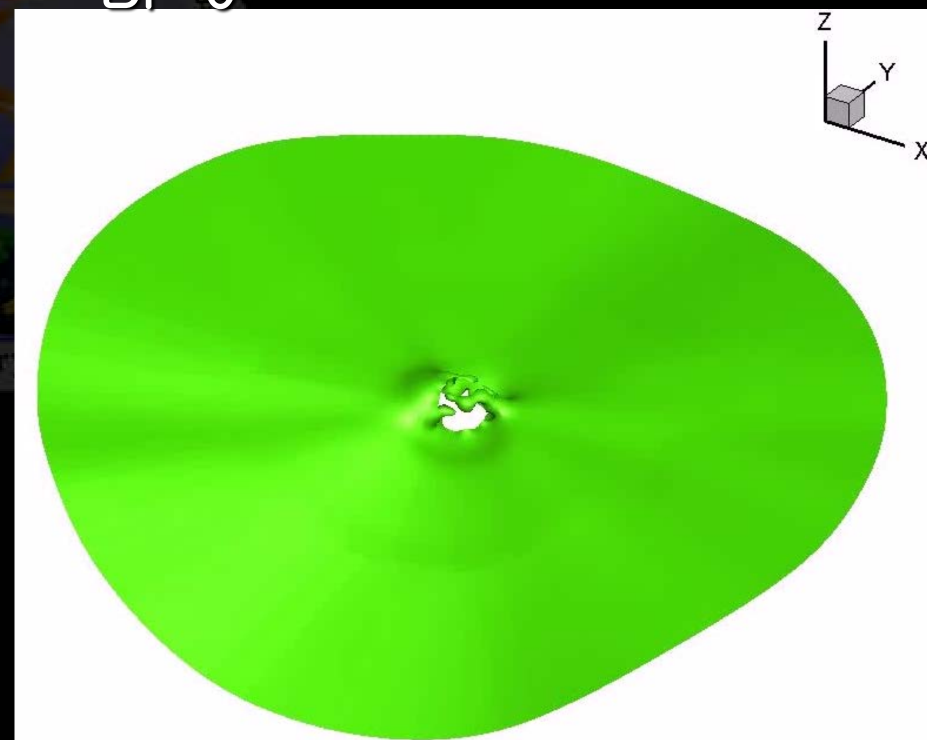
Simulation Results From 2008-07-01 to 2008-08-11

- **GONG consecutive 6-hour synoptic maps as input**
- **Can be continued with more synoptic map input**

Simulated Coronal Brightness



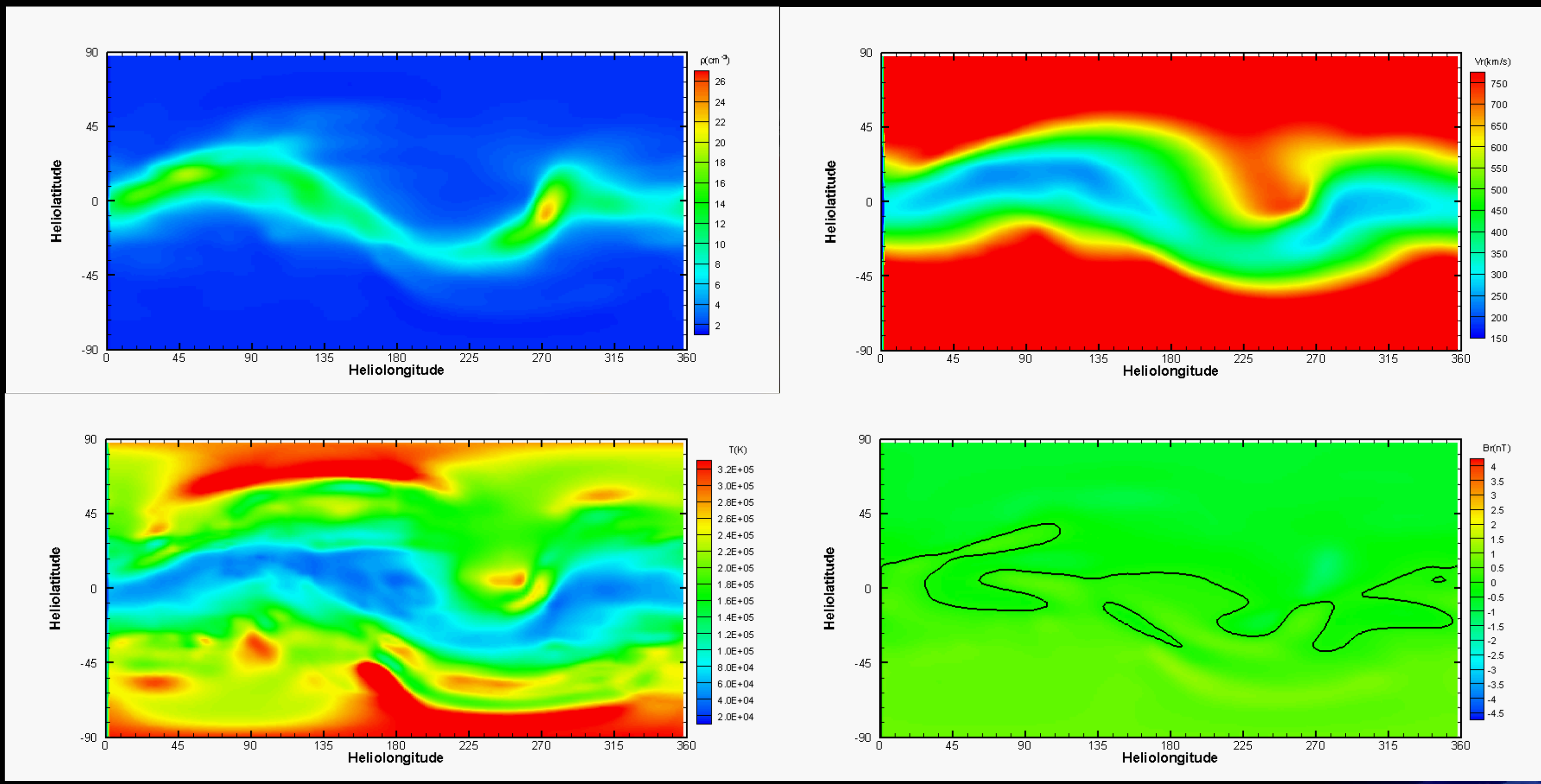
Heliospheric Current Sheet: Iso-surface of Br=0



Contours at 1AU

Number density

radial speed

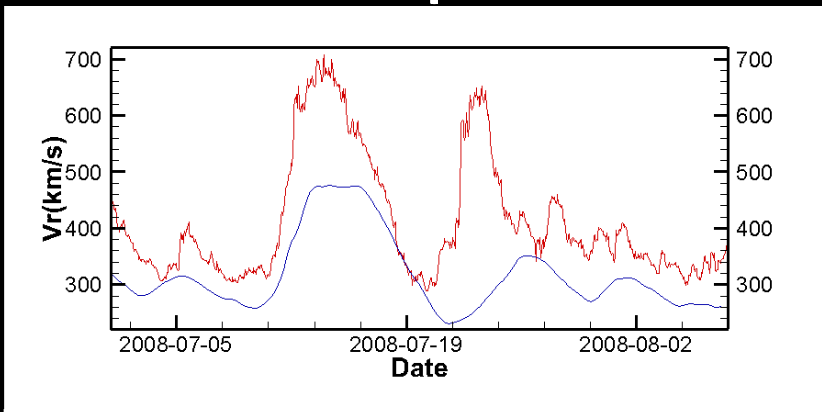


Temperature

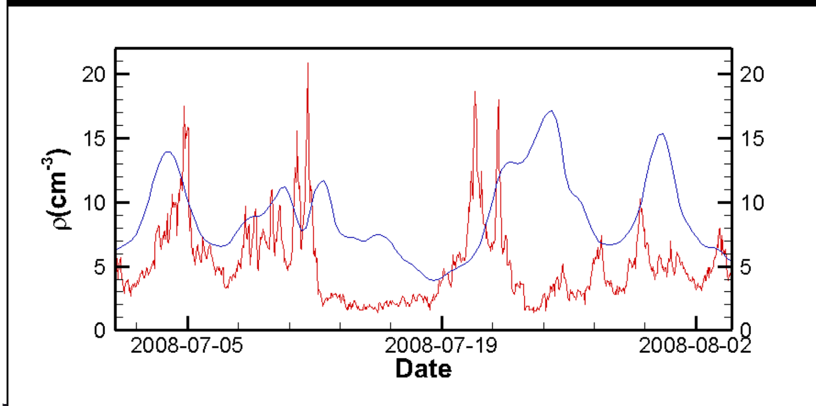
Br

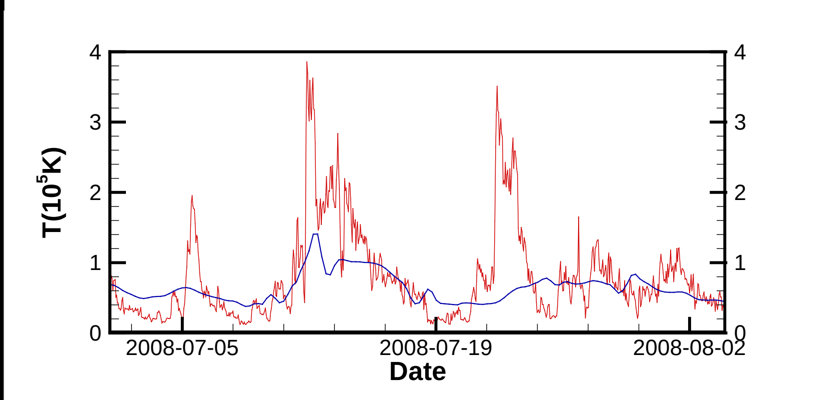
Compared with OMNI Data at 1AU

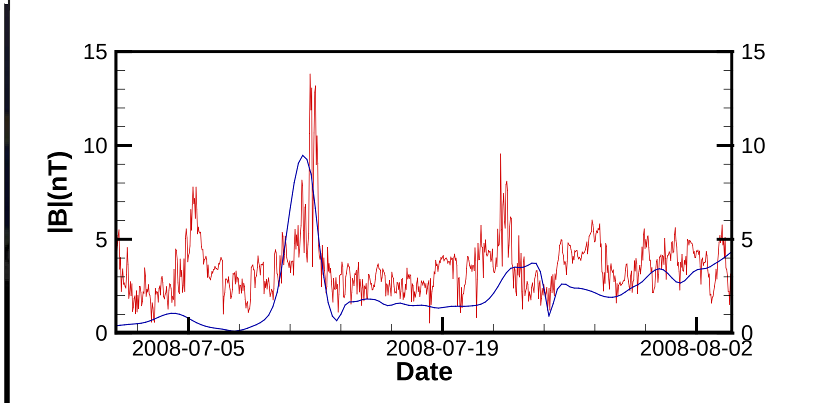
Radial speed



Number density







Temperature

B

In brief

With continuously observed magnetic field data as input, our model can be able

1. to simulate long-term evolution of solar wind (several Carrington rotations or even longer).

2. to give solar wind parameters from corona to 1AU, by providing time-dependent structures of the solar wind.

High time-cadence resolution magnetic field data will achieve high agreement with observation

3.2 Data-Driven Modeling for Active Region Evolutions and Eruptions

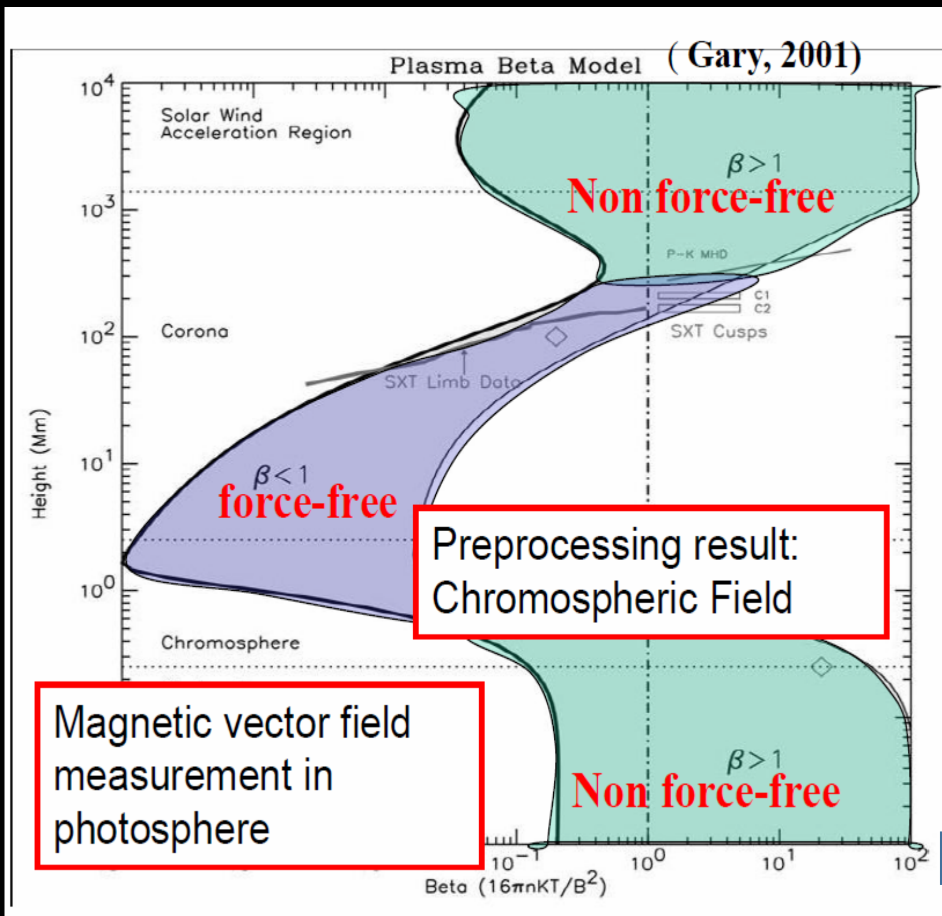
- Understanding how the coronal magnetic fields erupt to produce flares and coronal mass ejections (CMEs) is fundamental to solar physics and crucial in space weather forecasting

- Based on our models & the booming data provided by SDO, a realistic 3D evolution process for an eruption event from all over its formation to disruption can be produced

This kind of study can lead to understanding how the eruptions are triggered and driven

Why full MHD

The plasma beta changes with height： the non-force-free effects in the two beta regions which sandwich the mid-corona



Under condition beta<<1

Nonlinear Force-Free Coronal Magnetic Fields

$$(\nabla \times \mathbf{B}) \times \mathbf{B} = 0, \quad \nabla \cdot \mathbf{B} = 0 \quad \Longleftrightarrow \quad \nabla \times \mathbf{B} = \alpha \mathbf{B}, \quad \mathbf{B} \cdot \nabla \alpha = 0$$

Equivalent

used for coronal & active region mag field reconstruction

the unknown boundary conditions on the field and velocities

Full set of MHD is more suitable since coroa is not force-free verywhere

Data-Driven CESE-MHD Model for Active regions

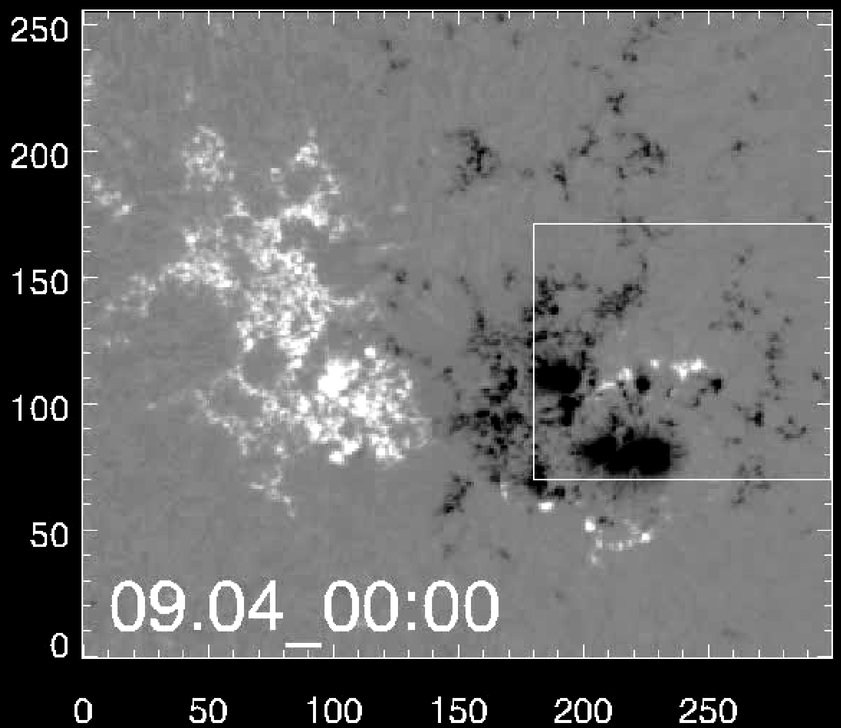
1. Full set of MHD Equations
2. Driven by pre-eruption time-sequence data of vector magnetograms for active region with HMI/SDO

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0,$$

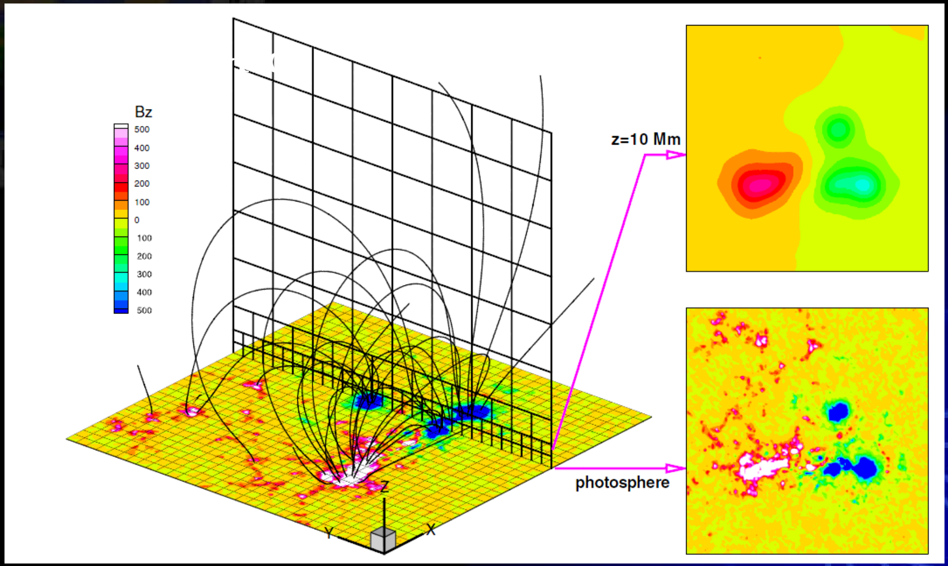
$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v}),$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}),$$

$$\frac{\partial T}{\partial t} + \nabla \cdot (T\mathbf{v}) = (2-\gamma) T \nabla \cdot \mathbf{v} + Q.$$



Finest grids match the magnetogram (e.g., 0.5 arcsec for HMI data); coarsest resolution~4 arcsec By AMR technique

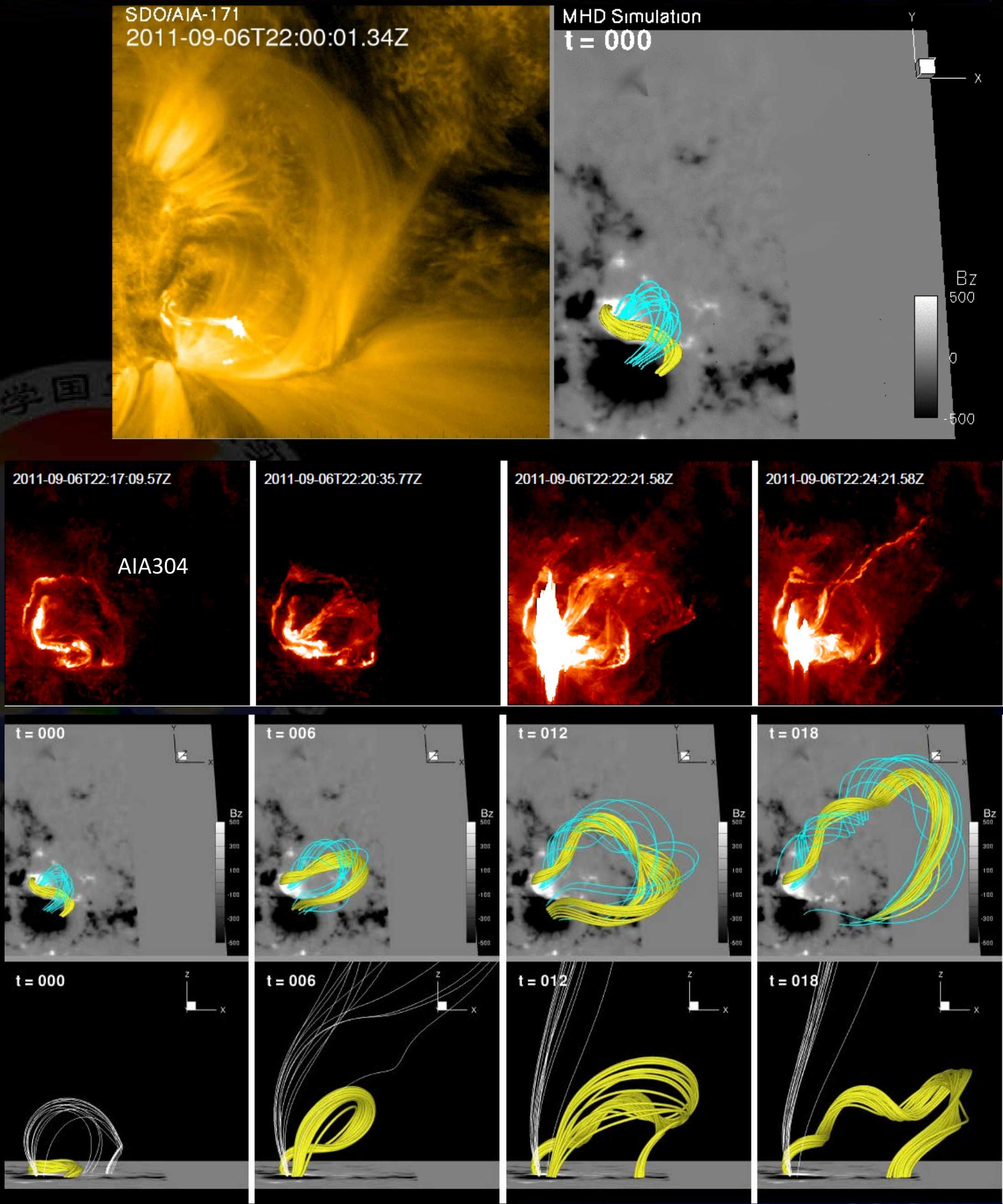


Formation and Eruption of a Sigmoid in AR 11283

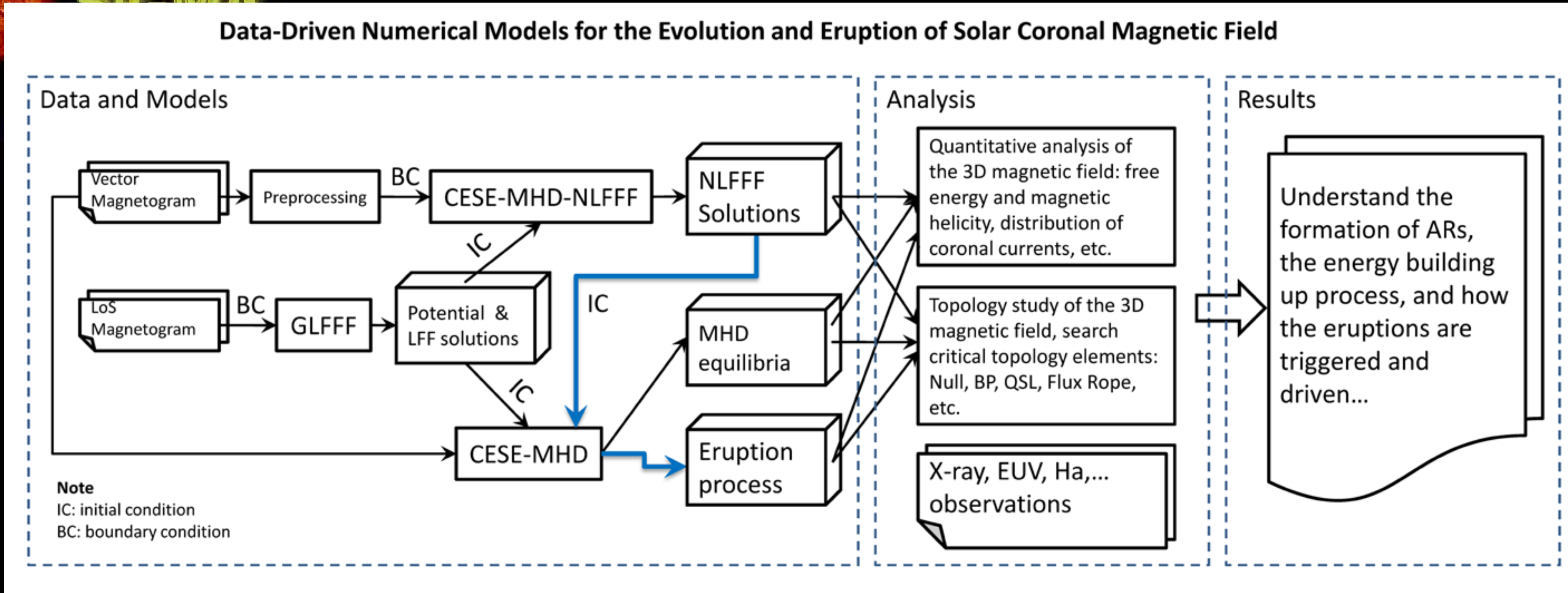
- Simulation confirms the general picture for eruption mechanism: overlying closed flux (white lines) , reconnected and opened, followed by the rapid rising of the sigmoidal flux rope

- basically good resemblance with AIA observed

Jiang, Feng and Wu, ApJL, 2013, 771: L30 ; ApJ,2014, 780:55



Yellow and Cyan lines are the core field lines, expand/erupt
White lines: field lines overlaying the sigmoid, reconnected/open



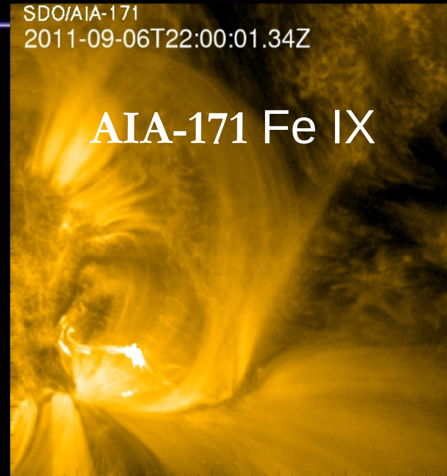
In brief: We can simulate the initiation process for the eruption event， as supported by observations

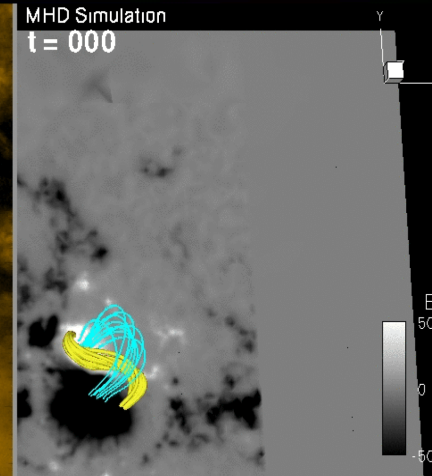
This MHD process for active region can be used for the evolution study of the solar eruption from the Sun to Earth.

Ref: Jiang & Feng et al 2012, ApJ; 2013, ApJL:ApJ,2014

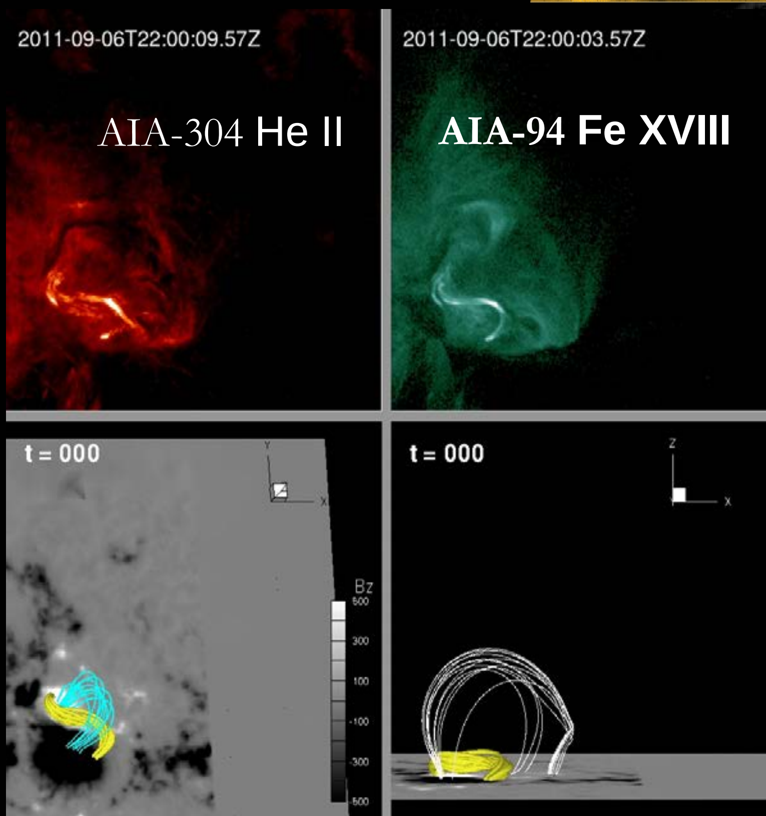
SIP-CESE-MHD model：CME evolution from the Sun to Earth

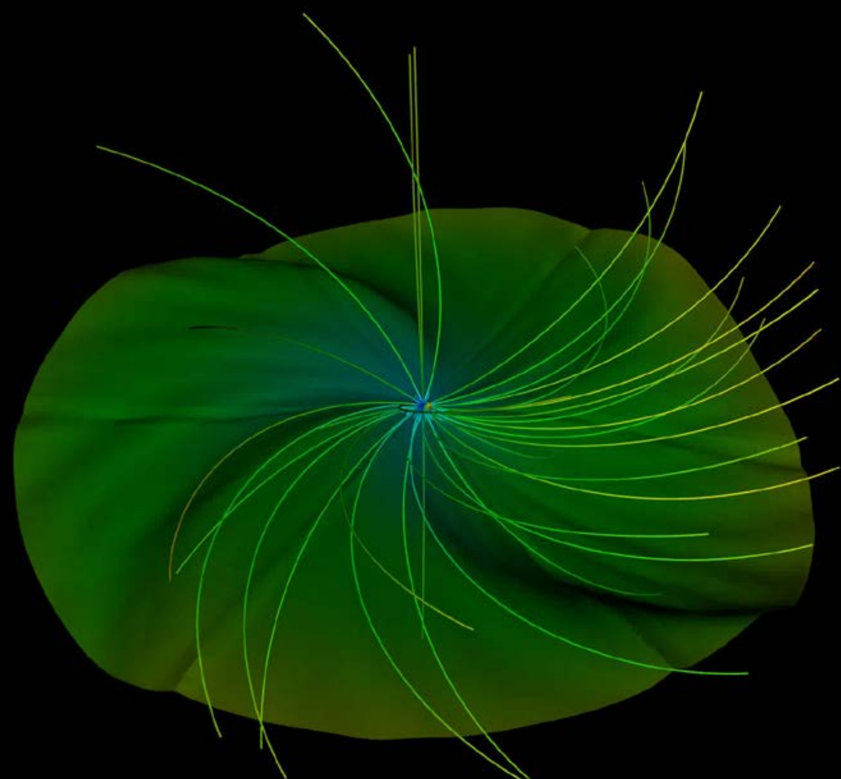
taking images that span at least 1.3 solar diameters in multiple wavelengths nearly simultaneously, at a resolution of ~ 1 arcsec and at a cadence of 10 s or better.





- Numerical results from active region MHD model + solar wind model driven by observed data (HMI/SDO、GONG data)





4. Future Avenue

There is tremendous progress in the physics based models!

- **Data-driven model seems promising to self-consistently combine eruption model and background model to avoid the ambiguity of eruption mechanism!**

- **Modeling and predicting solar storm is extremely challenging:**
  A) Disparate spatial and temporal scales!
  B) Diverse and complex physical systems!
  C) Limited observations!

- **Verification, validation and continuous testing are all required!**

Some Specifics for Future Avenue

◆To incorporate the new findings of coronal heating/solar wind acceleration, and the initialization process of CMEs into physics-based models.

◆To design different data assimilation methods to improve the prediction accuracy

◆Numerical schemes and computers have to keep up with the computational needs of the increasingly sophisticated models.

◆To facilitate input/output as well as in-situ visualization of massive data during calculation

All these above considerations will help the physics-based models to better track and predict the propagation of the solar storms from the Sun to Earth.

Thank you for your attention

Special thanks goes to all our organizers of SOC & LOC for the meeting