MHD Simulation of Interplanetary Propagation of Multiple Coronal Mass Ejections with Internal Magnetic Flux Rope (SUSANOO-CME)

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This work is accepted to Space Weather on Jan.14
http://onlinelibrary.wiley.com/doi/10.1002/2015SW001308/
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Science for Space Weather

@Goa, India, 2016.1.28

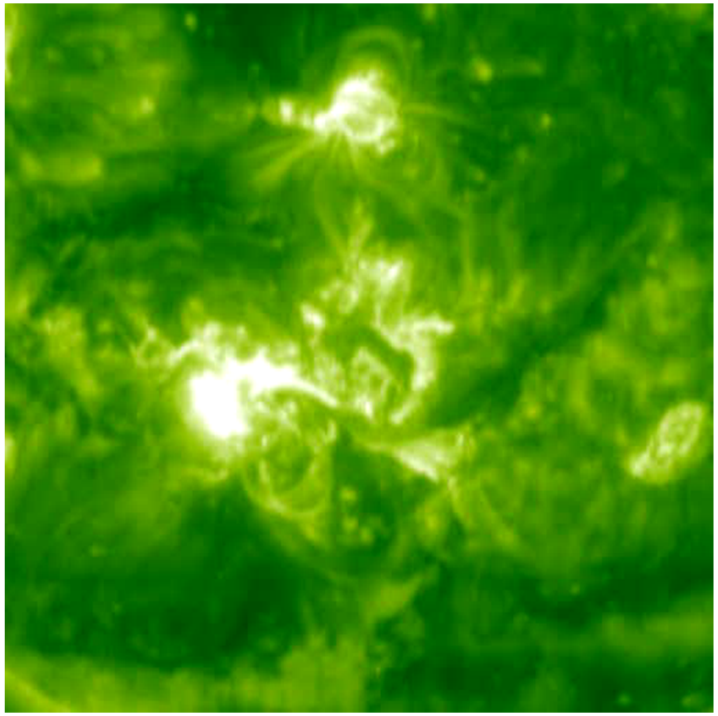
Outline of This talk

- Introduction
- Solar wind model: SUSANOO-SW
- CME model: SUSANOO-CME
- Discussion
- Summary

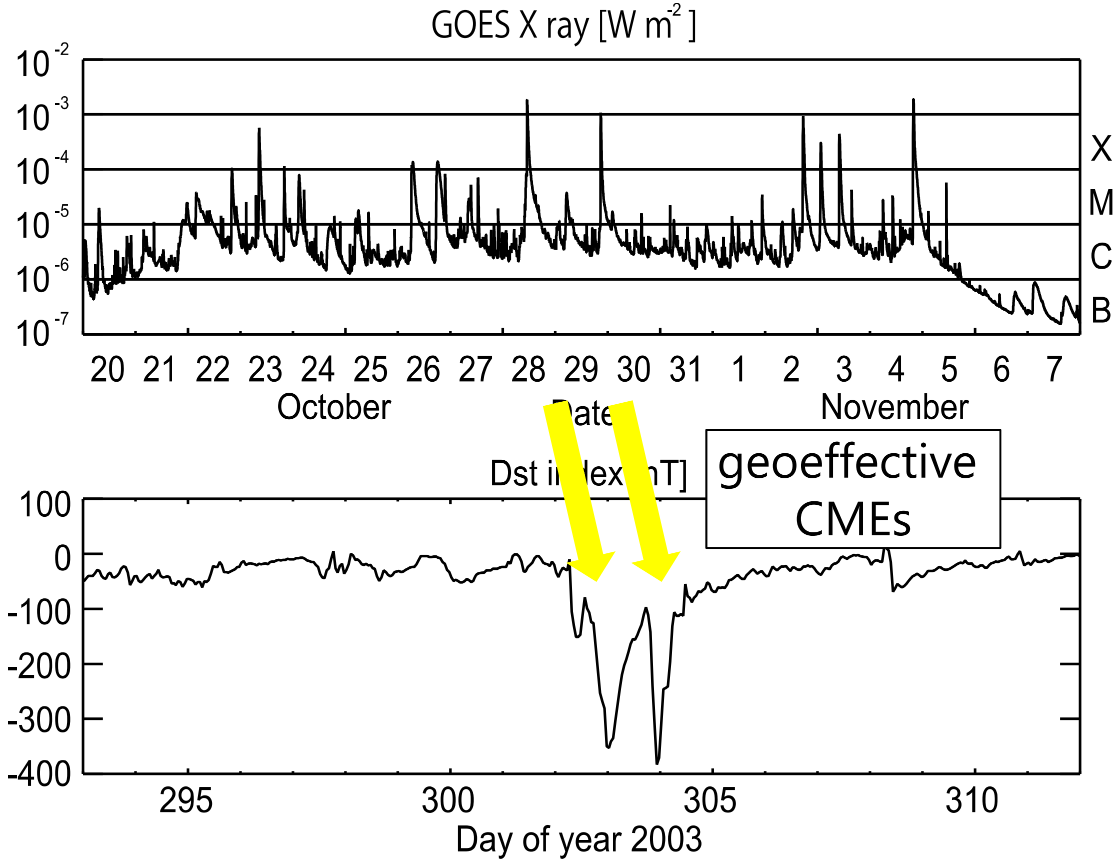
Flares and geoeffective CMEs

Flares-CMEs in October-November 2003 (the Halloween events).

- Many large solar flares occurred (ex. NOAA 10486)

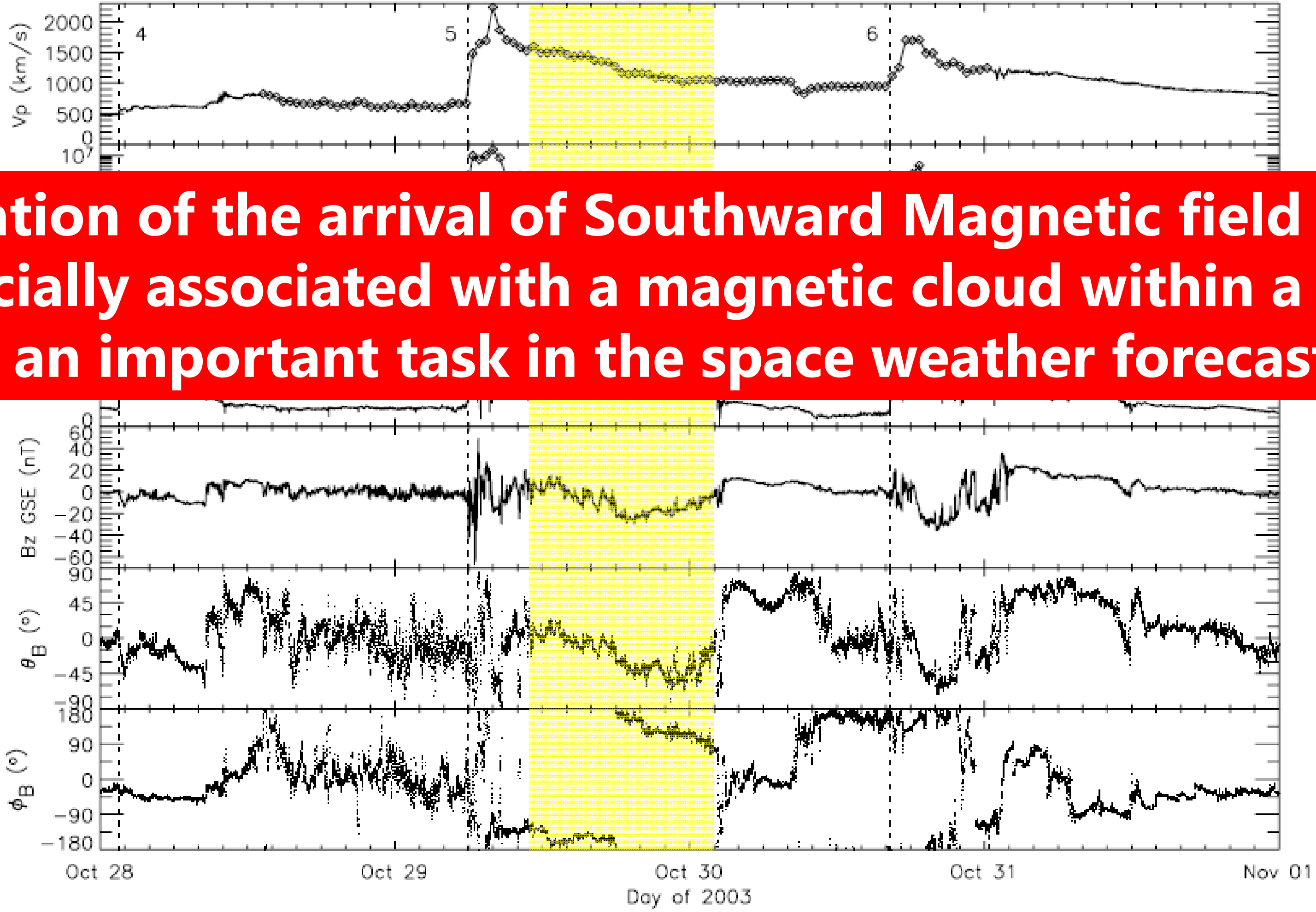


- EIT and LASCO movies of the flare on Oct. 28, 2003 (Halloween storm)



Important structures of geoeffective CMEs

Flux ropes (or Magnetic clouds)



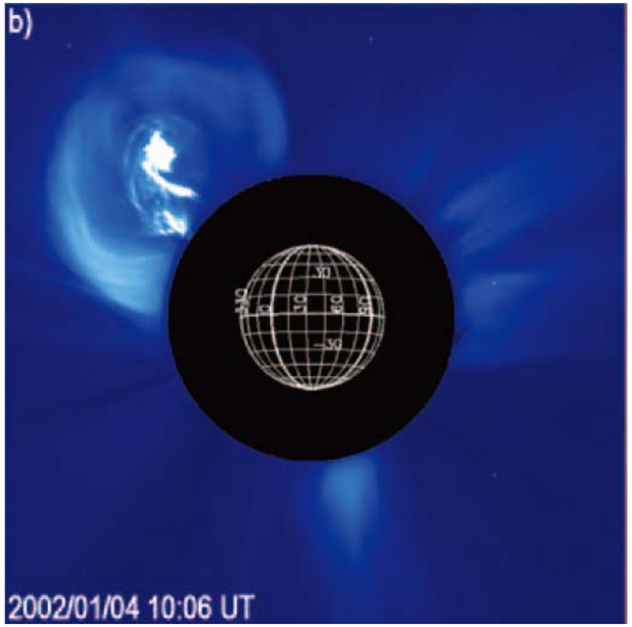
Estimation of the arrival of Southward Magnetic field (SBz) especially associated with a magnetic cloud within a CME is an important task in the space weather forecast

In situ measurement 4 days from Oct. 28, 2003 (Skoug + 2004)

Flux ropes within CMEs

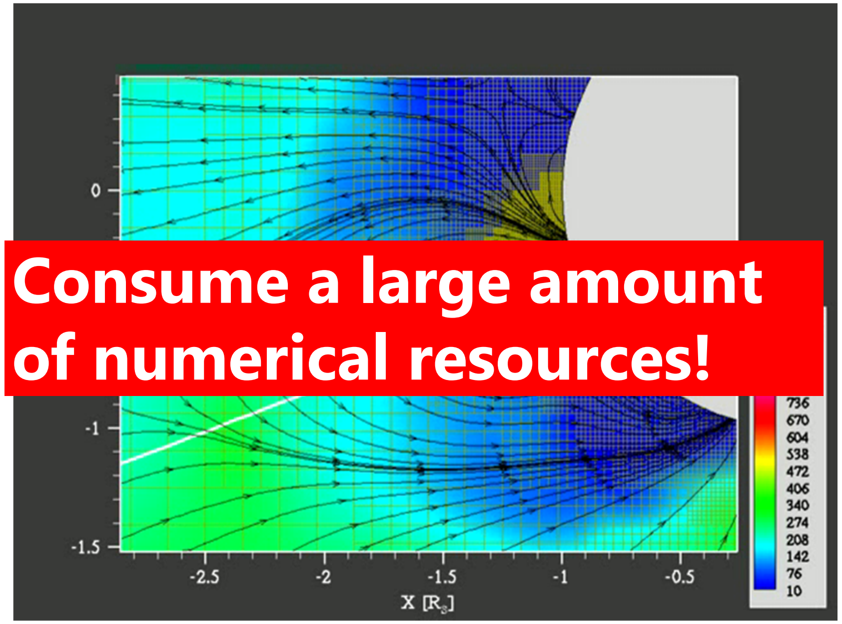
Modeling the magnetic field configuration of a flux rope
<= whole evolution of the flux rope from its origin

A helical flux rope formed as a result of a solar eruption



(Cremades & Bothmer 2004)

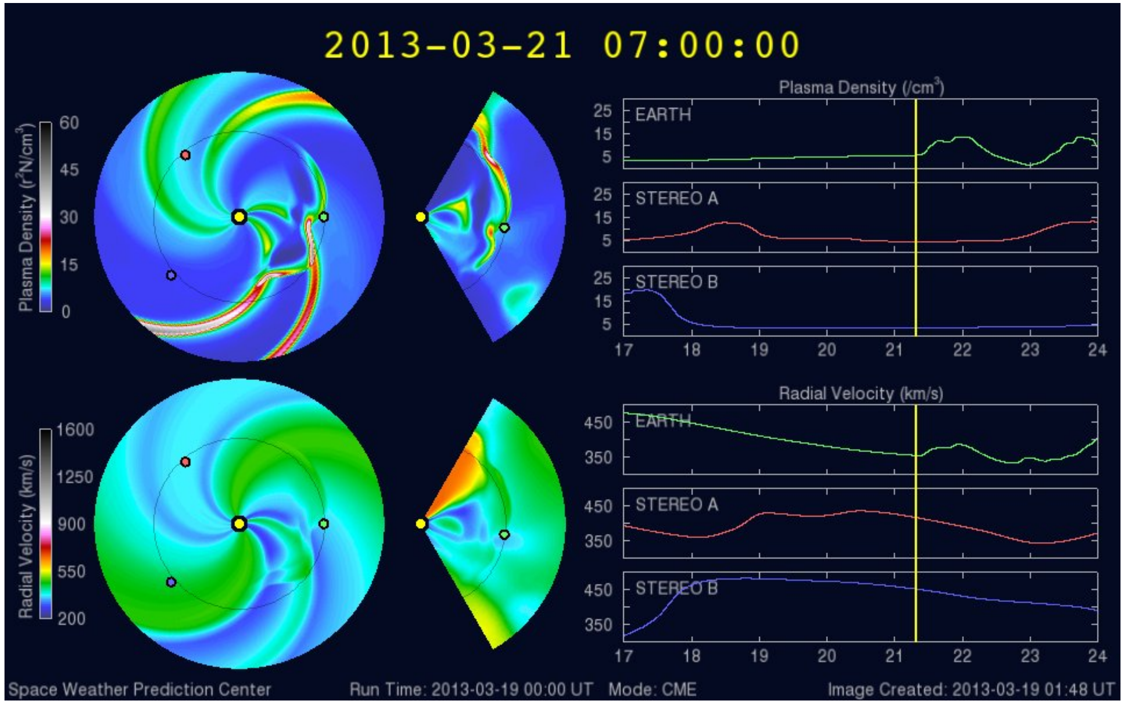
MHD simulation continuous from the solar corona



Consume a large amount of numerical resources!

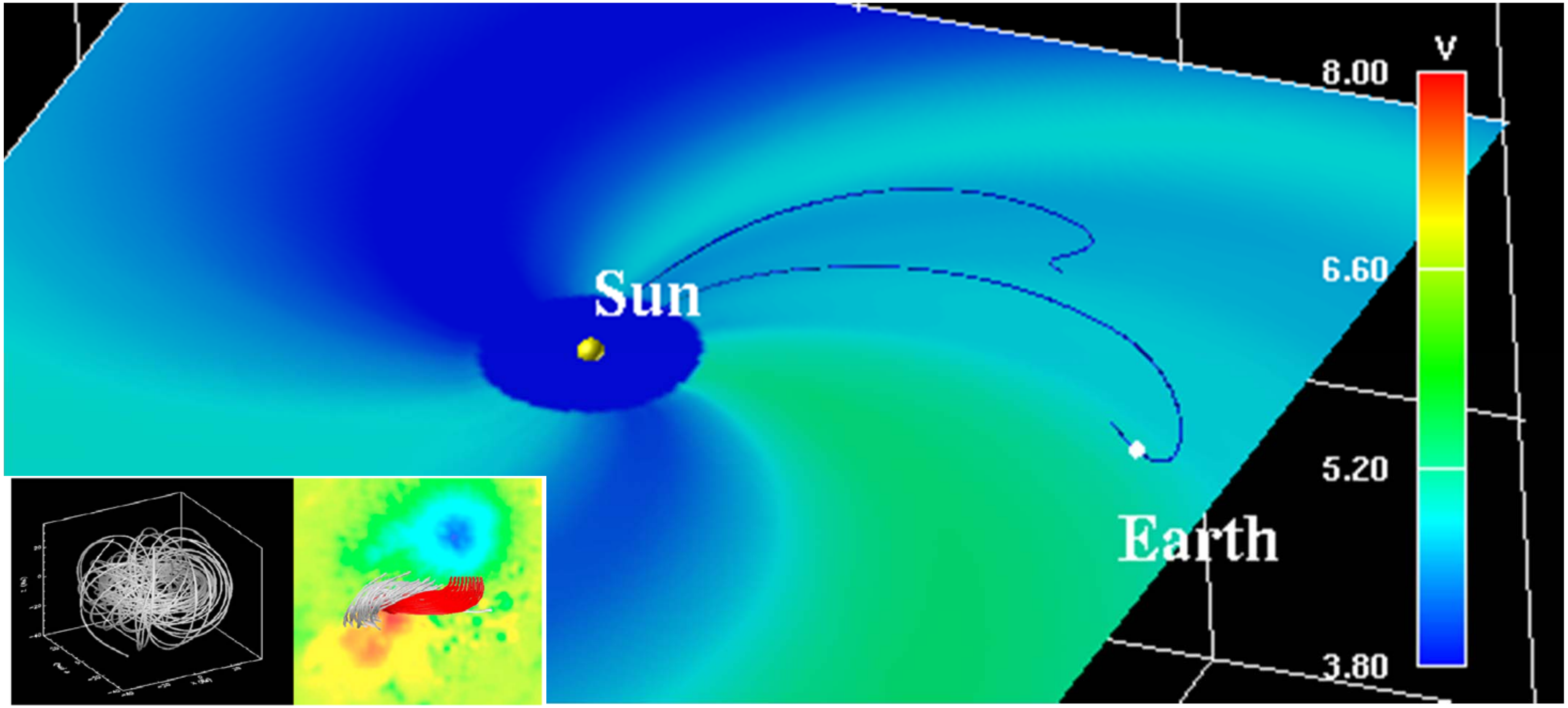
(Roussev + 2004)

WSA-ENLIL + cone model



- WSA-ENLIL(Odstrcil 2003) + cone model has been often used for space weather forecast operations in NASA and NOAA.
- The cone model incorporates **a hydrodynamic pulse (without internal magnetic flux rope)** into solar wind MHD simulation and hence is useful for a shock arrival time forecast but **not suitable to predict an intense magnetic storm** caused by the passage of a magnetic cloud within a CME.

CME model with internal magnetic flux rope



- Kataoka+ (2009) proposed a model to inject a **CME that includes an internal magnetic flux rope** into 3D solar wind.
- In this study, we modified the model specifying its parameters on the basis of solar observations. (SUSANOO-CME)

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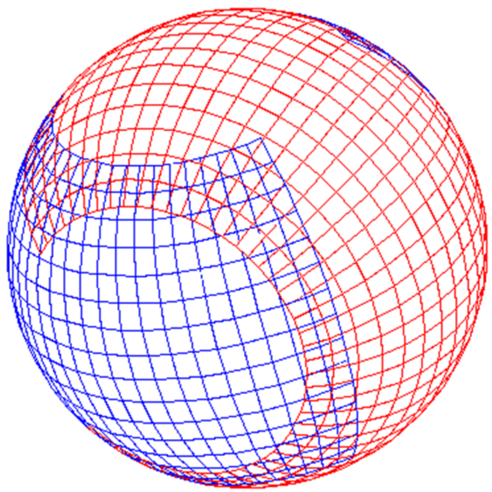
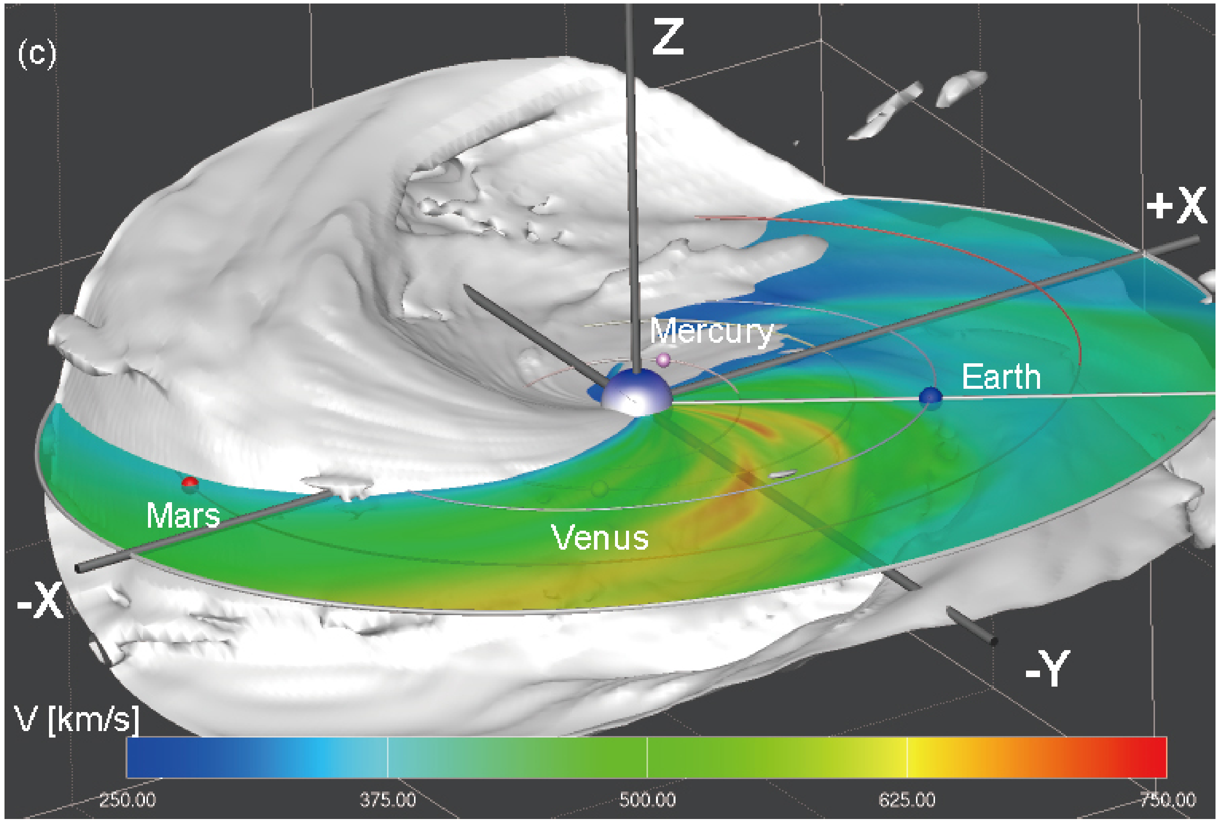
Solar wind MHD model: SUSANOO-SW

(Shiota+ 2014, Space Weather)

- Numerical domain in
  25 Rs ≦ r ≦ 425 Rs (~ 2 au)
- Yinyang Grid
  (202 × 68 × 192 × 2)
- Inner boundary
  solar wind map
  rotating and time-
  dependent
- Planets are revolving





Heliographic inertial coordinate
Solar wind map on the ecliptic plane
Colors: velocity on ecliptic plane
White surface: neutral sheet

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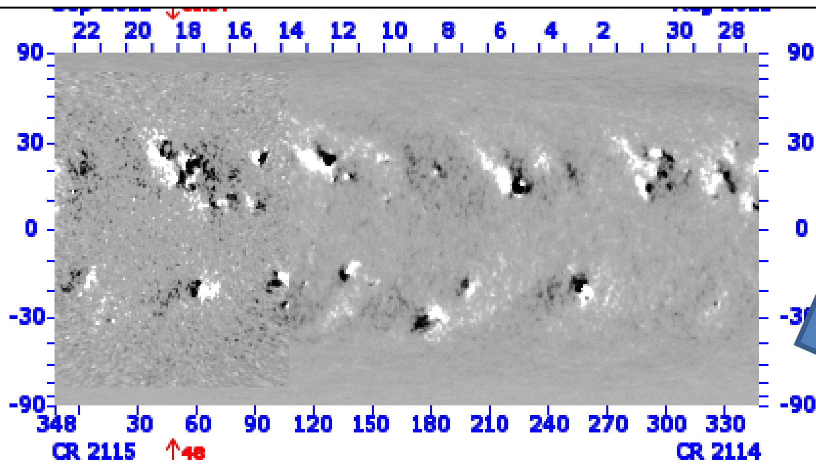
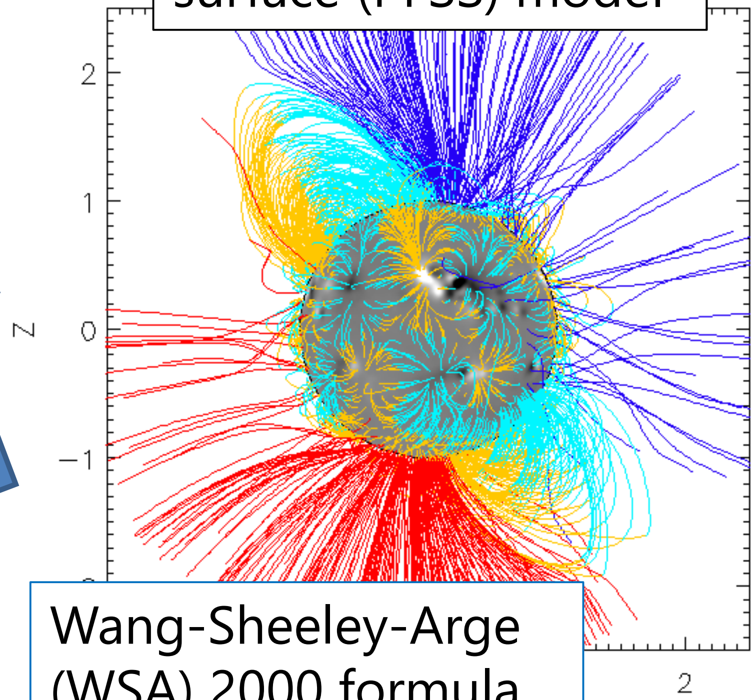
Coronal magnetic field and solar wind velocity

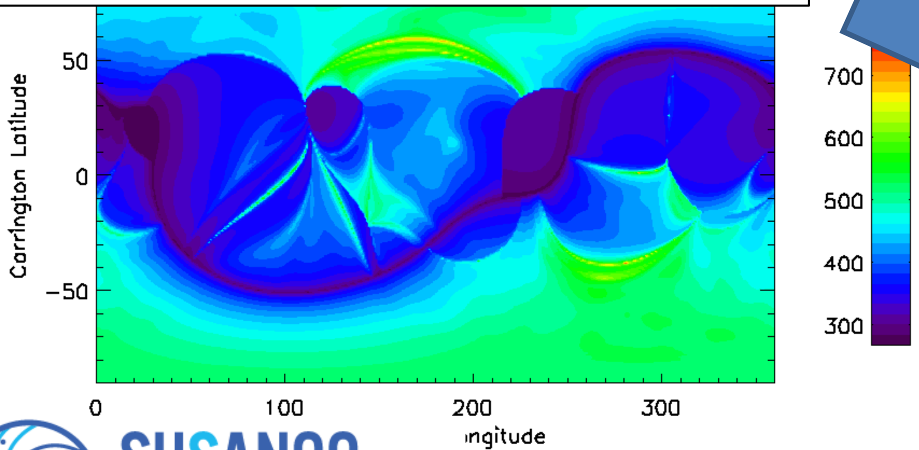
Photospheric magnetic field (GONG)



Potential field source surface (PFSS) model



Solar wind map at 25 solar radii



Wang-Sheeley-Arge (WSA) 2000 formula (Arge & Pizzo 2000) +Helios Observations (Hayashi + 2003)

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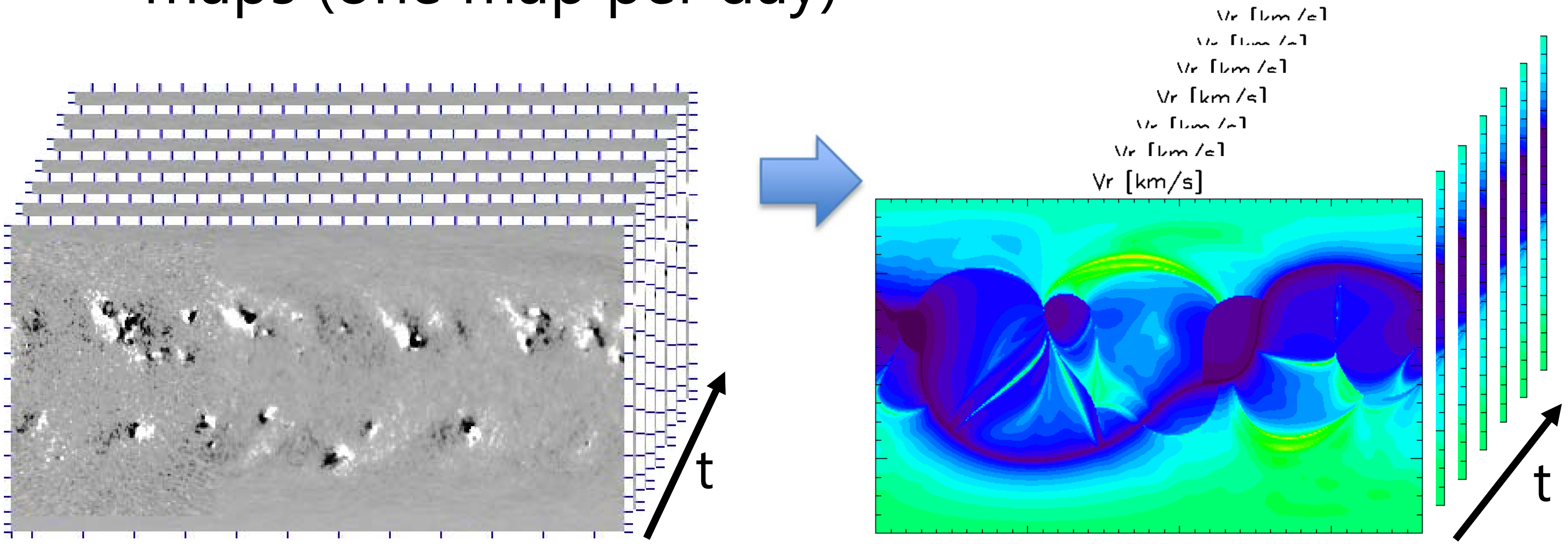
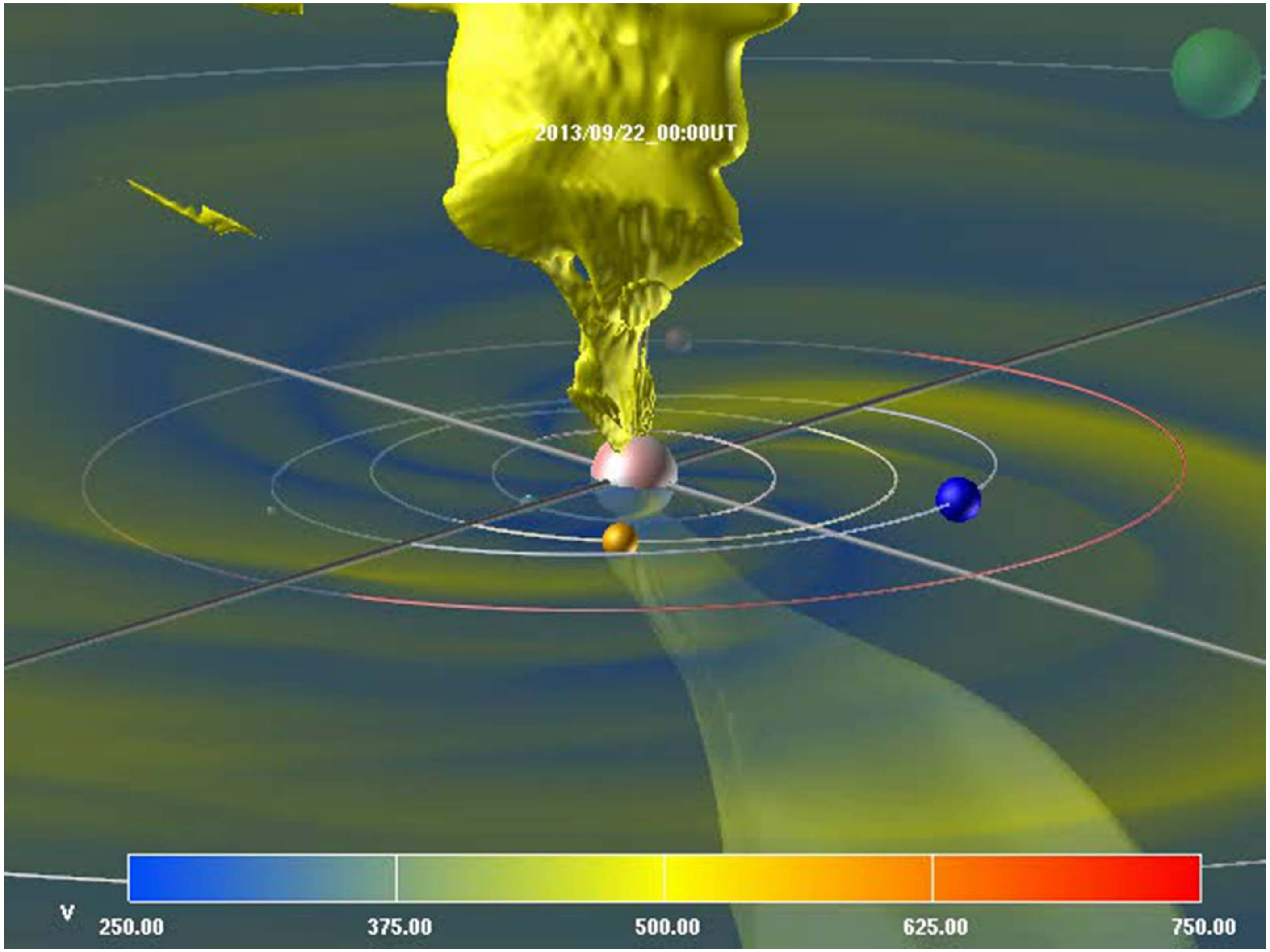
Time-varying inner boundary condition

- A time series of photospheric magnetic field maps (one map per day)



⇒ A time series of solar wind maps for the inner boundary condition of MHD simulation

Solar wind in 2013~2014



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blue: Earth, green: Jupiter, red: Mars, orange: Venus, light blue: Mercury

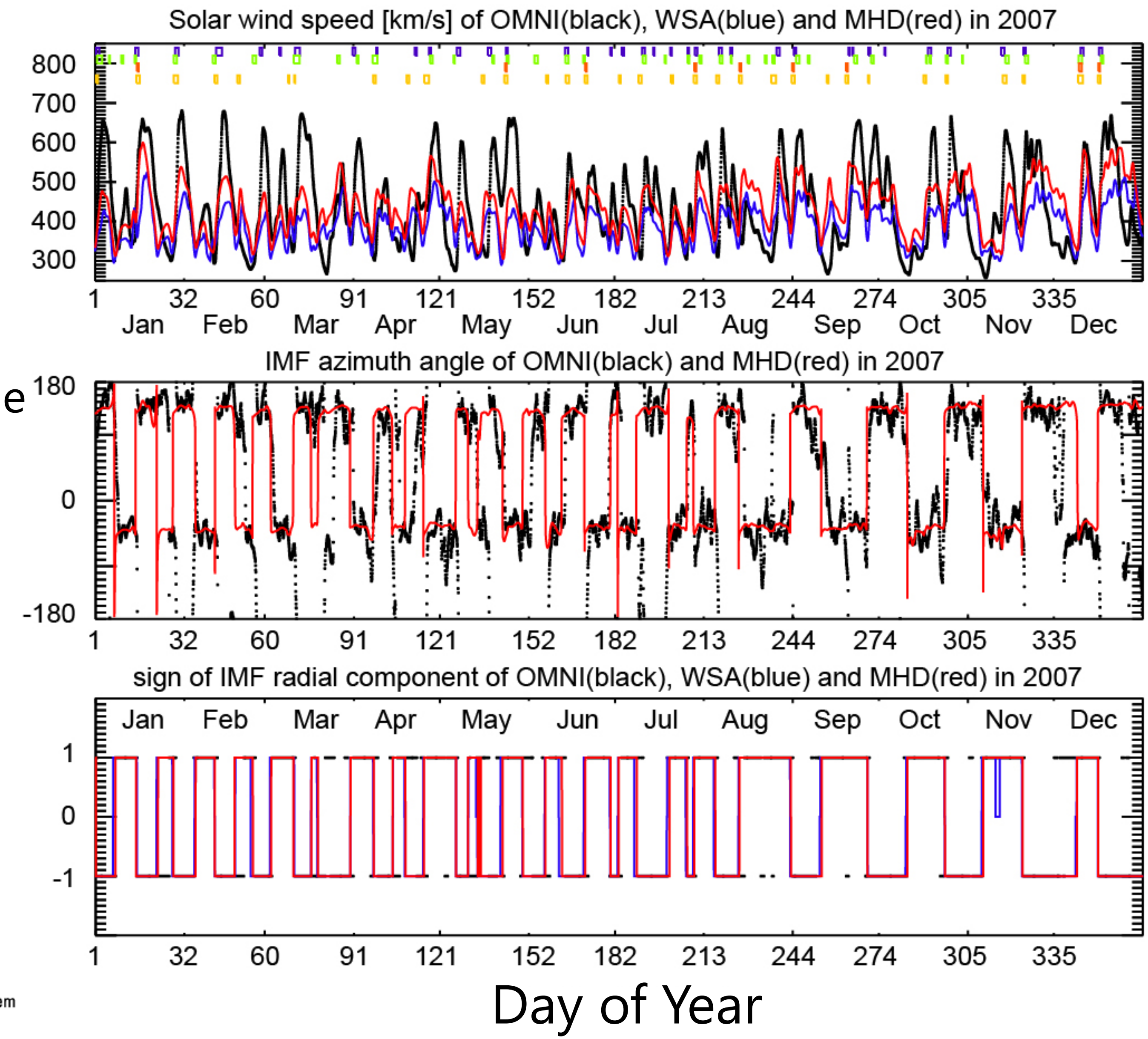
Solar wind in 2007 at Earth position

Velocity

in situ measurement
MHD simulation
kinematic model

Azimuth angle of IMF

Sign of IMF



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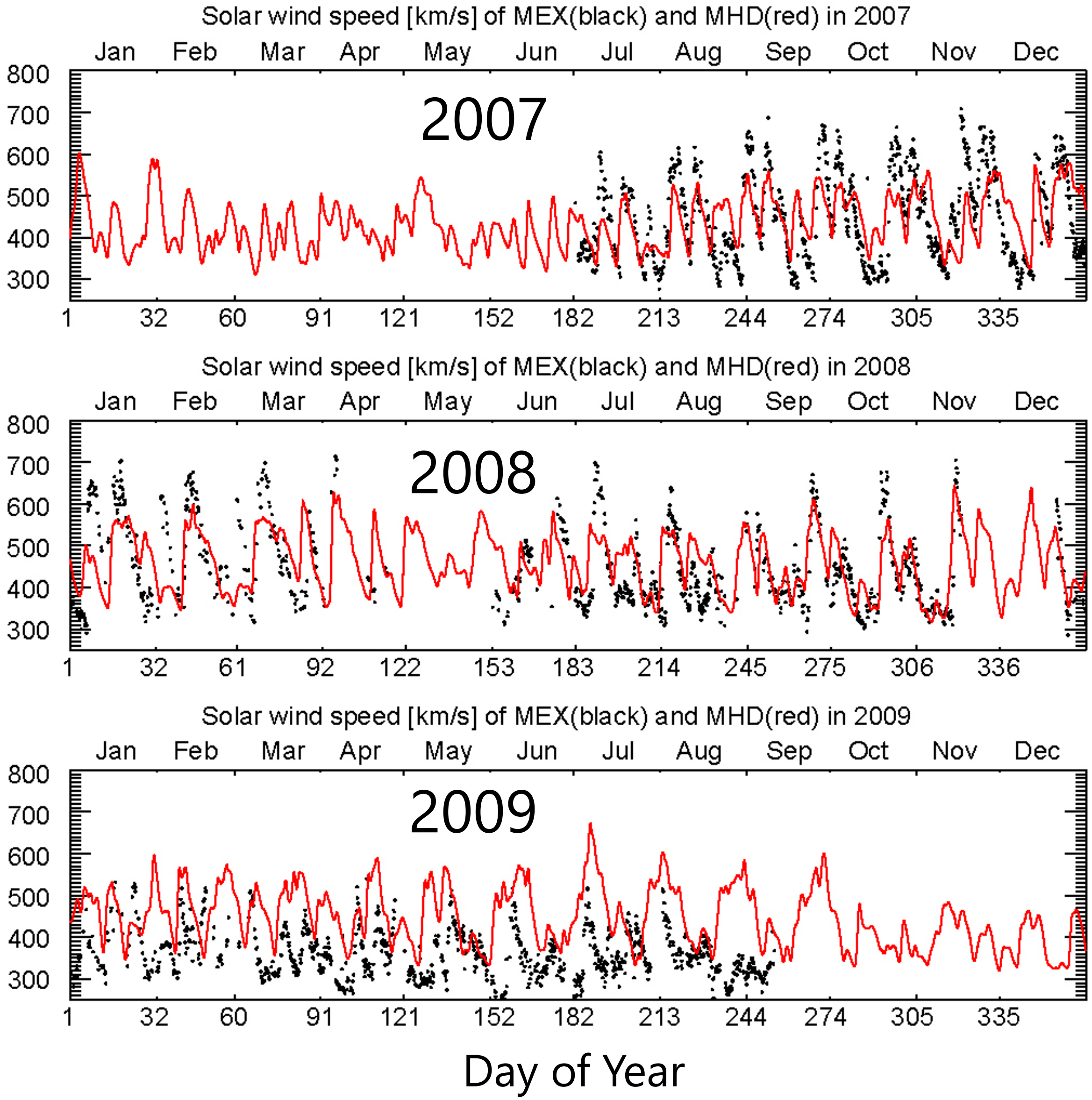
Solar wind at Mars position

- Solar wind speed <=Mars Express (MEX) plasma



in situ measurement

MHD simulation

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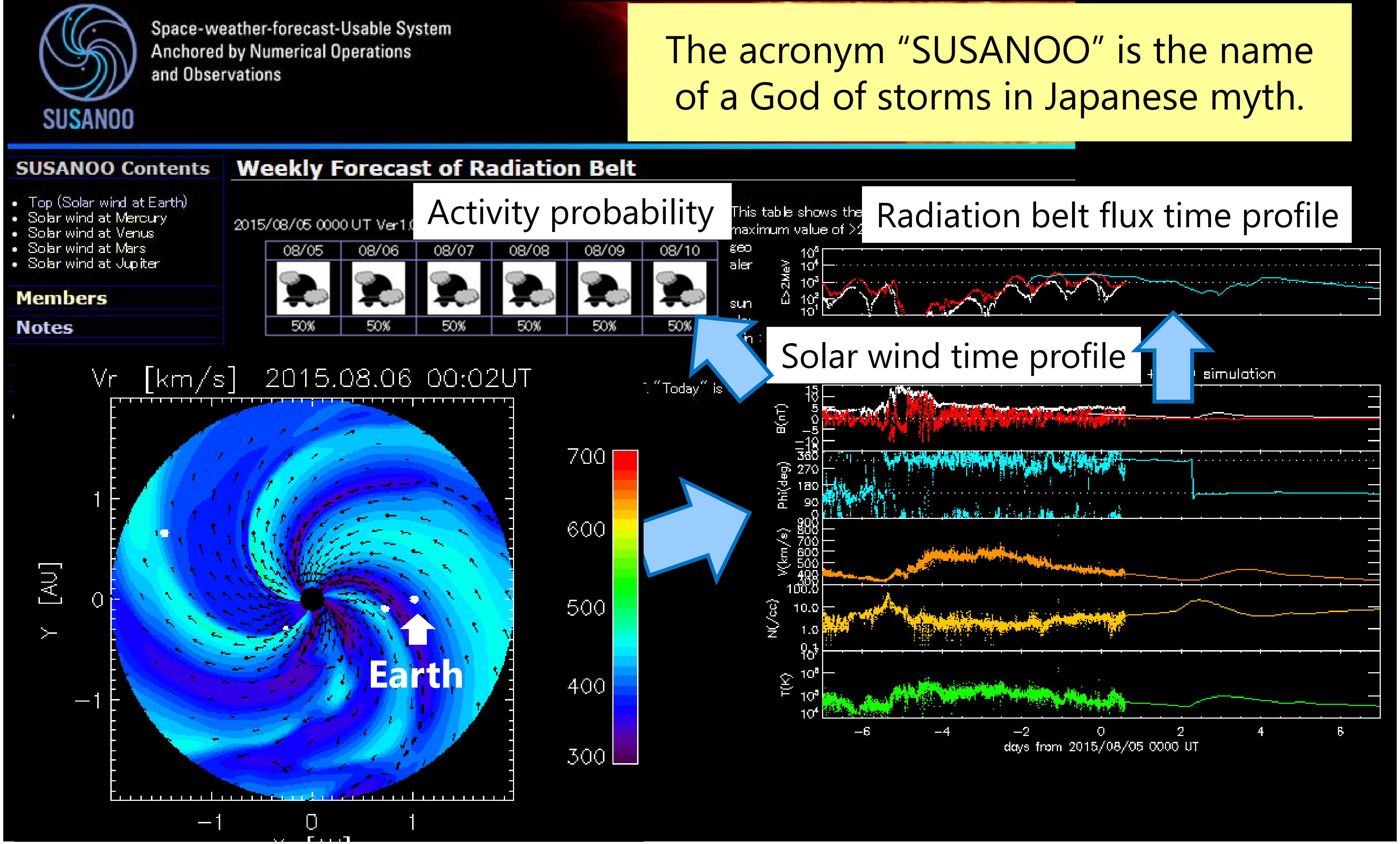
Automated forecast system (SUSANOO)

http://st4a.stelab.nagoya-u.ac.jp/susanoo/index.html

The acronym “SUSANOO” is the name of a God of storms in Japanese myth.



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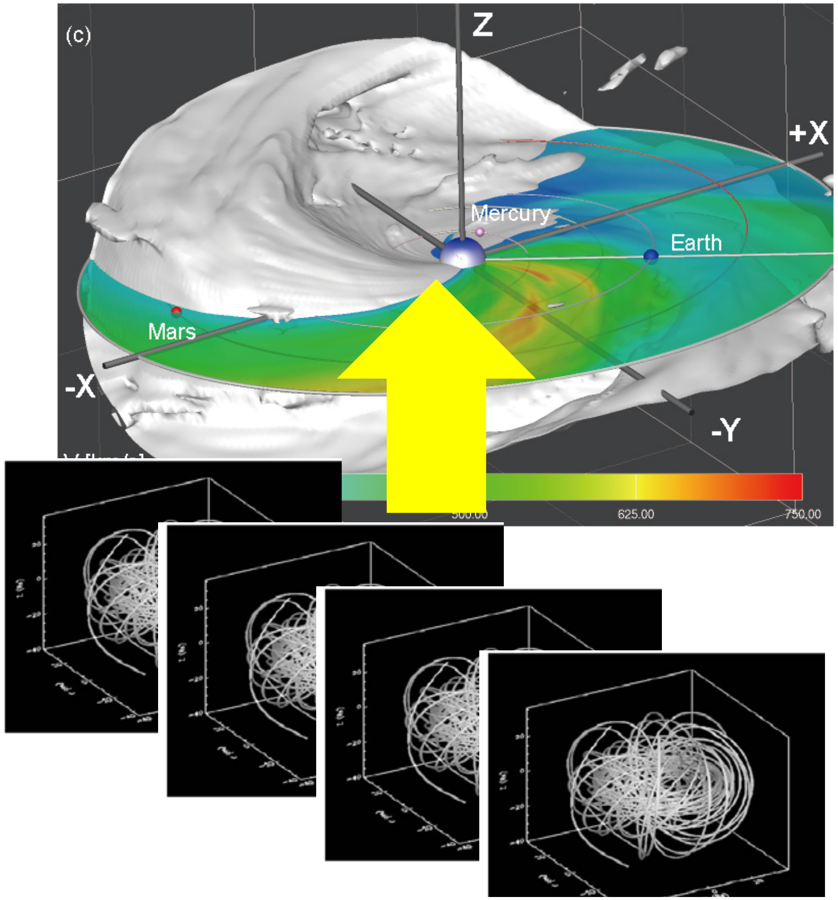
MHD model: SUSANOO-CME

Background: SUSANOO-SW



Multiple CMEs with internal flux rope

- Numerical domain in 30 Rs ≦ r ≦ 430 Rs (~ 2 au)

Purpose

- To establish MHD simulation capable of predicting southward IMF that arrive to the Earth associated with geoeffective CMEs

Method

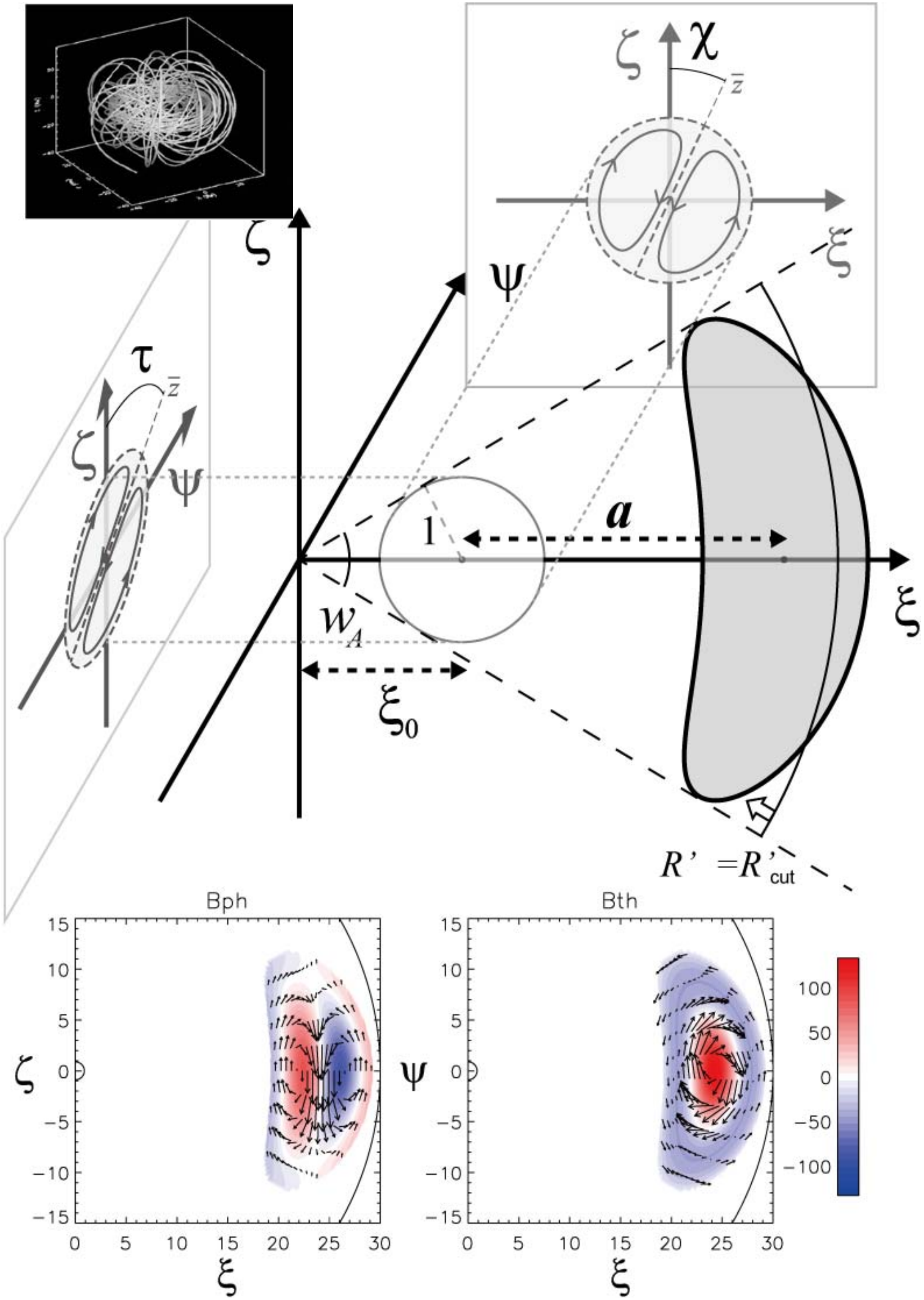
- MHD simulation is driven on the basis of the **solar observational data** obtained in near real-time (daily synoptic maps, solar flares, CMEs).
- For each CME, **an imaginary space** a flux rope is fixed in space and it is projected onto the real space with a function of time as a self-similar evolution (Low 1982, Gibson & Low 1998).

Flux rope model

A pancake shape of a CME (Riley & Crooker 2004, Savani et al. 2011)

This model has 10 parameters

- 6 parameters specify the structure of each CME
- 4 parameters specify the relationship between the imaginary space and real space for each CME.



(Shiota & Kataoka 2016, Space Weather, in press)

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Parameters of the CME model

Table 1. List of Parameters

Symbols	Explanation	Default Value	
t_{onset}	Onset time of CME	from LASCO CME catalog	
V_{CME}	Propagation speed of CME	from LASCO CME catalog	
λ_S	Heliographic latitude of CME source region	from the flare list in NGDC	observation
ϕ_S	Heliographic longtude of CME source region	from the flare list in NGDC	
τ	Tilt angle of spheromak	$\pm 90^\circ$ with Hale-Nicholson law	assume
χ	Inclination angle of spheromak	0°	
c_1	Chirality of helicity in spheromak	1, set -1 if opposite to Bothmer-Schwenn rule	observation
Φ_{mag}	Magnetic flux within CME	proportion to flare class	
w_A	Angular width of CME	60°	assume
w_r	Radial width of CME	$2R_s$	

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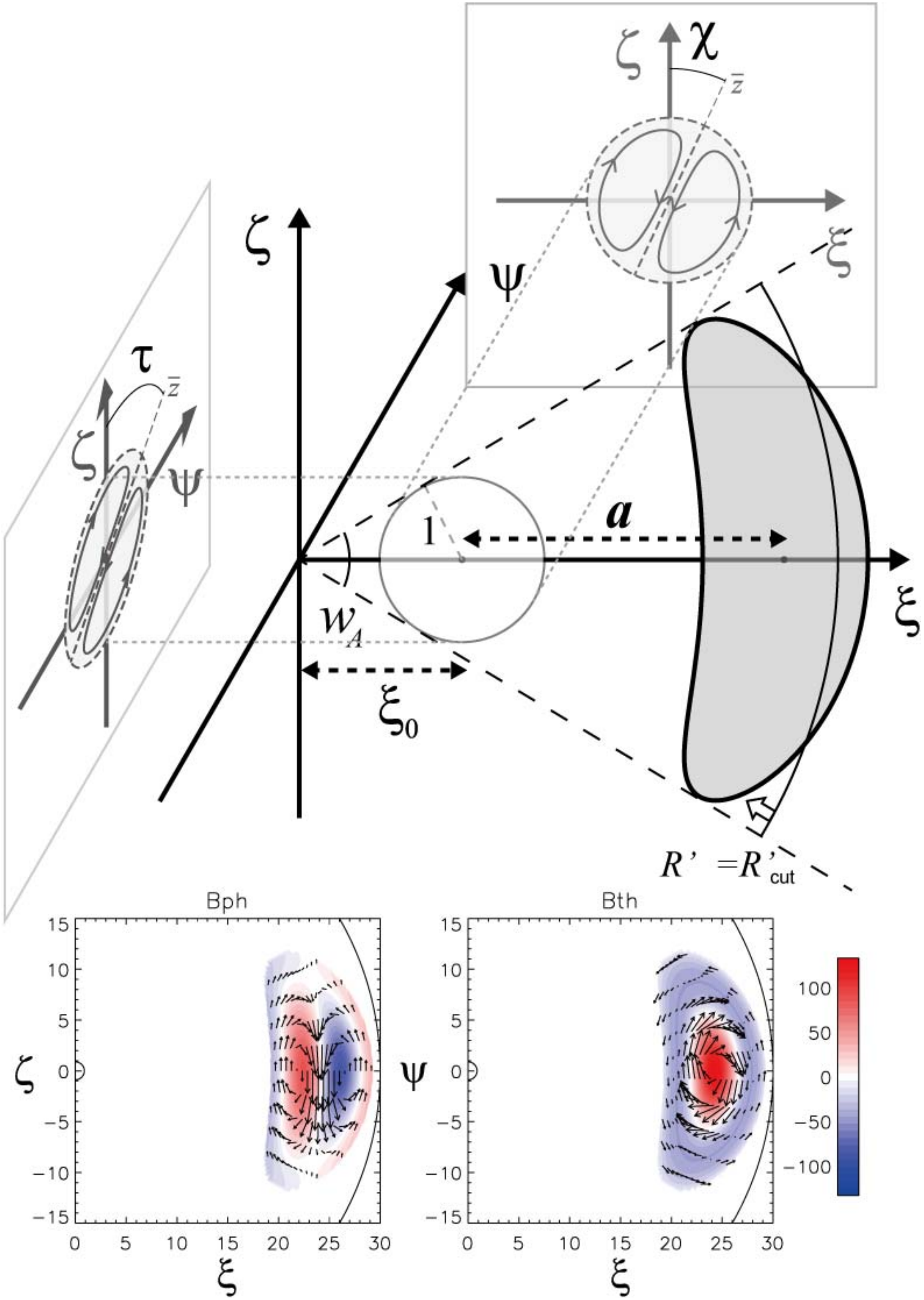

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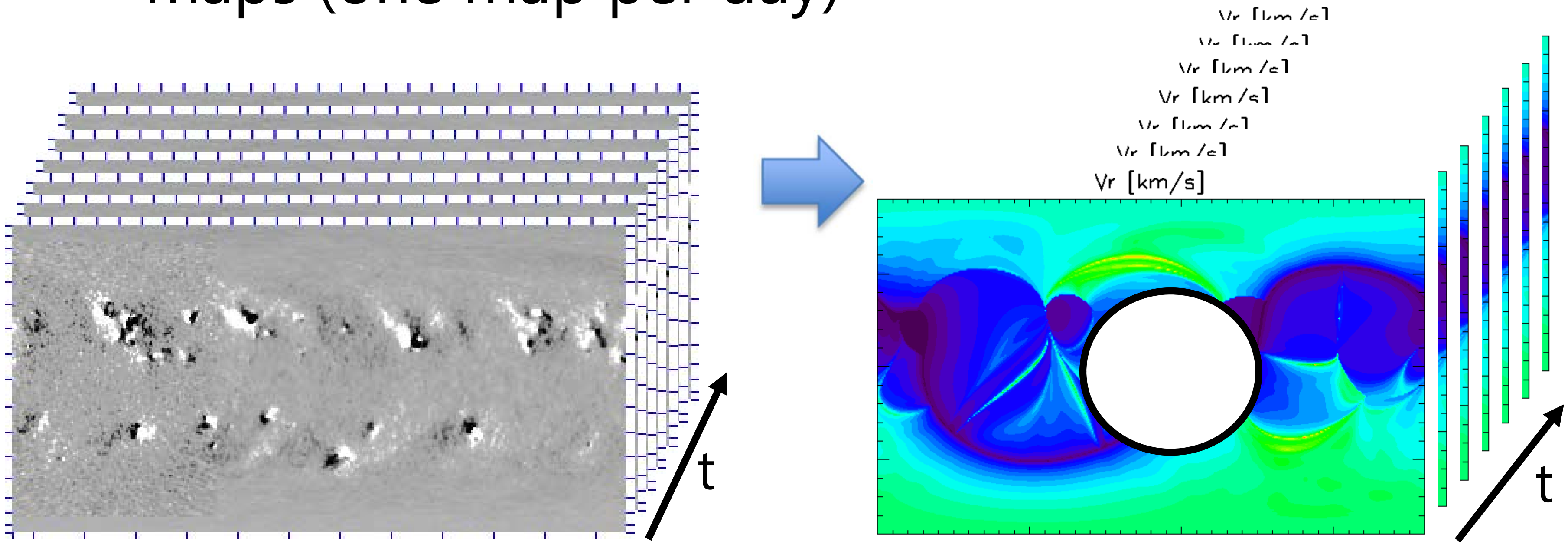
Technique to inject CMEs on the inner boundary condition

- A time series of photospheric magnetic field maps (one map per day)



⇒ A time series of solar wind maps for the inner boundary condition of MHD simulation

Information of CMEs are superposed on these boundary conditions

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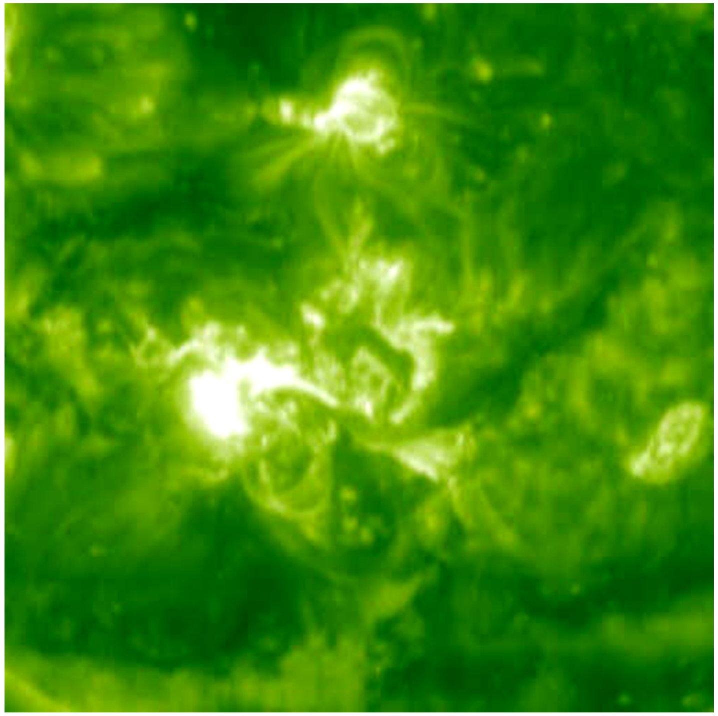
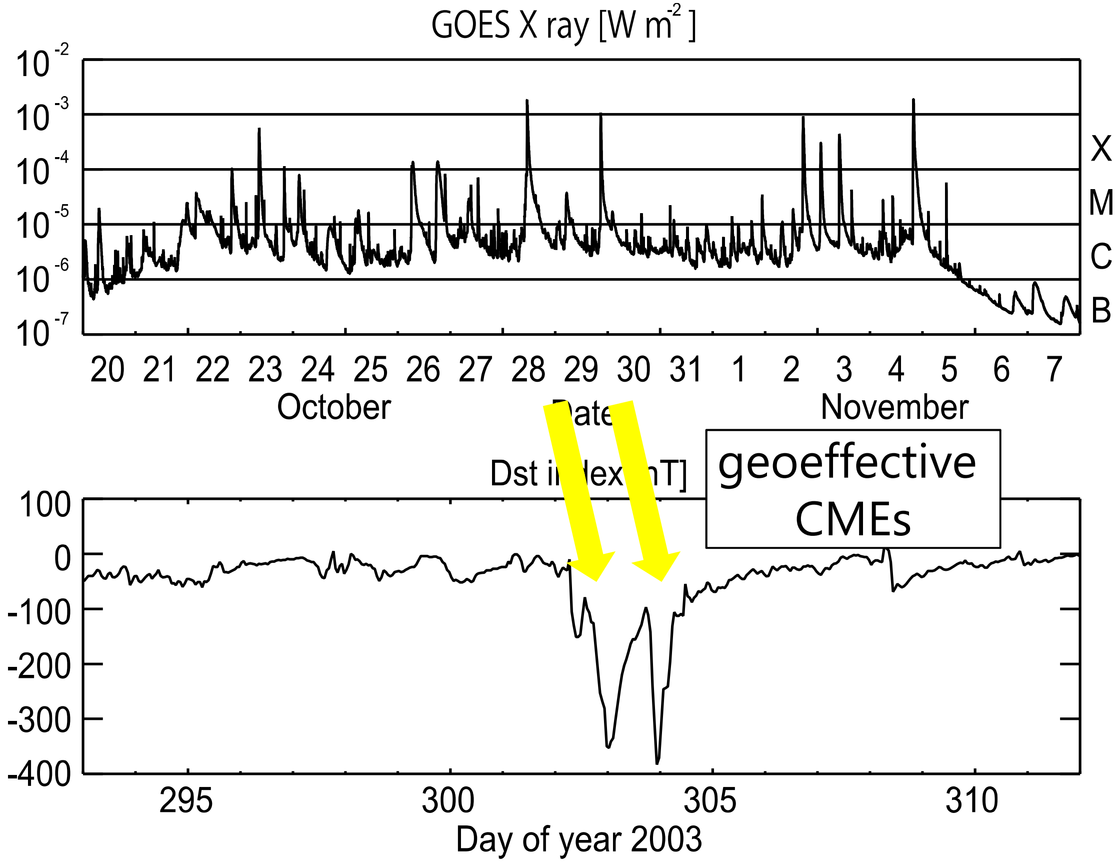
flares-CMEs in October-November 2003 (the Halloween events).

- Many large solar flares occurred (ex. NOAA 10486)





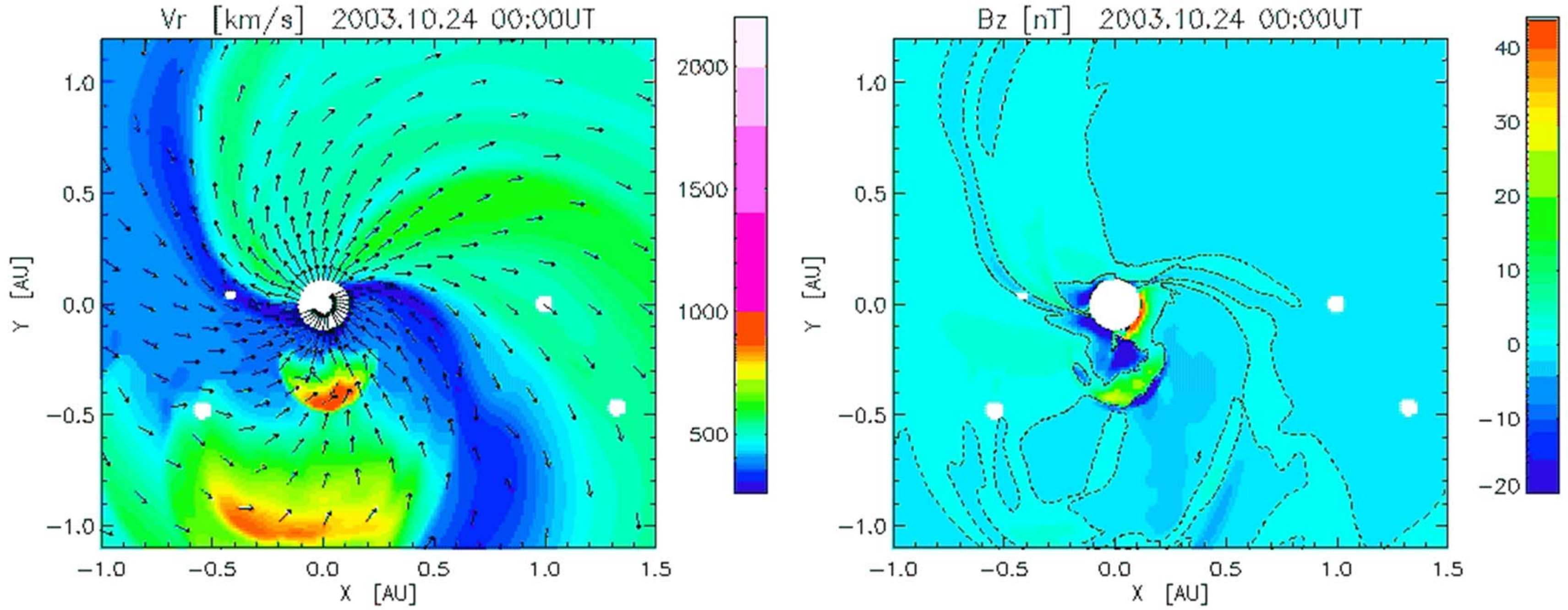
- EIT and LASCO movies of the flare on Oct. 28, 2003 (Halloween storm)

Numerical simulation of 2003 Oct-Nov

#		t_{onset}		V_{CME}	λ_S	ϕ_S	τ	χ	c_1	Φ_{mag}	w_A	w_r	NOAA #	flare
1	Oct	21	3:54	1500	3	-115	0	90	1	3.0E+20	60	2	back	—
2	Oct	22	3:54	1160	3	-102	0	-90	-1	3.0E+20	60	2	10486	M3.7
3	Oct	22	20:06	1080	3	-95	0	-90	-1	1.0E+21	60	2	10486	M9.9
4	Oct	23	8:54	1400	3	-88	0	-90	-1	1.0E+21	60	2	10486	X5.4
5	Oct	23	20:06	1130	-17	-84	0	-90	-1	1.0E+21	60	2	10486	X1.1
6	Oct	24	2:54	1050	-19	-72	0	-90	-1	3.0E+20	60	2	10486	M7.6
7	Oct	24	5:30	1230	-24	-74	0	-90	-1	3.0E+20	30	2	10486	M4.2
8	Oct	26	6:54	1370	-15	-44	0	-90	-1	1.0E+21	60	2	10486	X1.2
9	Oct	26	17:54	1540	1	38	0	90	1	2.0E+21	60	2	10484	X1.2
10	Oct	27	8:30	1050	0	45	0	90	1	3.0E+20	60	2	10484	M2.7
11	Oct	28	11:30	2460	-16	-13	0	-90	-1	6.0E+21	60	2	10486	X17.2
12	Oct	29	20:54	2030	-16	2	0	-90	-1	3.0E+21	60	2	10486	X10.0
13	Oct	31	4:42	2136	8	30	0	90	1	3.0E+20	30	2	quiet	M2.0
14	Nov	2	9:30	2040	-16	135	0	90	1	1.0E+21	60	2	back	—
15	Nov	2	17:30	2600	-14	56	0	-90	-1	2.0E+21	60	2	10486	X8.3
16	Nov	3	1:59	840	10	77	0	90	1	1.0E+21	30	2	10488	X2.7
17	Nov	3	10:06	1400	8	77	0	90	1	1.0E+21	60	2	10488	X3.4
18	Nov	4	12:06	1210	5	-150	0	90	1	1.0E+21	60	2	back	—
19	Nov	4	19:54	2660	-19	83	0	-90	-1	4.0E+21	60	2	10486	X28.0
20	Nov	6	17:30	1500	10	-150	0	90	1	1.0E+21	60	2	back	—
21	Nov	7	15:54	2270	10	150	0	90	1	2.0E+21	60	2	back	—
22	Nov	9	12:30	2080	-10	-110	0	-90	-1	2.0E+21	60	2	back	—

Numerical results

Time evolution of Velocity and Bz (GSE) on the ecliptic plane



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Synthetic solar wind measurement at Earth position

MHD
OMNI
ACE (Skoug+ 2004)

- Solar wind profile at the Earth position is compared with in situ measurements.
- The results reproduce well the profiles of solar wind speed and B_z strength following shock 2.

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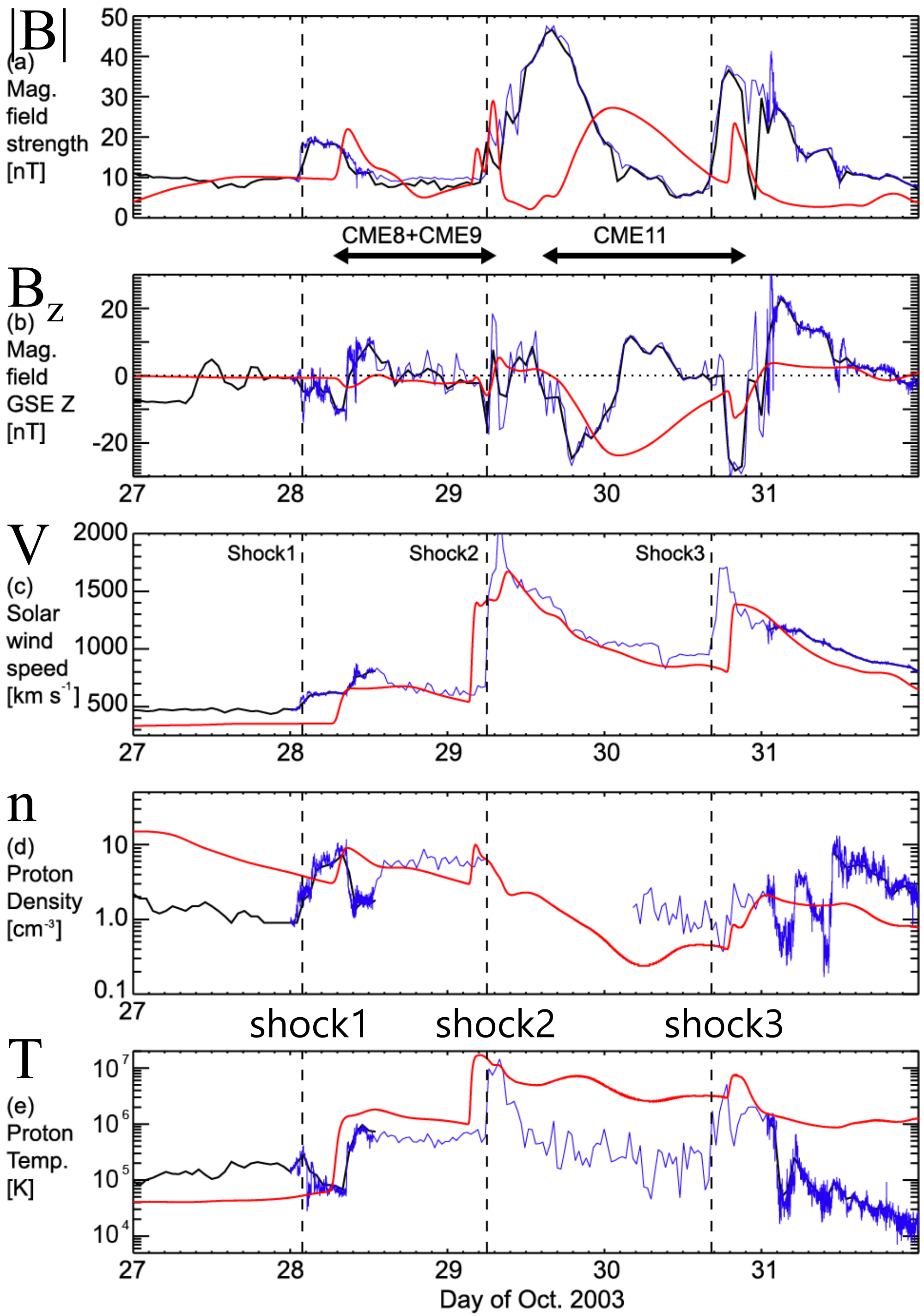
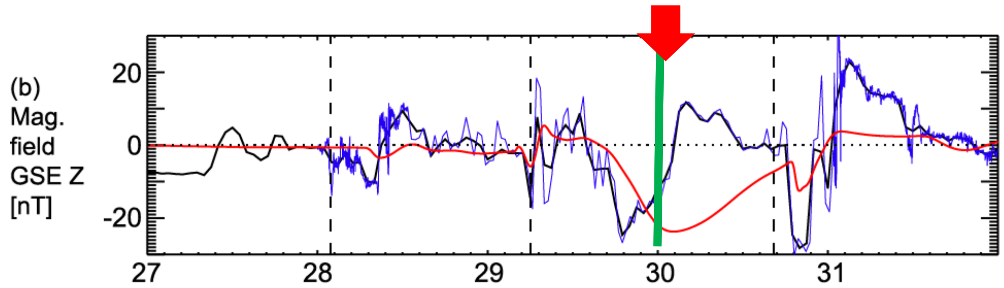
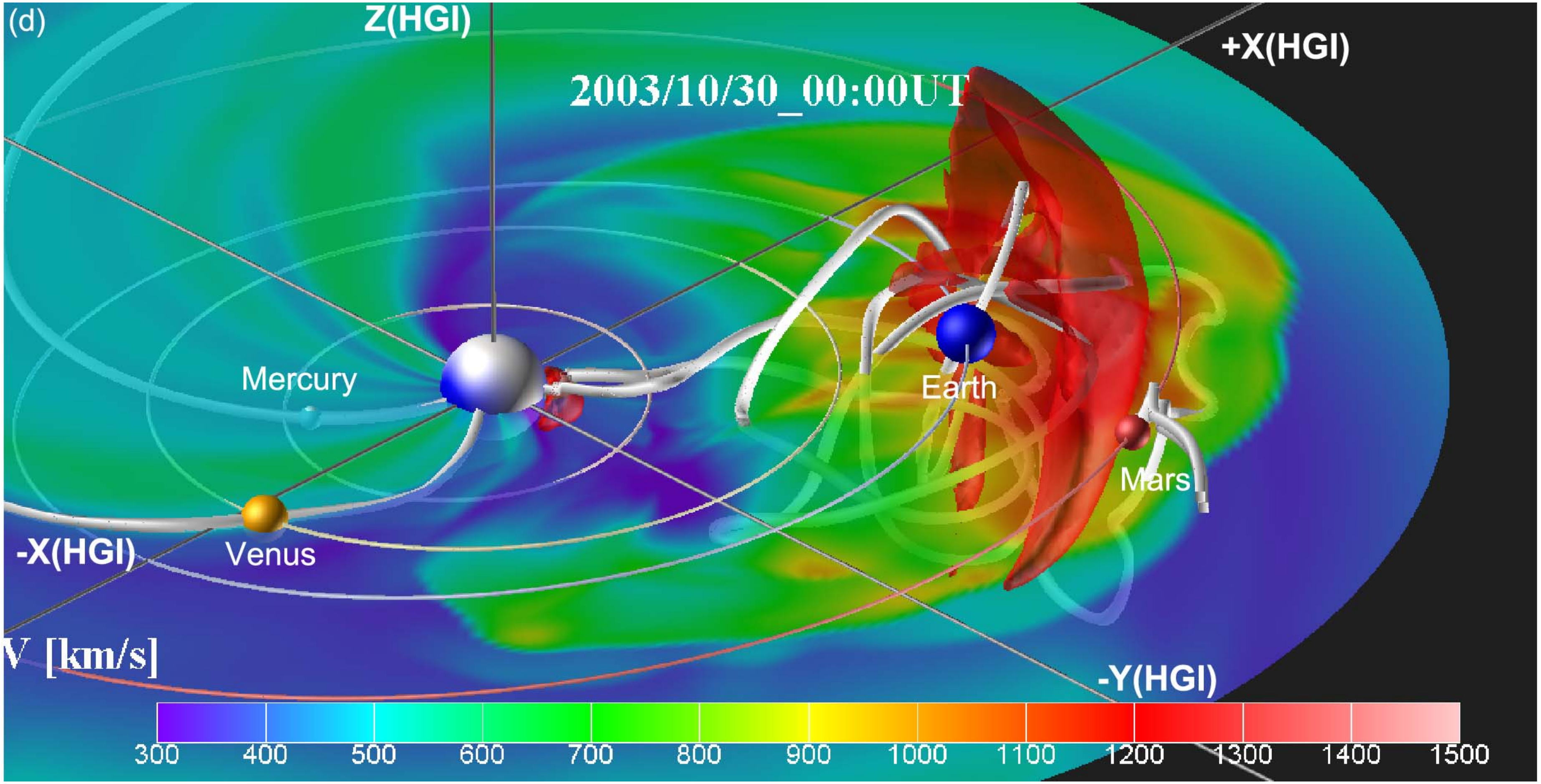


3D view of magnetic structure





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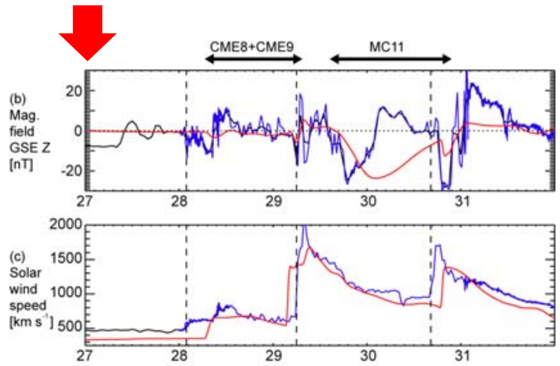
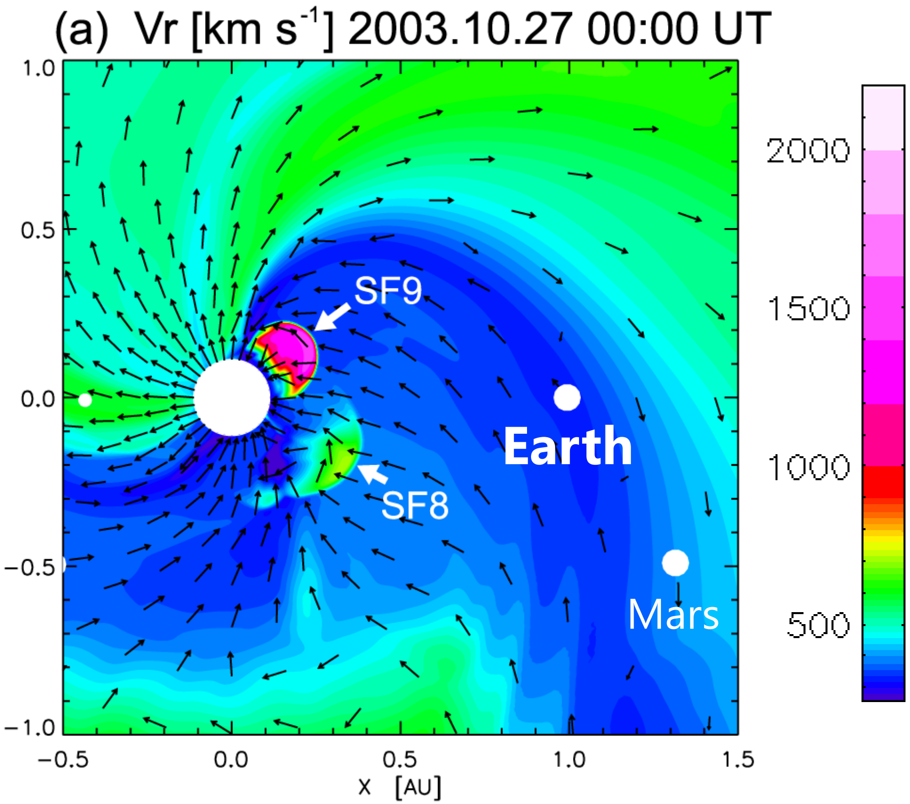
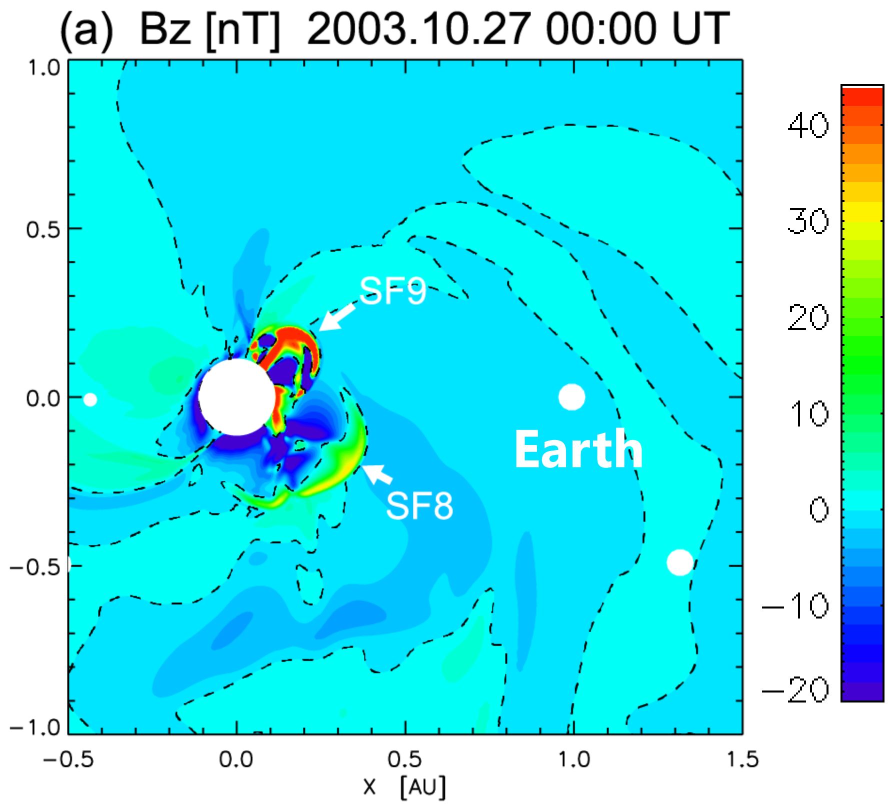
Propagation and CME-CME interaction







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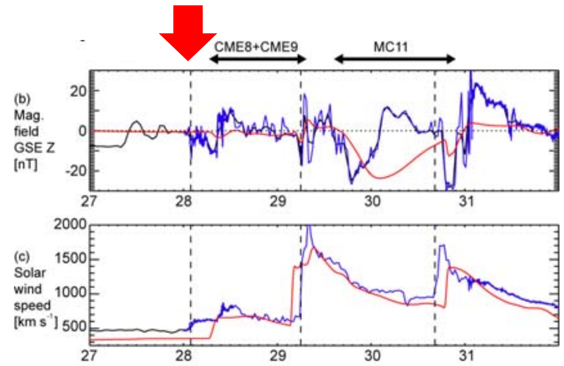

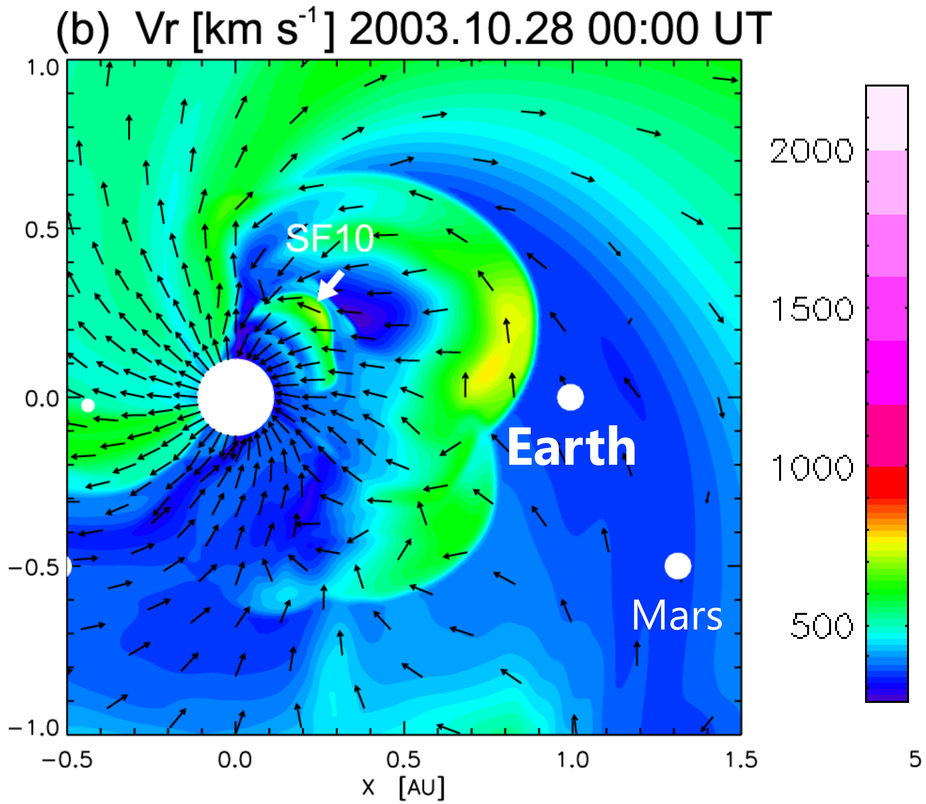

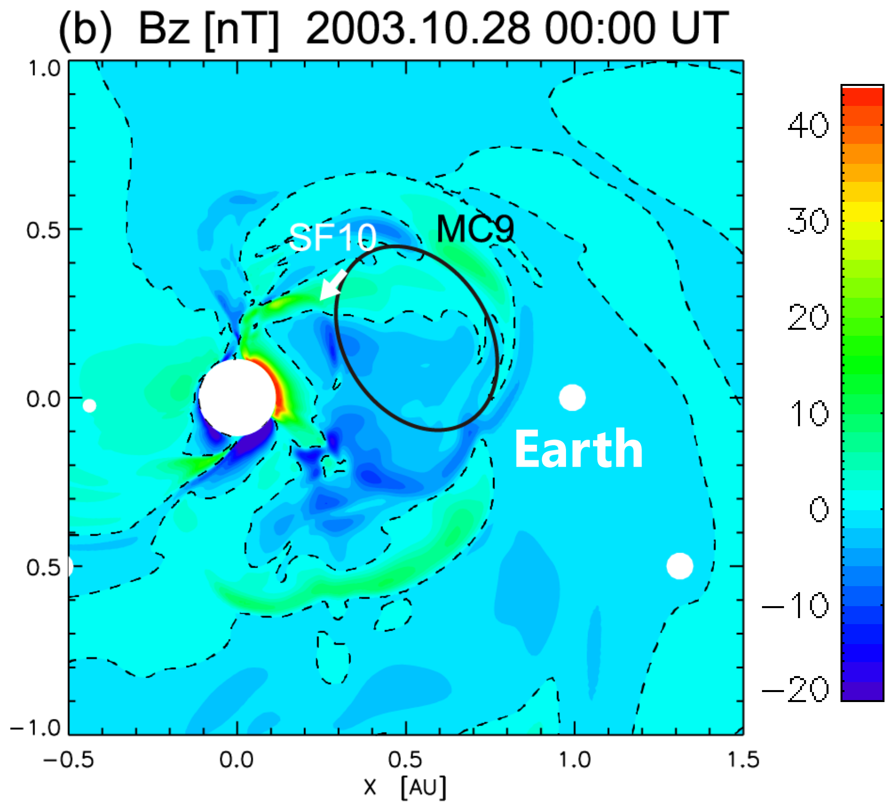

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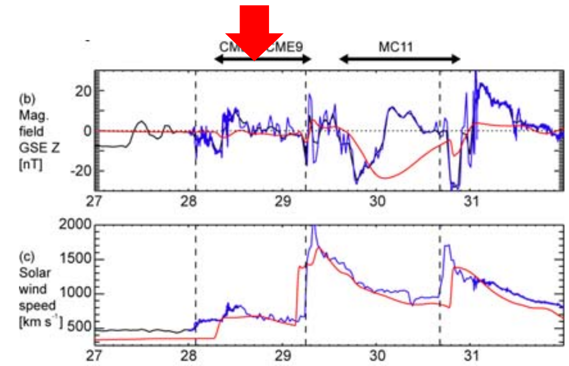

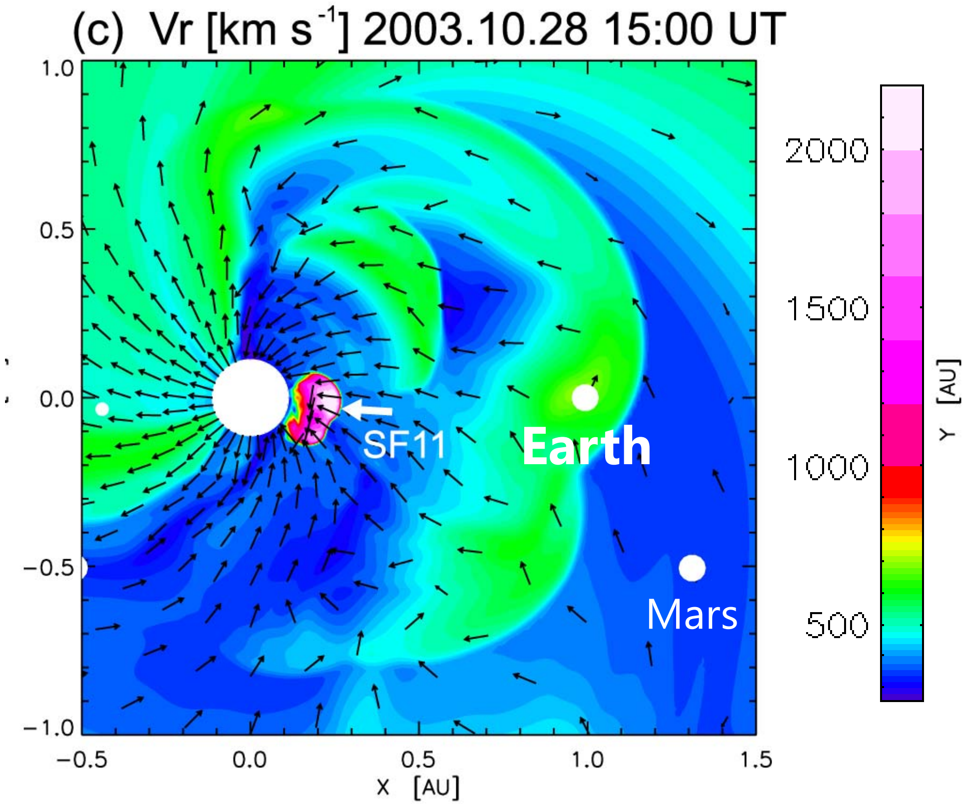

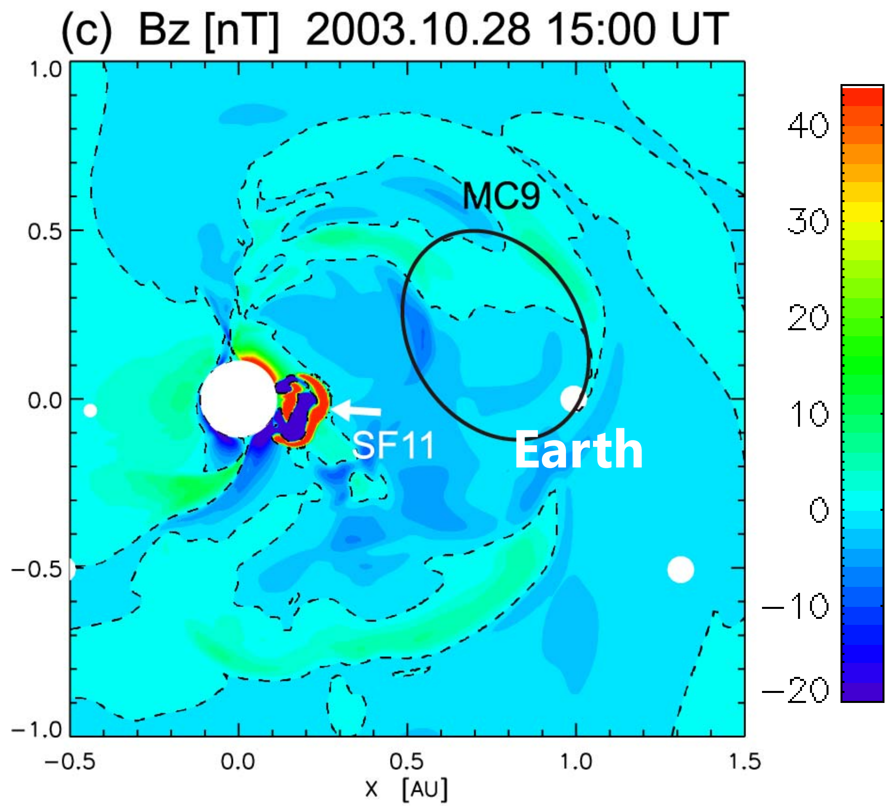

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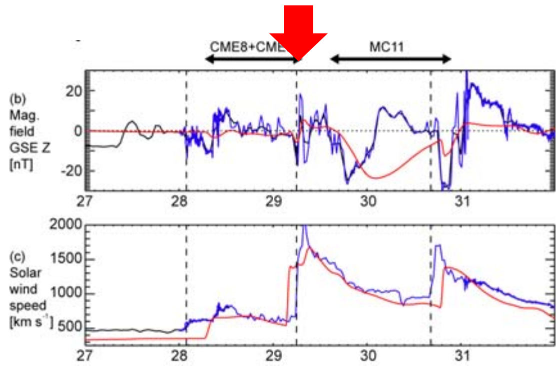

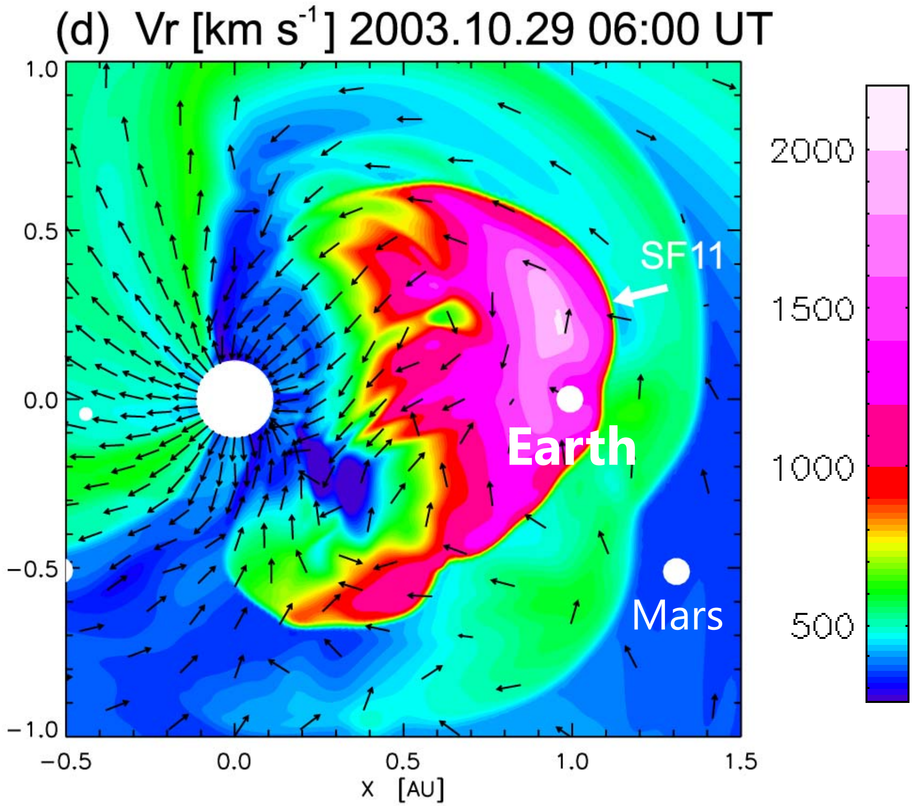

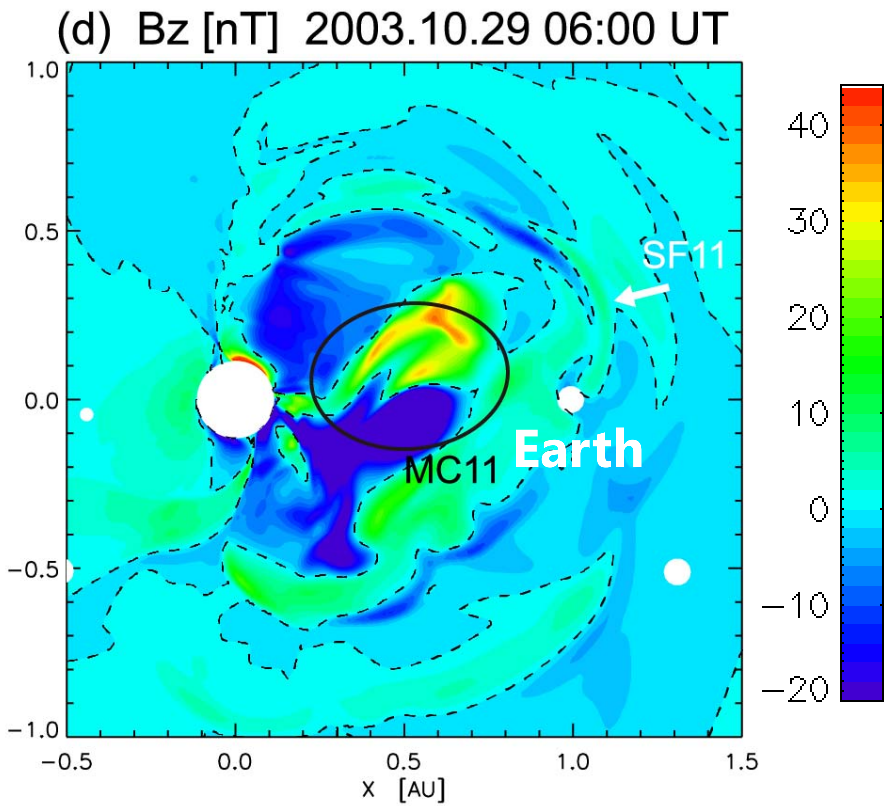

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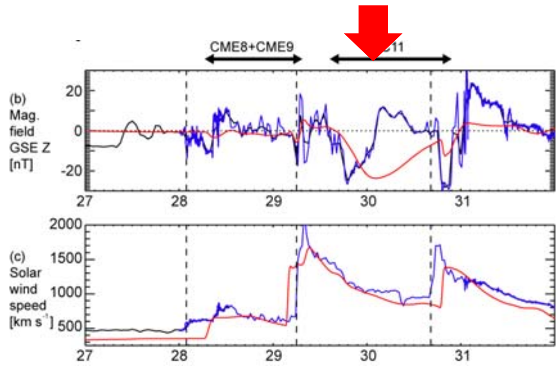

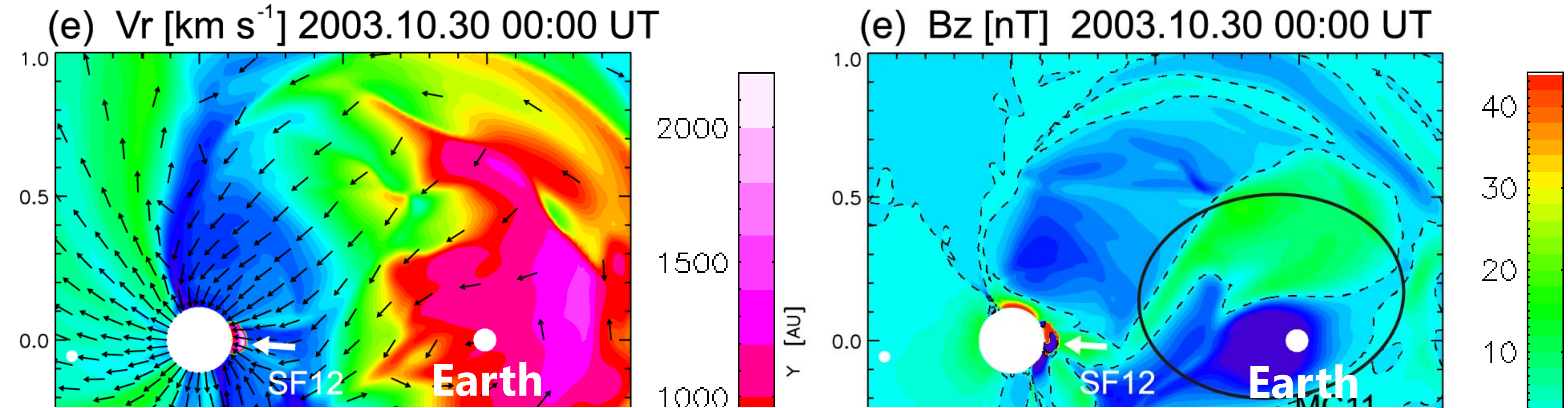

- CME11 that is launched from eastward λ_S =-13 but propagates westward of the Sun-Earth line
- This was observed in Grad-Shafranov reconstruction (Hu + 2005)

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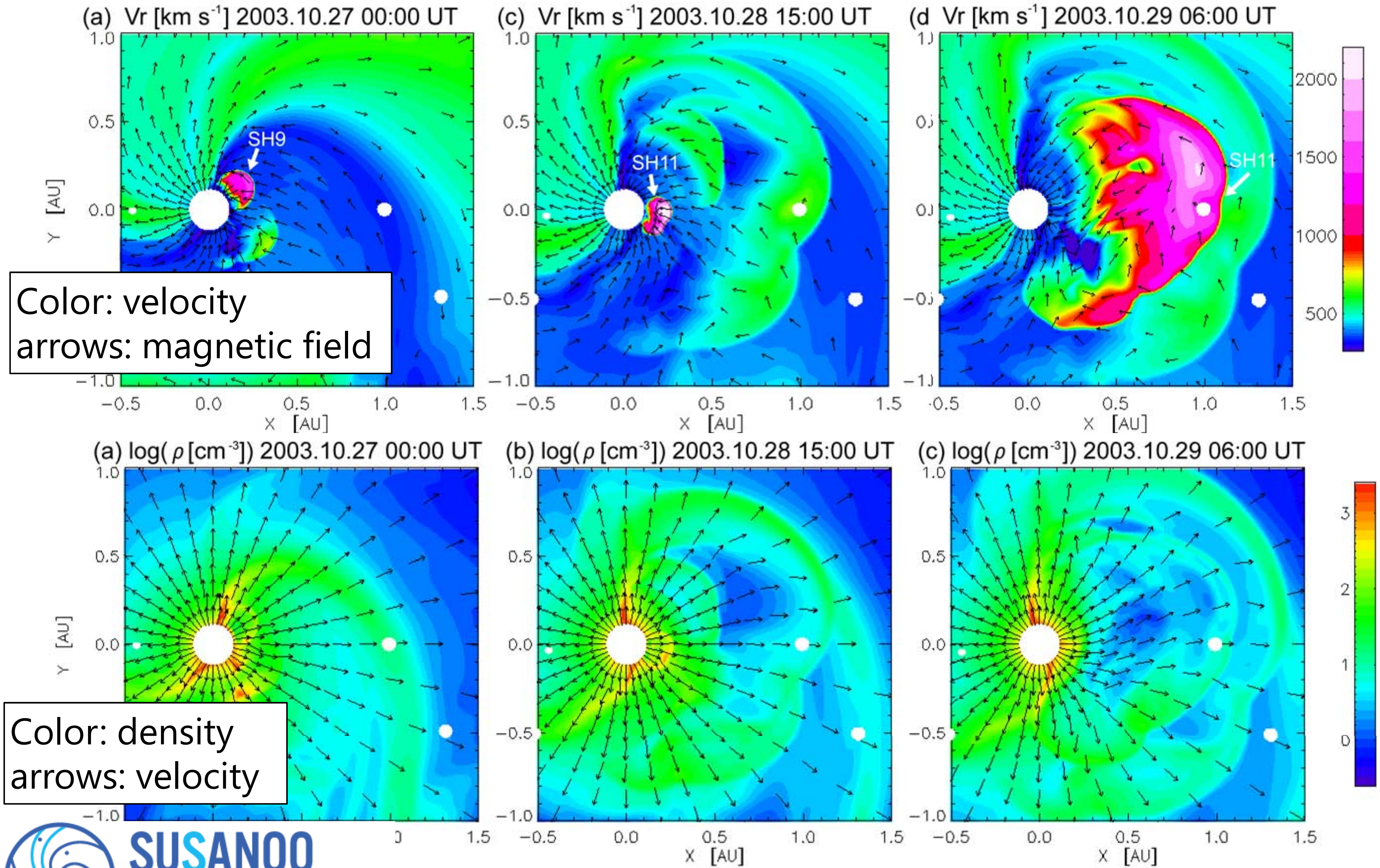
CME-CME Interaction



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Discussion

- Our new MHD model SUSANOO-CME reproduces reasonably good profiles of solar wind speed and IMF. The results provide many insights into the dynamics of the magnetic field structure during CME propagation.
- The CME model has many **free parameters**.
- The uncertain parameters are specified with some assumptions based on the observation in this study. However, the rule to specify the best set of all the parameters is still open.

Parameters of the CME model

Table 1. List of Parameters

Symbols	Explanation	Default Value
t_{onset}	Onset time of CME	from LASCO CME catalog
V_{CME}	Propagation speed of CME	from LASCO CME catalog
λ_S	Heliographic latitude of CME source region	from the flare list in NGDC
ϕ_S	Heliographic longtude of CME source region	from the flare list in NGDC
τ	Tilt angle of spheromak	$\pm 90^\circ$ with Hale-Nicholson law
χ	Inclination angle of spheromak	0°
c_1	Chirality of helicity in spheromak	1, set -1 if opposite to Bothmer-Schwenn rule
Φ_{mag}	Magnetic flux within CME	proportion to flare class
w_A	Angular width of CME	60°
w_r	Radial width of CME	$2R_s$

observation (t_{onset}, V_{CME}, λ_S, ϕ_S)

assume (τ, χ)

observation (c_1)

assume (Φ_{mag}, w_A, w_r)

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Discussion (cont.)

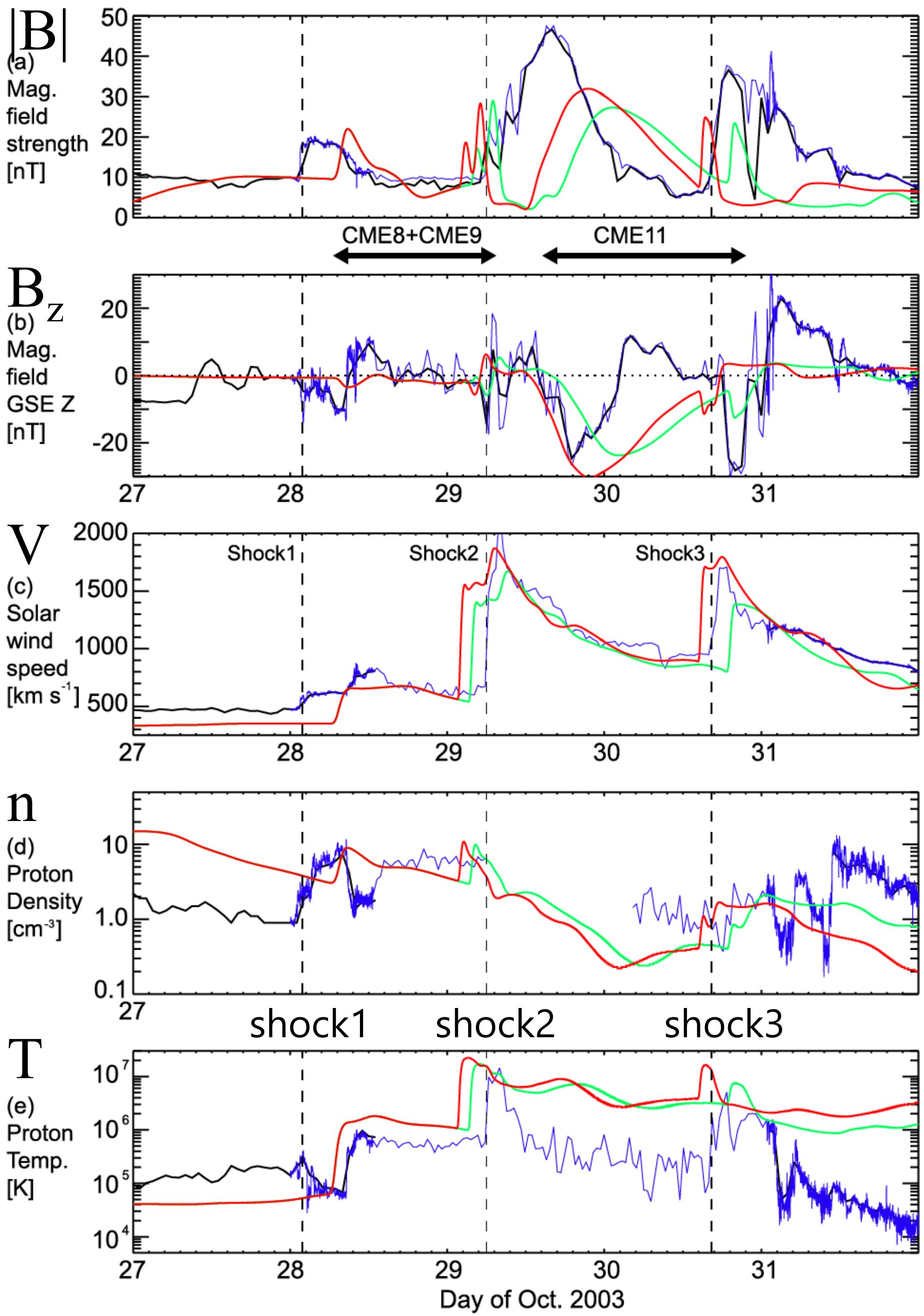
- SUSANOO-CME omits to solve the region of solar corona (1Rs≤ r ≤ 30Rs).
- The results of the dynamics in the coronal region should be taken into account to the parameters of each CME injected by SUSANOO-CME.
  - Deflection (Gopalswamy + 2009)
  - Rotation (Yurchyshyn + 2008, Shiota + 2010)
  - Interchange reconnection (deformation)
- Density and temperature is also the important parameters that are not included in this study.

Lager magnetic flux case

MHD MHD(original parameter)
OMNI
ACE (Skoug+ 2004)

- Magnetic flux
  6×10^{21}Mx(green)
  → 7×10^{21}Mx(red)

- Shock arrived earlier
- The following shock became faster



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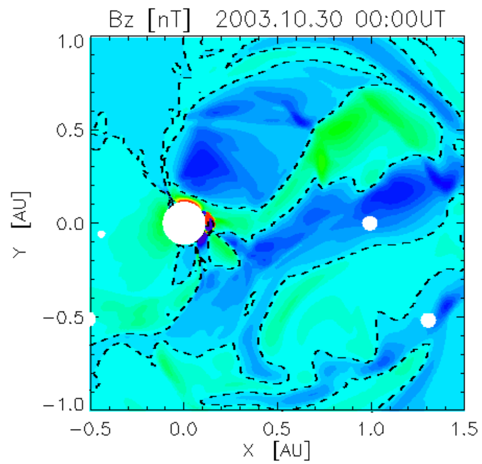
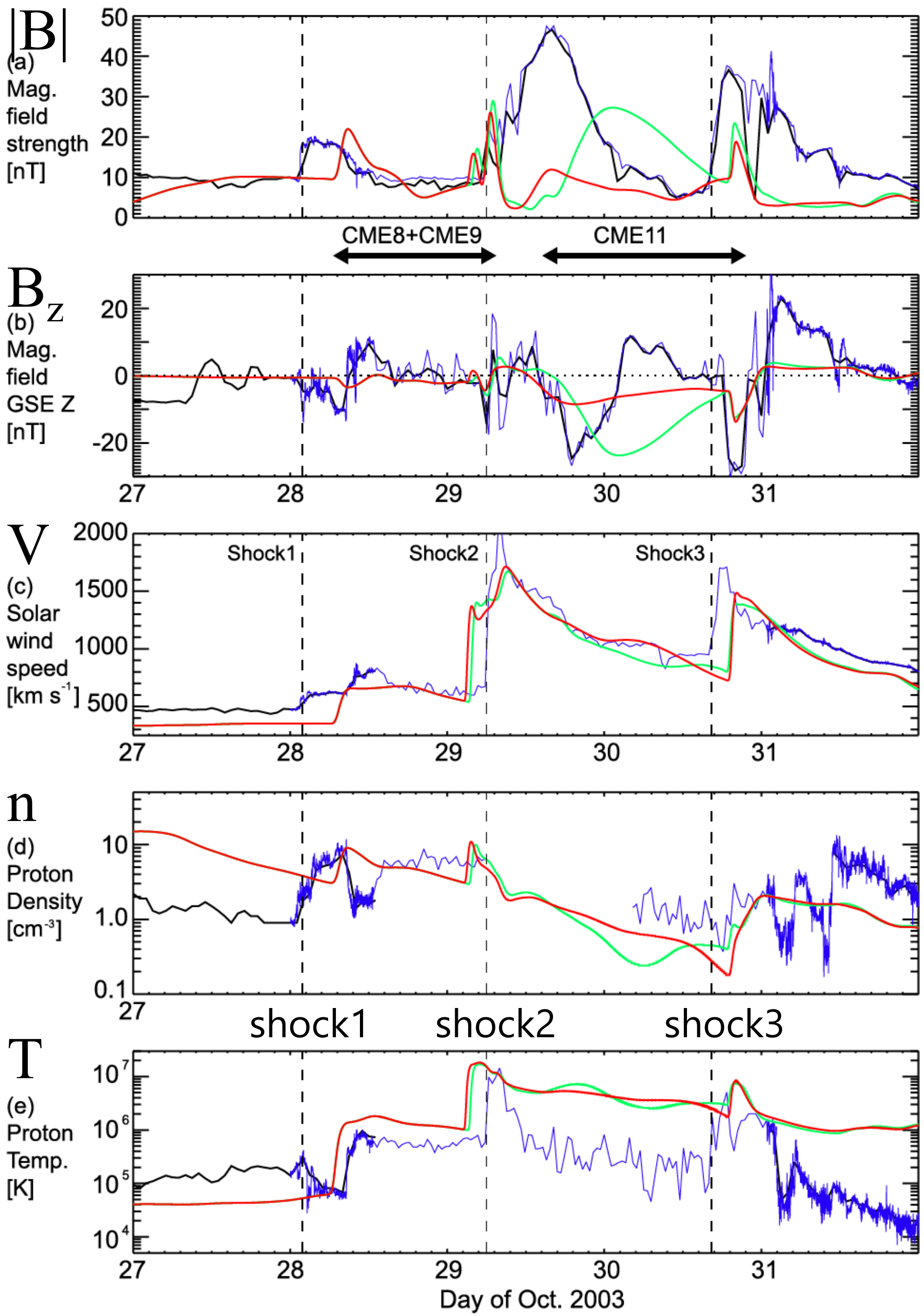
Western source case

MHD MHD(original parameter)
OMNI
ACE (Skoug+ 2004)

- Source longitude
  -13 (green) → -8 (red)
- The core part of the flux rope did not pass through the Earth position.





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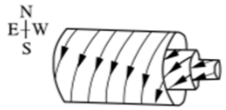
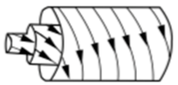
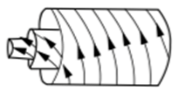
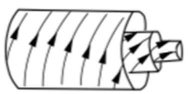
Summary

- We introduced our newly developed CME model (SUSANOO-CME) that injects **multiple CMEs** with **internal magnetic flux ropes** into a heliosphere MHD simulation.
- We presented the numerical results of the modeling of the **2003 Halloween storms** as a demonstration of the performance of the CME model. The MHD model provides **reasonably good results** for **velocity and the Southward Bz profiles** at the Earth of the Event on October 29.
- With further parameter optimizations, SUSANOO-CME simulation is **capable of predicting i.e., the magnitude of geomagnetic storms** as well as predicting shock arrival times. The new simulation therefore provides a significant progress in the field of space weather forecast.
- The numerical results also provide many insights into the dynamics of the magnetic field structures during CME propagation.

Helicity of Magnetic clouds (MCs)

2n cycle: North, South

2n+1 cycle: South, North

MC Type / Magnetic helicity / Number of MCs during 1974–1981	Variation of magnetic field vector	Direction of magnetic field on flux tube axis	Rotation of magnetic field vector in Bz-By-plane (Bx^*-By^*-plane)
SEN Left-handed  17	South ($-Bz$)→north ($+Bz$)	East ($+By$)	
SWN Right-handed  17	South ($-Bz$)→north ($+Bz$)	West ($-By$)	
NES Right-handed  6	North ($+Bz$)→south ($-Bz$)	East ($+By$)	
NWS Left-handed  6	North ($+Bz$)→south ($-Bz$)	West ($-By$)	
Orientations for high inclinations to the ecliptic SEN, NWS, SWN, NES	East ($+By$)→west ($-By$) West($-By$)→east($+By$)	North ($+Bz$)→south ($-Bz$) South ($-Bz$)→north ($+Bz$)	Rotations in By-Bz-(By^*-Bx^*-) plane

(Bothmer & Schwenn 1998)