2015 Oct. 1

MHD Simulation of Interplanetary propagation of Multiple Coronal Mass Ejections with Internal Magnetic Flux rope

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ISEST/MIniMax 2015 Workshop

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Outline of this talk

- Introduction
  - Physical processes of CMEs
  - MHD modeling of CMEs
- Solar wind model: SUSANOO-SW
- Solar wind & CME model: SUSANOO-CME
  - Model setup
  - Numerical simulation of 2003 Oct-Nov CMEs
  - Discussion (Advantage, limitation, and future direction)
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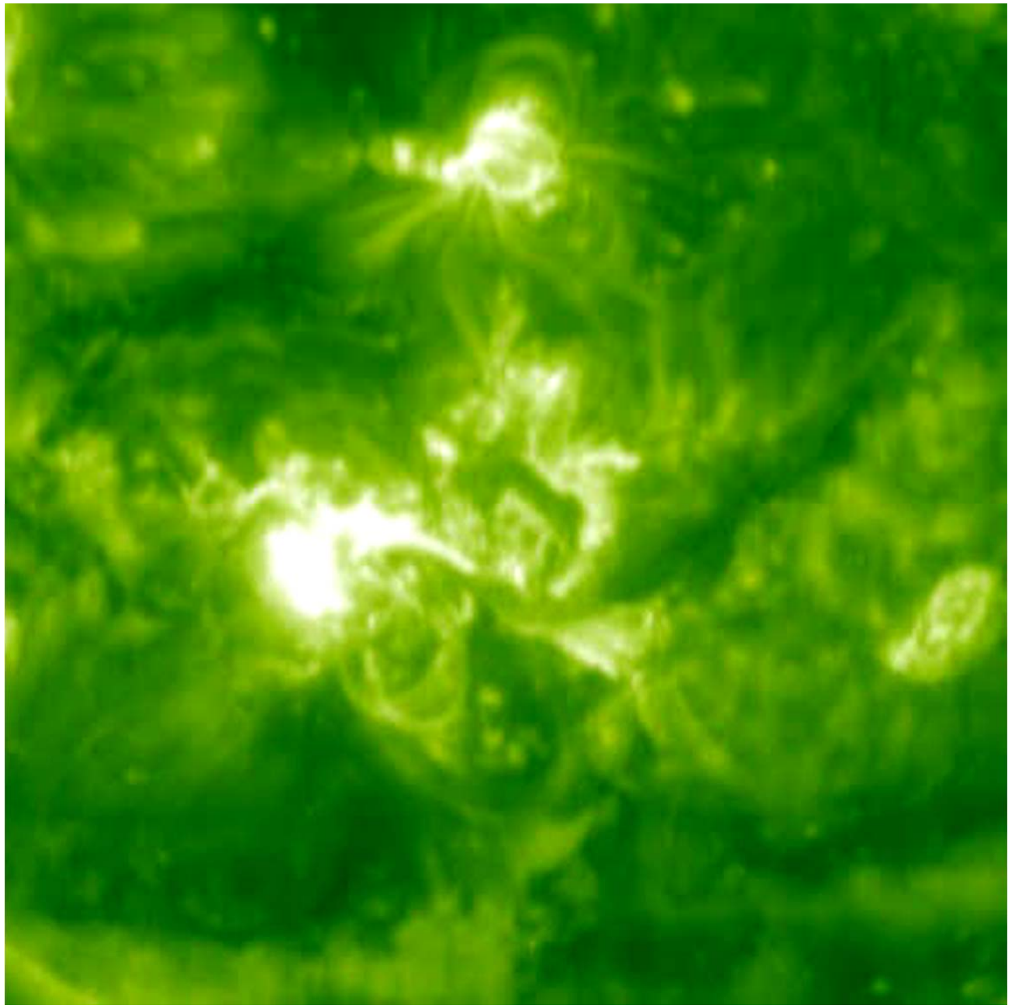
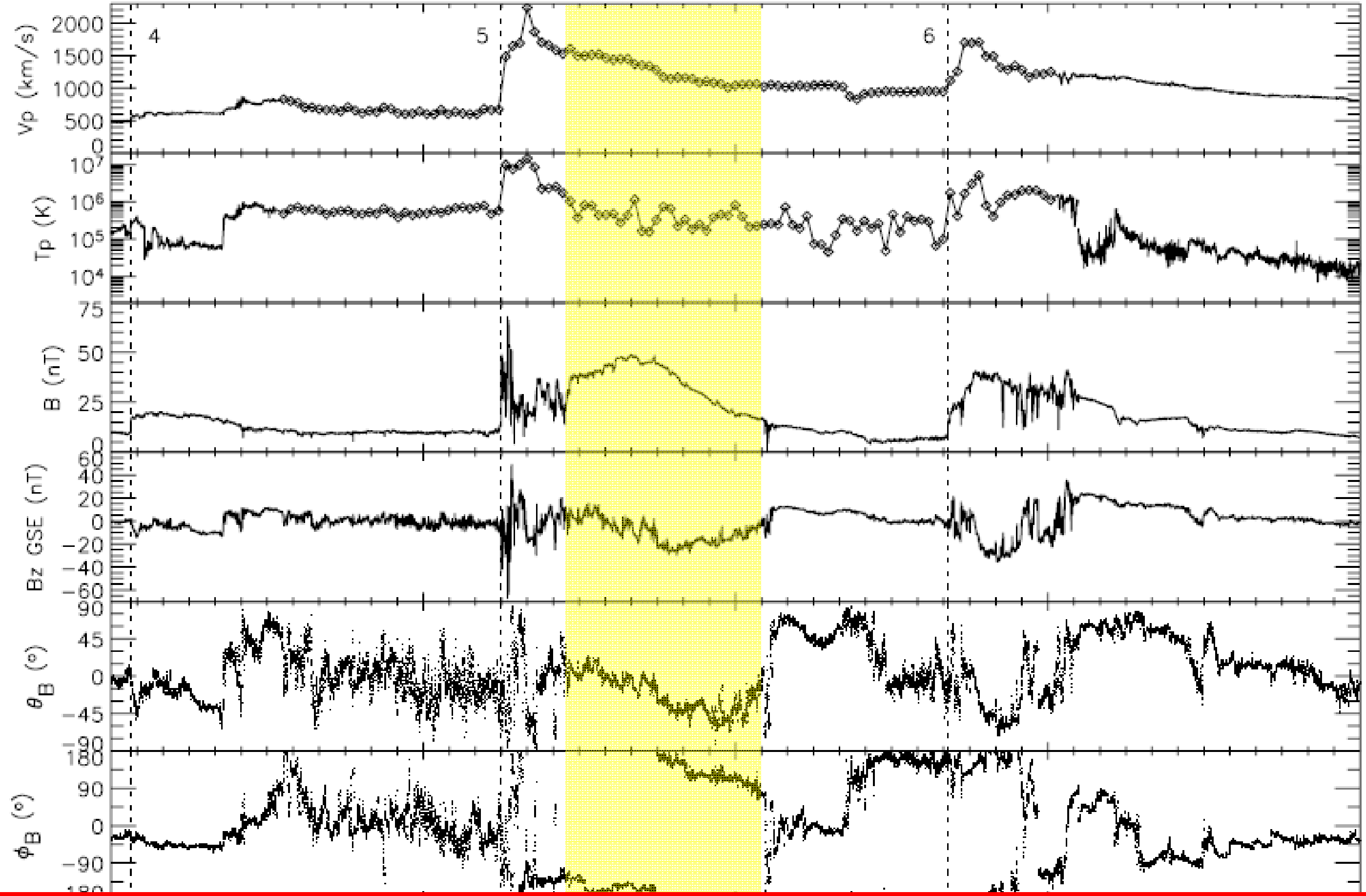
Solar flares and CMEs



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

Characteristic structure of CME: flux rope

Magnetic cloud = flux rope



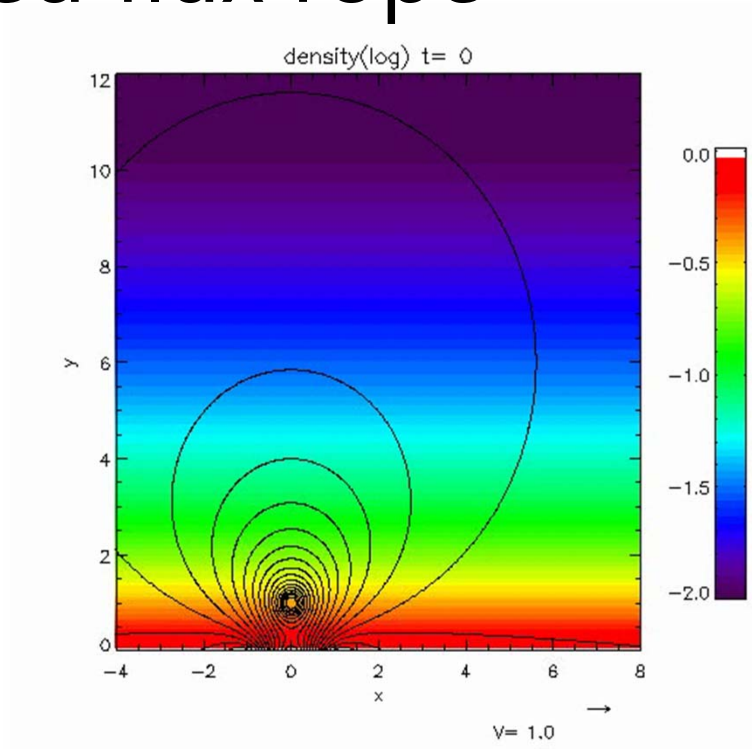
Estimation of the arrival of Southward Magnetic field (SBz) is a very important task in the space weather forecast

Origins of twisted flux rope

Two possibility

- A pre-existing coronal flux rope (sometimes associated with a prominence)

- Formation during an eruption via reconnection in a sheared coronal arcade

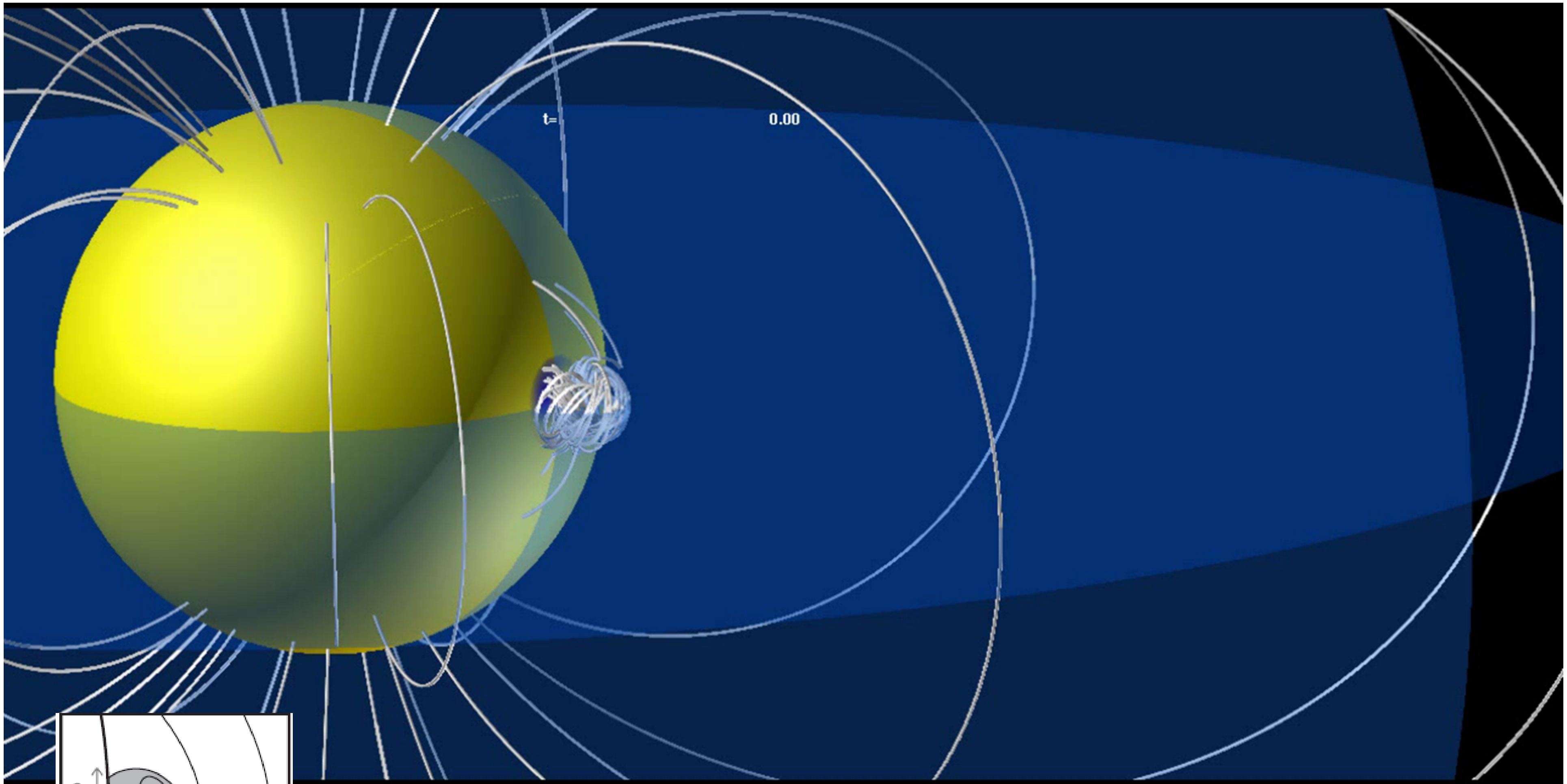


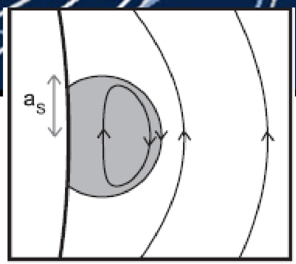
(Shiota + 2003, 2005, Shiota 2007)

From either origin, a twisted magnetic flux rope is commonly formed and ejected outward.

Interaction between flux rope and ambient field

The flux rope disappears because most of the magnetic flux is reconnected

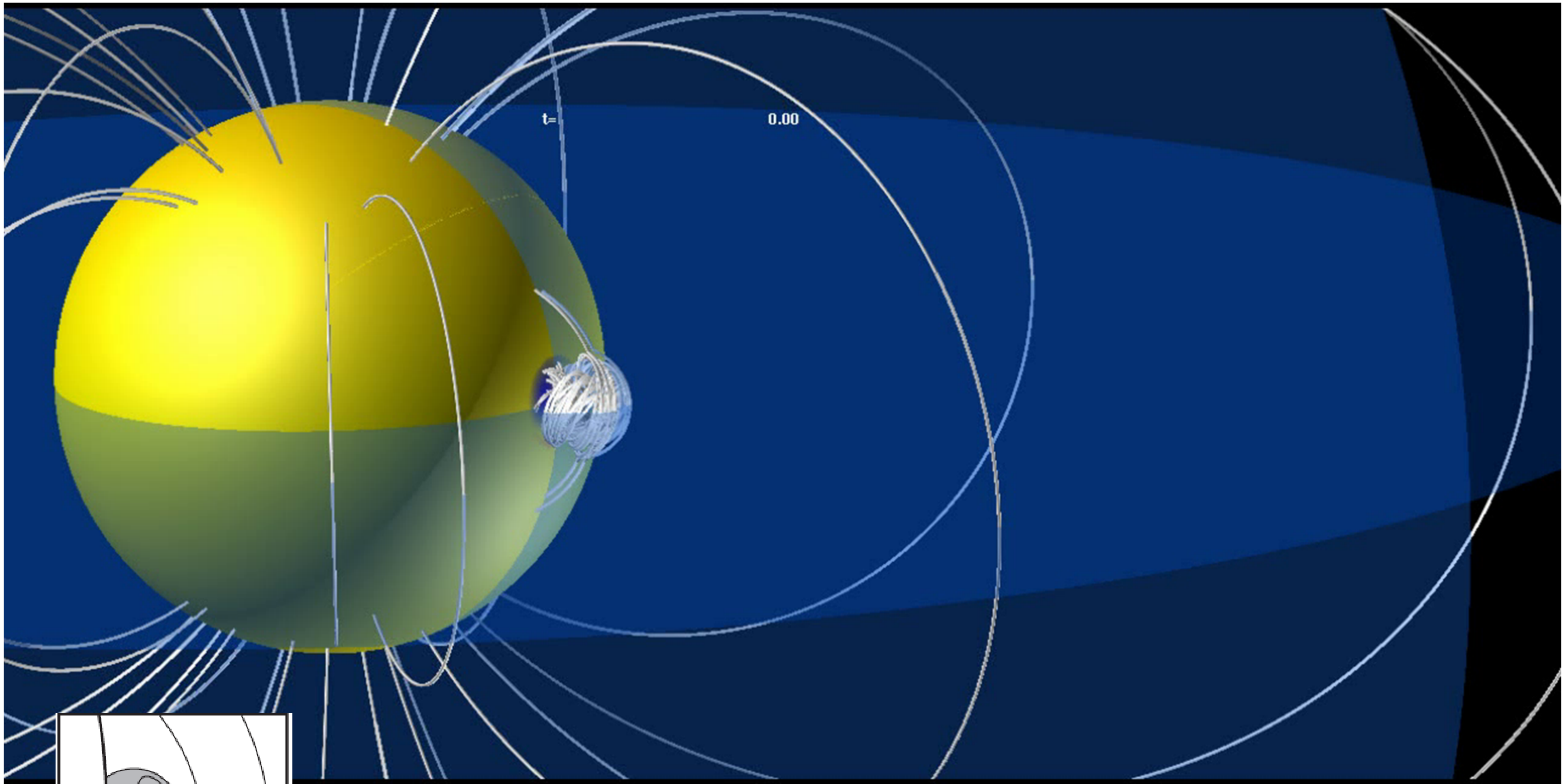


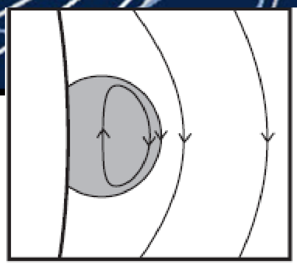


Tubes : magnetic field lines, background : Vr (Shiota + 2010)

Interaction between flux rope and ambient field

The flux rope escape to the outer boundary (formation of CME)



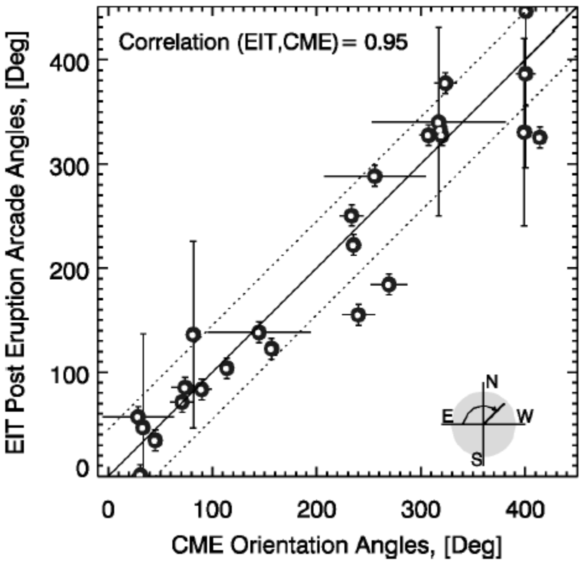


Tubes：magnetic field lines, background：Vr (Shiota + 2010)

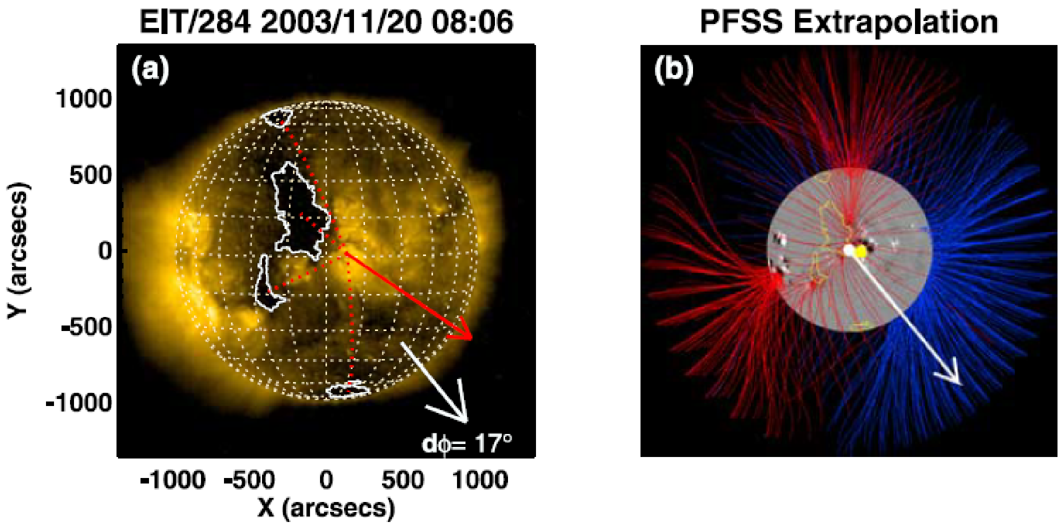
Interaction with ambient field

Interaction with the ambient field on the way

- success or failure of evolution to a CME
- the orientation of the flux rope
- deflection of the erupting flux rope



Yurchyshyn + 2008

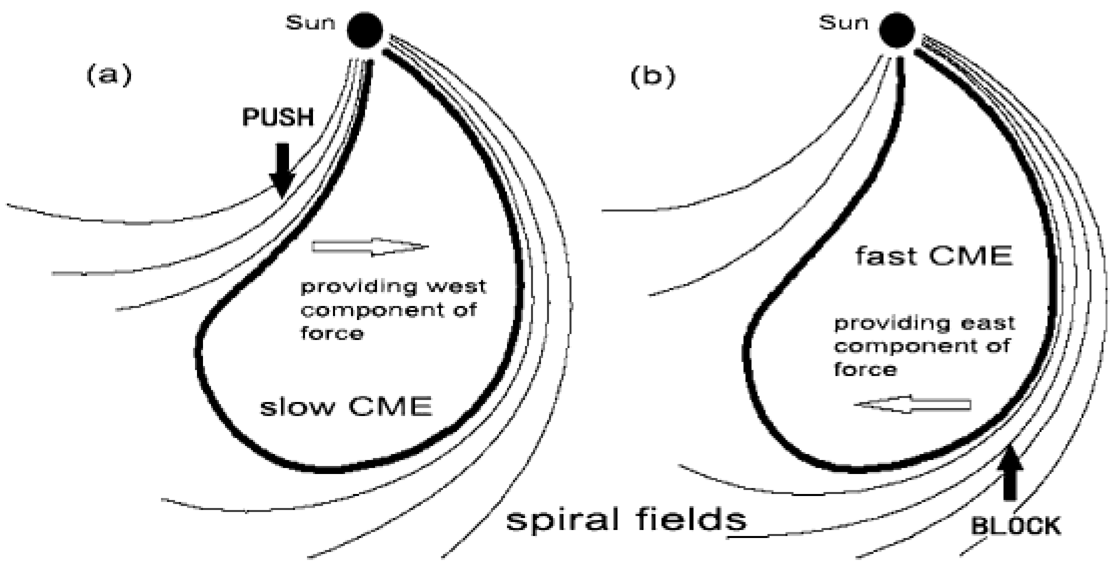


Gopalswamy + 2009

Interaction with solar wind

Background solar wind

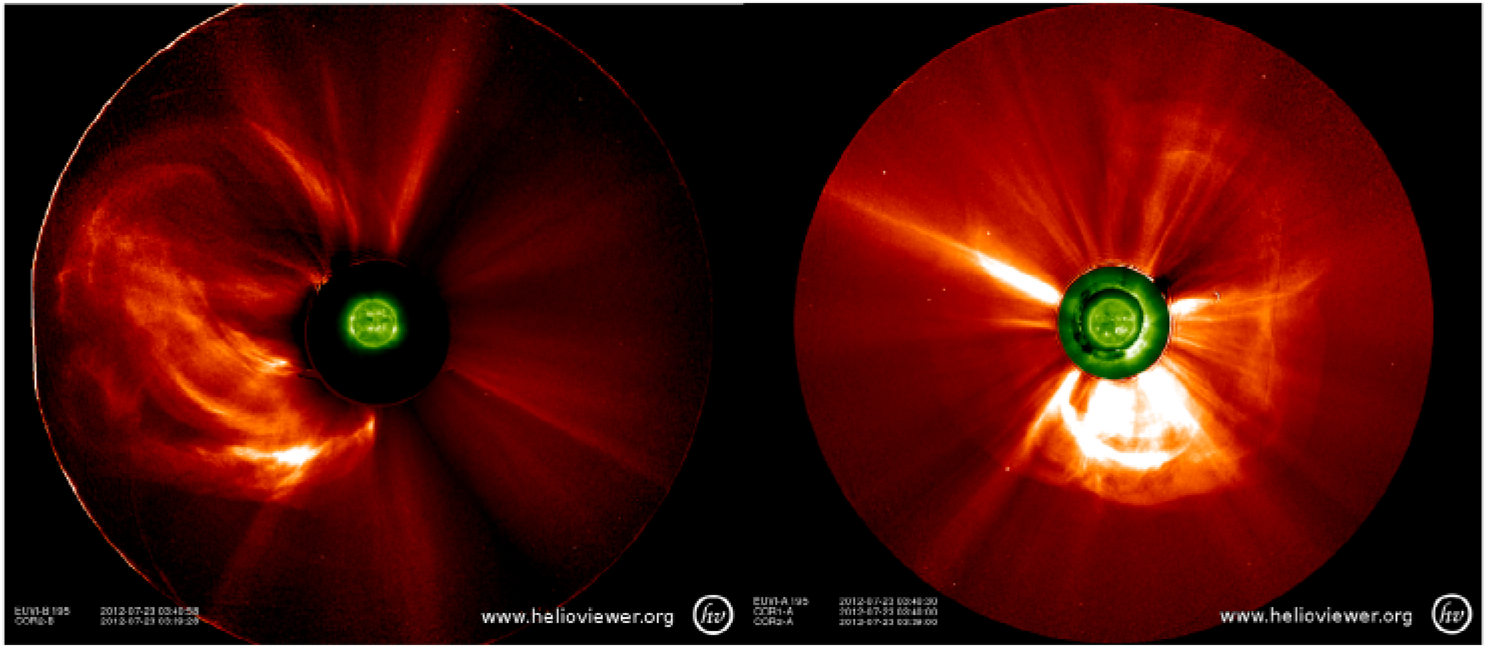
- drug fast CMEs backward
- push slow CMEs forward
- Longitudinal deflection CMEs



Wang + 2004

CME-CME interaction

- Interaction between successive CMEs can prevent expansion of flux ropes and lead an arrival of strong magnetic field (ex. 2012 July STEREO event, Baker + 2013, Liu + 2014).



Physical processes affect CME evolution

- Formation of twisted magnetic flux ropes
- Interaction with ambient
  - Interchange reconnection
  - Rotation
  - Deflection
  - Acceleration of deceleration
- Interaction between successive CMEs

There are many uncertainties

=> realistic modeling with MHD simulation

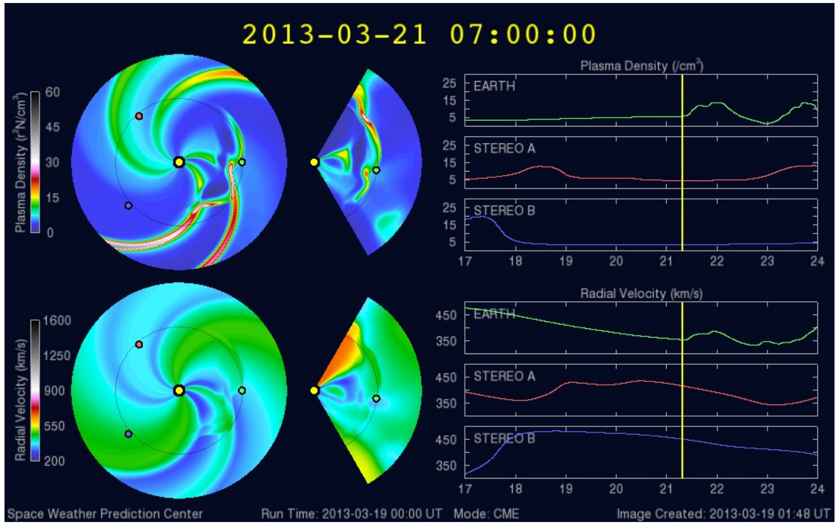
(validation with in situ measurement)

Realistic MHD simulation

- Several research groups have made so much effort to model the whole complicated processes (from 1 R_{sun} to 1AU) with **realistic 3D MHD simulations.**
- There are unknown physical mechanisms (flare trigger, coronal heating, solar wind acceleration).
- Any simulation needs some models to compensate such insufficient information.

- A MHD simulation of solar corona with realistic condition consumes a large amount of numerical resource.
  - **Not suitable for real-time operation use**
  - **Not suitable for parametric studies**

WSA-ENLIL + cone model



- WSA-ENLIL + cone model that skips the coronal region has been used for space weather forecast operation in NOAA/SWPC.
- In the model, a CME is injected as **a hydrodynamic pulse (without magnetic flux rope)**, and therefore the model is **not suitable to predict an intense magnetic storm** caused by the passage of a magnetic cloud within a CME.

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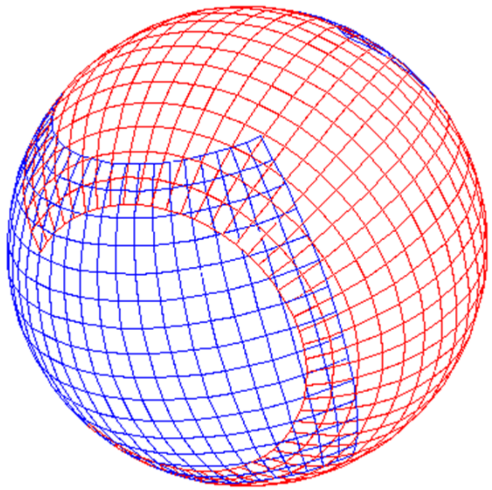
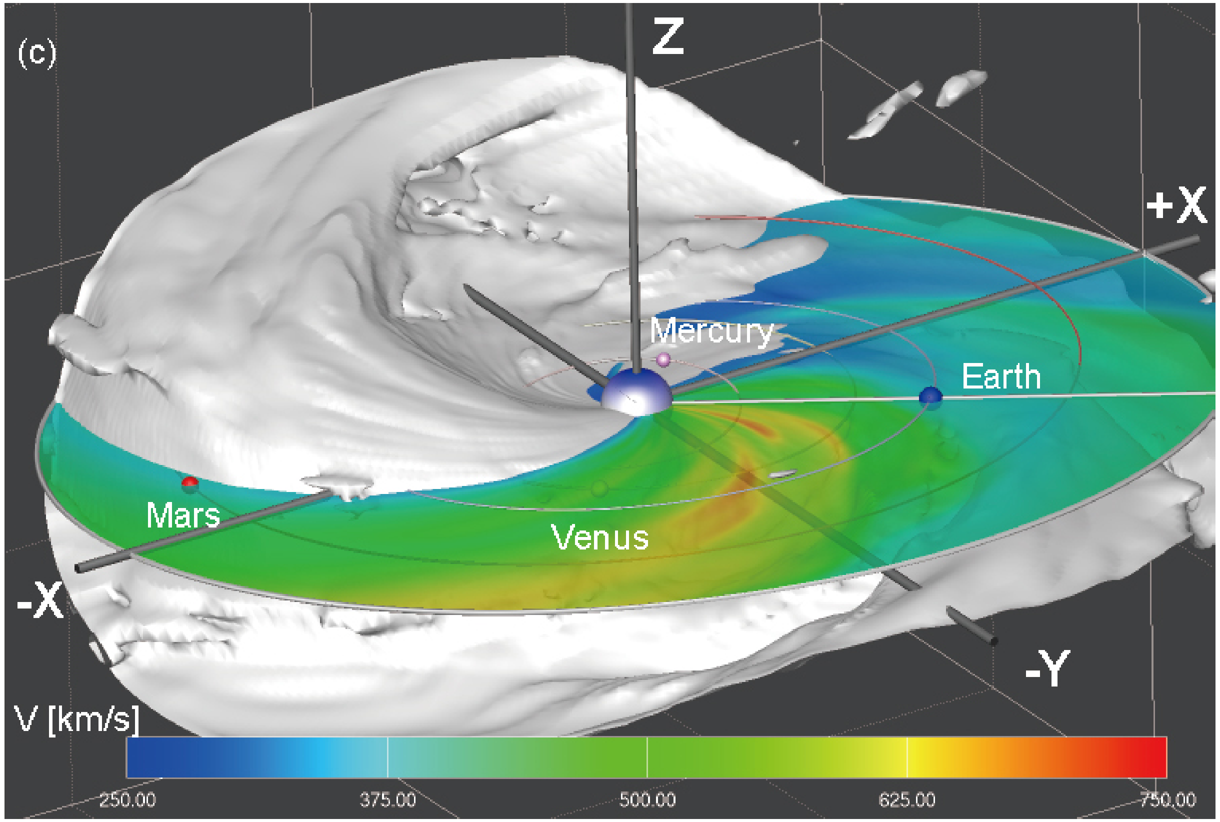
Solar wind MHD model: SUSANOO-SW

- 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

(Shiota + 2014)

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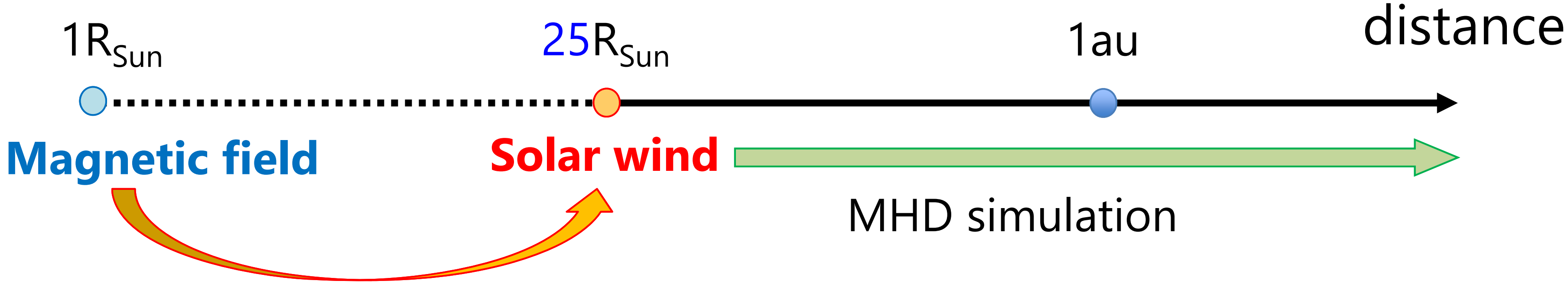
Outline of SUSANOO-SW

The model is based on observation of solar magnetic field



＋empirical laws

- Potential magnetic field (PFSS) model

  magnetic field map ⇒ coronal field and IMF x5

- Wang-Sheeley-Arge 2000 (Arge& Pizzo 2000)

  coronal field ⇒ velocity

- Helios observation empirical model (Hayashi+2003)

  velocity ⇒ density ＋ temperature

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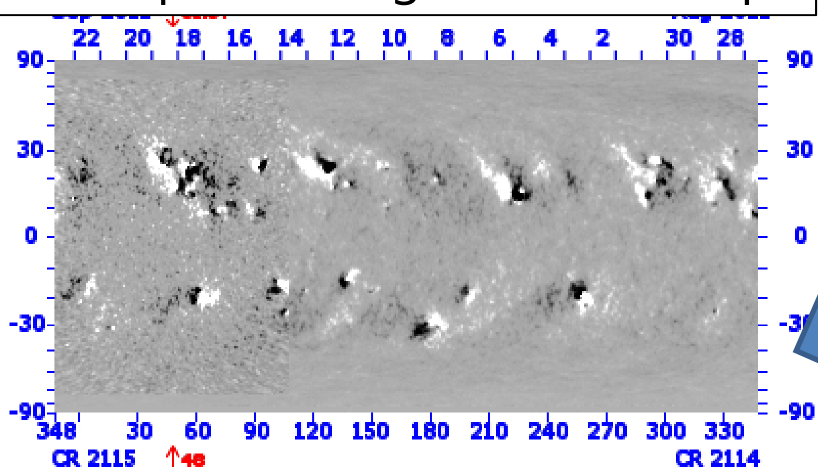
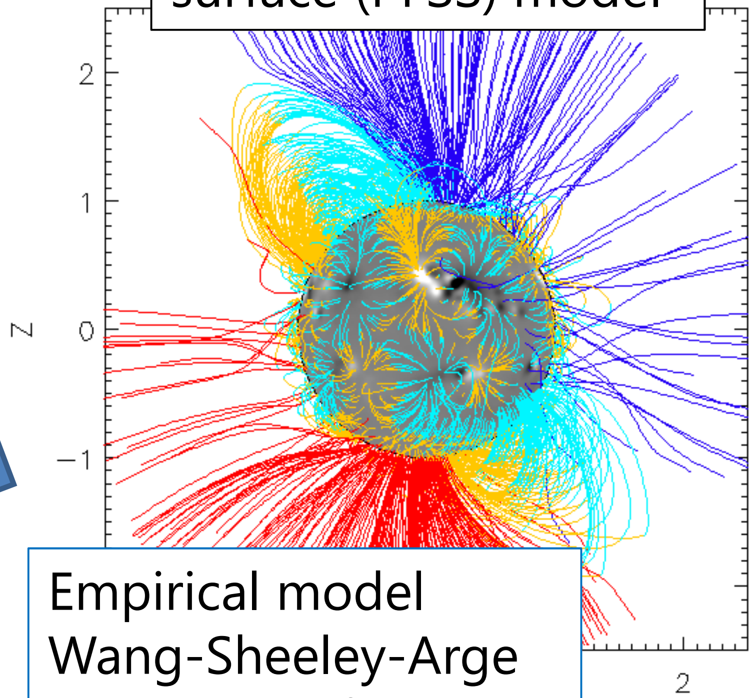
Coronal magnetic field and solar wind velocity

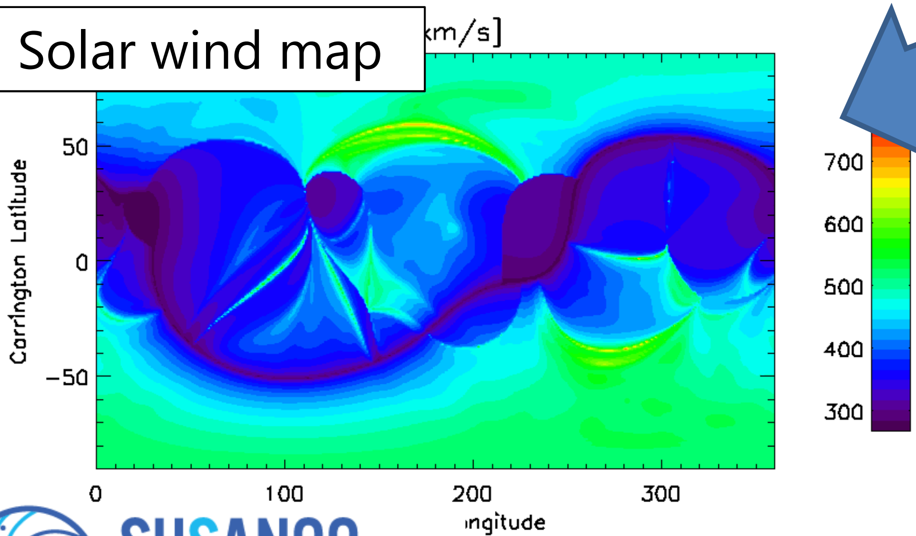
Photospheric magnetic field map



Potential field source surface (PFSS) model



Solar wind map



Empirical model
Wang-Sheeley-Arge (WSA) 2000 formula
(Arge & Pizzo 2000)
Helios Observations

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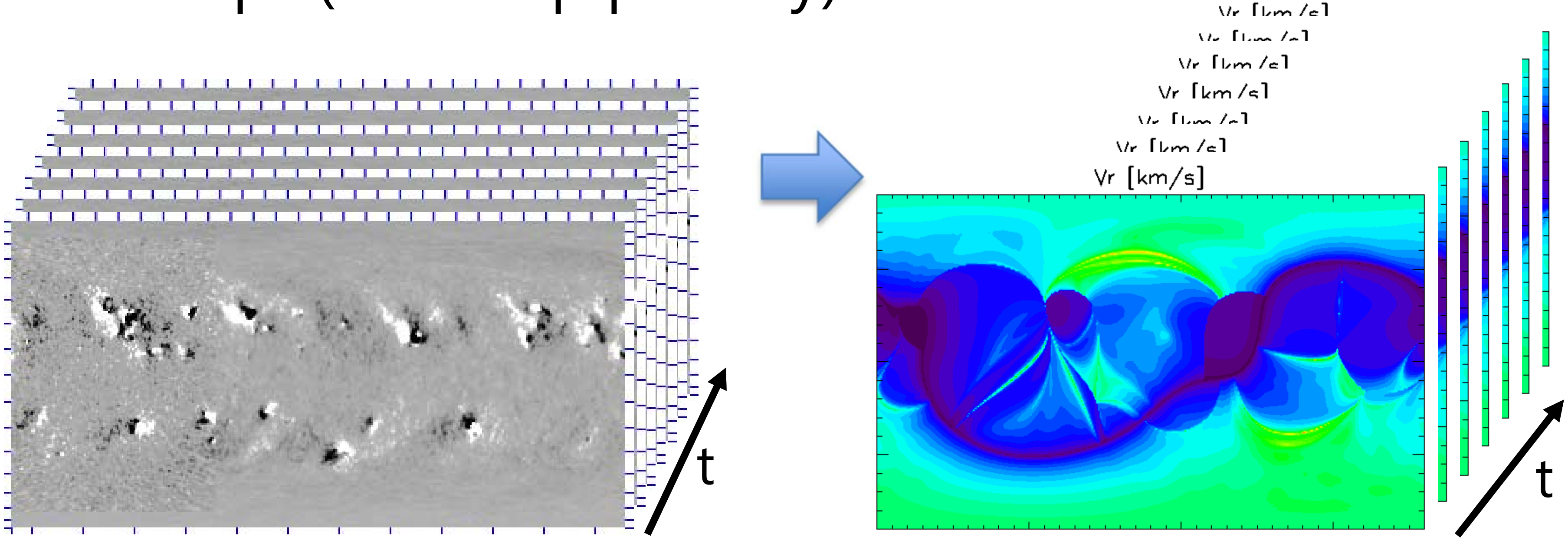
Time-varying inner boundary condition

- 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

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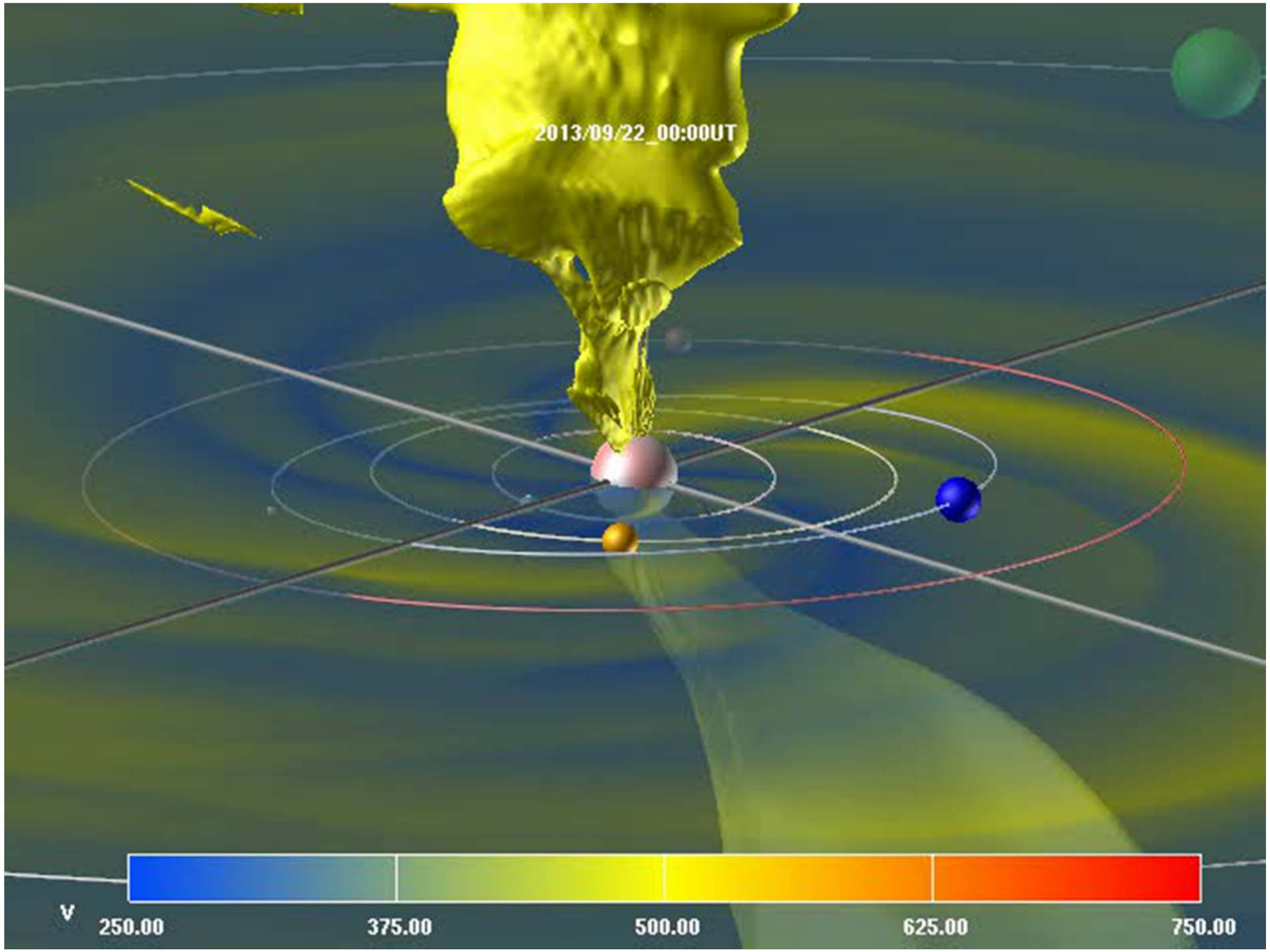
Solar wind in 2013~2014



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

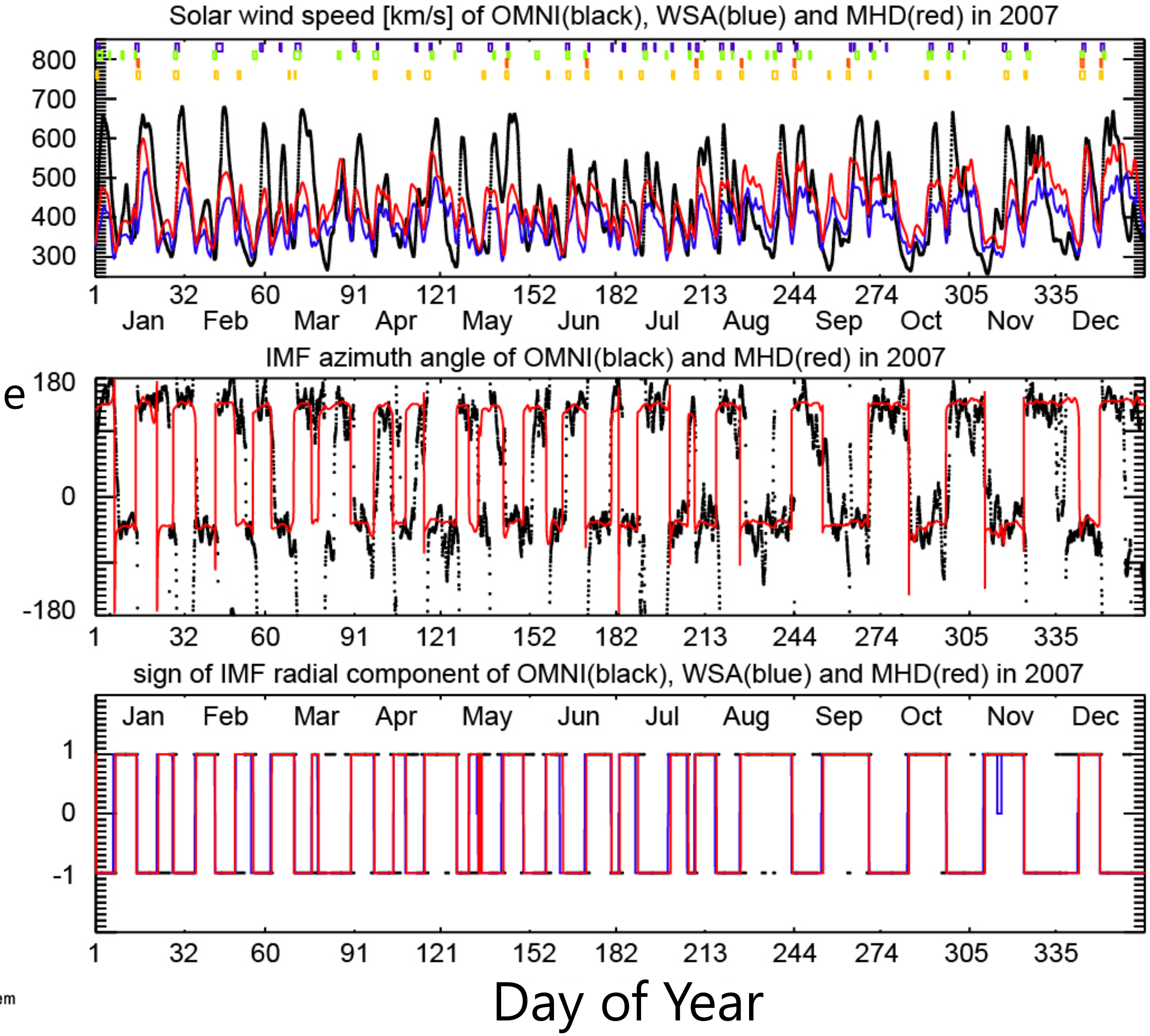
Solar wind in 2007 at Earth position

Velocity

in situ measurement
MHD simulation
kinematic model

Azimuth angle of IMF

Sign of IMF



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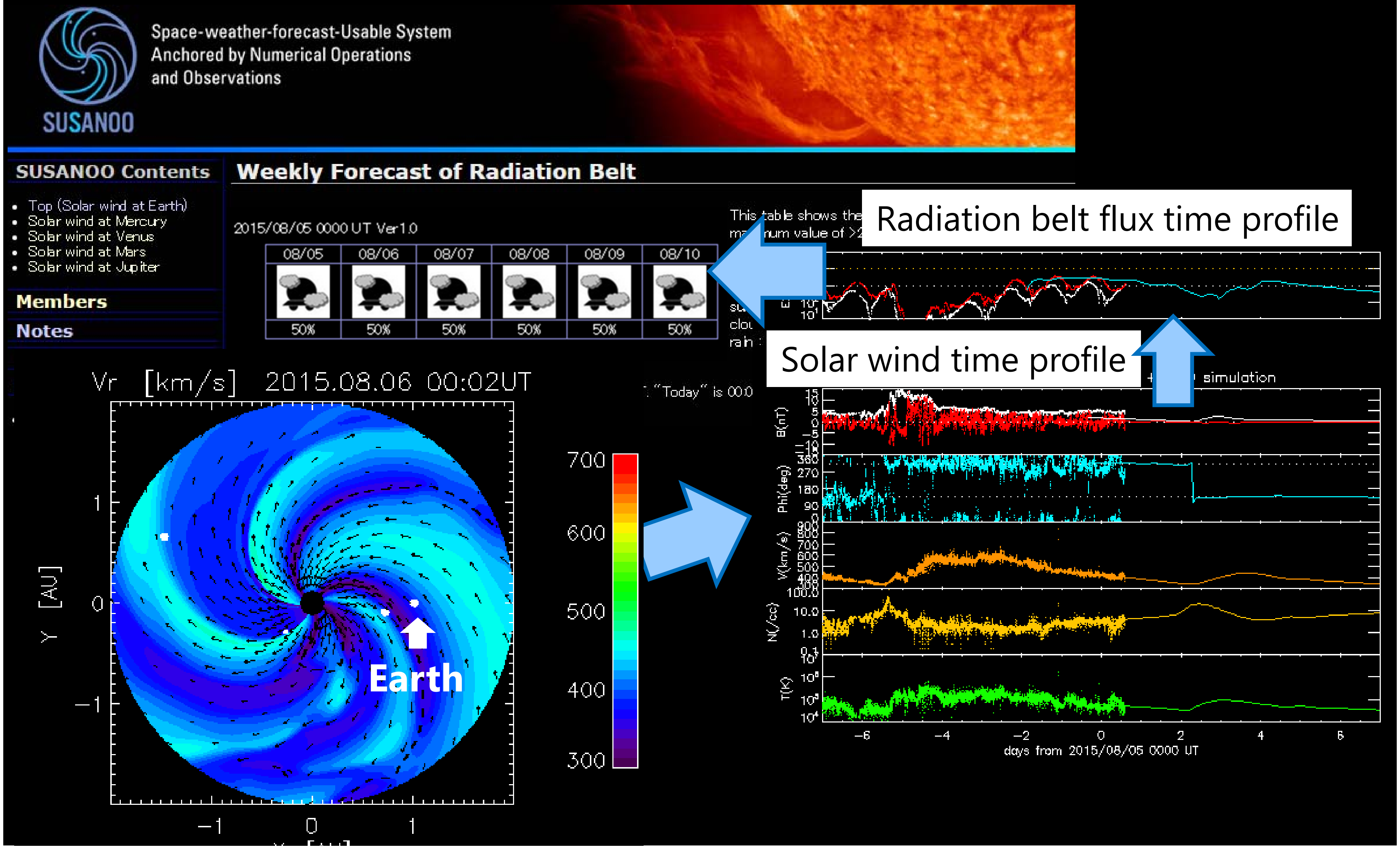
and Observations

Automated forecast system (SUSANOO)

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



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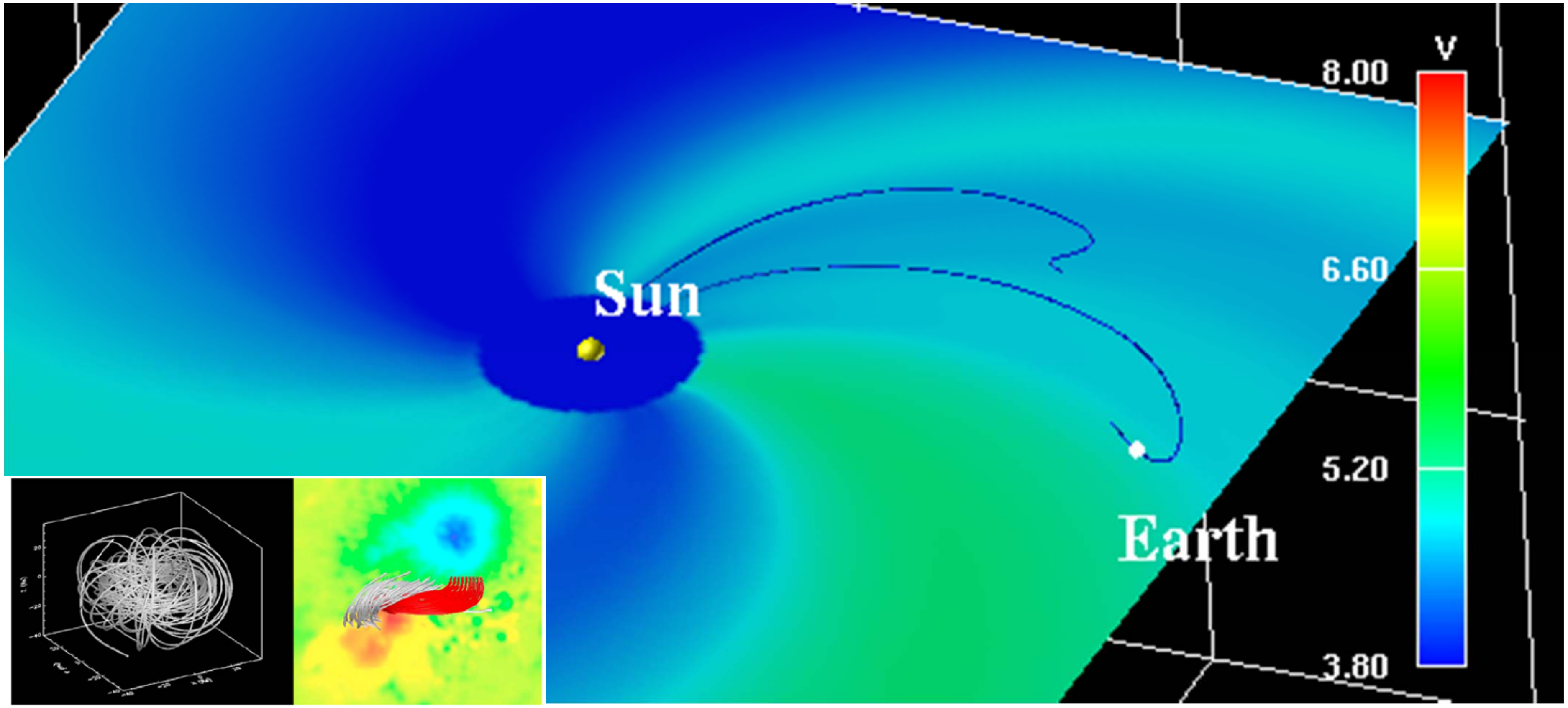
CME model with internal magnetic flux rope



- Kataoka+ (2009) proposed a model to inject a **CME containing a twisted magnetic flux rope** into 3D solar wind.
- We modified the model to specified the parameters on the basis of solar observations and combined to SUSANOO-SW.

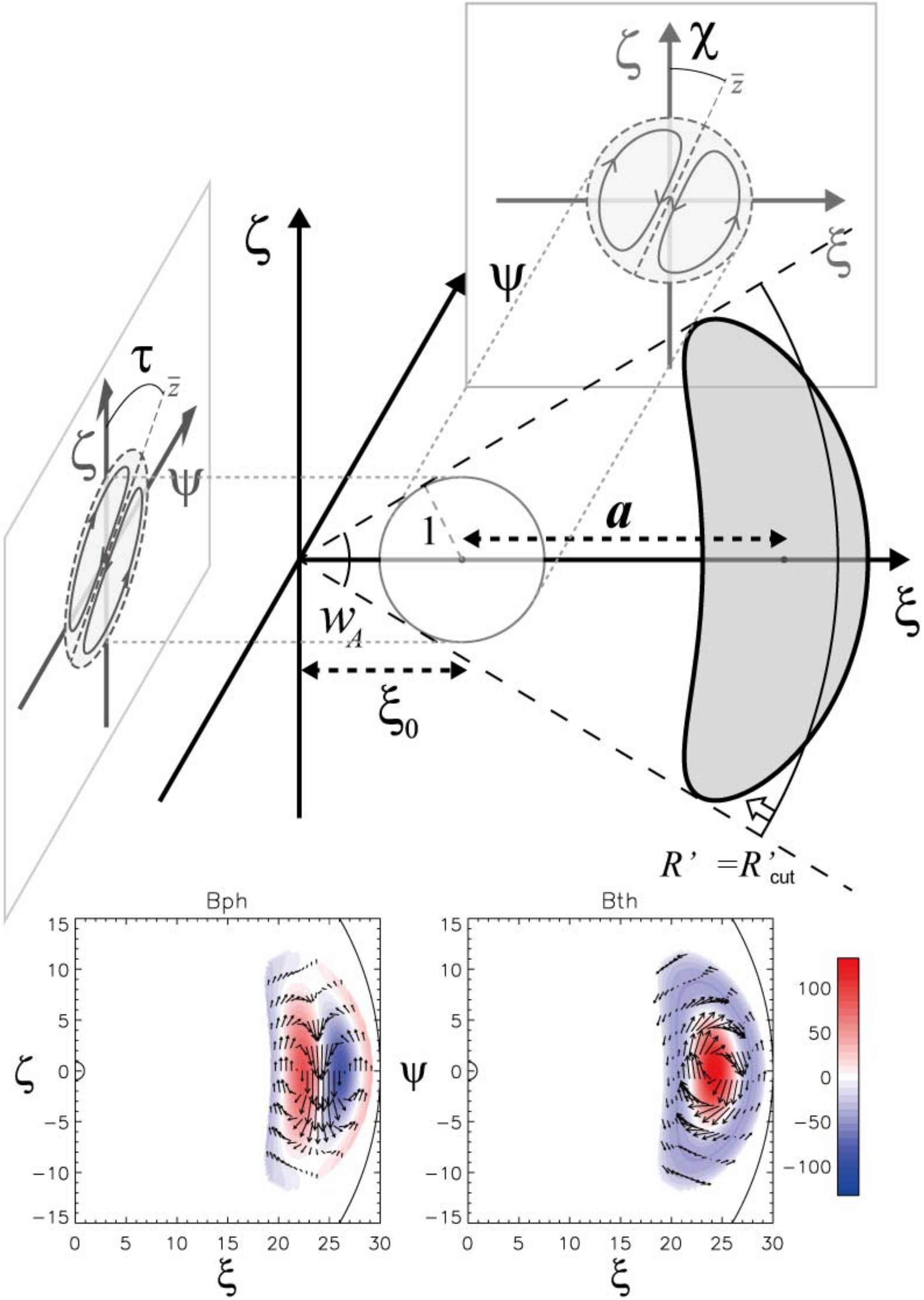
Flux rope model

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

This model has 10 parameters

- The temporal and spatial positions 3
- Velocity 1
- Shape of CME 2
- Magnetic structure (strength, chirality, direction of the spheromak) 4

(Shiota & Kataoka, submitted to SpaceWeather)



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Parameters of CME model

Symbols	Explanation	Default value	
t_{onset}	Onset time of CME	from LASCO CME catalog	observation
V_{CME}	Propagation speed of CME	from LASCO CME catalog	
λ_{S}	Carrington latitude of CME source region	from the flare list in NGDC	
ϕ_{S}	Carrington longtude of CME source region	from the flare list in NGDC	
τ	Tilt angle of spheromak	±90 degree with Hale-Nicholson law	
χ	Inclination angle of spheromak	0 degree	assume
c_1	Chirality of Helicity in spheromak	1, set -1 if oppsitite to Bothmer-Schwenn rule	
Φ_{mag}	Magnetic flux within CME	proportional to flare class	
w_{A}	Angular width of CME	60 degree	
w_{r}	Radial width of CME	2 Rs	assume

Rest: Obs.+assume

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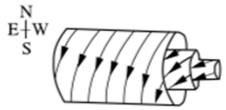
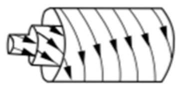
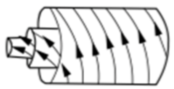
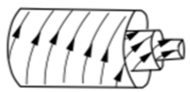
Helicity of Magnetic clouds (MCs)

	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)
2n cycle — North	SEN Left-handed  17	South ($-Bz$)→north ($+Bz$)	East ($+By$)	
2n cycle — South	SWN Right-handed  17	South ($-Bz$)→north ($+Bz$)	West ($-By$)	
2n+1 cycle — South	NES Right-handed  6	North ($+Bz$)→south ($-Bz$)	East ($+By$)	
2n+1 cycle — North	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)

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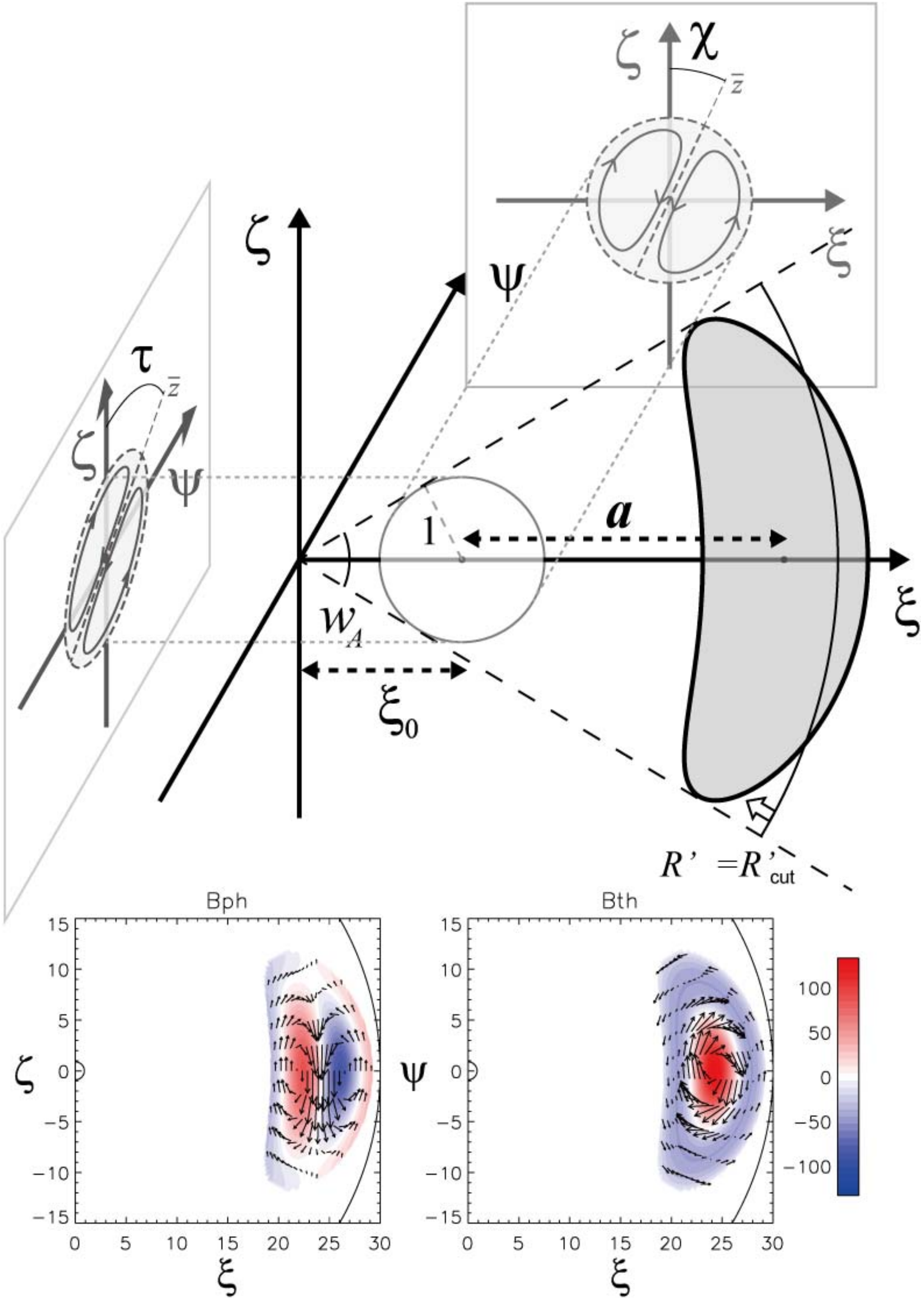

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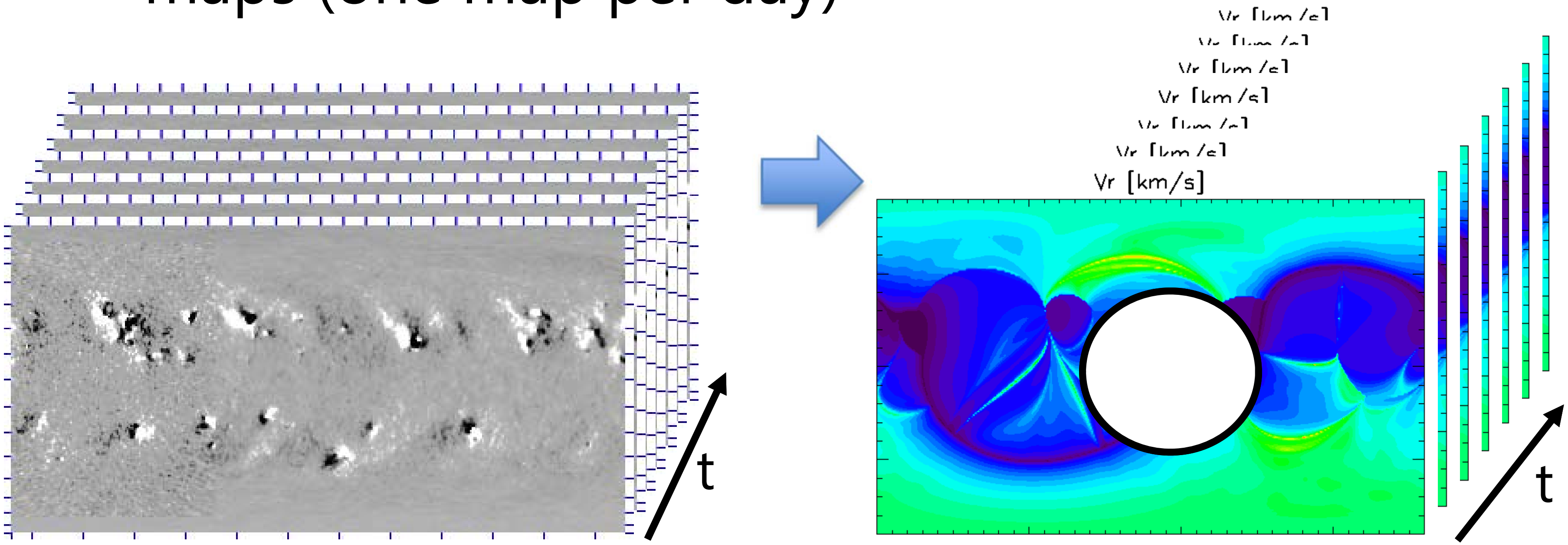
Time-varying inner boundary condition

- 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
Information of CMEs are superposed on these boundary conditions

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Capability of SUSANOO-CME

- Formation and eruption of flux ropes
- Interaction with ambient field
- Interaction between successive CMEs

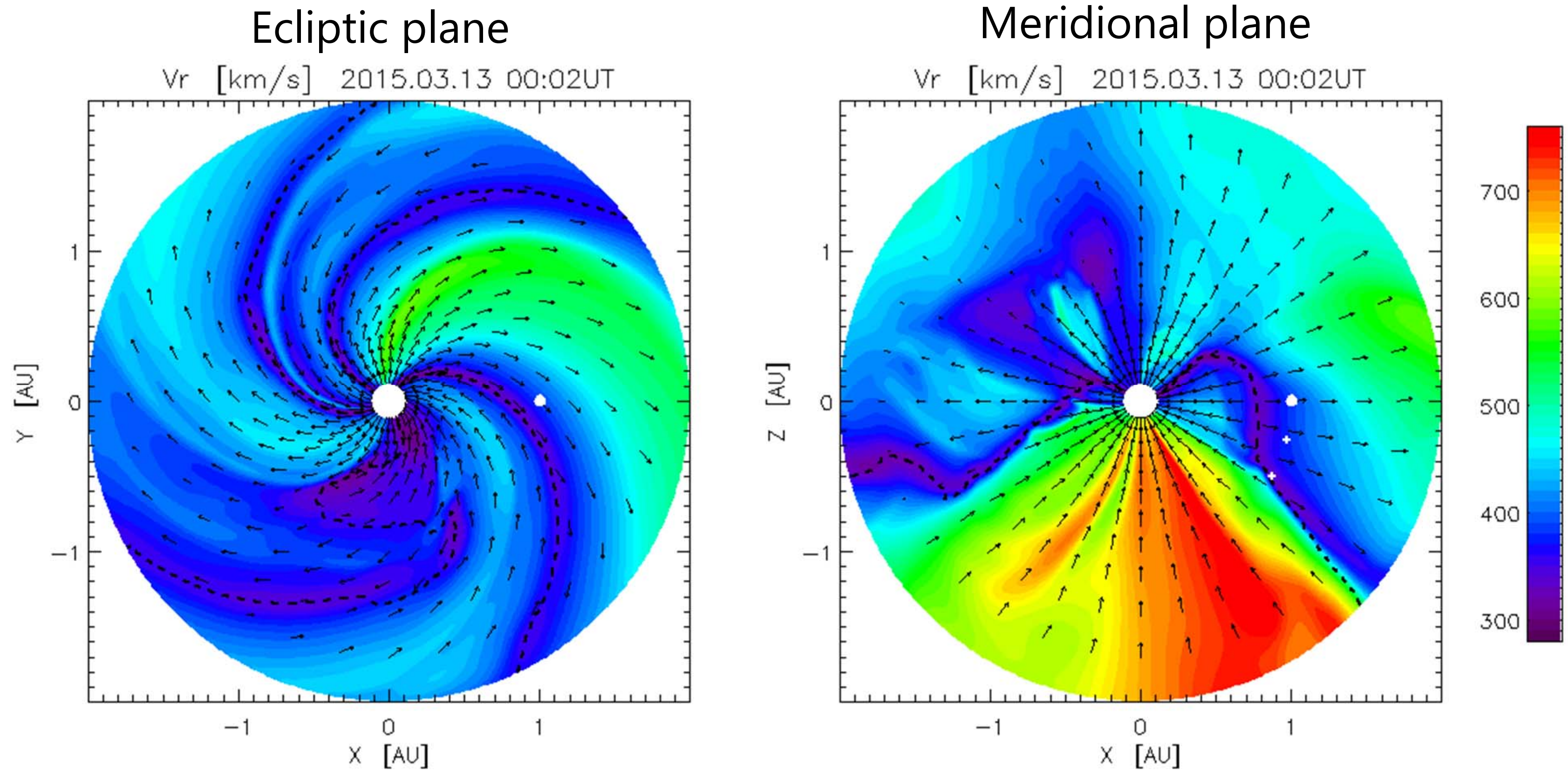
} parameters in CME model

Inner boundary of the MHD simulation $r=30R_{sun}$

- Propagation in the interplanetary space
  - Interaction with ambient solar wind
  - Interaction between successive CMEs

} simulate

Application to the St. Patrick day event



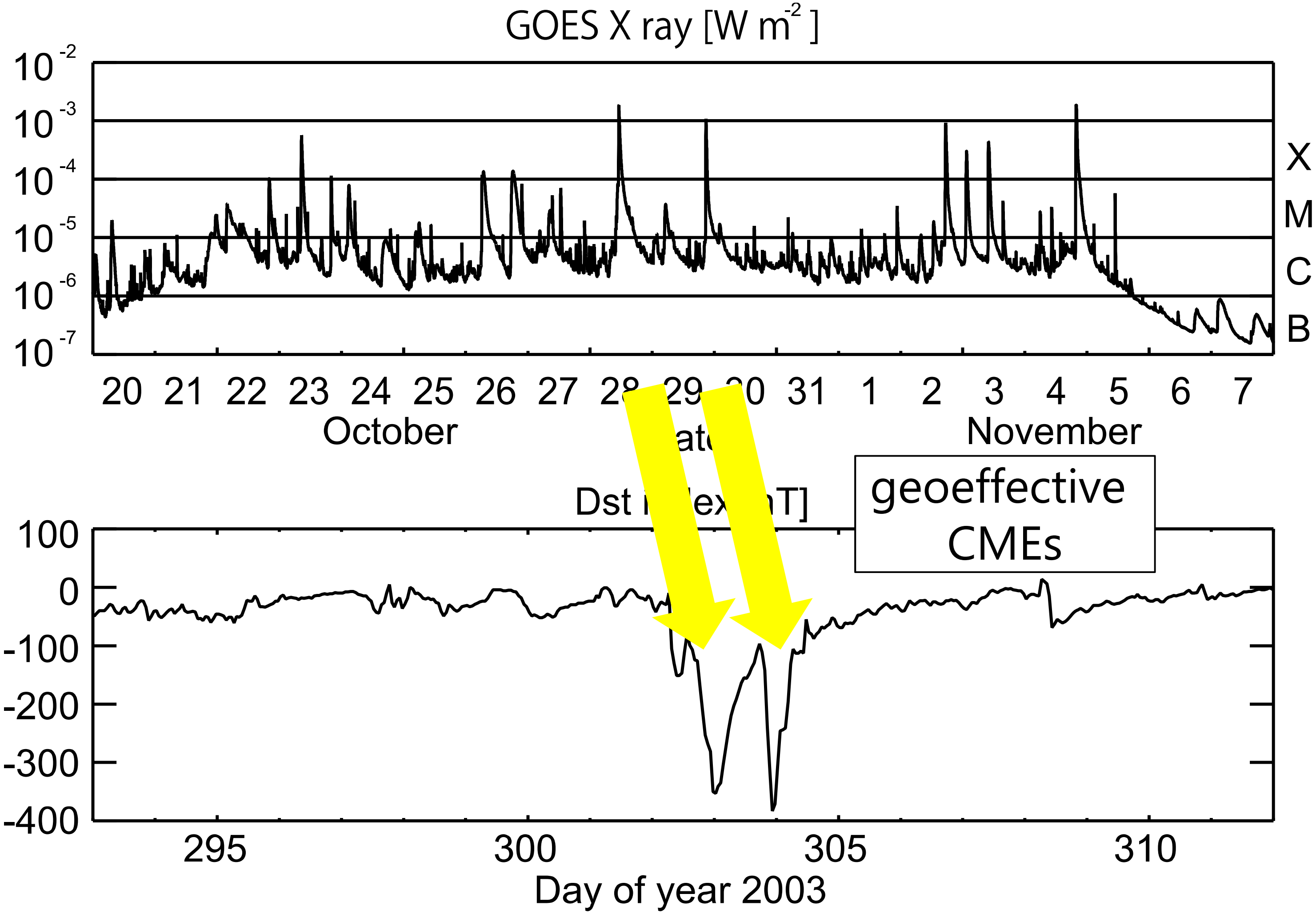
"Pileup accident hypothesis of magnetic storm on 17 March 2015"

Ryuho Kataoka, Daikou Shiota, Emilia Kilpua, Kunihiro Keika

GRL, 2015, **42**, doi:10.1002/2015GL064816. Published in July 2015

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

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

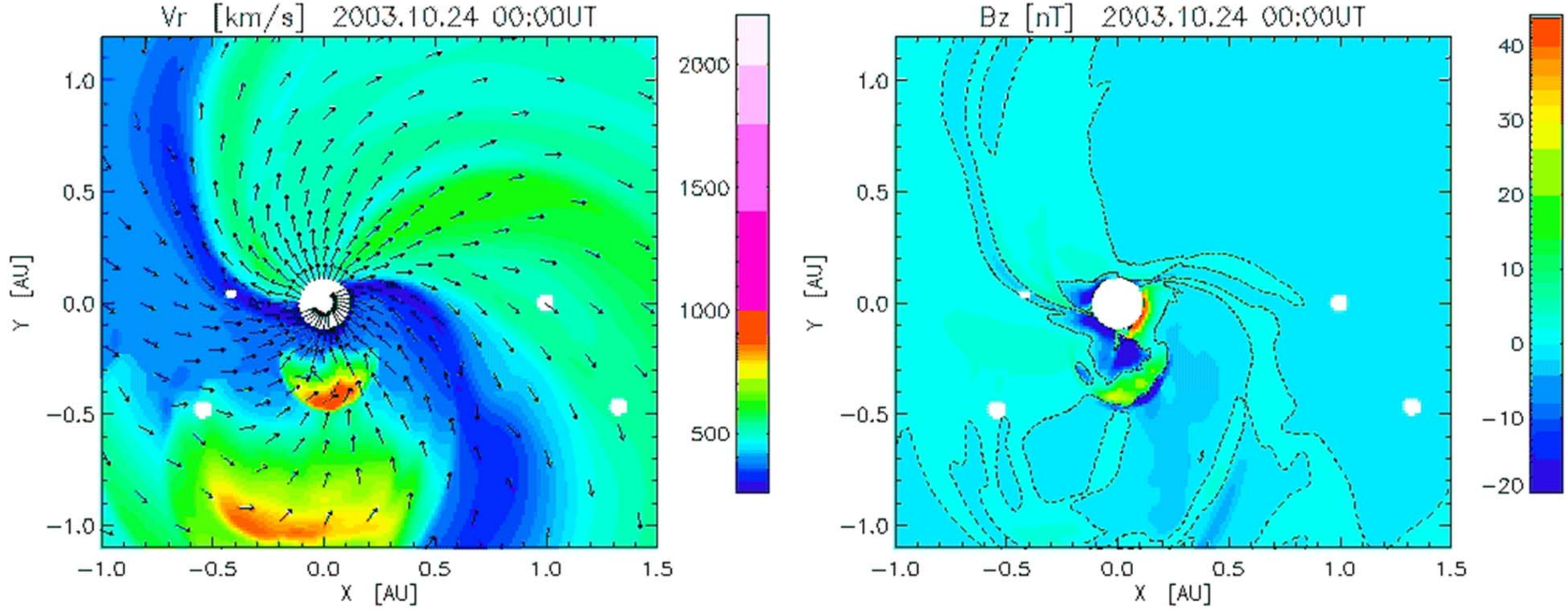


Numerical simulation of 2003 Oct-Nov

#			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

Velocity and Bz (GSE) on the ecliptic plane



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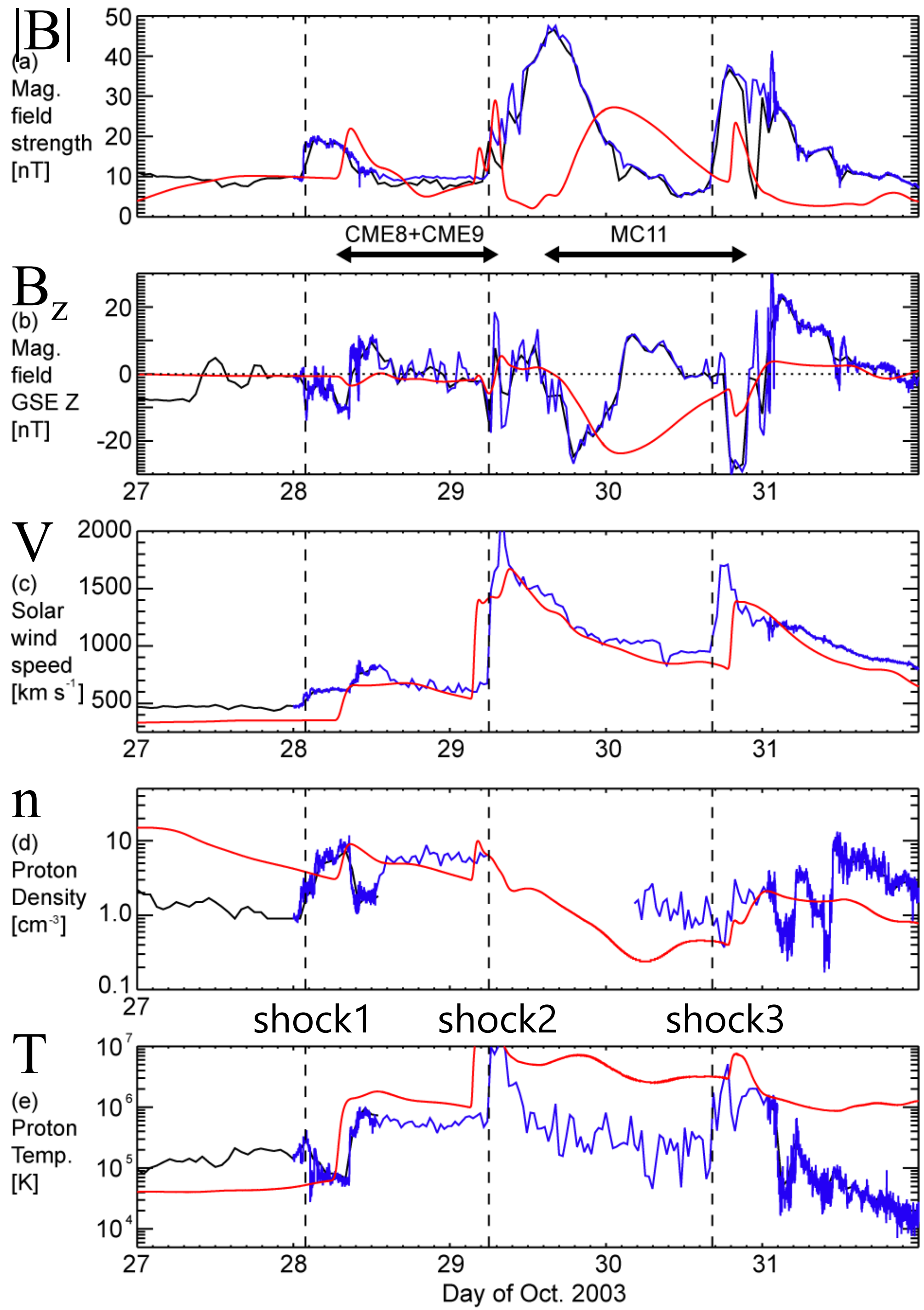
Comparison with in situ measurement

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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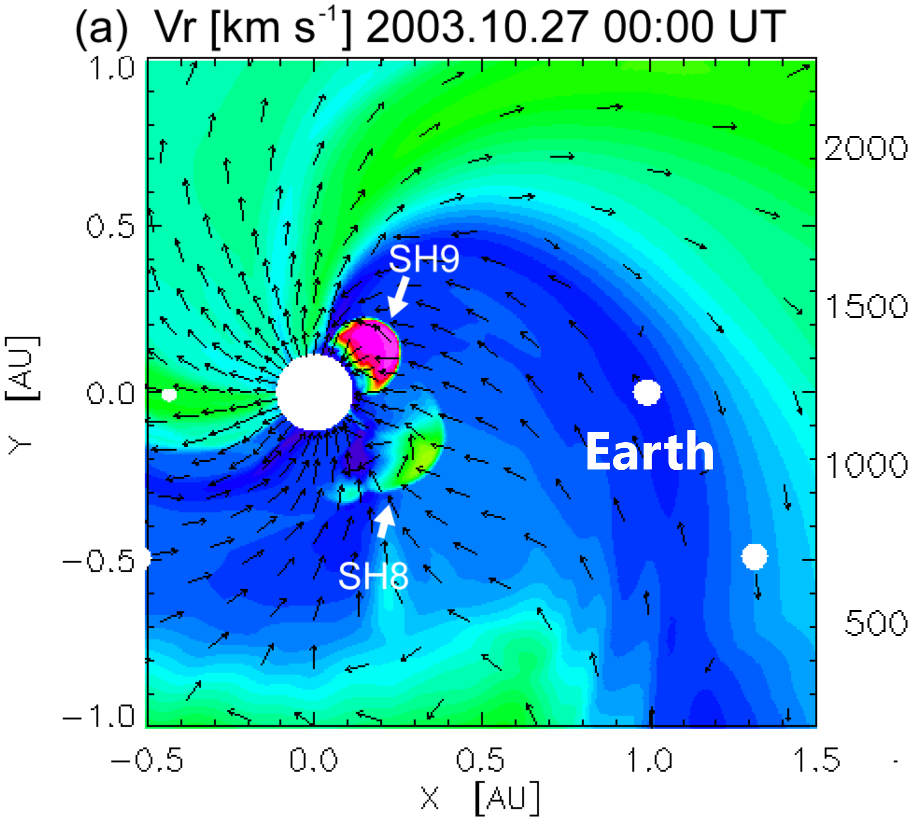
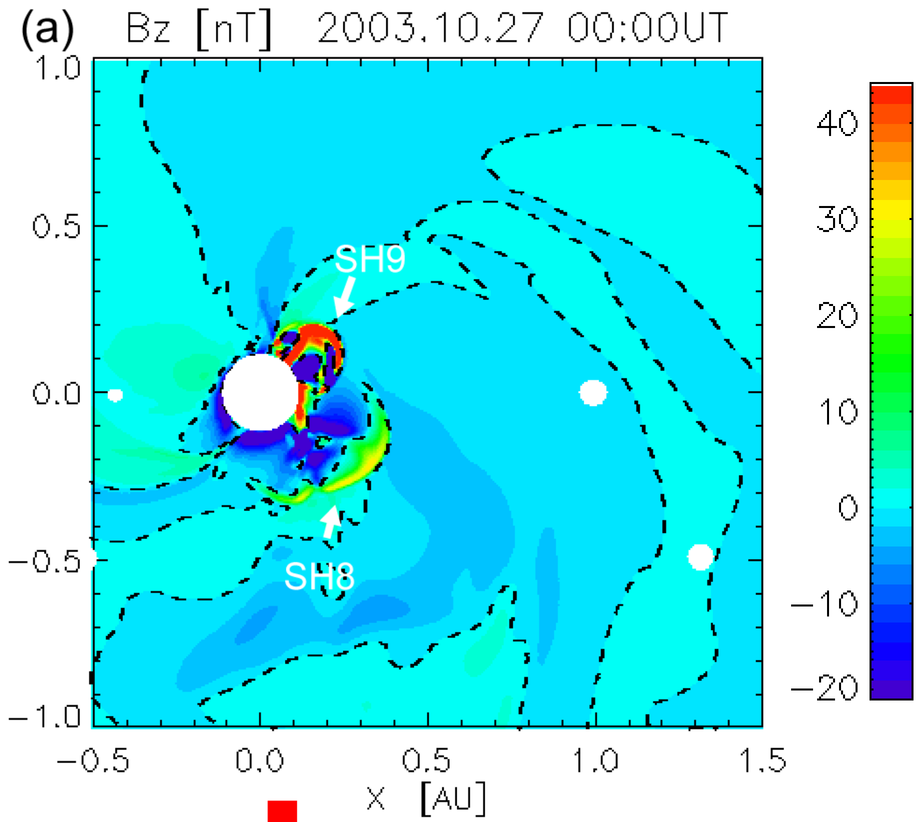
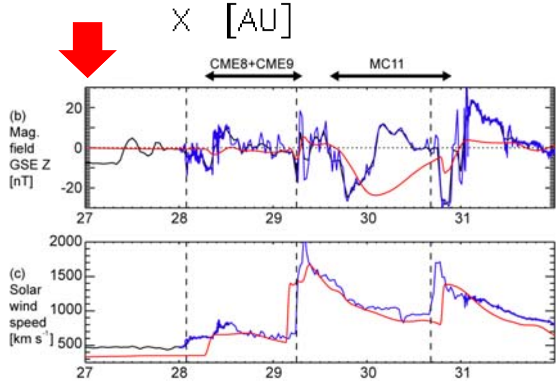
Propagation and CME-CME interaction







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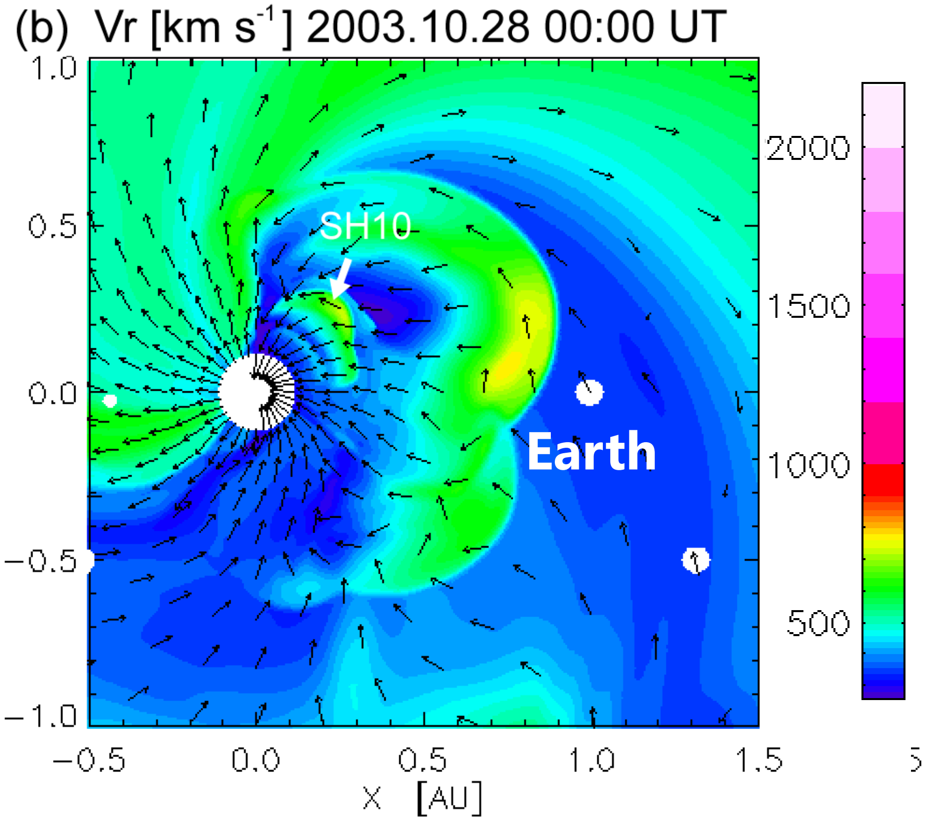
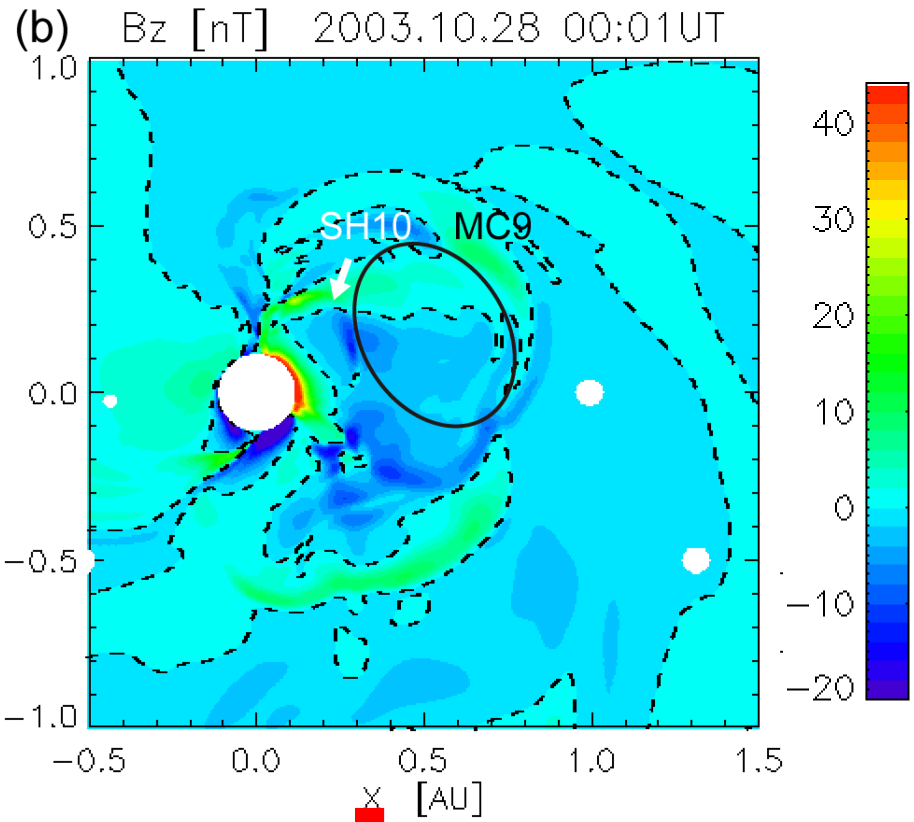
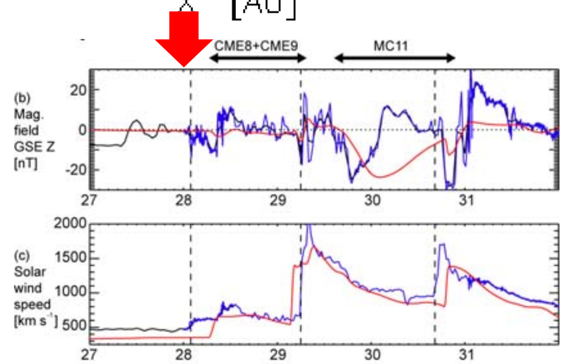
Propagation and CME-CME interaction







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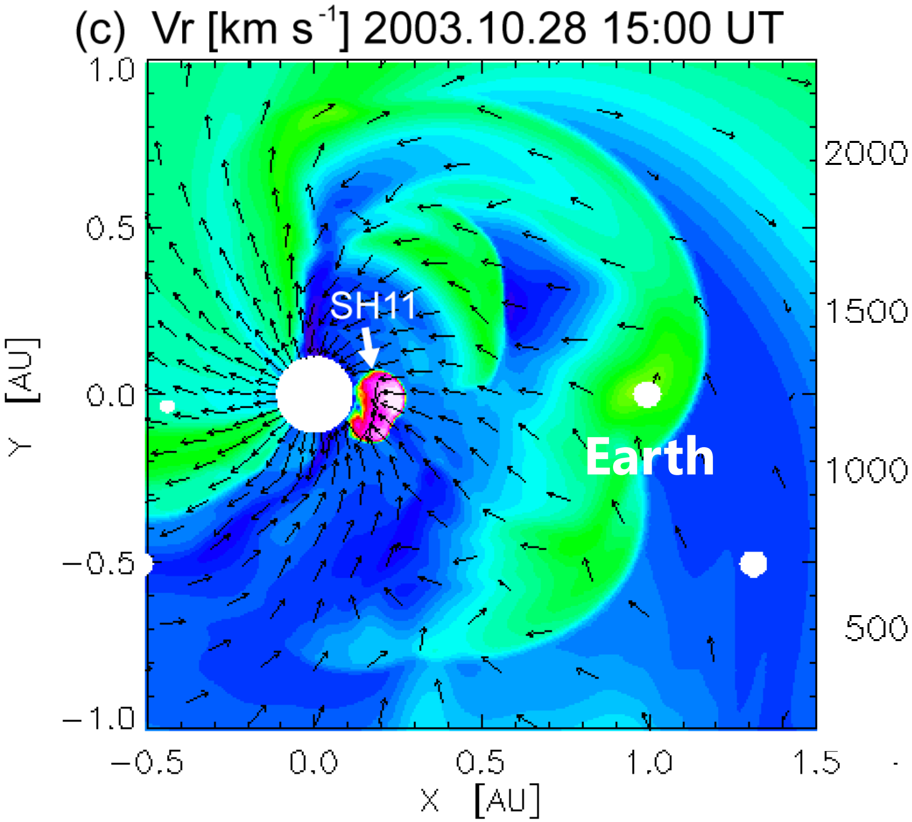
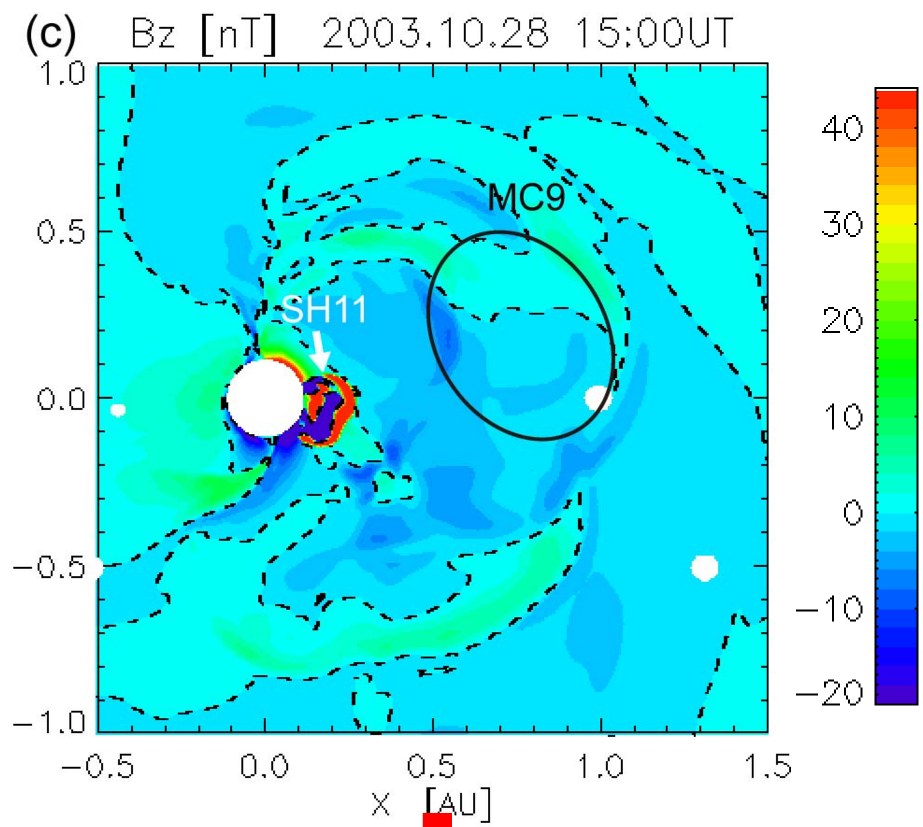
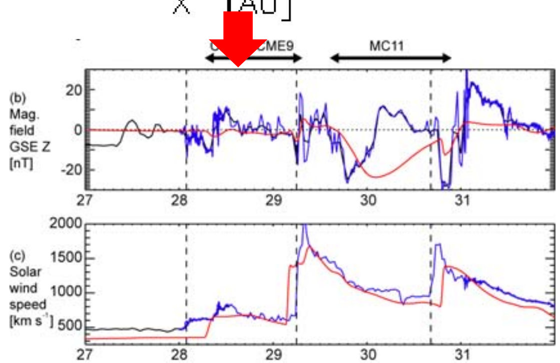
Propagation and CME-CME interaction







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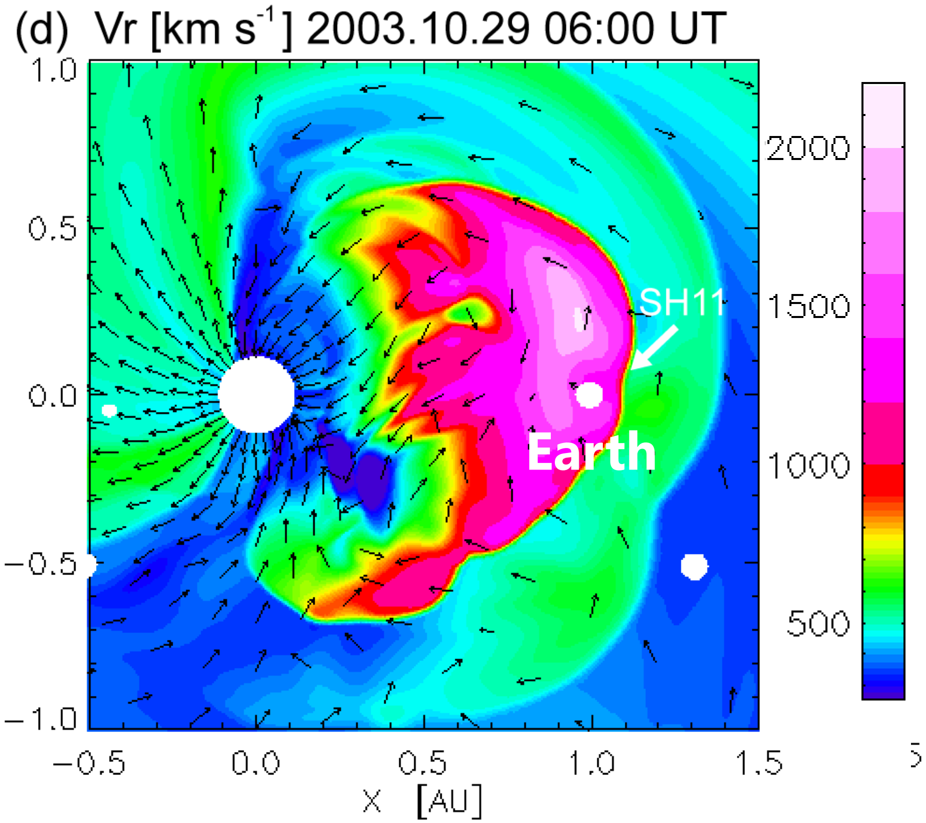
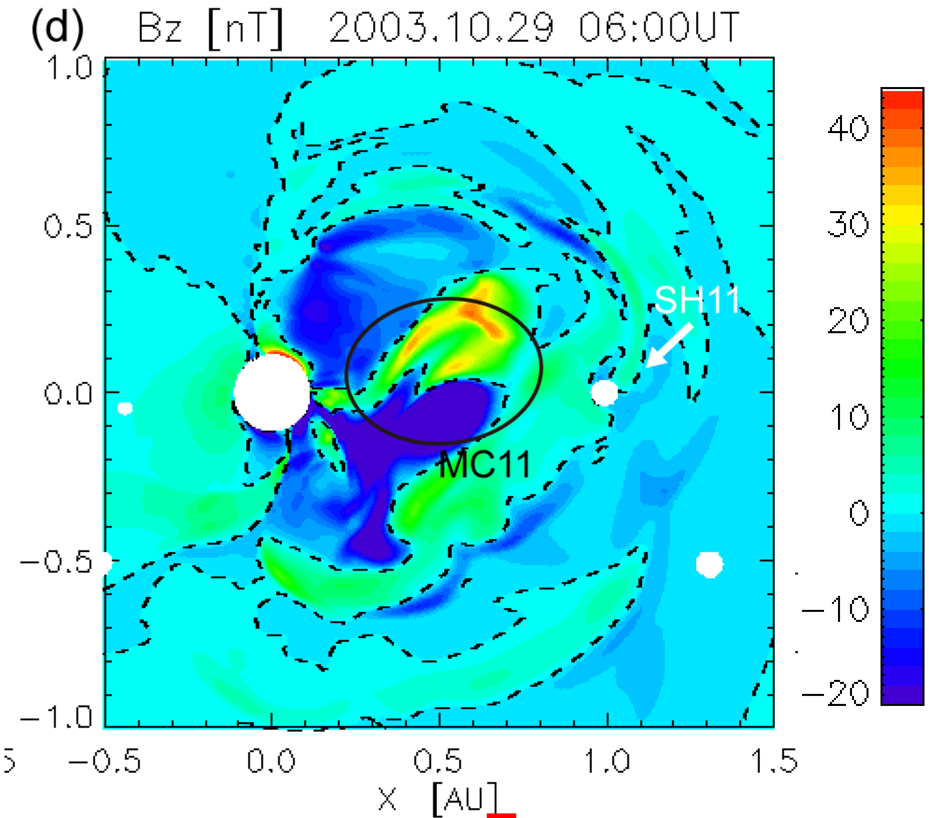
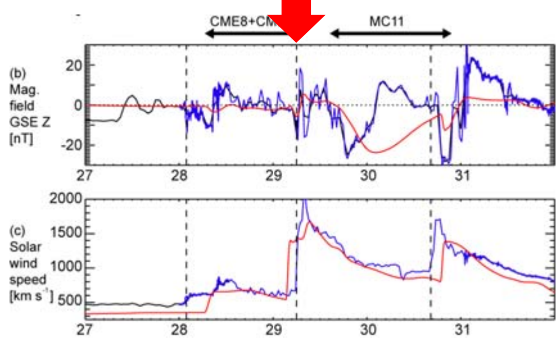
Propagation and CME-CME interaction







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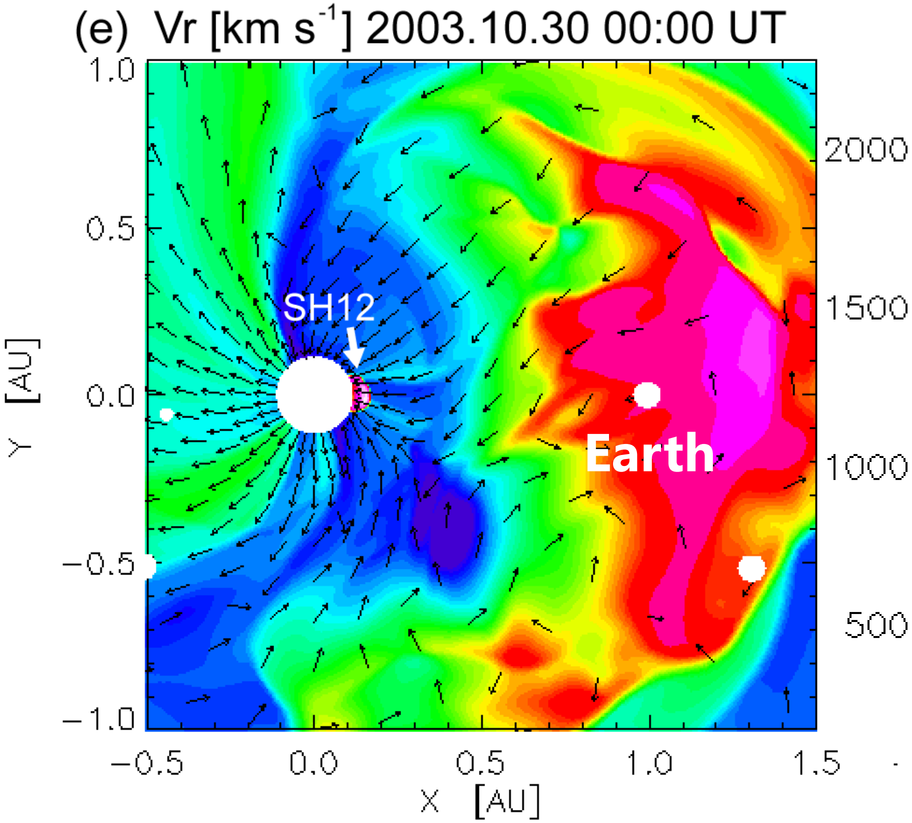
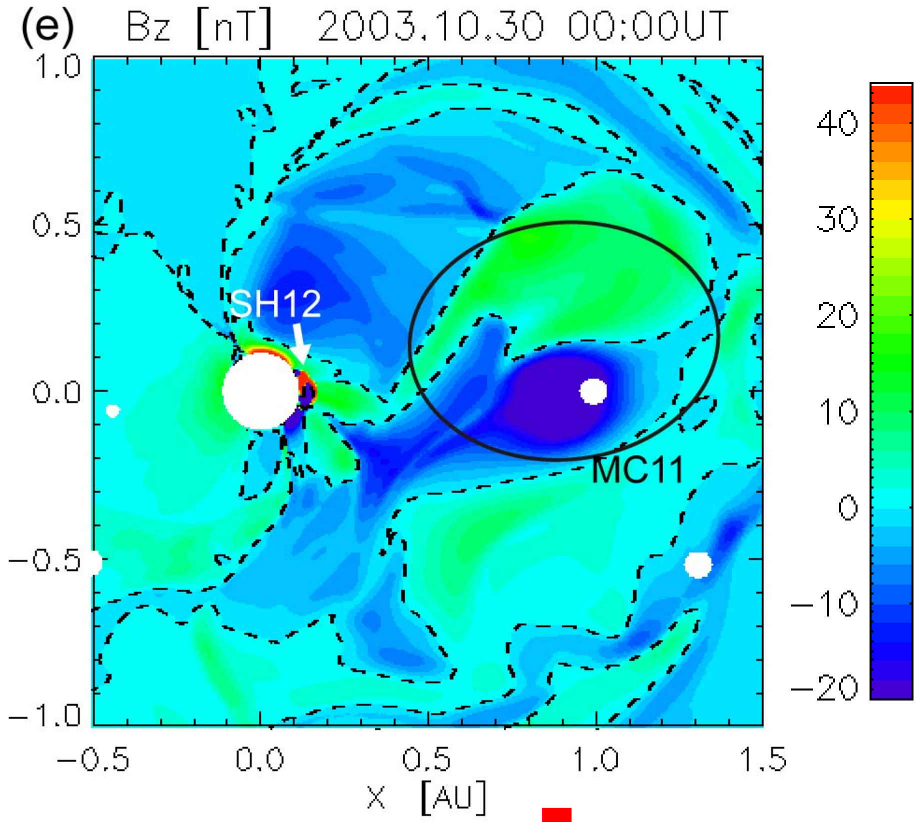
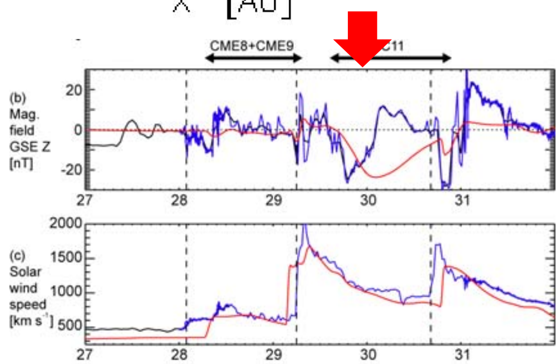
Propagation and CME-CME interaction





- CME11 that is launched λ_S =-13 propagates westward.



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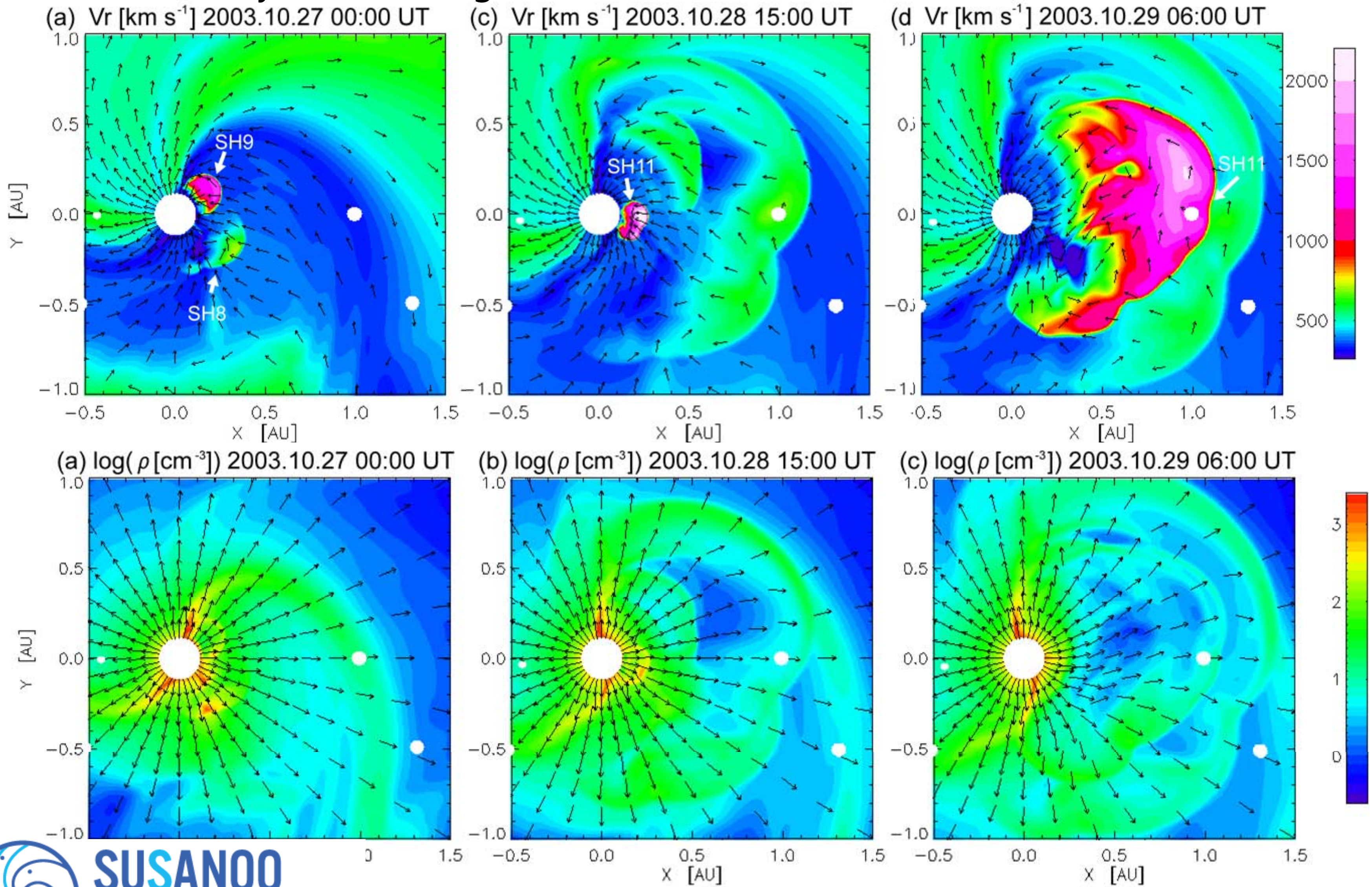
CME-CME Interaction

Color: velocity, arrows: magnetic field



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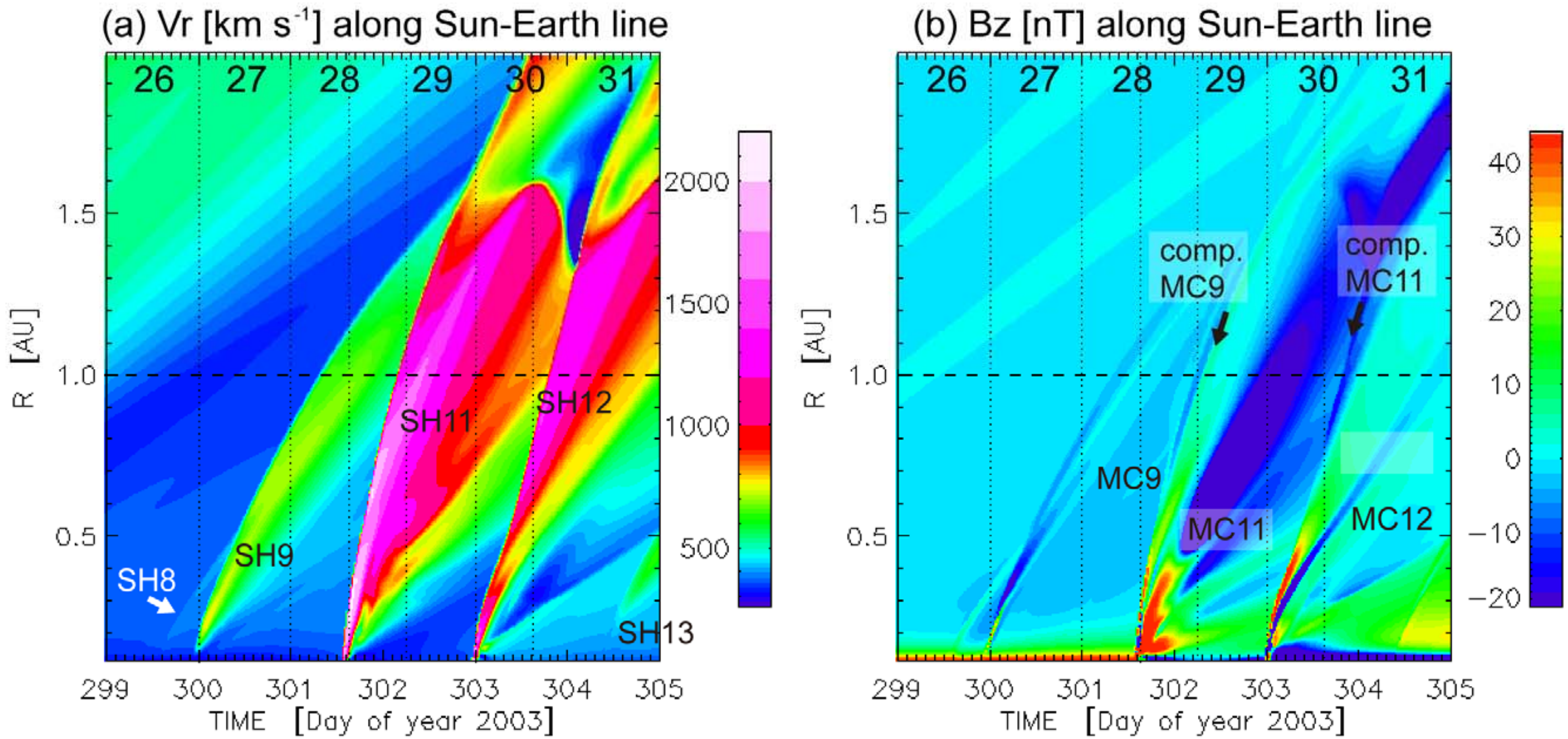
Color: density, arrows: velocity

CME-CME Interaction

A preceding CME can be compressed by a following CME



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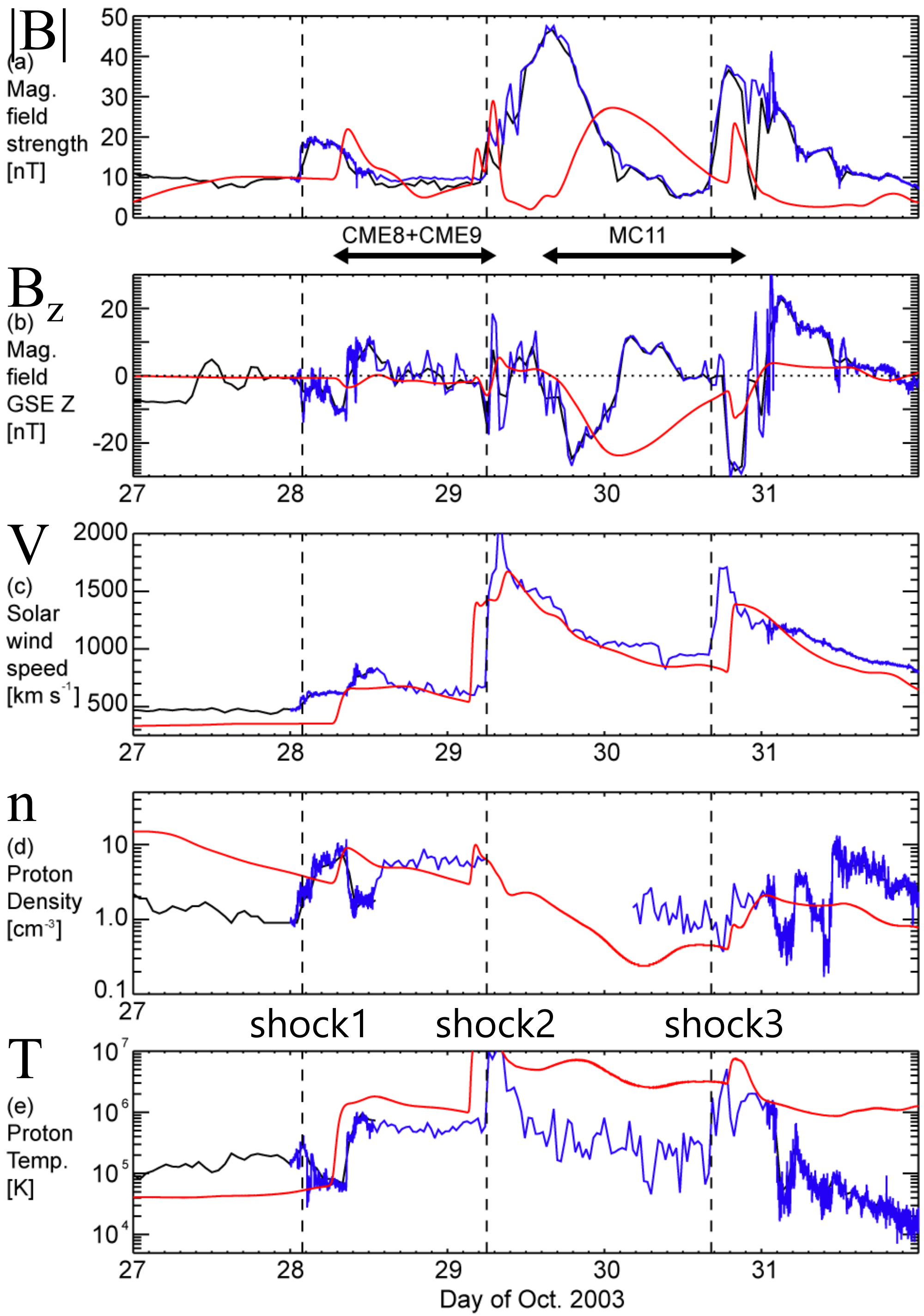
Numerical simulation of 2003 Oct-Nov

#	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	—

Comparison with in situ measurement

MHD
OMNI
ACE (Skoug+ 2004)



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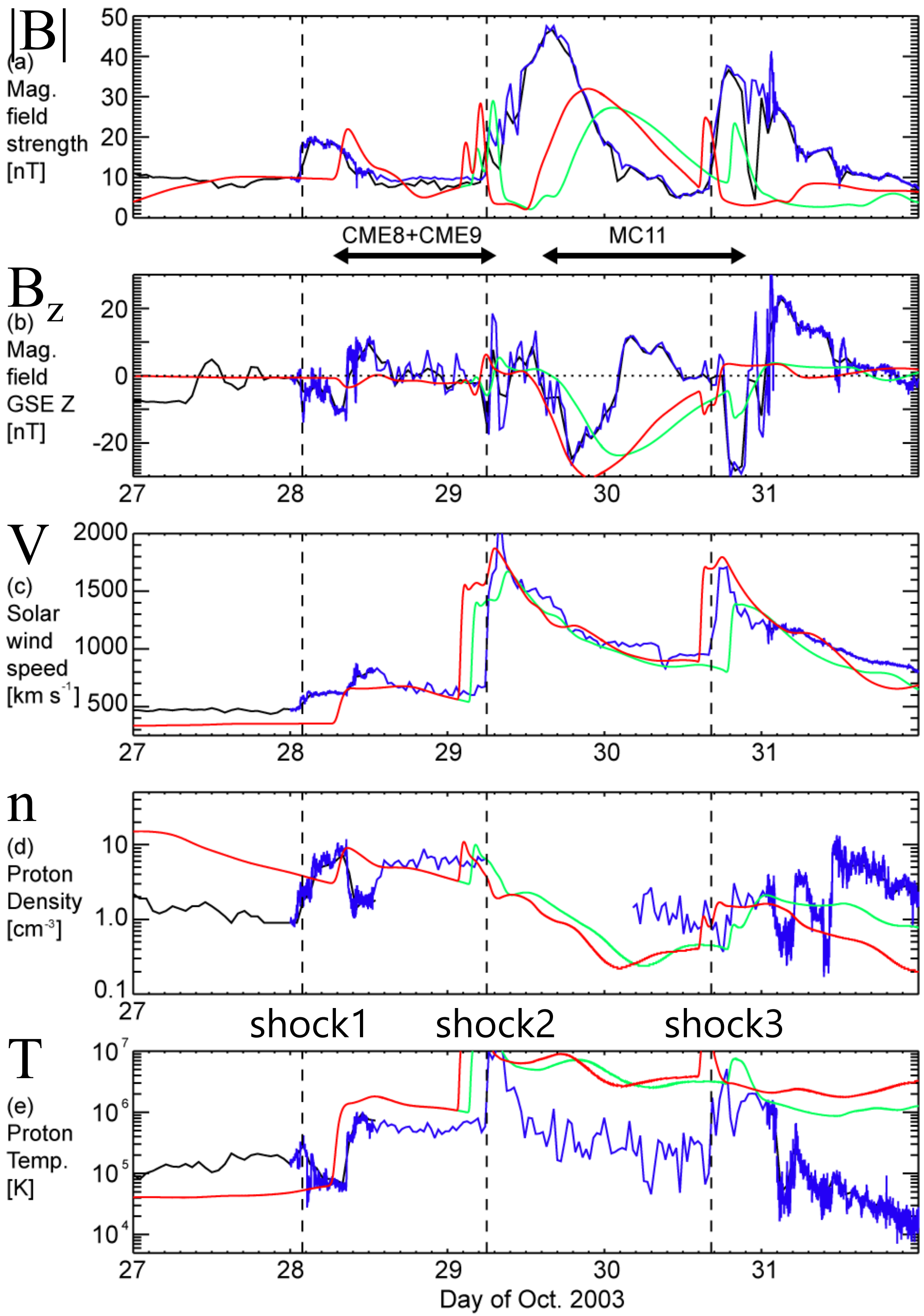
Lager magnetic flux case

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)

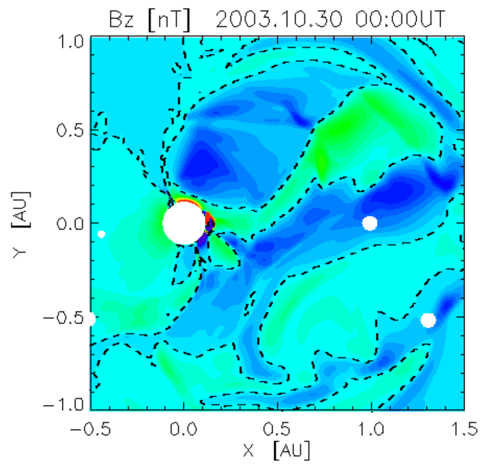
OMNI

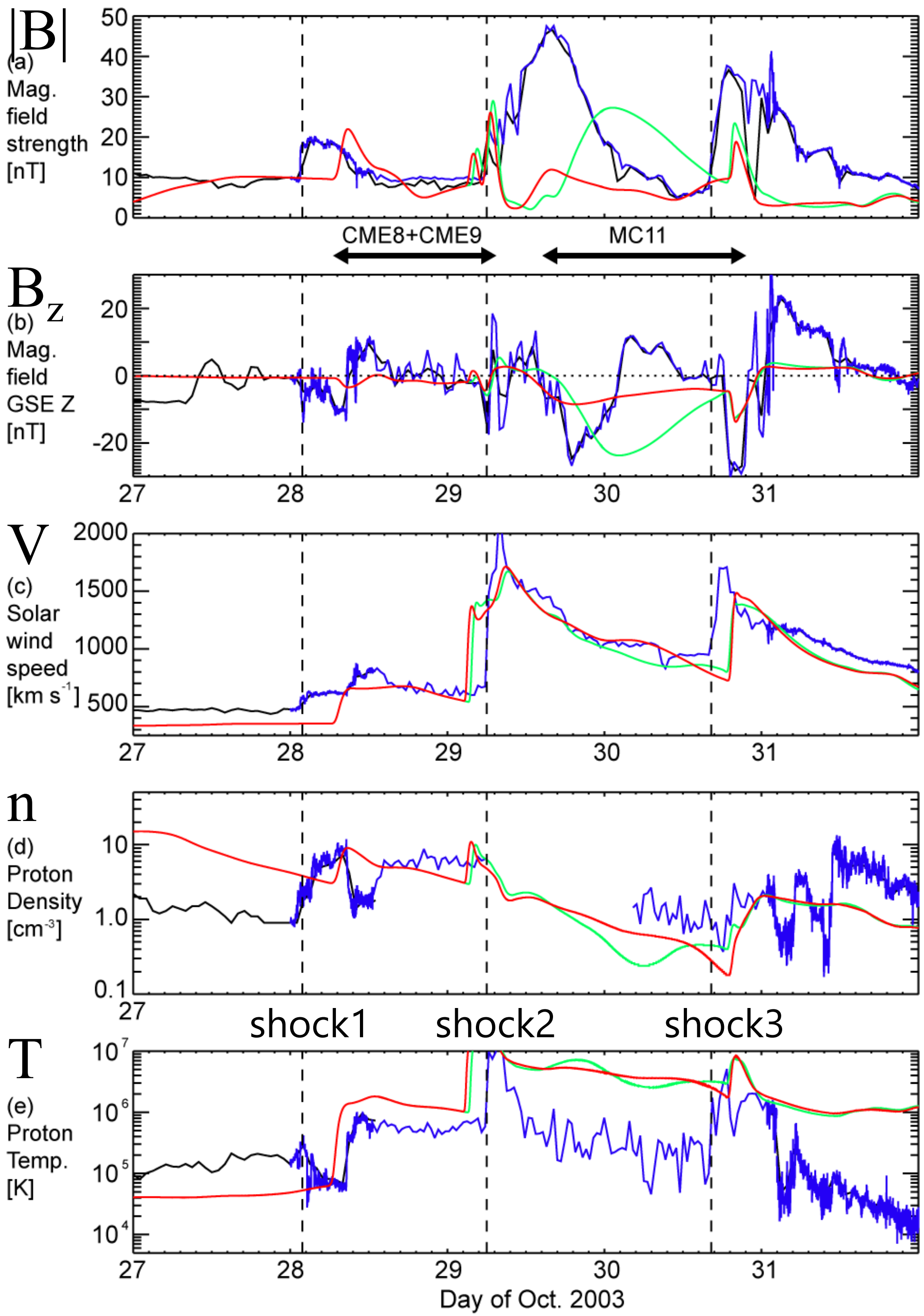
ACE (Skoug+ 2004)

- Source longitude

  -13 (green) → -8 (red)

- Core part of the flux rope did not pass through the Earth position.





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Discussion

- Our new model is capable of reproducing the SBz profile behind the shock of multiple CMEs, originating from the internal magnetic flux rope, omitting a simulation of the solar coronal region.

  Advantage

  - Fast computation => space weather forecast operation
  - Capable of parametric studies
  - dynamics and interaction of multiple CMEs during their propagation

  Limitation

  - No dynamics in the corona (simple magnetic field model)
  - Quantitative optimization of the parameters is needed.
  - Improvement of background solar wind is needed.

synergistic development

【Objective 1】

To answer fundamental questions of solar-terrestrial environment:

■ the onset of solar flares

■ the mechanism of radiation belt dynamics

■ The physical process whereby the sun affects climate

【Objective 2】

To build the base for next-generation space weather forecast system

■ Concrete prediction of the impact on each industrial activity

■ Assessment of severe space weather impact by Carrington-class events

Physics-based Modeling (flare, CME, mag&iono-sphere)
Network Observation（Hinode, ERG, ground-based obs.）

Summary

- Physical processes in CME evolution are summarized. A MHD simulation with realistic conditions is a powerful tool to understand them.
- We have developed an MHD model of interplanetary propagation of multiple CMEs with internal magnetic flux rope injected into solar wind MHD simulation. (SUSANOO-CME)
- We present a demonstration case: 2003 Oct. – Nov. The SUSANOO-CME reproduced well the in situ solar wind speed profile and Bz profile of magnetic cloud associated with the Halloween events.
- Furthermore, the numerical results provide much greater insight into the role of the magnetic field during CME propagation.

Thank you for your attention!