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

Daikou Shiota
Institute for Space and Earth Environmental Research (ISEE), Nagoya University
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)

• Summary
Solar flares and CMEs

- EIT and LASCO movies of the flare on Oct. 28, 2003 (Halloween storm)
Characteristic structure of CME: flux rope

$\text{Magnetic cloud} = \text{flux rope}$

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

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 $1 \text{ R}_{\text{sun}}$ 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 $25 \, \text{Rs} \leq r \leq 425 \, \text{Rs} (~ 2 \, \text{au})$
- Yinyang Grid
  $(202 \times 68 \times 192 \times 2)$
- 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)
Outline of SUSANOO-SW

The model is based on observation of solar magnetic field

- Potential magnetic field (PFSS) model
  - Magnetic field map \( \Rightarrow \) coronal field and IMF \( \times 5 \)
  - Coronal field \( \Rightarrow \) velocity
- Helios observation empirical model (Hayashi + 2003)
  - Velocity \( \Rightarrow \) density + temperature
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
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

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

Day of Year
Automated forecast system (SUSANOO)

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

Space-weather-forecast-Usable System
Anchored by Numerical Operations
and Observations

Weekly Forecast of Radiation Belt

2015/08/05 0000 UT Ver1.0

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Radiation belt flux time profile

Solar wind time profile
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• Summary
• 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)
## Parameters of CME model

<table>
<thead>
<tr>
<th>Symbols</th>
<th>Explanation</th>
<th>Default value</th>
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<tbody>
<tr>
<td>$t_{\text{onset}}$</td>
<td>Onset time of CME</td>
<td>from LASCO CME catalog</td>
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<tr>
<td>$V_{\text{CME}}$</td>
<td>Propagation speed of CME</td>
<td>from LASCO CME catalog</td>
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<td>$\lambda_S$</td>
<td>Carrington latitude of CME source region</td>
<td>from the flare list in NGDC</td>
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<td>$\phi_S$</td>
<td>Carrington longitude of CME source region</td>
<td>from the flare list in NGDC</td>
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<td>$\tau$</td>
<td>Tilt angle of spheromak</td>
<td>±90 degree with Hale-Nicholson law</td>
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<tr>
<td>$\chi$</td>
<td>Inclination angle of spheromak</td>
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<td>$c_i$</td>
<td>Chirality of Helicity in spheromak</td>
<td>1, set -1 if opposite to Bothmer-Schwenn rule</td>
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<td>$\Phi_{\text{mag}}$</td>
<td>Magnetic flux within CME</td>
<td>proportional to flare class</td>
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<td>$w_A$</td>
<td>Angular width of CME</td>
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<tr>
<td>$w_r$</td>
<td>Radial width of CME</td>
<td>2 Rs</td>
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Rest: Obs. + assume
## Helicity of Magnetic clouds (MCs)

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<th>MC Type</th>
<th>Magnetic helicity</th>
<th>Variation of magnetic field vector</th>
<th>Direction of magnetic field on flux tube axis</th>
<th>Rotation of magnetic field vector in $B_x$-$B_y$-plane ($B_x$-$B_y$-plane)</th>
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<td>SEN</td>
<td>Left-handed</td>
<td>South $(-B_z) \rightarrow$ north $(+B_z)$</td>
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<td>![Rotation Diagram for SEN]</td>
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<td>SWN</td>
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<td>South $(-B_z) \rightarrow$ north $(+B_z)$</td>
<td>West $(-B_y)$</td>
<td>![Rotation Diagram for SWN]</td>
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<td>NES</td>
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<td>North $(+B_z) \rightarrow$ south $(-B_z)$</td>
<td>East $(+B_y)$</td>
<td>![Rotation Diagram for NES]</td>
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<td>NWS</td>
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<td>North $(+B_z) \rightarrow$ south $(-B_z)$</td>
<td>West $(-B_y)$</td>
<td>![Rotation Diagram for NWS]</td>
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**North**

2n cycle

**South**

2n+1 cycle

**North**

(Orientation for high inclinations to the ecliptic SEN, NWS, SWN, NES)

East $(+B_y) \rightarrow$ west $(-B_y)$

West $(+B_y) \rightarrow$ east $(+B_y)$

North $(+B_z) \rightarrow$ south $(-B_z)$

South $(-B_z) \rightarrow$ north $(+B_z)$

Rotations in the $B_y$-$B_z$-plane

(Bothmer & Schwenn 1998)
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
- Velocity
- Shape of CME
- Magnetic structure (strength, chirality, direction of the spheromak)

(Shiota & Kataoka, submitted to SpaceWeather)
Time-varying inner boundary condition

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

$$\Rightarrow$$ A time series of solar wind maps for the inner boundary condition of MHD simulation

Information of CMEs are superposed on these boundary conditions
Capability of SUSANOO-CME

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

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

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

Parameters in CME model

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

- Many large solar flares occurred (ex. NOAA 10486)
Numerical simulation of 2003 Oct-Nov

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Numerical results

Velocity and Bz (GSE) on the ecliptic plane
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.
Propagation and CME-CME interaction

(a) $V_r \text{[km s}^{-1}]$ 2003.10.27 00:00 UT

(b) $B_z \text{[nT]}$ 2003.10.27 00:00 UT

SUSANOO
Space-weather-forecast-Usable System
Anchored by Numerical Operations
and Observations
Propagation and CME-CME interaction
Propagation and CME-CME interaction
Propagation and CME-CME interaction
Propagation and CME-CME interaction

- CME11 that is launched $\lambda_S = -13$ propagates westward.
CME-CME Interaction

Color: velocity, arrows: magnetic field

(a) \( V_r [\text{km s}^{-1}] \) 2003.10.27 00:00 UT

(c) \( V_r [\text{km s}^{-1}] \) 2003.10.28 15:00 UT

(d) \( V_r [\text{km s}^{-1}] \) 2003.10.29 06:00 UT

Color: density, arrows: velocity

(a) \( \log(\rho [\text{cm}^{-3}]) \) 2003.10.27 00:00 UT

(b) \( \log(\rho [\text{cm}^{-3}]) \) 2003.10.28 15:00 UT

(c) \( \log(\rho [\text{cm}^{-3}]) \) 2003.10.29 06:00 UT

SUSANOO
Space-weather-forecast-Usable System
Anchored by Numerical Operations and Observations
CME-CME Interaction

A preceding CME can be compressed by a following CME

(a) $V_r [\text{km s}^{-1}]$ along Sun-Earth line

(b) $B_z [\text{nT}]$ along Sun-Earth line
## Numerical simulation of 2003 Oct-Nov

<table>
<thead>
<tr>
<th>#</th>
<th>( t_{\text{onset}} )</th>
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Comparison with in situ measurement

MHD
OMNI
ACE (Skoug + 2004)
Lager magnetic flux case

- Magnetic flux
  $6 \times 10^{21} \text{Mx}(\text{green})$
  $\rightarrow 7 \times 10^{21} \text{Mx}(\text{red})$

- Shock arrived earlier
- The following shock became faster
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.
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.
【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&ionosphere) 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!