Solar simulation research focused on space weather

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The Sun is full of dynamic phenomena

Observed by Yohkoh
Various solar dynamic phenomena

- Prominence eruption
- Coronal mass ejection
- Solar flare
- Emergence of a subsurface magnetic field
Characteristics of the environment where these dynamic phenomena occur

Subsurface region (convective zone)
- high density, high pressure (high $\beta$ region)
- convective motion is active
- emergence of a twisted magnetic field

Photosphere
- high density, high pressure (high $\beta$ region)
- radiation becomes effective
- expansion of an emerging magnetic field

Chromosphere
- sharp change of density & pressure ($\beta \sim 1$ region)
- radiation is effective
- expansion of an emerging magnetic field

Transition region
- sharp change of temperature
- expansion of an emerging magnetic field

Corona
- low density & pressure, high temperature (low $\beta$ region)
- expansion & eruption of an emerging magnetic field

Transition region
- sharp change of temperature
- expansion of an emerging magnetic field

Corona
- low density & pressure, high temperature (low $\beta$ region)
- expansion & eruption of an emerging magnetic field
Targets of solar simulation research

Target I: Flux emergence

Target II: Coronal loops

Target III: Global phenomena

Target IV: Observational data assimilation
To reproduce the emergence of a subsurface magnetic field into the corona

Domain: convective zone ~ corona (highly stratified), local Cartesian

Essential ingredients: gas pressure, magnetic field, gravitational field, compressible, viscosity, thermal conduction, radiative cooling

Simulation features: fully compressive, ideal or diffusive MHD

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} \left( \rho u_i \right) &= 0 \\
\rho \left( \frac{\partial}{\partial t} u + u \cdot \nabla u \right) &= j \times B - \frac{\partial}{\partial x_k} \left( P \delta_{k} - \pi_{k} \right) + \rho g_0 \\
\rho \left( \frac{\partial}{\partial t} \varepsilon + \frac{\partial}{\partial x_k} \left( \rho \varepsilon u_i \right) \right) &= -P \frac{\partial u_k}{\partial x_k} - \frac{\partial \Psi}{\partial x_k} + \frac{j^2}{\sigma} - L_r \\
\frac{\partial B}{\partial t} &= \nabla \times \left( \nu \times B - \eta_{\text{diff}} \nabla \times B \right)
\end{align*}
\]
Formation of a sigmoid (precursor of a solar flare)

Inverse-S sigmoidal structure obtained from a simulation (emerging flux tube of left-handed twist)

Inverse-S sigmoidal structure obtained from an observation (Yohkoh)
Coronal mass ejection (filament eruption)

\[ \rho \frac{d^2Z}{dt^2} = F_M - F_T - F_G \]

\[ = \frac{B^2}{4\pi} \left( \frac{1}{H} - \kappa \right) - \rho g \]

- \( F_M = \frac{B^2}{4\pi} \frac{1}{H} \) ... magnetic pressure force
- \( F_T = \frac{B^2}{4\pi} \kappa \) ... magnetic tension force

\( \kappa \) ... curvature of an emerging loop (represents magnetic tension force)

\( H \) ... field-strength scale height of emerging field (represents magnetic pressure force)

Magara (2004)
Solar simulation research focused on space weather
Space weather model

1st Step
Global force-free field reconstructed from magnetogram data (SDO or Hinode)

2nd Step
Data-driven simulations for flares and CMEs in the target active region (preliminary result is shown below)

3rd Step
Embed flares & CMEs in the global solar wind model to reproduce disturbances

Final Step
Clarify the influence of propagating disturbances on the Moon-Earth system
Observational data assimilation

To reproduce the evolution of a real active region using observational data

Domain: corona (high temperature, weakly stratified), zero-\(\beta\) MHD

Essential ingredients: magnetic field, resistivity, (artificial) viscosity

Simulation features: zero-\(\beta\), no stratification, diffusive MHD

\[
\begin{align*}
\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_k} (\rho u_k) &= 0 \\
\rho \left( \frac{\partial}{\partial t} u + u \cdot \nabla u \right) &= j \times B + \mu \nabla^2 u \\
\frac{\partial B}{\partial t} &= \nabla \times \left( \nu \times B - \eta_{\text{diff}} \nabla \times B \right)
\end{align*}
\]
Global phenomena

To reproduce the global structure of a solar wind and interplanetary magnetic field

Domain: corona ~ interplanetary space (including terrestrial space), 3D global region

Essential ingredients: gas pressure, magnetic field, gravitational field, compressible

Simulation features: fully compressive, ideal or diffusive MHD
SOLAR WIND MODEL (MODIFIED FROM NAKAMIZO ET AL., 2009) : BASIC EQUATIONS

\[
\frac{\partial (\rho V)}{\partial t} + \nabla \cdot \left( \rho V V + p I + \frac{B^2 - B_0^2}{2\mu_0} I - \frac{BB - B_0 B_0}{\mu_0} \right) = 0,
\]

\[
= -\rho \frac{GM_s}{r^2} \hat{r} - 2\rho \Omega \times r - \rho \Omega \times (\Omega \times r),
\]

\[
\frac{\partial B_1}{\partial t} + \nabla \times (V \times B) = 0,
\]

\[
\frac{\partial U_1}{\partial t} + \nabla \cdot \left[ V \cdot \left( U_1 + p + \frac{B_1^2}{2\mu_0} \right) - \frac{B_1 (V \cdot B_1)}{\mu_0} - \frac{B_0 (V \cdot B_1)}{\mu_0} + \frac{V (B_1 \cdot B_0)}{\mu_0} \right]
\]

\[
= \rho V \cdot \left( -\frac{GM_s}{r^2} \hat{r} \right) - \rho V \cdot [\Omega \times (\Omega \times r)],
\]

\[
U_1 = \frac{\rho v^2}{2} + \frac{p}{\gamma - 1} + \frac{B_1^2}{2\mu_0},
\]

\[
B_1 (r, t) \equiv B (r, t) - B_0 (r) \quad \gamma = \frac{5}{3}
\]
Key factor in a modeling of global phenomena => grid system

Figure 14. Spherical coordinate (a) Cartesian (b) and triangular (c) grid systems
Avoid the singularity at the north and south poles and therefore relax tight Courant–Friedrichs–Lewy (CFL) conditions around the poles, both of which would arise in the spherical coordinate system (Tanaka, 1994).
# BOUNDARY & INITIAL CONDITIONS

<table>
<thead>
<tr>
<th>Calculation domain</th>
<th>50Rs ~ 300Rs</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inner boundary condition (50Rs)</strong></td>
<td>MHD-IPS tomography data during 1 Solar rotation (Hayashi et al., 2003): velocity ($v$), density ($n(v)$), pressure ($p(v)$), magnetic field (based on PFSS)</td>
</tr>
<tr>
<td><strong>Outer boundary condition (300Rs)</strong></td>
<td>Same as Nakamizo et al., 2009</td>
</tr>
</tbody>
</table>
| **Initial condition** | Density, pressure: decreases with $1/r^2$  
Vr: 400 km/s (other components are 0)  
Magnetic field: Extrapolated from PFSS |

![Diagram](https://via.placeholder.com/150)

- **Calculation domain**
- **MHD-IPS inner boundary data**
- **Outer boundary**
RESULT: Background solar wind (CR2142, solar maximum)
CME MODEL

• Simple spheromak type CME model

• Gibson and Fan (2008) discuss that this type of CME may be produced by magnetic reconnection

• Basic equation

\[
B_r = 2B_0 \frac{j_1(\alpha r)}{\alpha r} \cos(\theta)
\]

\[
B_\theta = -\frac{B_0}{\alpha r} \left(j_1(\alpha r) + \alpha r j'_1(\alpha r)\right) \sin(\theta)
\]

\[
B_\phi = B_0 j_1(\alpha r) \sin(\theta)
\]

where, \( j_1(x) = \frac{\sin(x) - x \cos(x)}{x^2} \), \( j'_1 = \frac{2 \cos(x) + (x^2 - 2) \sin(x)}{x^3} \)

and \( \alpha = 4.493409458 \alpha^{-1} \) to have a value \( B_r = 0 \) at \( r = a \).

(Kataoka et al., 2009)
Injection of an ICME

an ICME is injected gradually through the inner boundary

→ This is done by introducing a time-dependent inner boundary condition
How to inject a spheromak through I.B.

- \( r_c = r_0 + v^*t \) → known (if \( v \) is assumed)

- \( Q(r) \) : A certain physical variable as a function of \( r \) → Known (predetermined by some assumptions)

- From the condition \(|r_B| = 50Rs\) and \(|r| = \text{CME radius}\), we can obtain \( r(r_B) \) at each time step

- At each time step, \( Q(r_B(t)) \) is determined

\( r_B \) : Vector from the Sun to the crossing boundary (purple colored)
\( r_c \) : Vector from the Sun to the CME center
\( r \) : Vector from the CME center to the end point of \( r_B \) vector (\( r = r_B - r_c \))
RESULT

![Image of scientific plots]

- Temperature (T) distribution
- Particle density (Np) distribution
- Magnetic field (B) distribution

Colatitude = 90.7563

Key values:
- Np [m^(-3)]
  - 5.8e+03, 8.5e+07, 1.3e+08, 1.9e+08
- T [K]
  - 2.0e+04, 1.5e+06, 2.6e+06, 3.9e+06
- |div B|/|B| [V/m]
  - 0.0, 3.3, 6.7, 10.0
- Pr [N/m^2]
  - 2.1e-13, 2.3e-09, 4.7e-09, 7.0e-09
- Vr [km/s]
  - 220, 414, 608, 802
- B [nT]
  - -584, -120, 145, 410
PARAMETERS

Parameters for a spheromak type ICME model

• Magnetic field strength:
• Orientation of a spheromak:
• Twistness:
• Density:
• Pressure:
• (radial) Velocity:
• Propagation direction:
• Initial position:
• CME radius:
• Injection speed (function of v(t)):
• Magnetic field strength: Typical amount of magnetic flux $2.55 \times 10^{21}$ Mx (Kataoka et al. 2009, Shiota et al. 2010), magnetic field observation at a photospheric footpoint of an ICME etc.

• Orientation of a spheromak: Magnetic Field observation

• Twistness: Vector magnetogram + NLFF modeling, etc.

• Density: $2 \times$ background solar wind density, etc.

• Pressure: $4 \times$ background solar wind pressure, etc.

• (radial) Velocity: From average transit time from the Sun to the Earth, etc.

• Propagation direction: CME cone model (LASCO C3), etc.

• Initial position: By assuming radial propagation direction, etc.

• CME radius: CME cone model, free parameter, etc.

• Injection speed (function of $v(t)$): By assuming from averaged transit time from the Sun to the Earth, etc.
SUMMARY & DISCUSSION

• We developed 3-D MHD code to reproduce the structure of a solar wind, the propagation of an ICME.

• By using IPS data to derive the background steady solar wind, we can perform a more realistic data-driven simulation.

• We can investigate an ICME event by introducing a time-dependent boundary condition into a TVD scheme with an unstructured grid system.

• However, since there are many ambiguities and uncertainties in determining initial parameters of an ICME model, much more efforts are needed to derive realistic ICME properties.