ENLIL: Recent Enhancements

D. Odstrcil

University of Colorado & NOAA/SWPC

George Mason University & NASA/GSFC

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OUTLINE

- Driving Heliospheric Computations
- Space Weather Forecasting
- Launching of Hydrodynamic ICMEs
- Tracing of IMF and Interplanetary Shocks
- Heliospheric Mission Support
Driving Heliospheric Computations
Analytic, empirical, and numerical models and observational data can be used to drive ENLIL (green) by sharing data sets (grey) and using couplers (blue).
Driving by Analytic Models

CASE = 1
DAY = 12

INJECTED DENSITY (cm⁻³)
0.20  5.20

log₁₀ DENSITY (cm⁻³)
0.01  8.01

R=3 AU  θ=99.74°  φ=99.74°

P (nPa)  N (cm⁻³)  Vr (km/s)
Driving by WSA Model

CR 1896

VENUS

MERCURY

MARS

EARTH

v: 300 475 650
Driving by MAS Model

Self-consistent end-to-end numerical simulation of space weather event (in progress)
Driving by In-Situ Observations

- Heliospheric computations can be driven by accurate in-situ observations of solar wind parameters.
- This approach can be strictly applied only during times of radial alignment, and potentially important 3-D interactions are not accounted for.

Prediction of the solar wind flow velocity (left) and proton number density (right) at Ulysses. Red dots show observations by Ulysses and a solid line shows results from 1-D MHD simulations driven by values observed at Earth.
Driving by UCSD/IPS Model
Space Weather Forecasting
Prediction of Solar Wind Streams

2010-01-19 00:03:39

2010-01-24 -5.00 days

Ecliptic Plane

LAT = -4.9°

N90 LON = 0°

W180 R = 1.0 AU

Vr (km/s)

200 550 900 1250 1600

ENUL-2.6 medres-c3b2 WSA_Y2.0 GONG-2092_062

IMF polarity

Current sheath

3D IMF line
Prediction of Solar Wind Streams

Evolution of parameters at EARTH

2010–01–24

- $V_r$ (km/s)
- $N$ (cm$^{-3}$)
- $T$ (kk)
- $|B|$ (nT)

ENLIL-2.8 medres-a3b2 WGA.Y2.0 GONG-2092.D82

2010/200x380/mpl/unn1de-i.1.g15a0.2010-01-24 2010-01-25
Calibration of Ambient Solar Wind

Solar wind velocity and IMF lines at the inner boundary (21.5 or 30 Rs)

- WSA model provides: $V_r$ and $B_r$
- ENLIL further needs: $N$, $T$, and $B_{\phi}$

Radial profiles of the solar wind flow velocity for WSA and ENLIL

ENLIL needs to modify MAS or WSA solar wind flow speeds at the models interface boundary.
## Ambient Solar Wind Parameters

### Basic Mode – Association with the Coronal Model and Resolution

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Default</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>cr</td>
<td>Carrington Rotation number</td>
<td>1922</td>
<td>1890 – present</td>
</tr>
<tr>
<td>resolution</td>
<td>Numerical grid resolution</td>
<td>low</td>
<td>low</td>
</tr>
</tbody>
</table>

### Advanced Mode – Free Parameters at the Inner Boundary

<table>
<thead>
<tr>
<th>Name</th>
<th>Title</th>
<th>Default</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>vfast</td>
<td>Radial flow velocity of fast stream (km/s)</td>
<td>650.</td>
<td>600. – 700.</td>
</tr>
<tr>
<td>dfast</td>
<td>Number density of fast stream (cm(^{-3}))</td>
<td>150.</td>
<td>100. – 200.</td>
</tr>
<tr>
<td>tfast</td>
<td>Temperature of fast stream (MK)</td>
<td>0.6</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>bfast</td>
<td>Radial magnetic field of fast stream (nT)</td>
<td>150.</td>
<td>100. – 200.</td>
</tr>
<tr>
<td>gamma</td>
<td>Ratio of specific heats</td>
<td>1.5</td>
<td>1.05 – 2.</td>
</tr>
<tr>
<td>xalpha</td>
<td>Fraction of alpha particles (rel. to protons)</td>
<td>0.</td>
<td>0. – 0.1</td>
</tr>
<tr>
<td>dvexp</td>
<td>Exponent in N (V^{dvexp} = \text{const})</td>
<td>2.</td>
<td>1. – 2.</td>
</tr>
<tr>
<td>nptot</td>
<td>(=1 (=2)) if (P_{\text{the}} (P_{tot}) = \text{const})</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Date Range: 01-01 to 12-27

V (km/s) Graphs for Different Dates:
- 01-01 to 01-11
- 01-21 to 01-31
- 02-10 to 02-20
- 03-02 to 03-12
- 03-22 to 04-01
- 04-01 to 04-11
- 04-21 to 05-01
- 05-11 to 05-21
- 05-31 to 06-10
- 06-20 to 06-30
- 06-30 to 07-10
- 07-20 to 07-30
- 08-09 to 08-19
- 08-29 to 09-08
- 09-18 to 09-28
- 09-28 to 10-08
- 10-18 to 10-28
- 11-07 to 11-17
- 11-27 to 12-07
- 12-17 to 12-27

Parameters:
- obs=mdi
- res=medium
- amb=a2b2
- model=mp2ummn1de
- par=g15q04d
- Vmae=110.5
- Nmae=6.306
- Bmae=3.198

DATE 2005

\begin{center}
\begin{tabular}{ccc}
\text{obs}=\text{mdi} & \text{res}=\text{medium} & \text{amb}=\text{a2b2} & \text{model}=\text{mp2ummer}1\text{de} & \text{par}=\text{g15q0d4} & V_{\text{mae}}=80.31 & N_{\text{mae}}=5.638 & B_{\text{mae}}=2.060 \\
\end{tabular}
\end{center}

\begin{figure}
\begin{subfigure}{0.32\textwidth}
\includegraphics[width=\textwidth]{plot1}
\caption{\(\Delta V\) (km/s)}
\end{subfigure}
\hfill
\begin{subfigure}{0.32\textwidth}
\includegraphics[width=\textwidth]{plot2}
\caption{\(\Delta N\) (cm\(^{-3}\))}
\end{subfigure}
\hfill
\begin{subfigure}{0.32\textwidth}
\includegraphics[width=\textwidth]{plot3}
\caption{\(\Delta B\) (nT)}
\end{subfigure}
\end{figure}

obs=nso res=medium amb=a2b2 model=mp2umm1nde par=g15q0d4

Vmae=79.02 Nmae=4.893 Bmae=2.385
Launching of Hydrodynamic ICMEs
May 12, 1997 Halo CME

Running difference images fitted by the cone model [Zhao et al., 2002]
Transient Disturbances

Modeling of the origin of CMEs is still in the research phases and it is not expected that real events can be routinely simulated in near future. Therefore, we have developed an intermediate modeling system which uses the WSA coronal maps, fitted coronagraph observations, specifies 3D ejecta, and drives 3D numerical code ENLIL.
Limb vs. Halo CME Speeds

2008–02–04

\[ V_{\text{Limb}} = 859 \quad V_{\text{Cone}} = 316 \]
\[ W_{\text{Limb}} = 61^\circ \quad W_{\text{Cone}} = 65^\circ \]

2008–04–26

\[ V_{\text{Limb}} = 655 \quad V_{\text{Cone}} = 429 \]
\[ W_{\text{Limb}} = 52^\circ \quad W_{\text{Cone}} = 72^\circ \]

2008–05–17

\[ V_{\text{Limb}} = 1032 \quad V_{\text{Cone}} = 541 \]
\[ W_{\text{Limb}} = 47^\circ \quad W_{\text{Cone}} = 84^\circ \]

2008–05–25

\[ V_{\text{Limb}} = 295 \quad V_{\text{Cone}} = 210 \]
\[ W_{\text{Limb}} = 16^\circ \quad W_{\text{Cone}} = 44^\circ \]
Limb vs. Halo CME Speeds: 2008-02-04

Evolution of parameters at EARTH

Evolution of parameters at STEREO-A
Limb vs. Halo CME Speeds: 2008-02-04

STEREO Model

2008–02–07 06:04:00
FORECAST = +3.25 days

Cone Model

2008–02–07 06:01:35
FORECAST = +3.25 days

- Mercury
- Venus
- Earth
- Mars
- Messenger
- Stereo_A
- Stereo_B

Vr (km/s)  E90  IMF polarity
200  550  900  1250  1600
3D IMF line

0  1  2  3  4  5  6  7  8  9  10  11  12  13  14  15  16  17  18  19  20  21  22  23  24  25  26  27
Limb vs. Halo CME Speeds: 2008-02-04

STEREO Model

2008-02-07 06:04:00
FORECAST = +3.25 days

Cone Model

2008-02-07 06:01:35
FORECAST = +3.25 days

- Mercury
- Venus
- Earth
- Mars
- Messenger
- Stereo_A
- Stereo_B
2007 December 31 ICME Event

C2: 2007/12/31 02:06  EIT: 2007/12/31 02:00
2007 December 31 ICME Event

ENLIL-2.5 medres WSA-1.6 GONG 2007-12-31 00:01:09 2007-12-31 + 0.00 days

Vr (km/s) IMF polarity IMF line

200 375 550 725 900 1075 1250 1425 1600

Ecliptic Plane W90 LAT = -2.80°

N90 LON = -78°

Earth Planets Messenger Stereo_A Stereo_B
2007 December 31 ICME Event
ICME – Hydrodynamic Models

Cone Model

Rope Model
2007-12-31

**FLUX-ROPE MODEL**
- Latitude (deg): -25
- Longitude (deg): -80
- Width (deg): 79
- Time (hh:mm): 04:55
- Velocity (km/s): 972
- Thickness (deg): 24
- Gamma (deg): 0

**CONE MODEL**
- Latitude (deg): -25
- Longitude (deg): -80
- Width (deg): 79
- Time (hh:mm): 04:55
- Velocity (km/s): 972
2008 April 26 CME with Cone Model

2008–04–26 00:00:19

Mercury  Venus  Earth  Mars  Messenger  Stereo_A  Stereo_B

Ecliptic Plane  LAT = -4.5°  N90  LON = 0°  W180  R = 1.0 AU

Vr (km/s)

IMF polarity

Current sheath

3D IMF line
2008 April 26 CME with Rope Model
Limb vs. Halo CME Speeds: 2008-02-04

**STEREO MODEL**
- Latitude (deg): -6.9
- Longitude (deg): -23.0
- Width (deg): 60.5
- R 12:52:20 (Rs): 16.4
- R 13:22:20 (Rs): 18.6
- Velocity (km/s): 859.0

**CONE MODEL**
- Latitude (deg): -2.7
- Longitude (deg): -20.8
- Width (deg): 65.0
- R 12:52:20 (Rs): 17.1
- R 13:22:20 (Rs): 19.4
- Velocity (km/s): 316.1
Tracing of IMF and Interplanetary Shocks
Connectivity of Magnetic Field Line
Shock Detection Challenge

- IMF line connects geospace with an interplanetary shock under very large inclination angle because of: (1) spiralling IMF line and (2) bow-shaped shock front
- Thus determination of shock parameters from MHD values stored along the IMF line is very difficult because many numerical grid points are used across the shock structure and pre- and post-shock values are at differing solar wind
Shock Detection Challenge

Tracing Nearby IMF Lines

Four additional four IMF lines are traced from geospace, offset +/- 2° in latitude and longitude from the Earth location.

Using 3-D Data

- Shock front at \( t=t_1 \)
- Shock front at \( t=t_2 \)

Geometrically fitted parameters:
- shock inclination
- shock speed

Together with the pre-shock solar wind parameters, these enable application of the Rankine-Hugoniot formulae to determine shock jump conditions (Steve Ledvina, in progress)
Interplanetary Shock Tracing

ENLIL-2.6 module WSA-1.6 GONG

TIME = 24.02 h

2006-12-09 +1.00 days

Mercury  Venus  Earth  Mars  Messenger  Stereo_A  Stereo_B

Vshock = 1500
Mshock = 13.8
D1/D0 = 4.89
beta = 0.06
theta = 13.0

R\(^2\)*N (cm\(^{-3}\))

3D IMF line

Shock normal \times IMF line

R\(^2\)*N - R\(^2\)*Namb (cm\(^{-3}\))
Interplanetary Shock Tracing

ENLIL-2.6 medres WSA-1.6 GONG

TIME = 27.02 h

2006-12-09 +1.12 days

V_{shock} = 1367
M_{shock} = 12.2
D_{1}/D_{0} = 4.87
beta = 0.06
theta = 15.1
Heliospheric Mission Support
Interplanetary Shock Tracing – Type II Radio Bursts

- Interplanetary shocks can generate radio emission (type II radio bursts):
  \[ F_p(\text{kHz}) = 9 \left( N_e \text{ (cm}^{-3}) \right)^{1/2} \]
- Inner heliosphere: dm & km wavelengths can be detected by spacecraft

Numerical simulations:
- Conditions for observed radio emissions
- On-fly adjustment of numerical predictions
## Coupling Issues

### STEREO Beacon Data – NASA CDF File Format

<table>
<thead>
<tr>
<th>Old</th>
<th>cdf_varget,id_cdf,'Velocity_HGRTN',velocity,…</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>cdf_varget,id_cdf,'Velocity_RTN',velocity,…</td>
</tr>
</tbody>
</table>

### Trajectories of Planets and Spacecraft – NASA HelioWeb Database

<table>
<thead>
<tr>
<th>Old</th>
<th>YYYY DDD AU ELAT ELON HG_LAT HG_LON HGI_LON YEAR DAY RAD_AU HG_LAT HG_LON HGI_LON</th>
</tr>
</thead>
<tbody>
<tr>
<td>New</td>
<td>YYYY DOY AU HG_LAT HG_LON HGI_LON</td>
</tr>
<tr>
<td></td>
<td>YYYY DAY RAD_AU HGI_LAT HGI_LON</td>
</tr>
</tbody>
</table>