Lecture 13

Modeling 3-D Solar Wind Structure
Why is a Heliospheric Model Needed?

- Space weather forecasts require us to know the solar wind that is interacting with the magnetosphere.
- Solar events like CMEs can cause magnetic storms and our maximum warning comes if we can predict their paths from the Sun.
- On the way to the Earth they encounter structures in the solar wind and these interactions can modify their ability to cause geo-effective disturbances at Earth.
- Need computational models that include the propagation and evolution of the solar wind on the way to Earth.
Enlil was the Sumarian Lord of the Wind
Formulation of ENLIL: MHD Equations

\[ \frac{\partial}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \]
\[ \frac{\partial}{\partial t} (\rho \mathbf{V}) + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla \cdot \left( \frac{\mathbf{B} \mathbf{B}}{\mu_0} \right) + \rho \frac{GM_s}{r^2} \]
\[ \frac{\partial}{\partial t} (E) + \nabla \cdot (E \mathbf{V}) = -p \nabla \cdot (\mathbf{V}) \]
\[ \frac{\partial}{\partial t} (\mathbf{B}) = \nabla \times (\mathbf{V} \times \mathbf{B}) \]

- \( \rho \) is the mass density, \( \mathbf{V} \) is the mean flow velocity, \( \mathbf{B} \) is the magnetic field, \( P \) is the pressure (thermal, \( p \), and magnetic \( \frac{B^2}{2\mu_0} \)), \( \mu_0 \) is the permeability, \( G \) is gravity, \( M_S \) is the solar mass, and \( E \) is the thermal energy density \( \left( \frac{p}{\gamma-1} \right) \) with \( \gamma \) the ratio of specific heats.

- A thermal energy equation is used because it gives smooth profiles of thermal pressure and temperature but may interfere with shock capture.
Formulation of ENLIL: Additional Continuity Equations

- In some applications two additional contributions are included in the continuity equations
  \[ \frac{\partial}{\partial t} (\rho_c) + \nabla \cdot (\rho_c \mathbf{V}) = 0 \]
  \[ \frac{\partial}{\partial t} (\rho_p) + \nabla \cdot (\rho_p \mathbf{V}) = 0 \]
  these allow us to trace injected CME material ($\rho_c$) and magnetic field polarity ($\rho_p$).
Formulation of ENLIL: Solving the Equations

- The temperature is calculated from an equation of state
  \[ p = 2nkT \]
  where \( n \) is the number density.
- Available in Cartesian or spherical coordinates.
- Uses the Total-Variation-Diminishing Lax-Fredrich scheme.
- No artificial diffusion.
- Second order accurate.
- Field-interpreted central-difference approach is used to solve for B so that \( \nabla \cdot \mathbf{B} = 0 \)
- Uses adaptive mesh.
Launch a CME into the Streamer Belt

- Most CMEs are launched into the coronal streamer belt.

- Launch an over-pressured spherical plasmoid into tilted, slow and dense streamer belt.

- Launch CME at fast SW speed which is twice slow SW speed.
The CME will Interact with both the Slow Flow and the Fast Flow

• Cuts at two latitudes – green lines.
The Interaction

- As the CME passes through the streamer belt it decelerates.
- Leading edge of the fast stream interacts with the slow streamer belt flow and forms a pair (forward and reverse) of shocks.
- The CME is trapped between the fast coronal hole flow and the slow streamer belt – it is sandwiched with the CIR structure.
- The CME effects the CIR evolution as well – the trailing CIR is eroded.
Interaction between a CME and CIR

Forward Shock

Reverse Shock
A Slice Below the Equatorial Plane

- The bottom panel show a time series at same colatitude at 3AU and fixed azimuth.
- The shaded area indicates the CME material and the dotted line shows the injected number density profile.
- The CME penetrates into the trailing region of the preceding fast stream.
- The forward shock weakens and becomes a pressure wave.
- The reverse shock forms at leading edge of CME and propagates backward through the CME material.
Ambient Solar Wind

• Need to have a model of the ambient solar wind for the CME to propagate into.
• Radial magnetic field uses a potential source-surface model and observations from a solar observatory (Wilcox Solar Observatory in the example).
• The azimuthal magnetic field uses \( B_\varphi = -B_r \sin(\theta) \frac{V_{rot}}{V_r} \).
• The radial velocity at the Sun uses the Wang-Sheeley-Arge model.
• The meridional magnetic field \( (B_\theta) \) and the meridional and azimuthal flow velocities \( (V_\theta \text{ and } V_\varphi) \) are zero.
Source Surface Model and Velocity at 1AU

- Results are near solar minimum.
- Model has been altered slightly to give velocities between 275 and 625 km/s.
**CME on May 12, 1997**

- Cone model used to characterize halo CME.
  - Angular width of $50^0$ and central axis of the cone pointing to $3^0$ north and $1^0$ west.
  - Velocity of 650 km/s at $24R_S$
  - Accelerating at 18.5 m s$^{-2}$
- Input pulse was a spherical plasma cloud at the location, diameter and velocity given by the cone model parameters.
- Density set to be 4 times the mean value in fast stream.
- Temperature equal to value in fast stream.
Distribution of Solar Wind Parameters

- Background contains solar maps used—distribution is at 21.5\(R_s\)
- Circles show the spherical injection and values used.
Evolution of the Solar Wind Parameters at Earth

- Simulation black lines with shading.
- Wind observations are in red diamonds.
- Orange gives the injected density.
- Dashed line is the forward shock or compression.
- Solid vertical lines extent of CME material.
- Ambient solar wind ahead of CME in good agreement.
- Shock compression good agreement but smoothed.
Visualization of Propagating CME

- Background solar wind velocity on inner boundary and equator (0.1AU).
- Isosurface at $6 \text{ cm}^{-3}$ color coded with velocity.
- Contours ahead of CME are on isosurface at $20 \text{ cm}^{-3}$.
- Injected material covers large region but interaction with solar wind is greatest near equator.
Evolution of CME as Function of Radial Distance

- Time series of velocity at selected radial distances along Sun-Earth line.
- Dotted line is background solar wind- note high speed stream.
- With distance compressive pressure wave of CME merges with the CIR.
- Forward and reverse shock pair form about 0.4AU and separate.
Effect of Time Dependent Solar Models

• Previous calculation used one set of solar maps for the entire solar rotation - tried variable solar wind maps.
  – Odstrcil used a variable set of maps giving a “pseudo” time dependence to the solar input.
  – A potential field is assumed \( B = -\nabla \phi \) and observations are fit with spherical harmonics.
  – Pasted together pieces from CRs 1921, 1922, 1923 and then created 90 daily maps.
  – First map went from 180\(^0\) at CR 1922 (CR1922.180) and ended at CR1921:180, next CR1922:176 to CR1921:176
  – The first daily updated map was assigned central median passing time of CR 1922:000.
  – The results were similar fixed map at the Earth.

• Explosion of CME is more than just a centered spherical injection – sudden displacement model,
  – Sudden northward displacement of the southern fast stream boundary.
Comparison of Time Dependent Models and Sudden Displacement Models

- Top contains results from “pseudo” time dependent maps.
- Bottom contains results from sudden displacement model.
- Neither seems to be a great improvement.
- Model is sensitive to parameters at the Sun.
Results at Other Locations at 1AU - Fixed Rotation Model

- Time series at 1 AU at various.
- Circle shows the velocity.
- Vertical black lines give spread in injected material.
Results at Other Locations at 1AU - Sudden Displacement Model

- Models give different CME configurations.