Modeling the Heliosphere: Status and future directions

G.P. Zank, N. Pogorelov, V. Florinski, J. Heerikhuisen, H.-R. Mueller

Institute of Geophysics and Planetary Physics (IGPP)
University of California, Riverside

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Termination Shock (TS)
Where the fast supersonic solarwind transitions to a slow, hot subsonic flow.

Heliopause (HP)
Separates heated interstellar material of the outer heliosheath from hot subsonic solarwind plasma in the inner heliosheath.

Outer Heliosheath

Inner Heliosheath

Bow Shock (BS)
Separates supersonic interstellar flow from the deflected flow of the outer heliosheath.

Interstellar neutral and ion flow.

Hydrogen Wall
Between the bow shock and the heliopause plasma slows, heats and piles up. Interstellar neutral atoms charge-exchange preferentially in this region of elevated plasma density, creating a corresponding pile-up of hydrogen atoms.

Deflected Ions

AU

Observed radio emissions from the outer heliosphere.

1. A solar wind proton travels into the hot inner heliosheath where it charge-exchanges with an interstellar hydrogen atom to create an energetic neutral atom (ENA).

2. An interstellar neutral atom charge-exchanges in the supersonic solar wind to form a pick-up ion (PUI), which is energized at the termination shock to produce an anomalous cosmic ray (ACR).

Color contours of plasma temperature with streamlines from a self-consistent Monte–Carlo simulation by J. Heerikhuisen, V. Florinski and G. P. Zank.
Three Distinct Neutral Populations

REGION 1

REGION 2

REGION 3

plasma temperature
The Outer Heliosphere and the LISM

Inner Heliosheath

Outer Heliosheath

LISM

Region 3: $u_{\text{bulk}} >> v_{\text{therm}}$

$U_{\text{bulk}} \ll V_{\text{therm}}$

$U_{\text{bulk}} > V_{\text{therm}}$

$U_{\text{bulk}} > v_{\text{therm}}$

Sun

TS

HP

BS(?)
Charge Exchange Interaction

Inner Heliosheath

Outer Heliosheath

LISM

Sun

Region 3

Region 2

Region 1B

Region 1A
Plasma Interactions: plasma-neutral
Numerical Models of the Heliosphere: Atoms and Hydrodynamics

• Self-consistent models:
  – dynamic plasma and neutrals: four-fluid model,
  – Monte-Carlo Boltzmann, particle Boltzmann.
Four-Fluid Concept

Fluid 0: plasma
Origin: Sun and LISM, and all charge exchange (pickup ions)

Neutral Fluid 1
Origin: LISM, and charge exchange outside heliopause
≈ 20km/s, LISM direction; warm

Neutral Fluid 2
Origin: Charge exchange between termination shock and heliopause
≈ 100km/s, “random” direction; hot

Neutral Fluid 3
Origin: Charge exchange with solar wind (inside termination shock)
400km/s, radial direction; cold
Four-fluid model

Fluid 0: plasma
Origin: Sun and LISM, and all charge exchange (pickup ions)

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0,
\]
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mu u) + \nabla p = Q_m,
\]
\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho u^2 + \frac{p}{\gamma - 1} \right) + \nabla \cdot \left( \frac{1}{2} \rho u^2 u + \frac{u}{\gamma - 1} \rho u \right) = Q_m.
\]

Neutral Fluid 1
Origin: LISM, and charge exchange outside heliopause

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0,
\]
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mu u) + \nabla p = Q_m,
\]
\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho u^2 + \frac{p}{\gamma - 1} \right) + \nabla \cdot \left( \frac{1}{2} \rho u^2 u + \frac{u}{\gamma - 1} \rho u \right) = Q_m.
\]

Neutral Fluid 2
Origin: Charge exchange between termination shock and heliopause

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0,
\]
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mu u) + \nabla p = Q_m,
\]
\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho u^2 + \frac{p}{\gamma - 1} \right) + \nabla \cdot \left( \frac{1}{2} \rho u^2 u + \frac{u}{\gamma - 1} \rho u \right) = Q_m.
\]

Neutral Fluid 3
Origin: Charge exchange with solar wind (inside termination shock)

\[
\frac{\partial p}{\partial t} + \nabla \cdot (\rho u) = 0,
\]
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mu u) + \nabla p = Q_m,
\]
\[
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho u^2 + \frac{p}{\gamma - 1} \right) + \nabla \cdot \left( \frac{1}{2} \rho u^2 u + \frac{u}{\gamma - 1} \rho u \right) = Q_m.
\]
Hybrid Boltzmann model

**Kinetic description: neutral distribution function**
Origin: LISM, and all charge exchange

\[
\frac{\partial}{\partial t} f_H + \mathbf{v} \cdot \nabla f_H + \frac{F}{m_p} \cdot \nabla \mathbf{v} f_H = P - L
\]

**Fluid: plasma**
Origin: Sun and LISM, and all charge exchange (pickup ions)

\[
\begin{align*}
\frac{\partial p}{\partial t} + \nabla \cdot (p \mathbf{u}) &= 0, \\
\frac{\partial}{\partial t} \left( \frac{1}{2} \rho u^2 + \frac{p}{\gamma - 1} \right) + \nabla \cdot \left( \frac{1}{2} \rho u^2 \mathbf{u} + \frac{\gamma}{\gamma - 1} p \mathbf{u} \right) &= Q_m, \\
\frac{\partial}{\partial t} f_p + \nabla \cdot (\rho f_p \mathbf{u}) &= Q_e.
\end{align*}
\]

**Kinetic Side**
(neutral H)

- \(f_p, n_p, u, T_p\)
- \(\beta, v_{rel}, f_p\)

**Gasdynamic Side**
(plasma)

- \(N_p, u, T_p\)
- \(Q^m, Q_e\)

- \(n_H, u_H, T_H\)

- Boltzmann Equation\(f_H\)
Heliospheric Structure

2-shock model

1-shock model
Simulations

1. Quasi-equilibrium state
2. Instability triggered by perturbations from previous cycle
3. Instability develops. Mushroom-shape structures are a signature of R-T
4, 5: Structure is advected along the heliopause. Relaxation phase.
6. Return to the quasi-equilibrium

1 cycle = 100 years

TS oscillates with an amplitude of ~ 3 AU
2-Fluid simulation
Dynamical Solar Wind-GMIRs
The physics of atom-plasma coupling

From perspective of QM, one cannot refer to outgoing proton as either being the initial H atom nucleus (i.e., a CE encounter) or simply the initial proton that scattered off the H atom - the two processes are indistinguishable.

- Need to consider total elastic cross-section for interaction of H and H⁺
- Total cross-section much larger than usual CE only cross-section, but large proportion of collisions are small-angle.
The physics of atom-plasma coupling

From perspective of QM, one cannot refer to outgoing proton as either being the initial \( H \) atom nucleus (i.e., a CE encounter) or simply the initial proton that scattered off the \( H \) atom - the two processes are indistinguishable.

- Need to consider total elastic cross-section for interaction of \( H \) and \( H^+ \)
- Total cross-section much larger than usual CE only cross-section, but large proportion of collisions are small-angle.
The 3D Solar Wind
The Role of Interstellar Neutral H - 3D Models

Plasma temperature

Neutral density
We assume that the SW is spherically symmetric at the inner boundary and initially set $V_p = 450$ km/s, $n_p = 7$ cm$^{-3}$, and $T_p = 73600$ K.

In the LISM we put $V_{\infty} = 25$ km/s, $n_\infty = 0.07$ cm$^{-3}$, $M_\infty = 2$, $n_{H\infty} = 0.1$ cm$^{-3}$, and $B_\infty = 1.5$ µG. The direction of the ISMF is not well known and remains a parameter of the problem.
The importance of neutral atoms

ISMF parallel to the LISM velocity: without neutrals (a, b) and with neutral hydrogen atoms (c, d).
Multi-fluid modeling of the SW-LISM interaction

HCS instabilities due to charge exchange

Magnetic field magnitude distribution in the meridional plane
ISMF perpendicular to the LISM velocity vector and Sun’s rotation axis

\[ B_\infty = 1.5 \mu \text{G}, \]  
that is, LISM flow is superfast.
Side and front views of the heliopause draped by the ISMF lines
The angle between the ISMF and the LISM velocity is 45°.

Asymmetry of discontinuities with respect to the ecliptic plane become considerably less pronounced!
ISMF perpendicular to the LISM velocity and tilted 60° to the ecliptic plane.

Cross-sections of the widest and narrowest flaring of the heliopause
Comparison of MHD, 2-fluid, and 4-fluid models
HCS bending and rotation

SW streamlines starting above the ecliptic plane
(views from above and below the ecliptic plane)
V-shaped grooves on the surface of the heliopause (boundary conditions for the HCS)

(a) and (b) temperature distributions without H-atoms and with magnetic field eliminated in the 0.75°- and 0.375°- sectors symmetric with respect to the ecliptic plane. (c) and (d) plasma temperature and density in the presence of neutral atoms.
On the possibility of multiple crossing of the termination shock by IMF lines

Energetic charged particle latitudinal streaming anisotropy data can be explained by multiple crossing of the termination shock by IMF lines (Jokipii et al, 2004). The possibility of such crossings was discussed by Zank (1999). Here we show one of the calculated IMF lines that crosses the termination shock approximately at the Voyager 1 location.
The angle between the LISM H and He velocity vectors (LISM stagnation point displacement with respect to the ecliptic plane)

Lallement et al. (2005) determined an angle $\approx 4^\circ$ between the He and H velocity vectors. A possible reason is a displacement of the LISM stagnation point with respect to the ecliptic plane (Izmodenov et al., 2005, who considered a $45^\circ$ angle between $V_\infty$ and $B_\infty$ and neglected the influence of the IMF).

LISM velocity parallel to the interstellar magnetic field vector ($B_\infty = 1.5 \mu G$):

displacement $\sim 5^\circ$!
H-atoms streamlines
MHD CONCLUSIONS

1. 3D calculations of the SW-LISM interaction taking into account interplanetary and interstellar magnetic fields, and neutral hydrogen included using multi-fluid approach. Bending of the HCS is likely for most of the ISMF orientations.

2. Certain orientations of the interstellar magnetic field with respect to the LISM velocity and the solar ecliptic plane create asymmetric magnetic pressure distributions at the outer side of the heliopause - might explain of the observed distribution of radio emission sources in that region.

3. The IMF lines can exhibit multiple crossings of the termination shock and repeatedly penetrate from the supersonic SW region into the heliosheath.

4. Analysis of solutions for various ISMF strengths and directions with respect to the LISM velocity shows that small deviations between the He- and H-streams reported by Lallement et al. (2005) can be obtained for many different orientations of B.
Large step decreases in the CR modulation cycle are coupled to GMIRs, which are mainly associated with systems of transients near the Sun. The transient streams merge in such a way that beyond \(~ 20\) AU large-scale GMIRs form from overlapping MIRs which persist over several solar rotations, surround the Sun near the ecliptic plane, and extend to at least \(30^\circ\) in heliolatitude above the equatorial plane (Burlaga, 1993).

Consider the interaction of a steady-state heliosphere with a model spherically symmetric perturbation in the SW velocity, which increases 3 times within 60 days and then returns to its initial value after another 60 days.

\[
U(t) = 18 \times \left\{ 1 + 2.1 \exp \left[ -\left( \frac{t - 1.864}{0.57} \right)^2 \right] \right\}
\]
Magnetic field distribution caused by the GMIR propagation

Frames 1-25:

sequence of snapshots at t=0,

66.5, 121.7, 154.6, 179.5, 206.9, 242.7, 292.6, 346.2, 400, and 457.5 days.
The first 25 frames at twice larger interval
The next 50 time steps.

Magnetic field scaling is different from the previous two slides!
Density distributions

Frames 1-25
Temperature distributions

Frame 001  23 Mar 2005

Temperature levels:
- 5.7E+03
- 1.4E+04
- 3.4E+04
- 8.4E+04
- 2.1E+05
- 5.0E+05
- 1.2E+06
- 3.0E+06
- 7.4E+06
Neutral hydrogen distributions

Frames 1-25:
Sequence of snapshots at
$t=0,$
$66.5,$
$121.7,$
$154.6,$
$179.5,$
$206.9,$
$242.7,$
$292.6,$
$346.2,$
$400,$
$457.5$
days.
Neutral hydrogen distributions

Frames 26-55
Radial distributions in different directions from the Sun

Magnetic field slightly above the ecliptic plane
Magnetic field in the direction of Voyager 1
Neutral hydrogen density variation in the direction of Voyager 1
CONCLUSIONS

1. 3D calculations of GMIR propagation taking into account both interplanetary and interstellar magnetic fields. Neutral hydrogen atoms are modeled using the multi-fluid approach.

2. GMIRs create moving magnetic barriers in the solar wind region that are comparable or stronger than the compressed IMF at the inner side of the heliopause.

3. Bending of the HCS and/or IMF-ISMF lines reconnection cause substantial asymmetries in the time-dependent parameter distribution with respect to the ecliptic plane.

4. Perturbations of the heliopause lead to a noticeable increase in the ISMF strength in the outer heliosheath.
Magnetic field \( (B_j) \) is strongly amplified near the stagnation point and gets convected to higher latitudes creating a region of enhanced magnetic field (small diffusion). This is expected to filter lower energy GCR. 2D and 3D magnetic wall structures different.

Termination shock is not spherically symmetric.

Compressive flow in the heliotail caused by charge-exchange slowdown of the SW may accelerate GCR.
Magnetic field (interplanetary)

Note the modulation barrier

Diffusion coefficients

Note that thickness of barrier (65-100 AU) is significantly larger than commonly used in modulation models.

Galactic cosmic rays: global heliospheric modulation

Magnetic field (interplanetary)

Note the modulation barrier
No hydrogen atoms.

30 MeV protons

Cosmic-ray distribution in the inner heliosphere exhibits a typical "lobe" structure seen in many modulation models, which is caused by the change in kappa with heliolatitude.

Strong attenuation in the "magnetic wall" (heliosheath region).

500 MeV protons

Galactic cosmic rays: global heliospheric modulation

No hydrogen atoms.

30 MeV protons

Cosmic-ray distribution in the inner heliosphere exhibits a typical "lobe" structure seen in many modulation models, which is caused by the change in kappa with heliolatitude.

Strong attenuation in the “magnetic wall” (heliosheath region).

500 MeV protons
Hydrogen atoms included.

30 MeV protons

Note re-acceleration in the tail (convergent solar wind flow • u<0).

500 MeV protons

Galactic cosmic rays: global heliospheric modulation

Hydrogen atoms included.
**Galactic cosmic rays: global heliospheric modulation**

**GCR spectra (H atoms included):**

LISM (solid),
1.1\(r_s\) 0° (dashed),
1.1\(r_s\) 90° (dash-double-dotted),
800 AU 180° (dotted),
10 AU 0° (green).
10 AU with no H atoms (red)

Effect of the modulation cavity reduction due to neutrals is not significant (~5%) at small heliocentric distances.
Challenges to theoretical modeling: Concluding remarks

- The physics of the neutral – plasma interaction more complicated than simple CE. Kinetic and multi-fluid approaches are converging.
- Implications of modeling heavy atoms and their coupling to ACRs
- The 3D heliosphere: solar wind anisotropy, 2D vs 3D MHD modeling, inner heliosheath structure and HP structure unresolved, structural asymmetry when LISM B field included.
- Time dependence: solar cycle, solar wind disturbances, quasi-periodicity of current sheet, unstable jet, stability of HP due to neutrals.
- Galactic cosmic rays, diffusion coefficients, and the heliospheric boundaries.