The Voyagers at the Edge of the Heliospheric Bubble

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With thanks to the Voyager team and E. Mobius

Outline

1) Our place in the Galaxy
2) The Local Interstellar Cloud (LIC)
3) The Solar Wind - LIC interaction
4) The Voyagers at the Termination Shock
5) The Future
Apropos: Sticking Our Head Out
Our „County“ in the Cosmos: The Local Bubble

SN from Pleiades

D~120 pc
\( \Gamma = -1.1 \)
Massey et al. 1995

Local Bubble and Loop I are Interacting Bubbles!

Blasts from Past

From ISSI Workshop: From the Heliosphere to the Local Bubble

Breitschwerdt & deAvillez

ISM Cloud Flow

From ISSI Workshop: From the Heliosphere to the Local Bubble

E. Möbius UNH/SSC
If We Could See Our Heliosphere from Outside …

Sampling our Neighborhood With Absorption Spectroscopy
LIC neutrals are not bound by magnetic fields; some enter the heliosphere.

LIC neutrals are tied to plasma via charge exchange. Slowing of plasma in front of the heliopause creates the hydrogen wall.

Mueller et al.
Pattern of the Interstellar Gas Flow

GAS Image

Neutrals from Jupiter

Counts/sec

80 0 UV Stars

Longitude in the Milky Way

Interstellar Wind

Earth's Orbit

Witte et al., Banaszkiewicz et al.
LIC He from 3 Methods
(Efforts of an ISSI Team)

Measure 1. Neutrals 2. Pickup ions 3. UV

- **Velocity** = 26.3±0.4 km/s
- **Temperature** = 6300±340 K
- **Density** = 0.015±0.0015 cm$^{-3}$

- LIC H Density: 0.2 ± 0.02 cm$^{-3}$
Plasma Interaction with the LIC

 Plasma Density Contours

 Blue & Green Solar Wind

Bow Shock?

ISM ≈ 26 km/s

H & O

Charge Exchange

H⁺, O⁺

O, H

slow & hot

Orange - Pristine ISM

Red - Decelerated ISM

3D MHD Model T. Linde, Thesis

LISM O

v = 26 km/s
T = 6000 K

Secondary O

v = 21 km/s
T = 20,000 K

Simulation V. Izmodenov
• Neutrals dominate density outside \( \sim 10 \) AU

• Pickup ions dominate thermal pressure outside 30 AU

[Mewalt]
- Solar Wind Slowdown
- Can determine slowdown at solar max or when two spacecraft are at the same heliolatitude
- \( \frac{dV}{V} = \frac{6}{7} \frac{N_{pu}}{N_{sw}} \)
Solar Wind Slowdown
Does pickup ion energy heat SW? YES!

Temperature is not adiabatic; $T$ decreases to 25 AU, then increases by a factor of 3 by 80 AU.

Energy comes from isotropization of pickup ion ring distributions.

More heating with higher speeds.

About 4% of isotropization energy heats solar wind.
LECP V1 TS

V1 - no plasma data

Ions and electrons observed beaming in foreshock but isotropic in sheath

Used to estimate SW speeds - report slowing ahead of shock, -40 - 100 km/s in sheath (Decker)
Puzzle:
Where is the Anomalous Cosmic Ray Source

- Ions come from maximum acceleration region along B-Field (Schwadron & McComas)
- Acceleration in Heliosheath (Fisk & Gloeckler)
- Acceleration of Pickup Ions with anisotropic PADs provides gap in spectra (Florinski)

Schwadron & McComas 2006
Heliospheric Asymmetry.

V1 enters FS region At 85 AU, V2 enters At 75 AU.
Ly $\alpha$ Observations Have Revealed Deflected Flow of H

Asymmetric LIC Magnetic Field Deflects the Decelerated Flow

Direct Neutral Observations Desirable!

Lallement et al. 2005
Simulation of sheath (Opher)

Tilted LIC magnetic field gives asymmetry TS and HP closer in South than North.

This asymmetry observed by Voyagers
A 3D View of the TS Is needed!

The Termination Shock (TS) is blunt, as evidenced by streaming of foreshock beams at Voyager 1 and Voyager 2. It is also asymmetric: Voyager 2 sees TS signs earlier than for a symmetric Heliosphere.

Ed Stone

Meraph Opher
• TS Overview
• Speed decrease starts 82 days, 0.7 AU before TS
• Crossing clear in plasma data
• Flow deflected as expected
• Crossing was at 84 AU, 10 AU closer than at V1
TS location predictions

2-D model of Chi Wang uses V2 SW pressure as input
Normalized to V1 crossing
Predicts TS location ~3 AU closer than at the V1 TS crossing
Thus TS asymmetry is 7 AU
SW energy drops in discrete steps before TS (associated with MIRs?)

40% of sw flow energy is lost before TS
Energetic particles at V2 (Decker)
Voyager 2 Termination Shock Crossings

The graph shows data for different parameters, likely related to shock waves, with axes labeled as $V$, $N$, and $T$ (in K). The x-axis appears to represent time or another variable with a range from 242.0 to 245.0.
Belcher
Flow remains supersonic wrt thermal plasma in sheath.

Energy must reside in pickup ions.
• Neptune BS - TS comparison
• Normalize SW to values at TS
• Same time scale.
• Neptune BS much stronger and much more plasma heating
## Termination Shock Jumps

<table>
<thead>
<tr>
<th></th>
<th>Upstream</th>
<th>Downstream</th>
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<tr>
<td>$</td>
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<tr>
<td>NS</td>
<td>-5</td>
<td>-12</td>
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</tbody>
</table>
• Termination shock with classic structure: foot, ramp, shock. (Burlaga et al.)
Structure of first TS crossing is very different: there appear to be two ramps. Shock may be reforming downstream (Burlaga et al.)
• Flow directions: as expected, flow diverts in T and -N directions
• Flow in -N before shock
Will V2 cross TS again?

- Dynamic pressure at 1 AU (Wind)
- Decreases through 2007
Interstellar neutrals

Flow angle changes across HSH

Mueller et al.
• Flow turns across HSH and must be parallel to the HP at the HP.

• Decker et al. show that angle is changing; gives a HP thickness of 30 AU.
Heliosheath PDL?

- Axford-Cranfill postulate increased magnetic field at HP boundary.
- Models also suggest a magnetic barrier may form. (Pogorelov et al., 2006)
- Results in plasma depletion layer in model.
Relevant to Exploration: Cosmic Ray Shielding

Approximate Distances From Bow Shock [AU]

Fraction of Incident Galactic Cosmic Rays at ~ 100 MeV

0.0  0.25  0.50  0.75  1.00

Interstellar Flow

Bow Shock

Heliosphere

Termination Shock

Inner Heliosheath

Cosmic Ray Fraction

Courtesy: D. McComas
LIC He from 3 Methods
(Efforts of an ISSI Team)

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Summary

• Voyager 2 crossed the TS in Aug. 2007
• Showed heliosphere is asymmetric
• Shock strongly modulated by pickup ions
• TS effects start 0.7 AU upstream of TS
Why Interstellar Helium? (and not Hydrogen)

• Has the Highest Ionization Potential
  i.e. *Reaches 1 AU*

• Can be Observed with 3 Methods:
  *Neutrals, Pickup, Scattering of Solar UV*

• Second Most Abundant Species
  i.e. *Is an Important Species in the LIC*

• Not Affected by the Heliospheric Interface
  i.e. *Provides an Unbiased Account of the LIC*
How do LIC neutrals effect the SW?
They start the transfer of SW flow energy into heating of plasma and particles.
Energy acquired by pickup ions slows down SW 1 AU (IMP 8 and ACE) and V2 speeds.
V2 speeds in outer heliosphere are less than those at 1 AU.
Charge exchange: ion and neutral collide and ion takes an electron. $\text{H}^+ + \text{H} \rightarrow \text{H} + \text{H}^+$

New neutral H is moving with solar wind speed and escapes

New H+ has solar wind speed and energy equal to the solar wind energy (1 keV): is called a pickup ion.

The energy/momentum come from solar wind, so solar wind slows down.
Dynamic Pressure $\text{m}_n\text{V}^2$

Solar cycle dependence:
Factor of $>2$
change with peak after solar maximum

Graph showing P: 51-day running average over years 1980 to 2005.
Structure of first TS crossing is very different: there appear to be two ramps. Shock may be reforming downstream.