Surprises from the Edge of the Solar System: Modeling the Global Heliosphere and Data from Voyagers Spacecraft

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The solar system motion in the galaxy

Credit: Frisch & Huff
Superbubbles from successive epochs of star formation in Scorpius-Centaurus Association.
Learning from our heliosphere about astrospheres
Complex interacting system:

ionized(p+He), pickup ions, neutral H, magnetic fields, GCR, solar cycle effects, etc
Solar Minimum-Maximum

1996/05/02 10:58 UT

2000/12/31 21:12:49 UT

EIT
V1 is beyond 100 AU at 34.1° (latitude) and 173° (longitude) (HGI coord).

V2 is beyond 84 AU at -26.2° (latitude) and 216° (longitude)
PLS (plasma science experiment) - thermal plasma
LECP (low energy charged part.) - tens keV-MeV
CRS - galactic and ACR
MAG (magnetometer) - magnetic field
PWS (plasma wave) - plasma and radio waves
Voyager 1 crossed the Termination Shock in Dec 16, 2004

We have for the first time measurements in-situ of the boundaries of the heliosphere
Some of the surprises encountered by Voyager in the Heliosheath

Magnetic Bumps …
and holes...
No evidence of the source of anomalous cosmic rays...
Voyager observations in the heliosheath show a steady, omnipresent suprathermal power law tail with spectral index $-5$ extending to a few MeV (red and blue filled circles).

Heliosheath solar wind protons have low thermal speed and a density of $0.003 \, \text{cm}^{-3}$ (black curve) as reported by Richardson.

Pickup protons are modeled distributions.

Extrapolated $-5$ power law tail to intersect the pickup ion distribution $\sim 100$ times below the core plateau.

Acknowledgment: G. Gloeckler

Gloeckler & Fisk
Some Questions of “When Space-Astrophysical Plasmas Collide”:

How magnetic effects affect Shock Evolution?
Which type of flows we get in shocks?
How stellar winds affect shocks evolutions?
How MHD instabilities (such KH and RT) are affected?
Can we form small structures in shocks?
How reconnection affect the shock structures?
Summary:

Asymmetries in the Heliosphere:

Heliosphere present Asymmetries: North & South and East & West

Local Interstellar Magnetic Field Direction

Plane is in the HDP (hydrogen deflection plane) 60° from the Galactic Plane
The Global Structure of the Heliospheric Interface is determined by the boundary conditions

The (undisturbed by Sun) local interstellar medium:

- relative LIC/SW velocity, temperature and He atom number density of 0.15 cm\(^{-3}\) are well established
- interstellar proton number density 0.03-0.06 cm\(^{-3}\)
- interstellar H atom number density 0.17-0.21 cm\(^{-3}\)
- interstellar magnetic field strength and direction

Acknowledgement Vlad. Izmodenov
Computationally Challenging - BATS-R-US 3D, MHD, Multi-fluid, AMR

(Gombosi et al. 1999)

An interstellar magnetic field oriented obliquely to the interstellar velocity can produce a lateral (north-south asymmetry)
The Voyager 1 and 2 data seem to be revealing us Global features of the Heliosphere: Asymmetries
1. Asymmetry of the crossing of the TS by V2 and V1

2. V2 being connected to the shock for longer distances that V1 before crossing the shock

3. Anisotropy of streaming for V1 and V2

4. Radio Emissions in the Heliopause
We proposed in recent works Opher et al. *ApJL* 2006 Opher, Stone, Gombosi *Science* 2007

That a presence of an inclined interstellar magnetic field can explain the observations (asymmetry E-W; N-S; radio observations, particle observations)
The orientation that we obtained for the local interstellar magnetic field is in a direction inclined 60° to the plane of the disk of the galaxy with an angle of 30-45° between the $B$ and $v$.

Magnitude is 1.8-2.5 $\mu$G
When we started working on that we were trying to explain the first of the data set:

The streaming of particles to Voyager 1 at the beginning of 2003
Streaming Ions from the Termination Shock

Particles coming from the Termination Shock streaming along the magnetic field line (TSPs)
Blunt Termination Shock:
The fact that we detected *particles from the shock* before Voyager 1 crossed the shock suggested:

Voyager 1 connected to Termination Shock along magnetic field line that had crossed the shock and crossed back into the supersonic solar wind (*Jokipii et al.* (2004); *Stone* (2005))
A non-spherical shock

Non Spherical Shock:

Voyager 1 is 6° in longitude and 35° in latitude from nose - very close to the axis of symmetry

Is the distortion large enough and in right direction?

Can an interstellar magnetic field distort the termination shock?
Investigating the effect of Interstellar Magnetic field $B_{\text{ISM}}$

- H-Deflection plane (HDP) ($\beta=60^\circ$)
- $\alpha$ (direction between $B_{\text{ISM}}$ and $v_{\text{ISM}}$)
Orientations:

**Galactic plane (GAL)**
Frisch et al. 1990
Scales of parsecs (200,000AU)

**Hydrogen Deflection plane (HDP)**
Lallement et al. 2005
Scales of AU
Spiral Magnetic Field Crossing V1 and V2

Shock closer to the Sun near nose than in the flanks

In both Northern and Southern Hemisphere the cones intersect the Termination Shock closer to the equator near the nose
The distortion of the shock is such that the shock is closer to the Sun counterclockwise from Voyager 1.

2AU inside the shock
Voyager 1 was connected to the shock along a field line in the direction toward the Sun -> particles streaming outward along the field.
The distortion is such that the shock is closer to the Sun clockwise from V2 -> TSPs streaming *inward* along the field line.

The distortion is larger in the southern hemisphere -> field lines 5AU from the shock are connected to V2.
Voyager 1 started measuring the particles 3AU from a moving shock

Voyager 1 at 85 AU
V1 at 94 AU

Voyager 2 started measuring the particles 7AU from the Shock;

Voyager 2 crossed in August 30, 2007 the shock at 83.4 AU
V2 at 75 AU

Acknowledgments: Cummings et al.
Shock at ~ 89 AU at V1 latitude

TSP onset in 2002 at 85 AU

V1 observed TSPs 3-4AU upwind of the shock

Shock location: Acknowledgement J. Richardson et al.
Orientation of the Interstellar Magnetic Field

Radio Data: 2-3kHz
Particle Data: Streaming Ions (TSPs)

Opher, Stone, Gombosi Science 2007
2-3kHz Radio Emissions were detected each solar cycle

Kurth et al. ‘84
Gurnett et al. ‘93
Gurnett, Kurth and Stone, ‘03
Current accepted scenario is that the radio emissions are generated when a strong interplanetary shock reaches the vicinity of the heliopause (Gurnett et al. ‘03, Gurnett & Kurth ‘95)
Radio Source Locations

From radio direction-finding measurements from V1 and V2

Kurth & Gurnett 2003
Draping of BISM

Gurnett et al. 2006: radio emission at Earth’s bow shock and interplanetary shocks occurs where the magnetic field lines are tangential to the shock surfaces, or

\[ \mathbf{B} \cdot \mathbf{n} = 0 \Rightarrow B_{\text{ISM}} \cdot \mathbf{r} = 0 \Rightarrow B_r = 0 \]

\[ B_{\text{ISM}} \sim 46^\circ \pm 5^\circ \text{(plane PPG)} \]
Magnetic Field in the HDP plane with alpha (angle between B and V (ISM) $\alpha=45^\circ$)
Best Agreement: PPG ($\alpha=30^\circ$) (only differs from HDP by 16°)

The accuracy of the model is not adequate to distinguish between PPG and HDP
This suggest that the interstellar magnetic field in the Local Interstellar Cloud differs from a larger-scale interstellar magnetic field.
Turbulence in the Interstellar Medium

A Local Wiggle in the Turbulent Interstellar Magnetic Field

J. R. Jokipii

Recent observations, both remotely and in situ with the Voyager space probes, are clearing away some of the mystery about the interstellar magnetic field that lies just outside the solar system. On page 875 of this issue, Opher et al. (1) report a new analysis showing that previous measurements of the field (2, 3), initially indicating quite different fields, are in fact consistent with each other [also suggested by Gurnett et al. (4)]. Also, it now seems clear that the very local interstellar magnetic field points in a quite different direction from that obtained from numerous previous ground-based measurements, which were averages over large distances. This discrepancy can now be understood as a natural consequence of fluid turbulence in the interstellar medium, in which the magnetic-field direction changes dramatically over shorter scales than could be measured previously. The insights gained will help researchers better understand the interstellar medium and the nature of its interaction with the plasma environment around the Sun.

A stream of ionized particles—the solar wind—is continuously emitted by the Sun and has carved out a bubble in the interstellar plasma, called the heliosphere, which extends outward from the Sun more than 100 astronomical units (AU) (1 AU is the distance from the Sun to Earth) in all directions. The ionized regions of the interstellar gas and its magnetic field are largely excluded from this bubble. This local interstellar magnetic field, immediately outside of the heliosphere, is an important factor in determining the interaction of the interstellar medium with the heliosphere. The interaction determines, among other things, the effects of the heliosphere on the galactic cosmic rays, an important part of Earth's environment in space.

Until recently, observations of the interstellar plasma and magnetic field were restricted to effects averaged over long times of sight to distant objects, corresponding to spatial scales of tens of parsecs (1 parsec, or pc, is $3 \times 10^{18}$ cm, or 200,000 AU), more than a thousand times the scale of the heliosphere. These observations yielded accurate information about the interstellar plasma and the magnitude and direction of the magnetic field, but the spatial resolution was limited by the averaging to scales of several parsecs or more (5).

From these measurements, the magnetic field was found to be approximately in the galactic plane, along a spiral arm. However, there is a complication: The interstellar medium is turbulent, with pronounced fluctuations of fluid parameters such as density, with a coherence scale (typical scale of the largest fluctuations in the turbulence) on the order of 1 to 10 pc (6, 7). Because the interstellar plasma is a hydromagnetic fluid, there is no electric field in the frame of the fluid and the magnetic field is dragged with the plasma motions. As a result, plasma flows and magnetic field should vary on similar scales.
• Magnetic field is parallel to the edges of the LIC and G clouds and likely compressed by the relative motion of the two clouds.
SOME OPEN QUESTIONS:

- Which Flows/Fields we have in the Heliosheath: possible MHD instabilities? (Opher et al. 2003, 2004)
- Effect of $B_{\text{ISM}}$ on the flows in the Heliosheath
- Effect of Tilted HCS
- Solar Cycle
- Reconnection effects on HP
- MHD-kinetic neutrals
A lot of these effects walk-hand-by-hand

Frozen-in-field and flows: \( P_B \sim P_{TH} (1.5\mu G) \)
Close to the heliopause: \( P_B > P_{TH} \)

Maybe they are not exactly equal partner: \( B+n + nH(\text{kinetic}) \)
In progress...

- NASA GI: w/ Vlad Izmodenov and Moscow group (Kinetic Description-nH) (BATSRSUS multifluid (G. Toth)
Interaction of the Solar System
With the Interstellar Medium
END
Kelvin-Helmholtz Instability at the Current Sheet: Confirmed by resistive MHD code
Waiting for Voyager 2 with the plasma instrument to cross the Termination Shock

3D MHD
Sinuous mode

2D plane resistive MHD
Bettarini et al. Physics of Plasma 2006
Why didn’t previous studies see it?

RESOLUTION

\[ dx = 3\text{AU} \]

\[ dx = 0.75\text{AU} \]
...in 1977

Voyager 1 & 2
Characterizing the Heliosheath

- Termination Shock (TS)
- Outer Heliosheath
- Hydrogen Wall
- Inner Heliosheath
- Heliopause
- Interstellar Neutral Atoms
- Radio Emissions
- Deflected Ions
- Bow shock
- Heliotail
- Sun