Voyager Observations of the Outer Heliosphere and Interstellar Medium

John Richardson (M.I.T.) and the Voyager team

- **Plasma Science (Voyager 2)**

- **Low-Energy Charged Particles**

- **Cosmic Ray Subsystem**
  - E.C. Stone, A.C. Cummings, N. Lal, W.R. Webber

- **Magnetometer**
  - N.F. Ness, L.F. Burlaga

- **Plasma Wave Subsystem**
  - D.A. Gurnett, W.S. Kurth
BEFORE VOYAGER SHOCK AND HP DISTANCES WERE NOT KNOWN
Topics:

Highlights of Voyager in the Outer Heliosphere

1. Introduction to the heliosphere: structure and particles
2. The termination shock
3. The heliosheath
4. The heliopause
5. The local interstellar medium
Voyager locations

View from SUN towards nose of heliosphere: R is outward

V1 (133 AU)

V2 (109 AU)

Solar Equator
>70 MeV/nuc cosmic rays

>0.5 MeV/nuc
Pickup ions dominate
Thermal pressure outside
~30 AU

![Graph showing number density vs. distance from the Sun, with labels for Solar wind protons, Hydrogen atoms, Pickup protons, Bow Shock, and Heliopause.]
Interstellar Neutral Effects on the SW

- Solar Wind slowdown

\[
dV/V = \frac{6}{7} \frac{N_{pu}}{N_{sw}} = 17\% \text{ at TS}
\]

20\% of density in pickup ions

~30\% of SW flow energy lost before TS
Termination Shock

What we learned:

1) Location
2) Strength
3) Asymmetric
4) Acceleration
   thermal plasma – weak
   pickup ions – strong
   10 – 100’s keV ions – strong
   ACRs (> few MeV) - weak
Voyager 2’s trip through the Heliosphere

Termination shock

Weak: ~2.3

1) V down
2) N up
3) T up
4) B up
5) Flow angles up
6) Energetic particles up
So HP 40-60 AU beyond?

Tilted LISM B field can give this asymmetry.

Need strong B > 3nT.

~ 30° tilt
Only 20% of SW flow energy is kept by thermal plasma: Rest goes to pickup ions average energy ~several keV (predicted by Zank et al., 1997)
Pickup ions not directly observed
So need models:

Comparison of model results to V2 observations of the TS.

Observed B

Currents in the C-cup of the PLS Instrument

Model B with 25% pickup ions

Model currents: cut off at V2 threshold.
SWI lose ½ of flow energy in foot
Almost 90% of thermal energy is in the pickup ions.
Ripples cause lots of variability behind shock
Electrons gain negligible energy

Total ion dynamic pressure

\[ P_{\text{th}} + P_B \]
Termination shock:

Low energy particles accelerated.

ACR acceleration small

After TS crossing ion intensities were steady and isotropic in sheath.

Decker et al., 2005
Expected ACR spectrum at shock (black dashed line) not observed at V1 or V2 shock crossings (TSX).

V2 ACR intensity (~10-30 MeV/nuc) at shock was 7x that at V1 at its shock crossing and spectra evolved at both V1 and V2 in the heliosheath, mainly due to decreasing solar modulation between the source and the spacecraft.

Higher energy ACRs not modulated, lower energies are modulated.

(From Alan Cummings)
Align V1 & V2 based on TS

Krimigis et al.
Heliosheath

Why a stagnation region at V1?

Why are plasma flows and particle intensities so different at V1 and V2?
BEFORE VOYAGER SHOCK AND HP DISTANCES WERE NOT KNOWN
Puzzle: why a stagnation region? \( V \sim 0 \)

Flow expected to turn tailward as it moves across HSH; VR to \(~0\) at HP

Intensity \(~\)constant from 94-115 AU, then decreased from 2010 to dropout in 2012.

Radial speed near zero from early 2010 to dropout: 113-121 AU

Other flow components also small:

Stagnation region

Krimigis et al. (2013)
VOYAGER 2

$|V|$ average is constant:
Flow does not slow down.

RT flow angle is $\sim 60^\circ$:
Flow has turned tailward.

Flow in RN plane $\sim 30^\circ$:
Flow over the poles small.
Electrons 0.04-1.5 MeV in the Heliosheath

- Electrons 40-70 keV at V1 (red), and 35-61 keV (blue) & 35-1500 keV (greens) at V2
- V1 measured pre-TS HS electrons bursts and relatively steady intensity in the HS (with a factor ~2)
- By contrast, V2 has measured 3-4 episodes of HS electrons
- In most recent V2 episode intensities continue to climb

Hill et al.
Heliopause

Location

Change of particle intensities

Change in magnetic field
Heliosheath particles disappear

Galactic cosmic rays increase

Magnetic field increases

Magnetic field direction does NOT change

Still inside heliopause?
Densities are interstellar medium densities – so V1 crossed heliopause!
Emissions excited when ICMEs hit heliopause and accelerate electron beams.

Gurnett et al., Science, 2013
STRONG TWIST OF THE INTERSTELLAR MAGNETIC FIELD ahead of the Heliopause

Opher & Drake ApJL 2013

At large distances outside of the HP the interstellar field lines are inclined to the T direction (east-west direction) and then twist dramatically in the T direction as they approach the Heliopause.
Magnetic field is slowly rotating toward expected LISM direction.
Question: Where is the heliopause?

The helioclip (GCRs and B up, TSPs and ACRs down)?

Magnetic field direction change?

GCR increase, HSH e⁻ down?
**Question:** Why is the heliopause so close? At 121 AU, it is only 27 AU from TS. Models predict HP is 40-60 AU from TS.
One Solution? Borovikov and Pogorelov: Instabilities on the Heliopause
Local Interstellar Medium

Magnetic field magnitude and direction
Cosmic ray intensities (mostly) unmodulated
Solar disturbances propagating into the LISM
Source of radio emissions
Depletions observed in 90° pitch angle particle.
~4° in width
Void in Angular Distributions May be Due to Mirroring off of Multiple Magnetic Perturbations

\( \delta B / B \sim \text{few \%} \)

Source I \((J_0)\)

Source II \((J_0)\)

Distance along field line \((B)\)

B = |B|

\( B_0 \)

\( B_1 > B_0 \)

\( B_2 > B_1 > B_0 \)

Magnetic Field Directions

All non-zero intensities are \(J_0\) (from Sources I or II)

Based on poster Roelof et al. 2013

Cartoons of observational “pie plots” not pitch angle distributions (change from Roelof display).
Overview of Interstellar Disturbances Detected by Voyager 1.

MIRs drive pressure waves Through LISM
Comparison to Cosmic Ray Observations (2014 Event)
The Cosmic Ray Foreshock Model

Gurnett et al., 2015

Solar Plasma  Interstellar Plasma
Heliopause
Shock
Electron Beams
Plasma Oscillations
Incident IP Shock
Tangent Field Line
Radio Emission

Note: Scale Size is ~ 10,000x
Terrestrial Bow Shock
V1 H, He, C, and O spectra for 2012/342-2013/60. Also shown is H spectrum for 2012/274-2012/121.

Believe we are observing GCRs down to ~3 MeV/nuc for H and He; C & O down to ~10 MeV/nuc.

GCR H, He spectra peak at ~20-40 MeV/nuc and are in good agreement at higher energies with leaky box model from Webber & Higbie 2009 -- as is GCR C.

GCR C/O ratio ~1. ACRs not contributing to low-energy GCR spectrum, contrary to Scherer et al 2008.

Cummings et al, 2013
Gradients?

100 MeV H vs time from Strauss et al. 2013.

Gradient ~0.5%/AU for ~60 AU after heliopause.

Note: Kota and Jokipii, 2014, dispute the Strauss et al. conclusion that there is a gradient beyond the heliopause.
Intensity vs distance in four GCR energy bands of H.

Fits are shown.
When will V2 reach the Heliopause?

May resolve some of these issues.

Most simple extrapolation:
If it is 10 AU closer (like the TS) would be at 111 AU;
V2 would cross in 1 year.
When will V2 reach the heliopause?

Extrapolation of the turning of the flow in the RT plane to 90° gives 2.5 years.

~2.5 years
Near HP when GCR intensity equals that at V1 GCR increase?

Several more years to heliopause?

(Figure from Stone and Cummings)

Other V1 precursors:

Increase in B
Increase in spectral index of energetic particles

But – don’t know if these were HP precursors or stagnation region signatures. V2 shows no signs of entering a stagnation region.
Summary

1. V1 and V2 heliosheath have very different flow patterns and electron profiles: these differences are not understood.

2. The heliopause structure is complex: V2 may help understand this region.

3. The interstellar medium is a very active region apparently driven by solar activity.

4. Have measured LISM CRS intensities down to a few MeV and for many species.
Very weak turbulence  \( SD(\delta B)/B_{\text{ave}} = 0.023 \)

- \( L_c = 100 \text{ pc} \)
- \( L_c = 1 \text{ pc} \)
- \( B_0 = 3 \times 10^{-6} \text{ Gauss} \)
- \( \langle \delta B \rangle^2 = B_0^2 \)
- \( V = 20 \text{ km/s} \)
- \( L_c = 10 \text{ pc} = 30 \times 10^{18} \text{ cm} \)

Burlaga, Florinski, Ness
Heliopause signatures: predicted at 135-155 AU
Galactic cosmic rays increase and heliosheath particles decrease.
Cosmic ray overview – Earth to the LISM

Is V2 rate since 2012 depressed by increased solar modulation?

Modulation 2000 thru 2005
Max modulation 2001 thru 2004
Voyager 2

\begin{center}
\begin{tabular}{|c|c|c|}
\hline
\textbf{\(T\) (K)} & \textbf{\(N\) (cm\(^{-3}\))} & \textbf{\(\text{IVI}\) (km/s)} \\
\hline
5.0 \times 10^5 & 0.001 & 120 \\
1.0 \times 10^5 & 0.002 & 140 \\
1.5 \times 10^5 & 0.003 & 160 \\
2.0 \times 10^5 & 0.004 & 180 \\
\hline
\end{tabular}
\end{center}
Electrons 0.04-1.5 MeV in the Heliosheath

- Electrons 40-70 keV at V1 (red), and 40-60 keV (blue) & 35-3500 keV (greens) at V2
- V1 measured pre-TS HS electrons bursts and relatively steady intensity in the HS (with a factor ~2)
- By contrast, V2 has measured 3-4 episodes of HS electrons
- In most recent V2 episode intensities continue to climb
Why isn’t V2 in the sectored region given the large “tilt angle” at the Sun? (Plus one might expect the sector zone boundary to be swept up to higher absolute latitudes.)
B has rotated after the HP and continues to move away from Parker (consistent with Opher et al. MHD model)
Several more years to heliopause?

2009 was solar minimum at V1

Now solar maximum at V2
Too Close

Too Far

Peak O$^+$ ACR Intensities
16–20 AU past shock

103-107 AU

114 – 117.5 AU

Where is the ACR source?

Figures from G. Gloeckler
V1 and V2 velocity (left axis is TS for both V1 and V2; flows at V1 and V2 are very different. V1 flows are derived from energetic particle (LECP) fluxes using the Compton-Getting effect assuming isotropic protons. V2 flows are measured directly by PLS.

V2 LECP and PLS speeds match well except in two time periods. In period A, VR from LECP is larger than for PLS. The plasma in this region may contain oxygen ions, which would give an overestimate of the speed. In region B, VT from LECP is too large; in this region they observe particle streaming along the magnetic field so the Compton-Getting requirement of isotropy is violated.

So LECP and PLS speeds generally agree at V2, so we expect the LECP V1 speeds are accurate.

(Richardson and Decker, 2014)
Magnetic Reconnection? (Opher, Drake, Lazerian)

HCS are compressed, Reconnection could Lead to formation of Magnetic bubbles and Particle acceleration.
Shifted V1 to match V2 TS crossing

>0.5 MeV; V1 decreasing for year prior to HP
V2 has increased over last year
~25 MeV electrons; V1 2+ years before HP
~270 MeV He; V1 4 months before HP
> 70 MeV ~1 year before HP
Voyager 2
Prime Observation that we’re trying to explain.

V1 particle data (blue): slowly varying flux.

V2 particle data (red): “Rapidly” varying flux with up to 2 order-of-magnitude change over $\sim 10^4$ range in rigidity from $\sim 50$ keV local $e^-$ to $>200$ MeV GCR protons.

- Why so different?
- Why do so many particles vary coherently?
- Is there a relationship to the global magnetic field structure.

Electrons 0.04-1.5 MeV in the Heliosheath
Voyagers 1 and 2: 
Launched Sept 5 and Aug 20, 1977: 
38 years old! 
At 133 AU and 109 AU 
(~18 and 15 light hours) 
We receive 8-12 hours of data/day 
Plasma data only from V2.