The Heliosphere’s interaction with the interstellar medium: Observations and Models

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and the Voyager team
Helio = Sun
The Local Bubble

Sun is inside a hot local bubble formed by supernova explosions 10-20 million years ago.

The bubble has small denser cooler clouds, perhaps breaking off the bubble boundaries. The Sun is in one of these smaller clouds.

Local Bubble and Loop I are Interacting Bubbles.
Interstellar medium: neutrals observed by IBEX
$V \sim 23.5$ km/s, $T \sim 6000$ K, $N_N \sim 0.2$ cm$^{-3}$, $N_e \sim 0.06$ cm$^{-3}$
INTERSTELLAR SPACE!!

Interstellar Medium

V1

Sun

Termination Shock

Voyager 2

Heliopause

THE HELIOSPHERE
Astrosphere from Hubble
Voyagers 1 and 2:
Launched Sept 5 and Aug 20, 1977:
36 years old!
At 124 AU and 102 AU (~17 light hours)
Voyager took the first picture of the Earth and Moon 11.6 million km away
The Grand Tour: A few stops on the way out
Io (Jupiter)
Most active volcanos:
1000 kg/sec of S and O
Portrait of the Solar System
Voyager 1, February 14, 1990
From 40 AU
NASA press conference, Sept. 12, 2013: V1 has entered interplanetary space!
Talk Outline

Voyager 1 has crossed the heliopause into interstellar space.

I will discuss briefly

1) The history behind the Voyager plasma experiment

2) Data showing the effects of the interstellar medium on the heliosphere

3) Data leading up to the announcement Voyager crossed the heliosphere.

4) Data that still puzzle us.
The Italian Connection
Bruno Rossi: 1905-1993

Started the cosmic ray and space plasma groups at MIT

PhD.: University of Bologna

1938: Left Italy: worked with Bohr, Compton, Bethe, Fermi

WWII: joined the Manhattan Project

1946: Back to MIT, founded Cosmic Ray Group, which was the forefather of the Center for Space Science at MIT and is now called the Kavli Center.
Developed Faraday Cup plasma probe with H. Bridge and made first solar wind measurements with Explorer 10 in 1961
Faraday cups of similar design have flown on many missions, including Voyager, and are still being flown on new missions such as Solar Probe Plus. Voyager 1 – broke n 1980, V2 – still working well.
Solar Wind Spectra from the Voyager Plasma experiment

abs0: MAXWELLIAN SIMULATION, V2 IN CRUISE ON 1977 243 1207:55.167

![Graphs showing solar wind spectra with channels for different elements: H+, He++, O6+.]
LIC neutrals are not bound by magnetic fields; some enter the heliosphere.

LIC H is tied to plasma via charge exchange.

Slowing of plasma and neutrals in front of the heliopause creates the hydrogen wall.

Mueller et al.
Interstellar neutrals dominate density outside ~10 AU
• Pickup ions dominate thermal pressure outside 30 AU
• First effects of LIC on solar wind are from these neutrals.

[Mewalt]
Interstellar Neutral Effects on the SW

• Solar Wind Slowdown
• Can determine slowdown at solar maximum or when two spacecraft are at the same heliolatitude
• \( \frac{dV}{V} = \frac{6}{7} \frac{N_{pu}}{N_{sw}} \)
Approach to the termination shock: V1 TS Foreshock

V1 - no plasma data;

We did not know TS location.

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

The V1 TS crossing at 94 AU revealed the spatial scale of the heliosphere.
Voyager 2 Termination Shock Crossings

![Graph showing Voyager 2 Termination Shock Crossings with axes for V, N, and T (K) and data points labeled SW, HSH, and HSH.](image)
Asymmetry Observed: V2 crosses the TS in Aug. 2007 at 84 AU

- V2 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

Richardson et al., 2008
Heliosphere simulation (Opher et al.)

Tilted LIC magnetic field with $B > 0.3$ nT gives N-S asymmetry

$B$ up, direction change at HP

Flow parallel to HP - $VR \sim 0$

Interstellar magnetic field

Opher et al. 2006

Acknowledg. Ed Stone
• ICME sheath geometry (Liu et al., 2006)
• Also observed in magnetosheaths
• Study of these asymmetries is a key part of the joint MIT – Politecnico di Torino project.
Heliopause Signatures

1) Radial speed goes to zero.
2) Heliosheath particles decrease
3) Galactic cosmic rays increase.
4) Magnetic field increases.
5) Magnetic field direction changes
6) Plasma density increases

Voyager 1 has observed 5 of these 6 signatures:
But NOT at the same time!
Heliosphere shields the solar system from cosmic rays
Voyager’s trip through the heliosphere (V2 data)

Heliopause:

\( V \sim \) constant
\( N \) up
\( T \) down
\( B \) up/tilt
ACRs down
GCRs up

\[ N = \frac{\text{cm}^{-3}}{\text{s}} \]

\[ V_R = \text{km/s} \]

\[ T = \text{K} \]

\[ |B| = \text{T} \]

Distance (AU)
Comparison to Simulations

Green: Model values from Borovikov et al. 2011

Black: V2 daily averages

Red: Smoothed V2 data

Blue: Corrected RT angles

Red line: V1 LECP (Decker)

RT angle larger than model

Model VR between V1 and V2
Krimigis et al. (2013)

Intensity decreased from early 2010 to dropout in 2012.

Radial speed near zero since early 2010 until dropout.

Other flow components also small.
Fig. 1 Overview of energetic particle observations at V1, 2012.35 to 2013.40, showing the contrary behavior of GCRs and lower-energy particles. (A) Hourly averages of GCR activity and the pronounced boundary crossing on 25 August 2012 (day 238).
Fig. 1 Relationship between the magnetic field intensity and the energetic particle counting rate. Hour averages of magnetic field strength $B$ (A).

Voyager 1, 2012

Heliopause signature:

4) Magnetic field increases
Fig. 2 High-resolution observations of the magnetic field strength and direction. 48-s averages of the magnetic field strength $B$ (A), azimuthal angle $\lambda$ (B), and elevation angle $\delta$ (C), as a function of time measured from DOY 150 to 270, 2012.

**Voyager 1, 2012**

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<td>45</td>
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**DOY, 2012**

Heliopause signature: 5) Magnetic field direction changes

**NOT OBSERVED**

Published by AAAS

L F Burlaga et al. Science 2013;341:147-150
Gloeckler et al.
Heliopause signature:

6) Plasma density increase

Plasma wave emission gives an electron density of 0.08 cm\(^{-3}\), value expected in LISM.

No particle or magnetic field signatures.

PWS data courtesy of D. Gurnett.
Densities are interstellar medium densities – so V1 crossed heliopause!
Voyager Captures Sounds of Interstellar Space
Plasma densities say V1 is in the interstellar medium.
Mysteries

1. Why didn’t the magnetic field change direction?
Mystery: 2. Why is the heliopause so close? 121 AU, only 27 AU from TS. Models predict 40-60 AU from TS.
Mystery: 3. Why are speeds at V1 and V2 so different?

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RT angle larger than model

Model VR between V1 and V2
One Solution? Florinski et al: Instabilities on the Heliopause
The Future

• Sufficient power until the year 2025
• Voyagers will then wander the Milky Way
  – Voyager 1 within 1.6 light years of the star Gliese 445 in 40,000 years
  – Voyager 2 within 1.7 light years of Ross in 40,000 years
Where next? Ross 248

A nearby red dwarf, 10 light years away, in the constellation Andromeda
Summary

• After 35 years, Voyager 1 has left the heliosphere and is in the interstellar medium.
• Many puzzles still remain about the location, magnetic field direction, and plasma flows.
• Voyager 2, with a working MIT plasma experiment, will help resolve these issues.
• Voyager continue sending data until 2025.
• THANK YOU!!
Wideband spectrograms

5.62 kHz

3.11 kHz

1.78 kHz

Electric field amplitude (V/m)

Time (day of year) 100 110 120 130 140

3 hours

Voyager 1, 2013, R = 124 AU, H-Lat = 34.6°, H-Long = 174.2°
Charge exchange: ion and neutral collide and ion takes an electron. $H^+ + H \rightarrow H + H^+$

New neutral H moves with plasma speed

New $H^+$ is accelerated to plasma speed and has initial thermal energy equal to the plasma energy (1 keV in solar wind): is called a pickup ion.

The energy/momentum come from plasma flow, so plasma slows down.
V2 flow more in T than N direction.
Initially due to TS shape (blunter in T than N)
So Heliosphere is squashed, blunt, and asymmetric.
What is an Astronomical Unit (AU)?

Distance between Sun and Earth

~150 million kilometers
Or ~8.3 light minutes