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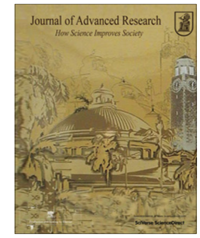


**REVIEW**

# Voyager observations of the interaction of the heliosphere with the interstellar medium

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**Abstract** This paper provides a brief review and update on the Voyager observations of the interaction of the heliosphere with the interstellar medium. Voyager has found many surprises: (1) a new energetic particle component which is accelerated at the termination shock (TS) and leaks into the outer heliosphere forming a foreshock region; (2) a termination shock which is modulated by energetic particles and which transfers most of the solar wind flow energy to the pickup ions (not the thermal ions); (3) the heliosphere is asymmetric; (4) the TS does not accelerate anomalous cosmic rays at the Voyager locations; and (5) the plasma flow in the Voyagers 1 (V1) and 2 (V2) directions are very different. At V1 the flow was small after the TS and has recently slowed to near zero, whereas at V2 the speed has remained constant while the flow direction has turned tailward. V1 may have entered an extended boundary region in front of the heliopause (HP) in 2010 in which the plasma flow speeds are near zero.



## Introduction

The matter between stars, the interstellar medium, varies considerably from region to region in our galaxy. The Sun is inside a very large structure called the local bubble, a region of hot tenuous gas formed by supernova explosions tens of millions of years ago [1–3]. Adjacent to the local bubble is a similar but larger bubble, also formed from supernova explosions. Inside the local bubble are smaller, denser clouds which may have broken off from the bubble interaction region. The Sun is now in one of these denser, cooler clouds. The H density of the local cloud is about 0.2 $cm^{-3}$, the temperature is about 6000 K, and the cloud moves about 23 km/s with respect to the Sun [4,5]. The magnetic field strength cannot be directly measured, but based on models is 3–5 nT [6,7].

The Sun is the source of the variable solar wind, with speeds measured near Earth ranging from 250 to 2200 km/s, proton densities from 0.01 to $>100$ $cm^{-3}$, and an average magnetic field strength of 5 nT. Since the solar wind and local interstellar medium (LISM) plasmas are both magnetized, they cannot mix, so the LISM flows around the heliosphere. The boundary between the LISM and solar wind is the heliopause (HP), analogous to Earth's magnetopause. Since the solar wind is supersonic, a shock (called the termination shock) forms upstream of the HP. At the TS, the solar wind becomes subsonic and be-

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gins to turn toward the heliotail, the stretched-out downstream region analogous to Earth's magnetotail. If the LISM were supersonic, a bow shock would form in the LISM upstream of the HP, but recent data and analysis suggest that the LISM flow is subsonic and thus the heliosphere does not have a bow shock [5].

Voyagers 1 and 2 were launched in 1977 and are now exploring the interaction between the LISM and the solar wind. They both have crossed the TS and are in the region of shocked solar wind between the TS and the HP that is called the heliosheath. In late 2011 V1 was 119 AU from the Sun and V2 was 97 AU, moving outward at 3.5 and 3.1 AU/yr, respectively. This paper reviews the observations made by these spacecraft as they enter unexplored regions of space.

## Pre-termination shock

The first observed influence of the LISM on the solar wind was from the LISM neutrals.

The neutrals are unaffected by the magnetic fields and flow into the heliosphere, where they are ionized in the solar wind and form hot, $\sim$1 keV, pickup ions. These pickup ions dominate the thermal pressure outside about 30 AU and play a major role in pressure balance structures outside this distance [8]. Accelerating the pickup ions to 1 keV slows the solar wind; this slowdown was first observed near 30 AU and by 80 AU the solar wind had slowed by about 20% [9]. Some of the energy from the pickup ions is transferred to the thermal protons, causing the temperature of the solar wind to increase with distance [10].

About 2.5 years before each TS crossing, the Voyagers detected a new energetic particle component with proton energies of tens of keV to tens of MeV flowing along the magnetic field lines [11,12]. This new particle component, called termination shock particles, signified that the Voyagers were entering a region analogous to Earth's foreshock, with particles accelerated at the TS streaming into the heliosphere along the magnetic field. For these particles to be observed, the TS distance had to be further at the flanks than at the nose so that magnetic field lines at the Voyagers would also pass through the TS. Thus the TS must be blunt, or flattened, in the nose direction [13]. The bluntness alone could not account for all the particle observations; an additional asymmetry in the heliospheric boundaries due to the interstellar magnetic field was also required [14].

## Termination shock

The realization that the supersonic solar wind must go through a termination shock to become subsonic was first reported by Parker [15]. The location of this shock is determined by the HP location and the upstream plasma parameters. The HP forms where the solar wind dynamic pressure is balanced by the total LISM pressure; the value of the LISM pressure is not well determined The distance to the TS, and thus the scale size of the heliosphere, were determined when V1 crossed the TS at 94 AU in 2004 [12,13,16].

Voyager 2 trails V1 by about 20 AU. It crossed the TS in 2007 at 84 AU [17–20], 10 AU closer than V1. Calculations of the TS motion based on changes in the solar wind dynamic pressure suggested that TS motion was responsible for only 2–3 AU of the distance change [17]. Thus the heliosphere is asymmetric, with the TS closer in the V2 than V1 directions. Models of the interaction of the heliosphere with the LISM show that an asymmetry occurs if the LISM magnetic field is tilted from the LISM flow direction and has a magnitude of $>3$ nT [3,4]. If these conditions held, the magnetic field would drape around the heliosphere so that the magnetic field strength builds up outside the southern part of the heliosphere, and the increased magnetic pressure would push the boundaries of the southern heliosphere inward.

The TS crossing provided other surprises as well. The TS was a weak shock, with a compression ratio close to two. At Voyager 2, the speed decrease started about 80 days before the TS crossing as the speed went from 400 to 300 km/s in three discrete steps [17]. The last step coincided with a sharp gradient in the energetic particle pressure, with the inward pressure gradient force large enough to produce the observed slowdown [21]. At the V2 TS (V1 does not have a working plasma instrument), the speed decreased from 300 to 150 km/s, the density and magnetic field increased by a factor of 2, and the ion temperature increased by a factor of 30.

A major surprise (but see Zank et al. [22]) was that the heating of the thermal ions was much less than the decrease in the flow energy. Thus the flow energy had to go somewhere else. About 15% went to heating the energetic (tens of keV) ions, but the majority seems to have gone into heating the pickup ions [17], which are not directly observed.

The TS was the source of the low-energy particles observed in the foreshock; the intensities of these particles peaked at the TS [12,19]. However, the anomalous cosmic ray (ACR) intensities did not peak at the TS as expected, at least not where crossed by V1 and V2 [12,19]. ACRs are singly ionized particle with 10–100 MeV/nuc; they were observed first near Earth and their origin was thought to be pickup ions formed from LISM neutrals which were then accelerated at the TS. Thus a peak in the ACR intensity was expected at the TS. The ACR intensity did not increase at the TS; no evidence an ACR source at the TS was observed at either of the Voyager crossing locations.

## Heliosheath

The heliosheath was thought to be, in analogy with planetary magnetosheaths, a highly turbulent region and this expectation has been correct [23–25]. Figs. 1 and 2 show the daily average plasma parameters obtained by fitting the observed spectra to convected, isotropic proton distributions. The broad envelope of the data and the 25-day running averages that are superposed show consistent trends. However, the individual sets of spectra very greatly on time scales of tens of minutes. The magnetic field also varies by factors of 2–3 over similar time scales [24], confirming the very dynamic and turbulent nature of this region. Although these fluctuations are large, they contain very little of the energy [25]. As V2 moves deeper into the heliosheath, these fluctuations decrease slowly in magnitude but remain significant.

By the end of 2011, V2 was 14 AU past the TS crossing distance of 84 AU. Models suggest that the TS has moved inward 8 AU since the TS crossing due the very low solar wind dynamic pressure during the recent solar minimum [26]. Thus V2 is about 22 AU deep into the heliosheath. The expectation was that the plasma speed would decrease across the heliosphere and the flow direction would turn tailward. Fig. 1