Voyager Observations in the Heliosheath: A Quasi-Stagnation Region Beyond 113 AU

E. C. Stone, A. C. Cummings

California Institute of Technology, Pasadena, CA 91125 USA

Abstract: Voyager 1 at 119 AU and Voyager 2 at 97 AU are exploring deep within the heliosheath where the interaction between the solar wind and the local interstellar medium becomes increasingly complex. Voyager 1 recently encountered a region where the wind has slowed as it approaches contact with the heliopause. Energetic protons accelerated at the termination shock diffuse along the spiral magnetic field as they are convected outward with the subsonic solar wind. The resulting anisotropy in the intensity provides a measure of the convective flow and field-aligned diffusive flows. Measurements by the Low Energy Charged Particle instrument indicate that the radial flow speed that was \( \sim 55 \text{ km s}^{-1} \) in mid-2007 had decreased to \( \sim 0 \text{ km s}^{-1} \) by April 2010 when Voyager 1 was at 113 AU. The longitudinal speed also decreased in late 2010, suggesting the flow turned northward. However, observations by the Cosmic Ray Subsystem reveal that the northward speed that was \( 75 \pm 9 \text{ km s}^{-1} \) on day 215 of 2007 also decreased to an average speed of \( 28 \pm 3 \text{ km s}^{-1} \) during the period from day 2010/126 through 2011/308. This indicates that the flow was not deflected northward, but had slowed, forming a quasi-stagnation region from \( \sim 113 \) to beyond 119 AU. Models suggest that the transient presence of such regions may be produced by variations in the dynamical pressure associated with Merged Interaction Regions or with the eleven-year cycle of high speed winds at higher latitudes.

Key words: solar wind, termination shock particles, Voyager

1 Introduction

Termination Shock Particles (TSPs) are accelerated at the termination shock and convected outward in the heliosheath by the flow of the subsonic solar wind. The solar wind instrument on Voyager 1 (V1) is not operational, but it is possible to estimate the flow speed from the resulting anisotropy observed in the TSP intensity. The Low Energy Charged Particle (LECP) instrument [1] has a low energy telescope mounted on a rotating platform, allowing the determination of the angular distribution of TSPs in approximately the \( R-T \) plane (\( R \) is the outward radial direction, \( T \) is parallel to the solar equator and in the direction of solar rotation; \( N \) completes the \( RTN \) coordinate system). LECP uses the Compton-Getting effect (see, e.g., [3]) to determine flow speeds from the observed anisotropy, \( \delta \), as given by \( \delta = -2(1-\gamma)V/v \), where \( V \) is the convection velocity, \( v \) is the speed of the energetic ions, and the spectral index \( \gamma \) is \( \frac{d\ln j}{d\ln E} \) [4, 5].

Using this technique, [2] reported that the radial solar wind speed \( V_R \) had decreased from \( \sim 55 \text{ km s}^{-1} \) in mid-2007 to \( \sim 0 \text{ km s}^{-1} \) in April 2010 (Figure 1). During most of this time the tangential speed \( V_T \) was \( \sim -40 \text{ km s}^{-1} \), decreasing to \(-10 \text{ to } -20 \text{ km s}^{-1} \) by late 2010. The question was whether the flow had been deflected in the \( N \)-direction as was expected to occur as the solar wind approached the heliopause.

We address that question with data from the Cosmic Ray Subsystem (CRS) instrument [6] on Voyager 1.

2 Observations

Using the CRS Low Energy Telescopes (LETs) it is possible to determine the anisotropy in the \( T-N \)

1) E-mail: ecs@srl.caltech.edu

DOI: 10.7529/ICRC2011/V12/106

Fig. 1. Twenty-six day averages of the inferred radial solar wind speed in the Sun-fixed reference frame from the LECP instrument [1]. (Adapted from [2].)

Fig. 2. The Voyager spacecraft and the RTN coordinate system. The spacecraft is normally oriented in a fixed attitude with the high gain antenna pointed towards Earth. From a distance of 100 AU, the direction of the antenna axis differs by less than a degree from the −R axis that points toward the Sun. About every two months the spacecraft is rolled about the antenna axis, allowing the CRS Low Energy Telescopes to measure the anisotropy in the T−N plane. During rolls of the Voyager spacecraft that occur approximately every two months for calibration of the magnetometer. Each set of rolls lasts 20,000 s, corresponding to 10 complete rolls about the spacecraft axis that is pointed at Earth (Figure 2). During the rolls LET-A, LET-B, and LET-D telescopes on CRS measure the variation of the counting rates of their front (L1) detectors, each with a geometry factor of 4.75 cm$^2$ sr, an acceptance angle of 120°, and a time resolution for LET-A of 48 s that corresponds to a rotation of 8.64° in the T−N plane. Until 2011 day 217 the LET-B and LET-D telescope rates were sampled at a frequency of one 48 s period out of 16. For the roll on 2011 day 217 and thereafter all three telescopes are in the high time resolution mode during the rolls. The counting rates are dominated by protons with energies between 0.5 and 35 MeV.

An example of the L1 intensity variation in LET-A for a set of 10 rolls on day 264 of 2007 is shown in Figure 3 in which the individual rolls are apparent. The lower panel of Figure 3 shows the combined data from all ten rolls as a function of the roll angle $\theta$, where $\theta$ is the telescope boresight angle counterclockwise from $N$ in the $T−N$ plane as viewed from Earth. The best fit of the function

$$I/I_0 = 1 + \delta \cos(\theta - \theta_0),$$

yields a first-order anisotropy of $\delta = 0.025 \pm 0.002$ in a direction of $\theta_0 = 129° \pm 5°$.

Fig. 3. The variation of the LET-A counting rate of mainly 0.5 to 35 MeV protons during the ten spacecraft rolls on day 264 of 2007. The points plotted in the upper panel are five-day moving averages and the solid lines in both panels are a best fit of $I_0(1+\delta \cos(\theta-\theta_0))$ to the individual 48-second data points without averaging. The $N$-axis is at 0° and the $T$-axis at 90°.

In Figure 4, the ten rolls in a given day have been averaged over 30° of rotation in the T-N plane to further reduce the statistical uncertainty. The anisotropy of 2.5% in 2007 decreased to less than 0.5% in 2011, indicating that the speed in the T−N plane did not increase as $V_R$ decreased. So, rather than turning northward, the solar wind in the heliosheath slowed down.

Vol. 12, 30
Fig. 4. The LET-A counting rate of mainly 0.5 to 35 MeV protons averaged in 30° sectors over 10 rolls on the indicated days. The solid lines are fits of $I_0(1 + \delta A \cos(\theta - \theta_0))$ to the sectored rates. The best fit anisotropy $\delta A$ is shown in the lower left corner of each panel and the factor for converting the anisotropy to a convective speed is shown in the upper right, including a 20% correction for the 120° opening angle of the telescope aperture.

If the anisotropies are due to convection, then the convection speed is given by $V = -1.2K_{CG} \delta$, where $K_{CG} = \langle v/(2(1-\gamma)) \rangle$ is averaged over the observed proton spectrum between 0.5 and 35 MeV. As the spectrum evolved from 2007.5 through 2011, $K_{CG}$ increased from $\sim 3200$ to $\sim 4700$ km s$^{-1}$. The factor of 1.2 corrects for the reduction in the observed anisotropy that is produced by the wide acceptance angle of the LET L1 detectors of 120°. As a result, the typical 1σ statistical uncertainty in $\delta$ of $\pm 0.002$ corresponds to a speed uncertainty of $\pm 8$ to $\pm 11$ km s$^{-1}$.

Using fits to data from all three telescopes and with the radial solar wind speed from the LECP (Figure 1), the convective speeds for $V_T$ and $V_N$ were derived for the rolls during the period from mid-2007 through the end of 2011 and are shown in Figure 5, along with $V_R$ and $V_T^*$ determined by [2]. Differences between CRS and LECP determinations for the $T$ component of the flow are partly due to the LECP scan plane being tilted 20 degrees from the $R-T$ plane (hence the LECP designation of $T^*$). Differences might also be expected because the CRS estimates are averaged over 20,000 s while the LECP estimates are averaged over 26 days. In addition, the speed of $\sim 2$ MeV protons that is typical for the CRS rate is $\sim 5$ times that of the 53 to 85 keV protons for the LECP rate, meaning that for a given convective speed $V$ the Compton-Getting anisotropy in the CRS rates will be smaller by a similar factor. As a result, the CRS rate could be more affected by the presence of diffusive flows.

The magnetic field is on average aligned with the $T$-axis, so field-aligned flows would have a larger effect on the CRS estimates of $V_T$ data. The larger $V_T$ estimates from CRS and their variability shown in Figure 5 may be evidence of episodic field-aligned flows, usually in the $-T$ direction, as would be consistent with a source in the $+T$ direction as suggested by [7] and also by [8, 9].

In contrast, the estimates of $V_N$ are unidirectional and typically smaller and less variable, consistent
with smaller contributions from field-aligned flows as would be expected. On day 215 of 2007 $V_N$ was $75 \pm 9$ km s$^{-1}$ and gradually declined until late in 2009. For the period from April 2010 through 2011, when $V_R$ was $\approx 0$ km s$^{-1}$ or less, the average $V_N$ was $28 \pm 3$ km s$^{-1}$ with an rms variation of 11 km s$^{-1}$. The average of the speed in $T-N$ plane was $V_{TN} = 45 \pm 3$ km s$^{-1}$, with an rms variation of 15 km s$^{-1}$. So, the flow has not been deflected in either the $N$ or $T$ directions, but has formed a quasi-stagnation region with relatively slow residual speeds in the $T-N$ plane. Voyager 1 entered the quasi-stagnation region in April 2010 at 113 AU and was still in it at the end of 2011 at 119 AU (Figure 6).

![Image of the location of the stagnation region observed by Voyager 1 at 35° north latitude. This may be a transient feature in a localized region.](image)

Fig. 6. Illustration of the location of the stagnation region observed by Voyager 1 at 35° north latitude. This may be a transient feature in a localized region.

3 Discussion

When Voyager 1 was at $\sim 103$ AU on day 215 of 2007, the solar wind speed in the heliosheath was $\sim 120$ km s$^{-1}$ and all three components of the solar wind velocity began decreasing (Figure 5) as the wind slowed rather than being deflected by the approach to the heliopause. However, only the radial speed $V_R$ slowed to $\sim 0$ km s$^{-1}$ while the tangential and northward speeds remained non-zero through 2010. There was no significant change in $V_N$ during 2011, but the estimated $V_T$ became erratic, possibly the result of field-aligned diffusive flows of the TSPs. The lack of radial flow combined with reduced but non-zero tangential and northward flows suggests the presence of a quasi-stagnation region from $\sim 113$ AU to beyond 119 AU.

A quasi-stagnation region where the northward and southward heliosheath diverge is a feature near the heliospheric equator of MHD models, but not at the latitude of Voyager 1 at 35° north. However, dynamical models show that such regions can occur at higher latitudes due to merged interaction regions that propagate into the heliosheath [10] or due to variations in solar wind speeds over the eleven-year solar cycle [11]. The quasi-stagnation regions are transient features with radial scales of 10 to 20 AU, so it will be important to observe the evolution of the quasi-equilibrium region as Voyager 1 approaches the heliopause over the next several years.

Acknowledgements

We appreciate the efforts of N. Lal in providing the high-time resolution counting rate data in an easy to use format. This work was supported by NASA under contract NAS7-03001.

References