Plasma flows in the heliosheath

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[1]   Voyager 2 is making the first plasma measurements in the heliosheath. The radial flow speeds in the heliosheath vary between 80 and 200 km/s with an average speed of 138 km/s. The flow in the T (azimuthal) direction is fairly constant and averages about 48 km/s; the flow direction is consistent with flow away from the heliospheric nose. Flow in the N (meridional) direction is also away from the nose and averages −14 km/s. These flows suggest that the shock is blunter in the T than in the N direction, so that the heliosphere is wider than it is high. The flow in the RN plane has quasi-periodic oscillation with a period of 110 days and an amplitude of 21 km/s. The oscillation in flow angle is about $6°$ in the RN plane and $17°$ in the TN plane and may result from periodic variations of the termination shock normal direction. **Citation:** Richardson, J. D., E. C. Stone, J. C. Kasper, J. W. Belcher, and R. B. Decker (2009), Plasma flows in the heliosheath, *Geophys. Res. Lett.*, *36*, L10102, doi:10.1029/2009GL038421.

1.   Introduction

[2]   Voyager 2 (V2) crossed the termination shock (TS) in 2007 [*Burlaga et al.*, 2008; *Decker et al.*, 2008a; *Richardson et al.*, 2008a; *Stone et al.*, 2008] and entered the heliosheath, the region of shocked solar wind between the TS and heliopause. The solar wind plasma is slowed, compressed, and heated at the termination shock and begins to turn toward its eventual path down the heliotail. V2 observed a relatively weak, quasi-perpendicular TS with a shock strength of about 2 [*Richardson et al.*, 2008a; *Burlaga et al.*, 2008]. The speed decreased from 400 to 300 km/s before the TS, then fell by a factor of 2 at the TS crossing. The non-radial flow components were oriented away from the nose of the heliosphere.

[3]   The heliosheath is the largest sheath region observed in situ, a factor of 1000 thicker at the nose than Jupiter's magnetosheath. The longest encounters with planetary magnetosheaths are of order a few days; the Voyagers are expected to remain in the heliosheath for 10 years or more. The planetary bow shocks and magnetopauses are in constant motion; changes in the magnetosheath boundary positions comparable to the scale of the system occur on time scales of hours. Thus the magnetosheath plasmas are constantly affected by the boundary motions. The helio-sheath boundaries move in response to large MIR driven shocks and to solar cycle changes in solar wind pressure, but these motions are small compared to the size of the heliosheath. Thus the Voyagers provide the opportunity to study a sheath relatively unperturbed by boundary effects.

[4]   Voyager 1 does not have a working plasma instrument. The Low Energy Charged Particle (LECP) 40–220 keV ion data provide estimates of the Voyager 1 (V1) plasma speeds in the heliosheath in the R and T directions using the Compton-Getting effect [*Decker et al.*, 2005]. We use the RTN coordinate system to look at the physics of the plasma flows since the solar equator is the natural symmetry plane in the solar wind. Figure 1 shows a schematic diagram of the RTN coordinate system, in which R is radially outward, T is a plane parallel to the solar equator and positive in the direction of solar rotation, and N completes a right-handed system. If one looks outward along the solar equator toward the longitude of the inflow direction of the local interstellar medium (roughly the heliospheric nose position) at heliographic inertial (HGI) longitude $178°$, then the Voyager spacecraft are roughly at the positions shown. V1 is about $6°$ in heliolongitude in the −T direction from the nose of the TS and V2 is about $38°$ from the nose in the +T direction. The interstellar medium inflow is from a heliolatitude about $5°$N; both V1 and V2 are at significant heliolatitudes, V1 at $34°$N and V2 and $28°$S.

[5]   *Decker et al.* [2005, 2008b] found that the radial speed in the heliosheath was about 100 km/s after the V1 TS crossing, became small and sometimes inward for 0.4 year, and then from 2005.5 to 2008 averaged 67 ± 16 km/s. The T component of the velocity averaged -42 ± 15 km/s from 2005.5 to 2008, for a total flow speed in the RT plane of 91 ± 19 km/s. The LECP sensor orientation does not allow the LECP team to determine the speed in the N direction. *Decker et al.* [2008b] also report that the flow angle in the RT plane is rotating as V1 moves across the heliosheath in a direction consistent with plasma turning to go down the heliotail. Voyager 2 has an operational plasma instrument which is observing the heliosheath plasma. This paper describes the flow of plasma observed by the Voyager 2 plasma experiment in the heliosheath.

2.   Instrument and Analysis

[6]   The Voyager plasma experiment (PLS) observes ions and electrons with energies from $10–5950$ eV in four modulated-grid Faraday cups [*Bridge et al.*, 1977]. Three of these cups are arranged around a cone whose central angle points toward Earth, roughly into the direction of the heliosheath flow. The most useful heliosheath PLS data are the lower-energy resolution L-mode spectra, which have an energy resolution $\Delta E/E$ of 29% and a time resolution of 192 s. The electrons in the heliosheath have energies below the 10 eV threshold of the instrument and are generally not observed.

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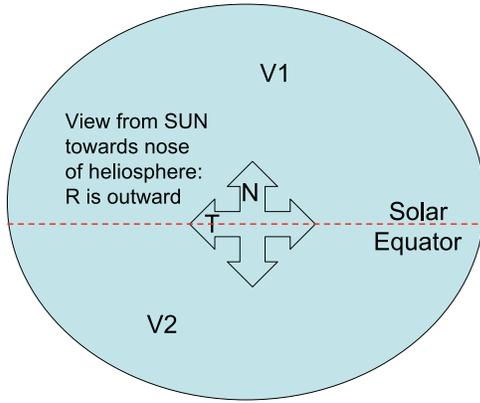[4]Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, USA.

Figure 1. Schematic diagram of the heliosphere looking outward from the Sun toward the longitude of the heliospheric nose showing the directions of the R and T axes, the location of V1 and V2, and the shape of the TS.

[7] The Faraday cups measure the reduced 2-D distribution functions of the heliosheath at different angles, so when signal is obtained in three cups the full vector velocity can be derived. We fit the observed currents with convected isotropic Maxwellian proton distributions. The instrument is sensitive to only the perpendicular temperature in the heliosheath since the magnetic field is azimuthal and the detectors look in the −R direction (toward the Sun), so temperature anisotropies would not affect the analysis. Instrument noise, low densities, and unfavorable flow directions (i.e., sunward flows) limit the number of spectra which can be analyzed. We are able to determine vector velocities for about 15%, or 9,000, sets of heliosheath spectra through day 335 of 2008.

3. Results

[8] Figure 2 shows daily averages of the three components of the plasma velocity starting on day 250 of 2007. V_R has substantial variations from 70 km/s near day 320 to 230 km/s in the transient event near day 590, and approaches 200 km/s several other times. The average radial speed is 138 km/s, roughly twice as large as the speed observed by the LECP instrument by V1. V_T increases from about 25 km/s near the TS to a nearly constant value of about 50 km/s after day 290 (except for the large transient near day 590). The average value is about 48 km/s, comparable to the values observed on V1. V_N has an average value of −14 km/s and shows a quasi-periodic variation in speed. The top panel also shows the V2 radial speeds determined from the LECP data through day 480. These data track the plasma data very well; peaks and valleys tend to have higher amplitudes in the LECP data but the average V_R, 127 km/s, is very close to the value determined by the plasma instrument. This comparison gives us confidence the speed values determined by LECP at V1 using the same technique are also correct.

[9] Figure 3 shows the velocity magnitude |V| and the flow angles in the RT, RN, and TN planes with sine wave fits to the RN and TN data superposed. The average of |V| is 152 km/s. The flow angle in the RT plane has an average and median of about 20° and is fairly constant across the

heliosheath. The oscillations in the flow angles are shown in the bottom two panels. The RN angle has a median and average of about −6° and this average angle is relatively constant. This angle varies quasi-periodically and can be fit with a sine wave with a period of 110 days and an amplitude of 8°. The TN plane angle shows more dramatic oscillations, with an average angle of −15° and a median of −17°. The best fit sine wave has a period of 110 days and amplitude of 17°.

[10] Figure 4 shows periodograms of the power in the heliosheath plasma parameters. The largest relative power is in V_T with a peak near 112 days, with a smaller peak with the same period evident in V_R. The peak in the thermal speed W is at a 10-day shorter period and inspection of the data indicates it is unrelated to the speed changes. No significant power is observed in V_T or the density.

4. Discussion

[11] The plasma flow data from the heliosheath have produced two unexpected results. The first is that the V2
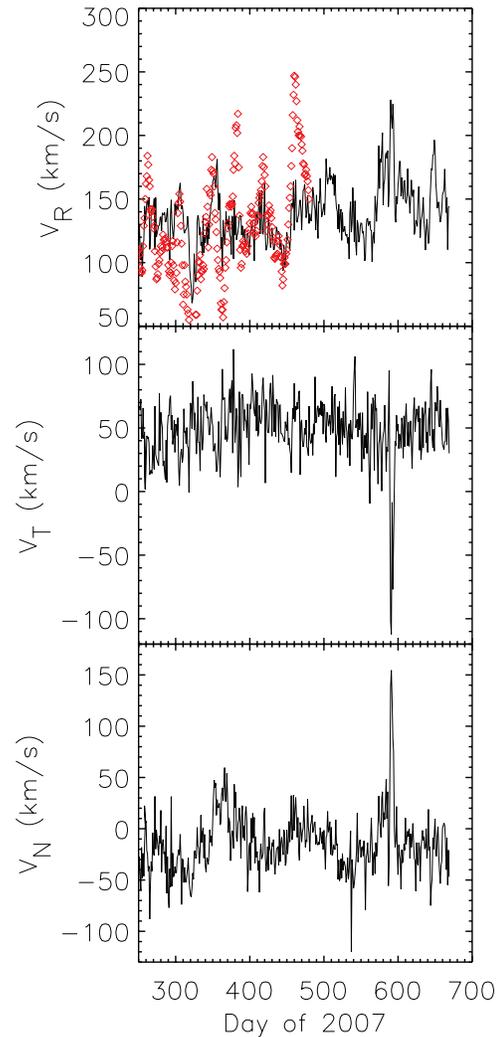

Figure 2. Daily averages of the three velocity components derived from the plasma data in the heliosheath. The diamonds in the top plot show V_R values derived from LECP data.
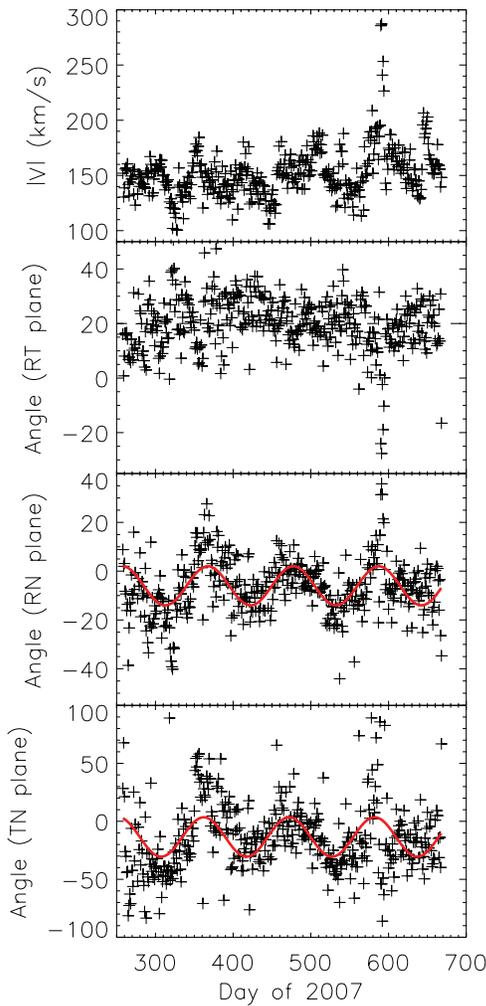
Figure 3. Daily averages of the speed ($|V|$) and flow angles in the RT, RN, and TN planes. A sine wave fit to the data is shown on the RN and TN plots.

radial speeds are much larger than those observed by V1. The second is the quasi-periodic oscillation of V_N and (to a lesser extent) of V_R.

[12] The average V2 radial speed is about twice that observed by V1. The V1 speeds are derived from LECP measurements of energetic particle fluxes with energies of tens of keV [*Decker et al.*, 2005]. These results are sensitive to gradients in the particle intensities. Figure 2 and Table 1 show that the speeds at V2 derived by LECP and those measured by the PLS instrument are comparable, so the differences in the measurement techniques are probably not responsible for the speed discrepancy. V_N is not known at V1, but V_T at V1 is comparable to that observed at V2 (but in the opposite direction, as expected since it is on the opposite side of the nose of the heliosphere). Models do not predict that the radial speeds would be very different at V1 and V2 [see *Zank*, 1999] and we do not understand these differences.

[13] The component of the flow perpendicular to the shock normal does not change across a shock. Since the velocity component parallel to the normal decreases in magnitude, the flow angle increases. The plasma beta in
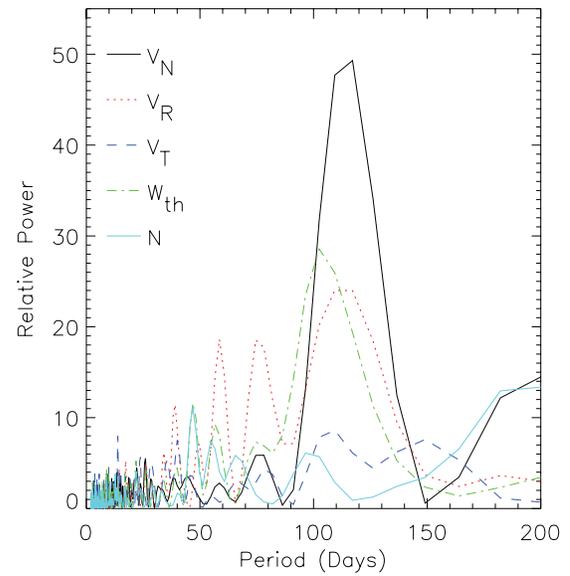

Figure 4. Periodogram of the relative power of plasma parameters V_R, V_R, V_N, $|V|$, W (thermal speed), and N (density) in the heliosheath. The most power is in V_N with a peak between 110 and 120 days.

the heliosheath is high, so the plasma drives the flow and carries the magnetic field.

[14] In the solar wind, the observed non-radial flows are small in the outer heliosphere. Most of the non-radial flow observed just after the TS crossing is probably generated by the angle of the TS to the solar wind flow. The TS is blunt [*Zank*, 1999; *Jokipii et al.*, 2004; *Opher et al.*, 2007], so the radius of curvature is larger than that of a similar size circle. A radially outward solar wind flow thus has a velocity component perpendicular to the TS normal and directed away from the nose of the heliosphere. For a 300 km/s solar wind, a TS normal in the RT plane about 20° from radial would give the 42 km/s (V1) and 48 km/s (V2) V_T components observed. The value of V_T for the 30 days immediately after the V2 TS crossing was about 25 km/s; if that value reflected the shock deflection, then the TS normal would point about 10° from radial. An average TS normal angle in the RN plane of about 5.5° would give the observed V2 V_N flow.

[15] These heliosheath plasma velocities serve as a remote sensor of the TS shape. The flow angles are larger in the RT than RN plane, so the TS is more blunt in the RT than RN planes. Figure 1 shows that the TS shape, when viewed from upstream in the interstellar medium, is a flattened disk, wider in the RT plane than in the RN plane.

[16] A few flow periodicities have been observed or predicted in the solar wind or heliosheath. A meridional flow

Table 1. Heliosheath Flows (405 Points): The Uncertainties in the PLS Values are the Standard Errors of the Mean[a]

Parameter	V1 (LECP)	V2 (PLS)
V_R (km/s)	67 ± 16	138 ± 1
V_T (km/s)	−42 ± 15	48 ± 1
V_N (km/s)		−14 ± 1
RT angle	−32°	20 ± 0.4°
RN angle		−6 ± 0.5°

[a]The transient near day 590 has been removed.

variation with a period of roughly a solar rotation (25 days) was reported in the last two solar minima [*Richardson and Paularena*, 1996; *Burlaga and Richardson*, 2000], but this period is much shorter than the 110-day period reported here. *Borovikov et al.* [2008] predict heliosheath flow deflections could be caused by HP instabilities, but the magnitude of their predicted fluctuations is small (1°) and the period is also too short (30–45 days).

[17] The flow angle in the RN plane was fit with a sine wave with an 8° amplitude; if this angle variation results from quasi-periodic changes in the TS normal, the TS shock normal angle would have to vary between 0.5 and 6.5° in the RN plane. The lower envelope of the RN angle data is about −25°, which would be produced by a shock normal angle of −11.5° and the upper envelope of about 15° would require a shock normal angle of 6.9°. Thus if the RN plane flow angles result from deflection at the TS, they imply a sinusoidal oscillation of the TS normal in the RT plane with a period of 110 days and an amplitude of 3.5°, but excursions in angle of thrice that amount.

[18] What produces the 110-day quasi-periodicity in the flow angle (and in the TS angle if that were the cause of the flow changes)? In the RT plane, the solar rotation smooths out longitudinal variations in the solar wind source. Helio-latitudinal variations in the source can persist to the outer heliosphere and cause the TS shape to change (for example, if polar coronal holes increased the dynamic pressure at high-latitudes, the TS might become more blunt). We have looked at the tilt angle of the heliospheric current sheet (HCS) in this time period and find periodicities of 150 days, too long to explain the V2 observations. Similarly we looked at coronal hole boundaries and the solar wind observed at 1 AU and found no evidence of a 110-day period. If the source of the periodicity were the upstream solar wind the cause is not obvious.

[19] The fast mode speed in the heliosheath is probably determined by the pickup ions, which have a density of about 20% of the total plasma density and a temperature of about 6 keV [*Richardson et al.*, 2008a, 2008b; *Richardson*, 2008]. If the average heliosheath magnetic field were 0.2 nT, the fast mode speed would be about 900 km/s, or slightly faster than 2 AU/day. For a heliosheath width of 30 AU this would give a round trip wave time of about 110 days. We do not know if this wave reflection could/would translate into a periodic motion of the TS in the RN plane. Several modes could produce these TS angle changes. The whole helio-sphere could rotate up and down, or waves could move along the shock surface, or the TS could change shape. Without understanding the driving force it is hard to distinguish between these possibilities.

5. Summary

[20] V2 PLS observations of the plasma flow in the heliosheath show that the radial speeds are significantly higher (by a factor of 2) than those observed by V1. This large difference is not predicted by models and is not yet understood.

[21] The V_N component has a quasi-periodic oscillation with a period of about 110 days and amplitude of 20 km/s above and below the baseline of −13 km/s. These speeds give flow angle oscillations of 8° about the baseline of −6°

in the RN plane and of 15° about the baseline of about −14° in the TN plane. V_T and the flow in the RT plane are fairly constant. A quasi-periodic oscillation of the TS angle in the RN plane of about 3.5° could account for this flow oscillation. We do not know what drives this oscillation.

[22] If we assume that the flow deflection observed near the TS results from deflection at the TS, then the flows can be used to determine the shock shape. The TS is more blunt in the RT plane than in the RN plane, giving a heliosphere which is wider (in the longitudinal direction) than it is tall (in the latitudinal direction). This prediction will tested by the Interstellar Boundary Explorer (IBEX).

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