Plasma and Variability in the Heliosheath

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Abstract. Voyager 2 (V2) is making the first direct plasma measurements of the heliosheath and is moving outward about 3 AU/yr. This paper has two foci. It provides an update on plasma conditions in the heliosheath out to 108 AU and discusses the variability of plasma parameters in the heliosheath. The plasma speed continues to be on average constant across the heliosheath and the flow continues to turn tailward, with a flow angle greater than 70° in 2014. The average density and temperature have remained roughly constant since an increase in 2011. The heliosheath continues to be highly variable; this paper shows examples of small-scale variability and shows the changes of the plasma parameters on various scales. Future observations of plasma in the local interstellar medium (LISM) are discussed.

1. Introduction
V2 crossed the termination shock in 2007 [1,2,3,4]. The V2 plasma instrument (PLS) has provided observations in the heliosheath from the crossing at 84 AU to the distance in mid-2015 of 108 AU. The V1 PLS does not provide useful data, so these are the first observations of plasma in the heliosheath. V1 plasma flow speeds have been derived from V1 Low Energy Charged Particle experiment (LECP) and Cosmic Ray Subsystem (CRS) data [5,6,7,8,9], but plasma densities and temperatures cannot be determined.

This paper describes the plasma observations in the heliosheath. The data analysis is described, including how corrections are made in the flow angle to account for the instrument response. The plasma parameters are shown and discussed. The heliosheath is a highly variable region; an attempt is made to quantify these variations. Finally the expected observations in the LISM are illustrated.

2. Data
The V2 PLS instrument observes ions and electron currents with energies/charge from 10-5950 eV/q every 192 seconds using four Faraday Cups [10]. The observed currents are fit with convected isotropic proton Maxwellian distributions to find the plasma velocity, density, and temperature. Three of the cups point towards Earth and the fourth points at right angles to the V2-Earth line. The angular responses of these cups are flat to 45°, then decrease to 0 at 60°. The average plasma flow angle is now over 70° from radial, so plasma is often not detected in the three cups necessary to determine the velocity. If the flow were steady then flows could never be determined given the high average flow angle. However, the heliosheath plasma velocities, densities and temperatures have remained highly variable throughout the heliosheath. This high variability allows the PLS instrument to observe sufficient currents to determine plasma
11-day running averages of the plasma speed, density, and temperature observed by V2 in the heliosheath. The combination of large angle flows, tracking gaps, and noise allow only about 5% of possible spectra to be analyzed. Maxwellian distributions fit the observed spectra well when data are available in three of the cups.

Figure 1 shows the heliosheath proton speed $V$, density $N$, and thermal speed from the termination shock at 84 AU out to 108 AU. The average speed has remained constant across the heliosheath, although excursions in speed from as low as 120 km/s to as high as 180 km/s have persisted for several months. These observations are in sharp contrast to those at V1, where the speed decreased to near zero five years into the heliosheath.

The density jumped at the termination shock by a factor of 2 to $0.002 \text{ cm}^{-3}$, then decreased by a factor of 2 in 2008, perhaps associated with solar minimum reaching the outer heliosphere. The density increased back to its pre-2008 level in 2011, perhaps marking the end of solar minimum. If these density changes are related to solar minimum, they could be due to V2 at $30^\circ$ heliolatitude observing more high-speed, low-density wind [11]. However, the speed does not change in this low-density region as one might expect if V2 were in high-speed wind. Factor of 2 changes in the density are observed after 2011 but the average has remained constant.

Figure 2 shows 11-day running averages of the flow angles in the RT and RN planes. The RTN system has R radially outward, T in the plane of the solar equator and positive in the direction of solar rotation, and N completes a right-handed system. Since the observable flow angles are limited by the instrument response, the RT angles must be corrected to account for this limitation. This correction is done with the assumption that the distribution of angles is a Gaussian. This assumption is valid for the plasma density, velocity components, and thermal
speeds throughout the heliosheath, and also for the flow angles when they are small [11]. As
the RT angle increases, less of the Gaussian distribution is observed and only the tail of the
distribution can be used for the fit. Figure 3 shows the distribution of RT angles in 2015. The
instrumental cutoff is at about 50°; the data decrease rapidly beyond this cutoff. The Gaussian
fit to the data (up to 49°) is very good in the low-angle tail where data are available and gives
an average RT angle of 70° in 2015 with a 1-sigma error of 2°. The width of the distribution is
21 km/s with a 1-sigma error of 1 km/s, consistent with the widths in previous years [11].

Figure 2 shows that the flattening of the RT angle in the 11-day averages is an instrumental
effect. The corrected RT angle values increase with distance and in 2014 the average RT angle
was 70°. Since the RT angle is expected to be near 90° at the heliopause as VR becomes small,
this result suggests V2 is getting close to this boundary. The RN angle is much smaller than
the RT angle. Flow is moving around the sides of the heliosphere at the V2 position, not over
the pole. The RN angle is slowly increasing and was approaching 30° in 2014. McComas and
Schwadron [12] suggest that the flow at V2 is not away from the nose of the heliopause but
away from the highest pressure observed by IBEX, which is below the nose. Flow away from
this direction would give the observed V2 flow directions.

As discussed above, the heliosheath is a region with large fluctuations in plasma parameters.
Fig.4 shows an example of three spectra from the PLS B-cup, which looks most directly into the
flow, in 2011. These spectra span 35 minutes of time and show a remarkable variation in plasma
over this short time scale. In the left panel, the peak currents are at the lowest energies. The
Figure 3. The distribution of RT angles observed in the data (solid line) and the best fit of a Gaussian distribution to these data (dotted line). The dashed line shows the instrument cutoff and the fit parameters are given.

Figure 4. Three V2 PLS B-cup spectra from a 35 minute period in 2011. The best fit parameters are given in each plot. The channels number show a roughly logarithmic energy scale from 10-5950 eV.

parameters derived from fits to all the cups are shown in the figures. The currents in the middle panel peak in the third channel; in 25 minutes the speed increased by 40 km/s, the density decreased by a third, and the thermal speed doubled. Ten minutes later the peak current is in channel 2 and much higher in amplitude. The speed has decreased to the original level but the density is up by roughly a factor of two and the thermal speed is up by 25%. These changes are clear from the spectra; they are not artifacts of the fits.

The variability of the plasma in the heliosheath has not been quantified previously. The next section shows the changes observed in the plasma on a variety on time scales. The data set consists of all the spectra analyzed in the heliosheath. Some of these are undoubtedly spurious
Figure 5. Top: number of data points with the separation given by the x-axis; separations are multiples of 192 sec. Middle, Bottom: the observed changes in $V_R$ and density for four different separations in time as color-coded on the plot.

fits with noise being treated as data. However, since data in three of the four detectors are required to perform these fits, most of the 41,500 fits should be reliable. Previous work shows that the errors in $V_R$ are about 10%, in N about 20%, and in W about 25% [9]. A set of spectra is obtained every 192 sec, so this is the minimum separation. The top panel of Figure 5 shows that about 9,000 points have this minimum separation and about five points have 100 times this separation at the right-hand side of the plot.

The middle and bottom panels show the distributions of the changes in $V_R$ and density for different separations of spectra. Distributions for changes in consecutive spectra (dT = 192 sec) are shown by the black lines, for spectra separated by about 13 minutes, 32 minutes, and 1-3 hours the distributions are shown by red, blue, and green lines, respectively. The distributions are multiplied by the factors shown on the plot to facilitate comparison of the distributions. For $V_R$ the shape of the distribution is similar for the 3-32 minute distributions; the 3 minute
distribution is slightly more peaked but this effect is not large. The 1-3 hour distribution is broader, indicating scale lengths in the heliosheath are shorter than a few hours. For the density the profiles do not change shape for time scales up to a few hours.

Figure 6 shows differences in the plasma variation in different regions of the heliosheath. We divide the plasma into three regions: before the decrease in density at 2008.5, during the low density region, and after the density recovery at 2011.5. For each separation in spectra from 192 sec to about 2 hours the plot shows the average relative change between spectra, so for \( V_R \) the plot shows \( (V_R(t+1) - V_R(t))/V_R(t) \). The red +’s show the data after 2011.5, the black diamonds show data from before 2011.5 and after 2008.5 (the low-density region), and the blue *’s show data from before 2008.5. The average errors in the fit parameters are about 10% for \( V_R \), 27% for \( N \) in the low-density region and 22% for \( N \) outside the low density region. For both \( V_R \) and \( N \) the percentage change increases with distance into the sheath for short time separations. For \( V_R \), the change is comparable to the uncertainty for the smallest DT and increases to almost 0.2 at DT 30 minutes, then flattens out. The other two regions also show increases to about 30 minutes, then flatten out, but on average maintain the relative order of larger changes at larger distances. The density profiles are very similar to the \( V_R \) profiles, increasing to DT 30 minutes than flattening out. The average ordering of the three regions again remains the same. These data suggest a correlation length in the heliosheath of 30 minutes, which for an average speed of 150 km/s gives a distance of 270,000 km.

3. Plasma observations in the LISM
Voyager 2 may be approaching the heliopause and LISM. It crossed the termination shock 10 AU closer to the Sun than V1. V1 crossed the heliopause at 121 AU; for V2 a 111 AU heliopause crossing would occur within a year. Of course the plasma flows look very different from those observed at V1 so comparison is difficult. The V2 flow direction is changing rapidly and is about 70° from radial. If the flow continues to turn at the current rate it would be at 90°, roughly the angle expected at the heliopause where \( V_R \) is small, in the next couple of years. Although plasma waves at V1 have given density values at a few places in the LISM, measurements of speed, temperature, and the full density profile must wait for V2. What will V2 observe in the LISM? Since the flows are not directly into the detectors (they are away from the three main sensor cups and likely about 60° from the side sensor) the amount of current observed is very dependent on the thermal speed (temperature). Simulations of the currents in the PLS detectors have been performed for nominal plasma temperatures. The proton flow speed is 26 km/s and the plasma density of order 0.08 cm\(^{-3}\). The LISM temperature has recently been revised upward to 9000K to enable fits to both the Ulysses and IBEX data [13]. As the LISM plasma nears the heliopause it is compressed and heated by a factor of 2-4 [14]. Figure 7 shows the currents expected in the sideways-looking D-cup for \( T = 18000 \) K and 36000 K, 2 and 4 times the LISM temperature. In each case currents well above the threshold are observed. For the 36000K case current is also observed in the B-cup, not shown, so a 2D speed, density, and temperature could be derived. For the 18000 K case the speed normal to the detector, density, and temperature could be derived. The right panel shows a prediction of the observed currents using parameters from the Fisk and Gloeckler model [15] of the heliosphere, which suggests that V1 is still inside the heliopause; in this case V2 would observe no currents when it crossed the heliocliff.

4. Discussion and Summary
Voyager 2 continues to see heliosheath flow at a constant average speed which is turning fairly rapidly tailward. Most of the turning is in the RT plane and suggests that the heliopause crossing will occur with a few years. These observations are very different from the flow slowdown into a stagnation region observed at V1. The heliosheath plasma continues to be highly variable.
Figure 6. The average change in $V_R$, density, and thermal speed for each separation in time. The different symbols and colors show different regions of the heliosheath as indicated by the labels.

Changes in plasma parameters on time scales of tens of minutes persist, and have increased in magnitude, across the heliosheath. The plasma is a high-beta plasma, but the pickup ions which likely dominate the plasma pressure are not directly observed, complicating efforts to understand this region. When V2 does enter the LISM the plasma instrument should be able to measure this plasma directly and provide information on the plasma parameters and their variability.

4.1. Acknowledgements

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Figure 7. Simulated currents in the V2 PLS D-cup for LISM temperatures at the heliopause of 18000 and 36000 K and for the heliosheath values predicted past the heliocliff [14]. The dashed horizontal lines are the instrument threshold.

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