Plasma and Flows in the Heliosheath

John D. Richardson¹ and Robert B. Decker²

¹ Kavli Center for Astrophysics and Space Sciences, Massachusetts Institute of Technology, Cambridge, MA 02139 USA
² Applied Physics Laboratory, Johns Hopkins University, Laurel MD USA

E-mail: jdr@space.mit.edu

Abstract. Voyager 2 (V2) is now 20 AU deep into the heliosheath; if the heliosheath width were similar to that in the Voyager 1 (V1) direction, then V2 is 2/3 of the way to the heliopause. We present recent V2 observations, compare with observations from V1, and compare with model predictions. The speed of the flows observed by V2 in the heliosheath are, on average, remarkably constant at 150 km/s. The flow angle has changed dramatically, however, and is now over 60° from radial, with more of the turning occurring in the RT than RN planes. These flows are very different than those at V1, where the speed was always below 100 km/s and decreased across the heliosheath. Models predict VR at V2 well, but the flow angle predictions differ from the observations. The average density and temperature of the plasma decreased by a factor of two in 2008, recovered in 2011, and have not changed significantly since 2011.

1. Introduction

Voyager 2 has observed plasma in the heliosheath since the termination shock crossings at 84 AU in 2007 [1,2,3,4]. Since the V1 plasma instrument (PLS) is not working, 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. The exception is recent V1 plasma wave data from outside the boundary at 122 AU where low-energy particle intensities decreased and galactic cosmic ray intensities and the magnetic field increased [10,11,12,13]; this boundary may be the heliopause. These data show plasma waves at a frequency which implies a density of 0.06-0.08 cm⁻³ [14], consistent with V1 being in the local interstellar medium. The plasma emissions may be triggered by the arrival of merged interaction regions at V1. If this boundary were the heliopause V2, which crossed the termination shock 2.5 years after V1, could be within a few years of a heliopause crossing. This paper presents V2 heliosheath plasma data out to 104 AU, compares these data to the V1 observations and to V2 flows derived from LECP data, and discusses the implications of these results.

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 [15]. The observed currents are fit with convected isotropic proton Maxwellian distributions to find the plasma velocity, density, and temperature. The cups have acceptance angle responses which are flat to 45°, then decrease to 0 at 60°. To determine the velocity, currents must be observed in at least three of the four
Figure 1. The plasma speeds, density, and temperature measured by the plasma instrument on V2.

Faraday cups; flow angles outside the cup acceptance angle and noise allow only about 15% of the spectra to be analyzed. When data are available in three cups, Maxwellian distributions fit the data well.

Figure 1 shows the plasma speed, density, and temperature in the heliosheath from the termination shock out to 105 AU. The speed has remained constant at about 150 km/s throughout the heliosheath, a major surprise [16]. It has fluctuated from 120 to 180 km/s, but on average has not changed contrary to model predictions of a speed decrease. These observed speeds are very different from those observed at V1, where the speed after the termination shock was only 100 km/s and the speed decreased monotonically with distance until it approached zero in 2010.

The density just after the termination shock was 0.002 cm-3, about twice that in the upstream solar wind. The density then decreased by a factor of 2 in 2008 and remained low until 2011,
**Figure 2.** Distributions of the flow angles in the RT plane observed by V2 (solid line) and a Gaussian fit to the data with angles below 50° (dashed line). The years and days used for this analysis and the average RT angles and distribution widths from the fits are given in each panel.

when increased back to its pre-2008 level. This period of low density corresponds to solar minimum in the outer heliosphere so it seems likely this decrease is a solar cycle effect, with V2 observing more high-speed, low-density wind [17]. However, the speed does not change in this region as one would expect if V2 were in high-speed wind.

The average flow angle in the RT direction is about 60°. (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 response of the cups goes to zero at 60°, many spectra cannot be analyzed. The heliosheath is a highly fluctuating region, so flow angles are constantly changing and V2 rarely remains in flow at too high an angle to derive plasma parameters for more than a couple hours at a time. These large fluctuations in the heliosheath plasma give a wide distribution of plasma parameters which are well fit by Gaussian distributions [18]. In the case of the RT flow angles, we assume the distributions are Gaussian and fit the data below the instrument cutoff; the Gaussian fit parameters then give the average flow angle of the data. Figure 2 shows the Gaussian fits to the RT angles for days 1-183 in 2008 and 2011 and for days 1-142 in 2014. The cutoff in the observed distribution occurs at about 50°. In 2008 this effects only a few percent of the observations. In 2011 the peak in the RT angles is very close to the cutoff value. In 2014 the peak is well beyond the cutoff, but the Gaussian fit to the data below the peak gives an average flow angle of 66° in the RT plane.

The top panel of Figure 3 shows the three components of velocity. The VT component has
not been corrected for the instrument response. VR decreases across the heliosheath from 130 to about 90 km/s; this decrease is much less than that observed at V1. VT increases from 40 km/s to over 100 km/s, where it asymptotes due to the instrumental effects. VN increases in magnitude across the heliosheath from -20 to -80 km/sec. The velocity components are strongly correlated, with magnitudes of all components moving together. The tendency of VR, VT, and VN to all increase and decrease simultaneously tends to keep the flow angles relatively constant.

The bottom panel of Figure 3 shows the flow angles in the RT and RN planes; the diamonds show the corrected RT values obtained by fitting Gaussian distributions to 6 months of data. The flow angles in the solar wind are near zero in the outer heliosphere. At the termination shock, the RT angle increased to about 20° and RT continues to increase across the heliosheath.
to the present value above 60°. The RN angle increased at the termination shock to about 10°, fluctuated in the beginning of 2008 then decreased monotonically to about 30° in 2014. The RN angle is consistently about 1/2 of the RN angle, indicating most of the plasma flow is moving around the sides, not over the poles, of the heliosphere.

3. Discussion

As mentioned above, one puzzle has been the very different plasma flows observed at V1 and V2. The plasma instrument on V1 does not work, so the V1 flows are derived from LECP and CRS data using a Compton-Getting analysis on the low-energy particle data [5,6,19]. The LECP instrument scans in the RT plane and thus the flow speeds can be derived in those planes. At V1, the spacecraft is rolled occasionally to allow LECP to determine VN [20]; the CRS instrument also provides VN values during magnetometer rolls which occur every few months [8]. The Compton-Getting analysis assumes the ion composition is known and that the observed anisotropies arise from the convective flow.

One way to test the LECP speeds is to compare the LECP flows derived from V2 data with those observed by the V2 plasma instrument. Figure 5 shows a comparison of the flows observed by the PLS and LECP instruments in the RT, R, and T directions [9]. The LECP speeds are derived from 28-43 keV ion (generally proton) angular data using a linear Compton-Getting analysis. The Compton-Getting analysis assumes that the ion composition is known and that the observed anisotropies arise from the convective flow. The VR speeds are similar after the termination shock until 2009.3, then from 2009.3-2010.5 the LECP values are much larger (period A in the VR panel). The speeds match fairly well after 2010.5 except from 2012.7-2013.3 and near 2013.7 where the LECP values are higher then the PLS speeds. The LECP and PLS VT data both show increases through the heliosheath and similar speeds except from 2012.7-2013.3 (period B in the VT panel). We think the differences in the LECP and PLS VR values during 2009.3-2010.5 are caused by the LECP detector observing pickup oxygen ions. The ion detector measures the total energy, so the 28-43 keV proton channel will also measure 4-7 keV oxygen ions [21]. The Compton-Getting analysis assumes the ions were protons to derive the flow estimates in Fig. 5. If some of these ions were oxygen, the predicted convection speed would be too high because protons have a higher speed than pickup oxygen ions at the same energy. We do not understand why these heavy ions are prevalent at V2 during 2009.3-2010.5. However, pickup oxygen ions have been measured by the V1 and V2 LECP low-energy ion channels in high speed solar wind [22]. A small acceleration at the termination shock would enable pickup oxygen detection in the low speed heliosheath flow. From 2012.7 to 2013.3 ions from at least 28 keV to several MeV stream are observed to stream along the magnetic field. Thus convective flow does not cause all the observed anisotropy and the Compton-Getting analysis is unreliable. Except for regions A and B, where LECP speeds cannot be reliably determined, the PLS and LECP speeds are comparable. Both LECP and PLS observe much higher values of VR than LECP observed at V1. They both observe a very slow decrease in VR across the heliosheath, not the rapid decrease to zero observed at V1. Both PLS and LECP observe an increase in VT across the heliosheath, whereas at V1 a constant low-speed VT was observed. We note that where LECP and PLS disagree the LECP values are larger than the PLS values; similar problems with Compton-Getting at V1 would also give larger values of VT and VR, not lower values as observed. The data thus are consistent with the flow speeds in the V1 and V2 directions being very different; this difference does not appear to be an instrumental effect.

We also note that models generally do not match both the V1 and V2 speed profiles. Pogorelov et al. [23] use Ulysses data as input for their heliosphere model. Their model radial speed profile matches V2 VR observations well, but for V1 the model values are much higher than those observed. They find VT comparable to VN at V2, whereas observations find VT is twice VN, and they find less turning of the V2 flow than observed. Other models have similar
The timing of the V2 crossing of the heliopause is of great interest. Knowledge of the plasma parameters should provide conclusive evidence of whether the boundary observed by V1 is the heliopause. We will also learn if the stagnation region observed by V1 [7] is a transient or permanent feature of the outer heliosphere. The location of the heliopause itself will greatly enhance our understanding of heliospheric asymmetries. The plasma flow data provides some clues as to when the heliopause crossing may occur; at the heliopause we expect the flow to become tangential to the boundary, mostly in the T and N directions. The dashed line in the bottom of Figure 3 shows a linear fit to the corrected RT angles. The fit has a slope of $6.3 \pm$
1.0 °/year, so the flow angle would reach 90° (and V2 would reach the heliopause) in about 4 years.

3.1. Acknowledgements

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