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PLASMA NEAR THE HELIOSHEATH: OBSERVATIONS AND INTERPRETATIONS

J. D. Richardson[1,2] and C. Wang[2]
[1] Kavli Center for Astrophysics and Space Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA; jdr@space.mit.edu
[2] State Key Laboratory for Space Weather, Chinese Academy of Sciences, Beijing, China; cw@spaceweather.ac.cn
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ABSTRACT

Voyager 2 (V2) has observed heliosheath plasma since 2007 August. The plasma flux decreases by 25% before the termination shock (TS), then, as V2 moved into the heliosheath, the plasma density, temperature, and flux all decreased by an additional factor of 2. We suggest three effects combine to cause these decreases. (1) V2 moved into the lower-flux transition region between the low- and high-speed solar wind. This hypothesis is consistent with *Ulysses* observations of the transition location, explains the 25% decrease in solar wind flux observed before the TS crossing, and can reconcile discrepancies between the V2 and Voyager 1 heliosheath speeds and between the V2 speeds and model results. (2) The weaker source at the Sun. (3) The heliosheath plasma turning and flowing toward the heliotail.

Key words: interplanetary medium – solar wind

Online-only material: color figures

1. INTRODUCTION

Voyager 2 (V2) has measured plasma parameters in the heliosheath since 2007 August. The heliosheath plasma and magnetic field are turbulent and dynamic (Burlaga et al. 2005). The plasma parameters in the heliosheath provided several surprises. The thermal plasma is cool compared to that in planetary magnetosheaths; most of the flow energy dissipated at the termination shock (TS) goes into heating the pickup ions (Richardson et al. 2008; Richardson 2008). The plasma velocity in the heliosheath is also different than expected. The radial speed at V2 is twice as large as that at Voyager 1 (V1) and larger than model predictions. Models predict the radial speed should decrease across the heliosheath (HSH); this decrease is observed at V1 but not at V2 (through 2009 July), where the speed has remained constant (Richardson et al. 2009).

This solar minimum has been longer than average and characterized by very low solar wind magnetic fields, fluxes, and pressures (McComas et al. 2008). These unusual solar wind parameters propagate to the heliosheath where they are observed directly. The low pressures also cause an inward movement of the TS and inner heliosheath which modifies the heliosheath properties. As of 2009 August, V2 had moved outward 6 AU from the TS crossing at 84 AU. We report on changes in plasma parameters observed as V2 moves through the heliosheath and on the expected motions of the TS during that time period.

2. THE DATA

The Voyager plasma experiment (PLS) observes ions and electrons with energies from 10 to 5950 eV in four modulated-grid Faraday cups. Three of these cups are arranged around a cone whose central angle points toward Earth, roughly to the direction of the heliosheath flows (Bridge et al. 1977). The time resolution is 192 s in the heliosheath. The electrons in the heliosheath have energies below the 10 eV threshold of the instrument and are generally not observed. The data are fit with convected isotropic Maxwellian distributions to determine the plasma velocity, density, and temperature; these distributions provide good fits to the observations.

Figure 1 shows an overview of the heliosheath data through 2009 July. The solid line shows daily averages and the dashed line shows 25-day running averages. The speed has remained essentially constant at about 150 km s^{-1} across the heliosheath. The density fell by a factor of 2 between the TS crossing and 2008.5 and has remained at about 0.001 cm^{-3}. The temperature also decreased from the TS to 2008.5, then remained constant at roughly 1/2 the post-TS value. The density and temperature variations are both less after 2008.8. The flow angles increased after 2008.6 as V2 moved deeper into the heliosheath, as expected and as observed in the *RT* plane on V1 (Decker et al. 2006). (We use the standard *RTN* coordinate system, where *R* is radially outward, *T* is parallel to the solar equator and positive in the direction of solar rotation, and *N* completes a right-handed system.)

Figure 2 shows 101-day running average solar wind flux data from the OMNI (near-Earth) data set, from *Ulysses*, and from V2. We concentrate on the flux data because the flux should be conserved across the TS (assuming that the average TS motion is small, which we verify in Section 3.2). The top panel shows the heliolatitudes of the spacecraft. The OMNI and *Ulysses* data are time-shifted forward one year to account for the propagation time to V2. Before 2007.8 (all times mentioned henceforth are the shifted times shown in Figure 2), all three fluxes match reasonably well. The V2 and *Ulysses* fluxes are slightly higher than the OMNI fluxes. The decrease in flux at *Ulysses* from 2006.8 to 2007.3 occurred as *Ulysses* moved into the high-speed, low-density polar solar wind. The *Ulysses* flux decreases by about 25% from 2006.8 to 2007.3, then continues to slowly decrease until 2009. The OMNI and V2 fluxes begin to diverge near 2007.5, when the V2 flux decreased to near the levels observed by *Ulysses*. The V2 flux continued to decrease with time as V2 moved across the heliosheath.

3. DISCUSSION

3.1. *Flux Decrease Due to Transition from Slow to Fast Solar Wind*

The total solar wind flux has decreased by about a factor of 2 from 1 AU to the heliosheath; we consider possible causes of this decrease. We first investigate mechanisms which might cause the solar wind flux decrease of about 25% which occurred about 60 days before the TS crossing. Gloeckler et al. (2005)

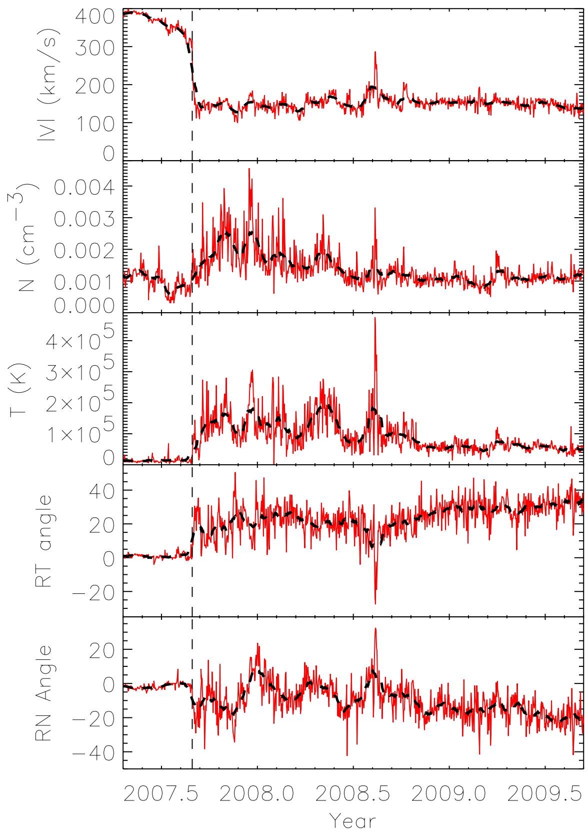

Figure 1. Daily averages of the velocity magnitude, density, temperature, and flow angles in the heliosheath. The dashed line shows the TS location.

(A color version of this figure is available in the online journal.)

suggest that hot electrons from the shock could ionize neutrals in a small region near the TS and produce the 100 km s^{-1} speed slowdown observed in the 80 days before the TS. This mechanism would produce a decrease in the observed flux, since the pickup ions cannot be observed. However, to ionize enough neutrals to produce the observed slowdown, all the electrons must have energies near 100 eV. These hot electrons are not observed.

Given the lack of other options, we hypothesize that the flux decrease before the TS results from V2 entering the transition region from slow to fast solar wind. Figure 3 shows the solar wind flux and speed observed by *Ulysses* during the fast latitude scan in 2007. The speed and flux both have large ranges in the low-latitude region, but the speed transition is more gradual than the flux transition. V2 is at the heliolatitude where *Ulysses* observed this transition. The transition region thickens with distance as the streams interact. The flux at V2 decreases by 25% from 2007.5 to 2007.7, from roughly the value observed in the low-latitude slow solar wind by *Wind* and *Ulysses* to the lower value observed by *Ulysses* at higher latitudes in the fast solar wind. When *Ulysses* crossed the equator during the fast-latitude scan, the flux at *Ulysses* returned to that observed at 1 AU, verifying that the flux change is a latitude effect.

Figure 1 shows that the flux decrease at V2 results mainly from the decrease in density, although the speed also decreases. The speeds observed before the V1 TS crossing were much lower than those observed by V2, dropping from 300 km s^{-1} to 120 ± 120 km s^{-1} (Decker et al. 2005). We suggest that at V2 the speed decrease associated with the approach to the TS is partially compensated for by the speed increase due to the faster polar flow. The magnetic field data show that V2 is more often in the southern sector than the northern sector, with a long unipolar region at the beginning of 2008 (Burlaga & Ness 2009). These data show that the tilt of the heliospheric current sheet (HCS) is comparable to the V2 heliolatitude. Roelof et al. (2010) show that polar holes have moved equatorward in the southern solar hemisphere in this time period, consistent with our hypothesis. V1 is at higher latitudes (34°N) but does not enter the high-speed wind for two reasons: (1) the coronal holes are observed at low latitudes only in the southern hemisphere (Roelof et al. 2010)

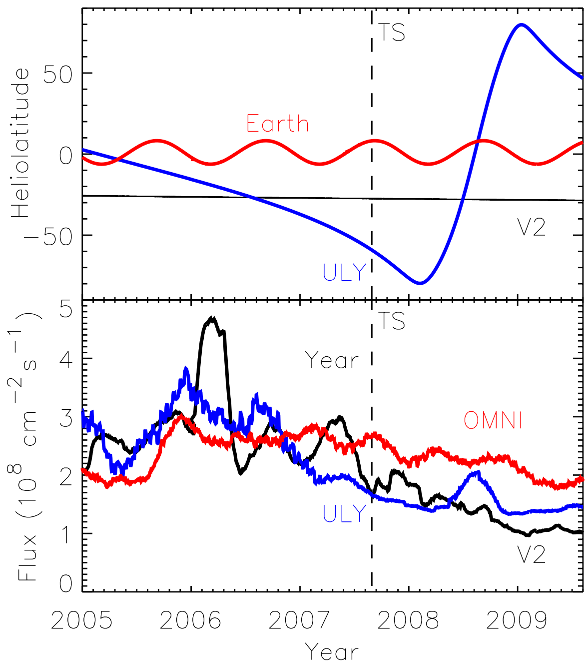

Figure 2. Comparison of solar wind fluxes observed at 1 AU (OMNI), *Ulysses*, and V2. The top panel shows the heliolatitudes of these spacecraft, the middle panel shows the fluxes, and the bottom panel shows a blow up of the heliosheath. The dashed line shows the TS location.

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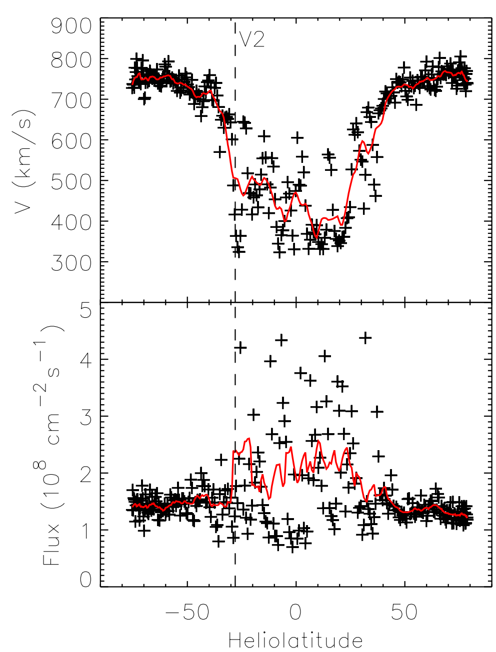

Figure 3. Daily averages (+) and 13 day running averages (lines) of the speed and proton flux observed by *Ulysses* during the fast-latitude scan of 2007. The dashed line shows the position of V2.

(A color version of this figure is available in the online journal.)

and (2) the heliosheath flow is more poleward at the V1 than V2 locations, so the slow wind is carried to latitudes poleward of V1 but not poleward of V2 (Borovikov et al. 2009).

If V2 is the transition region to the fast solar wind, the heliosheath flow differences observed at V1 and V2 could be reconciled. V1 observed an average radial speed in the heliosheath of 68 km s^{-1} through the end of 2007 (Decker et al. 2005), consistent with the low solar wind speeds Low Energy Charged Particle reported before the V1 TS given the shock strength of about 2.5 (Stone et al. 2005; Burlaga et al. 2005). Radial speeds in the HSH at V2 average about twice those at V1, 138 km s^{-1} (Richardson et al. 2009), and were constant through 2009 July. The V1 and V2 speed difference and the constant radial speed at V2 are contrary to model results which predict similar speeds at V1 and V2 and a monotonic speed decrease across the HSH (Pogorelov et al. 2010). If V2 entered the transition region to fast solar wind in 2007, the decrease in speed upstream of the TS would be less than observed by V1 and the speeds in the HSH would also be higher. A slow transition to higher speed flow could compensate for the expected decrease in speed as V2 moves through the HSH; this effect is observed in models (Pogorelov et al. 2010). So a transition to high-latitude flow starting upstream of the TS could explain the observed flux decrease upstream of the TS and, at least qualitatively, reconcile the radial speeds observed at V2 with both the observed speeds at V1 and model predictions.

The region downstream of the TS has large variations in density, temperature, and flow angle through 2008.6. Given the quietness of the Sun over the past few years of solar minimum, these variations are probably not driven by solar transients. They are probably driven by corotating interaction regions (CIRs) which should be numerous in the transition region. The higher speed wind observed by *Ulysses* has much less variation than the low-speed wind; the lack of structure in the heliosheath after 2008.8 suggests that V2 has left the transition region and is immersed in the high-speed wind.

3.2. *Flow Diversion Down the Heliotail?*

The decrease in flux relative to that at *Ulysses* as V2 crosses the HSH may at first result from V2 moving deeper into the low-flux, high-speed region. However, the V2 flux continues to decrease after the TS crossing and in 2009 is 25% below that observed by *Ulysses*. We consider below several mechanisms to produce this flux decrease, but to quantitatively test these hypotheses we need to know how far V2 has moved into the HSH.

McComas et al. (2008) report a decrease in the solar wind flux to near the lowest levels observed in the space age. The decrease in flux and dynamic pressure in the inner heliosphere affects the observations at V2 directly as shown above. The decrease in solar wind pressure also causes the TS to move inward. The heliosphere is a large and complex system; changes in the TS distance lag the changes in solar wind dynamic pressure. We use the OMNI data as input to an MHD model which includes neutrals; we propagate the OMNI data out to 30 AU using a one-dimensional MHD model, then use a two-dimensional gasdynamic model (Wang & Belcher 1999) to determine the TS location.

Figure 4 shows TS locations normalized to the V2 TS crossing on day 241 of 2007 at 84 AU. The measured pressure profile (101 day running averages) is shown in the bottom panel. The model profile predicts a slow outward motion of the TS position at the time of the V2 TS crossing. Inward motion of the TS in response to the decrease in solar wind dynamic pressure does not occur until 2009.2. Until this time the average TS speed is small (a 1 AU $year^{-1}$ change in TS location corresponds to a speed of 4.7 km s^{-1}). Thus, V2 conditions differ from the V1 TS crossing, when the model predicts inward TS motion immediately after V1 crossed the TS which is consistent with observations (Jokipii 2005). We note that the V1 TS is 9 AU further out than the model profile (which is normalized to the V2 TS crossing) predicts; thus, the asymmetry in the heliosphere in the V1 and V2 directions derived using the OMNI data in the model is of order 9 AU, similar to the 7–8 AU reported by Richardson et al. (2008) who used V2 data to determine the TS positions.

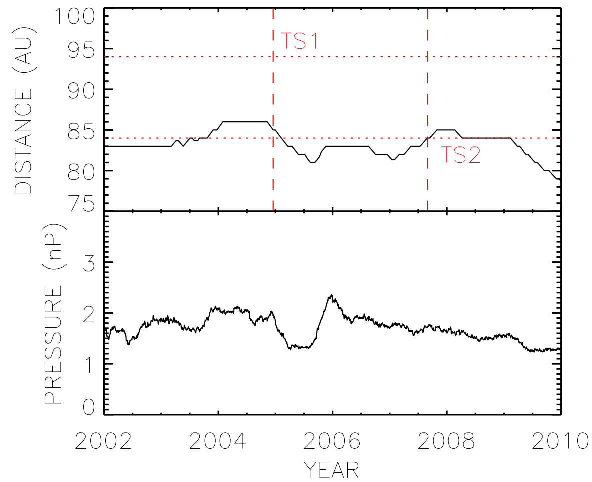

Figure 4. Location of the TS based on a two-dimensional MHD model. The top panel shows the predicted locations of the TS, with the profile normalized to the observed V2 TS crossing. The bottom panel shows 101 day running averages of the solar wind dynamic pressure at 1 AU. The vertical lines show the TS crossing times and the horizontal lines show the crossing distances.

(A color version of this figure is available in the online journal.)

V2 entered the heliosheath at 84 AU and is now at 90 AU; the TS has moved inward to 81 AU according to the model, so V2 at 90 AU observes plasma which has been in the heliosheath for 9 AU. The flux at 2009.5 is about 25% below that observed by *Ulysses*. One way to reduce the observed flux is if the thermal plasma charge exchanges with neutral interstellar H; the new pickup ions would not be observed and so in the data this process would look like a reduction in plasma flux. However, using a charge exchange cross section of 2×10^{-15}, the observed heliosheath speed of 150 km s^{-1}, and an interstellar H density of 0.1 cm^{-3} gives only a few percent loss of the plasma in the first 9 AU of the heliosheath.

Another possibility is that V2 is deep enough in the heliosheath that a significant amount of the plasma has moved out of the nose region as it diverts toward the heliotail. V2 is located at an angle $A \sim 45°$ from the nose of the heliosphere. The flux of solar wind plasma through the TS while V2 has been in the heliosheath is given by $2\pi({R_{TS}}^2(1 - \cos(A))\ F_{SW} = 5.4\text{–}5.7 \times 10^{28}\ s^{-1}$, where $R_{TS} = 84$ AU is the TS crossing distance and F_{SW} is the solar wind flux. The range of values is obtained by using either the average flux observed by V2 in the heliosheath or the high-latitude flux values observed by *Ulysses*. By the time the solar wind reaches the heliopause, this plasma must turn sideways on its way to the heliotail. The observed non-radial flux $F_{NR} = \sqrt{(V_T^2 + V_N^2)}N$, where N is the density, can be used to calculate the outflow from the nose region, $2\pi R_{V2} \sin A \times 9\ \text{AU} \times F_{NR} = 8 \times 10^{27}\ s^{-1}$. We assume V2 is 9 AU from the TS in mid-2009; the average distance of V2, R_{V2}, is 85.5 AU. Thus, about 15% of the plasma has already moved tailward by the time it reaches V2 at 90 AU in mid-2009. This value is roughly consistent with the decrease in flux observed across the heliosheath to a value 25% less than that observed by *Ulysses*.

This result suggests that V2 is more than 1/7 of the way through the heliosheath. The plasma flows should continue to turn away from radial as V2 moves deeper into the heliosheath, so it is likely that V2 is farther than 1/7 of the way to the HP, giving an upper limit to the HSH thickness of 63 AU. Decker et al. (2006) show that the flow angle on V1 has rotated about 10° year^{-1}, suggesting the heliopause crossing would be about 10 years, or 35 AU, after the TS crossing (assuming a constant rotation rate).

4. SUMMARY

We address several outstanding questions concerning the plasma flux near the TS and in the heliosheath. The solar wind flux decreases by about 25% just before the TS crossing. We show that a similar change is observed by *Ulysses* at roughly the same heliolatitude and hypothesize that the flux change at V2 signals that it has entered the transition region from the low-speed, higher flux solar wind to the high-speed, lower-flux solar wind. We note that a transition of V2 from the low- to high-speed wind would explain the discrepancies between the V2 and V1 speeds and between the V2 speeds and model predictions. We show that the heliosheath flux decreases across the sheath, due to a decrease in density, and show that the amount of this decrease is consistent with observations of the plasma flow turning tailward.

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