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PLASMA IN THE HELIOSHEATH: 3.5 YEARS OF OBSERVATIONS

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ABSTRACT

Voyager 2 (*V2*) has observed heliosheath (HSH) plasma since 2007 August. We describe how the plasma has evolved across the HSH. We show that the low solar wind dynamic pressure leads to an inward movement of the termination shock (TS) of about 10 AU to a minimum position of 73 AU in 2010. Near the TS large fluctuations are present in the HSH, but these fluctuations decrease as *V2* moves further from the TS. The radial speed slowly decreases and the plasma flow slowly turns tailward. The temperature decreases across the HSH. The radial speed in 2011 remains above 100 km s^{-1}, which implies that *V2* is a substantial distance from the heliopause.

Key words: solar wind – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

Voyager 2 (*V2*) crossed the termination shock (TS) into the heliosheath (HSH) in August of 2007 and began observing the shocked solar wind plasma. Other sheath regions have been observed near planets and behind interplanetary coronal mass ejections, but the HSH is by far the largest sheath region observed. The most analogous sheath region is the nose region of the Jovian magnetosheath; the *Voyagers* crossed this region in about 0.5 day whereas *Voyager 1* (*V1*) has been in the HSH since 2004. *V1* (which does not have a working plasma instrument) may be nearing the heliopause (HP) as the radial flow speed is near zero (Krimigis et al. 2011). *V2* continues to see a strong radial flow; this Letter describes the plasma observations made by *V2* in the HSH and their interpretation.

2. TERMINATION SHOCK MOTION

The HSH and its boundaries, the TS and HP, move inward and outward in response to changes in the dynamic pressure of the solar wind. Early modeling of the time-dependent heliosphere showed ≈15 AU motions of the TS and ≈3–4 AU motions of the HP in response to a sinusoidal factor of two variation of dynamic pressure with an 11 year period (Karmesin et al. 1995; Wang & Belcher 1999). To understand the observations made in the HSH, it is important to know the HSH boundary locations so we know how deep into the HSH the spacecraft have traveled. We use the model of Wang & Richardson (2001) to calculate the TS motion. This hydrodynamic two-dimensional model includes the effect of pickup ions. We use *V2* data to calculate the TS position until it nears the TS and the OMNI data from 1 AU after this time. The *V2* data best represent the plasma conditions affecting the TS until the solar wind is modified by the TS. After 2007.5, we use a one-dimensional code to propagate the OMNI solar wind data from 1 AU to the inner boundary of the model at 30 AU and then run the two-dimensional model. The dynamic pressure is constant with latitude (Richardson & Wang 1999; McComas et al. 2008), so the OMNI data should give a reasonable estimate of the dynamic pressure change over the whole heliosphere.

Figure 1 shows the TS location and the dynamic pressure at the TS from the *V2* and OMNI data sets. The pressure shows the well-known solar cycle variations (Lazarus & McNutt 1990) with a total change of about a factor of two. Since about 1995 the trend in pressure has been downward, by a factor of three from 1995 to 2010. The pressures observed in 2010 are the lowest observed since the 1960s (McComas et al. 2008). The TS location, which responds to these pressure changes, is shown in the top panel. The TS location was normalized to that of the actual *V2* TS crossing at 83.7 AU. The TS location moved inward from 94 AU in 1994 to 83 AU near solar maximum in 2002, stayed near 80–85 AU for several years, and then from 2009 to 2011 moved inward about 10 AU in response to the very low dynamic pressures. Note that when *V2* crossed the TS, the TS was slowly moving outward and stayed near *V2* for the first year after the TS crossing, then moved rapidly inward so that in 2010 *V2* was 20 AU deep into the HSH. This large inward motion corresponds to an average inward speed of 5 km s^{-1} over these 2 years. Assuming the same change at *V1*, *V1* would be about 30 AU deep into the HSH in early 2011.

3. THE HELIOSPHERIC CURRENT SHEET

Another factor that influences the observations is the location of *V2* with respect to the heliospheric current sheet (HCS). Solar minimum in this recent lengthy solar cycle occurred at the Sun late 2009 when the HCS tilt was a minimum. These low tilts were observed for only about four months, much less than for previous minima. At solar minimum, the latitudinal gradient of speed and density are large, with higher speeds and lower densities away from the equator. Figure 2 shows the HCS tilt in the southern hemisphere provided by the Wilcox Solar Observatory with the *V2* trajectory superposed. The tilt data are time-shifted 1.5 years to approximate the propagation time of the solar wind from the Sun to *V2*. This plot suggests that *V2* should be in the lowest tilt region in early 2011, when one could expect to observe larger speeds and lower densities. This simple picture is complicated by the poleward HSH flow component, which would displace the HCS to higher latitudes (Borovikov et al. 2011).

4. 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 into

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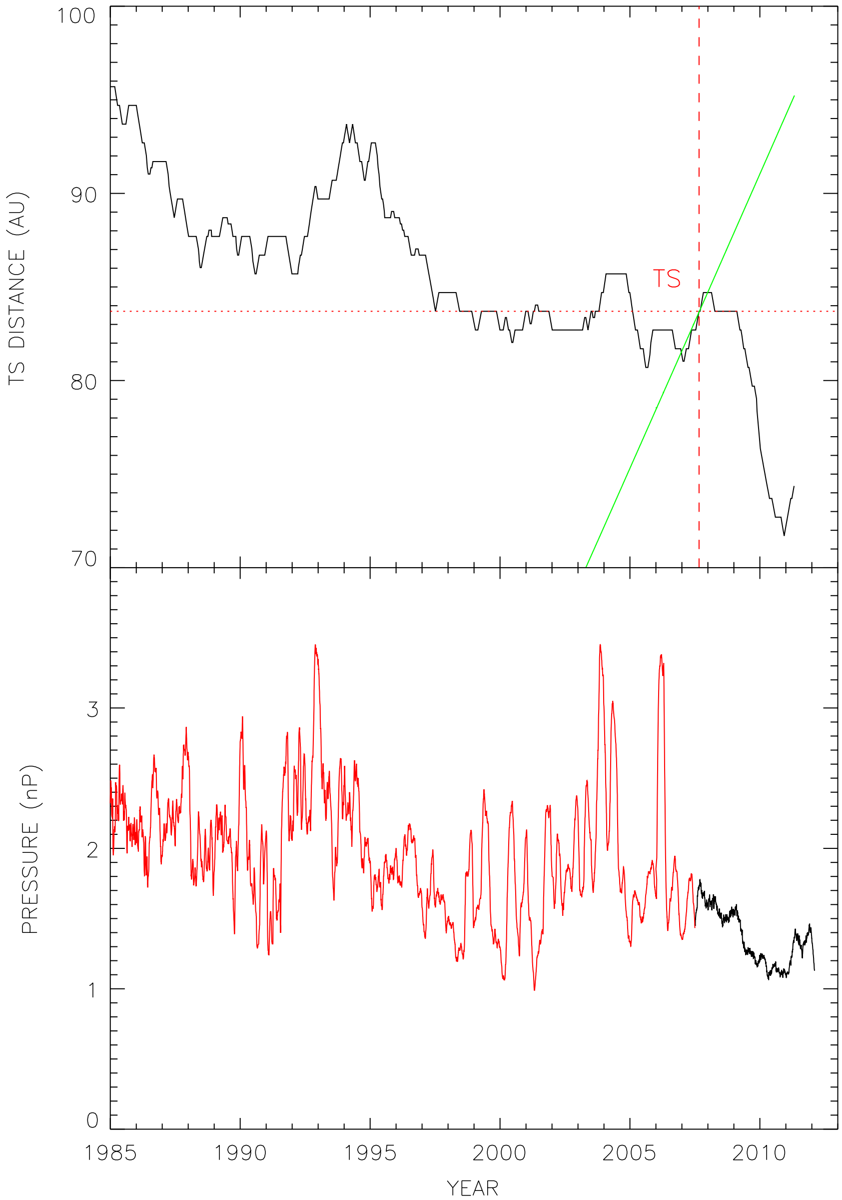

Figure 1. Predicted location of the TS and the solar wind pressure derived from the *V2* and OMNI data sets time-shifted to the *V2* location. (A color version of this figure is available in the online journal.)

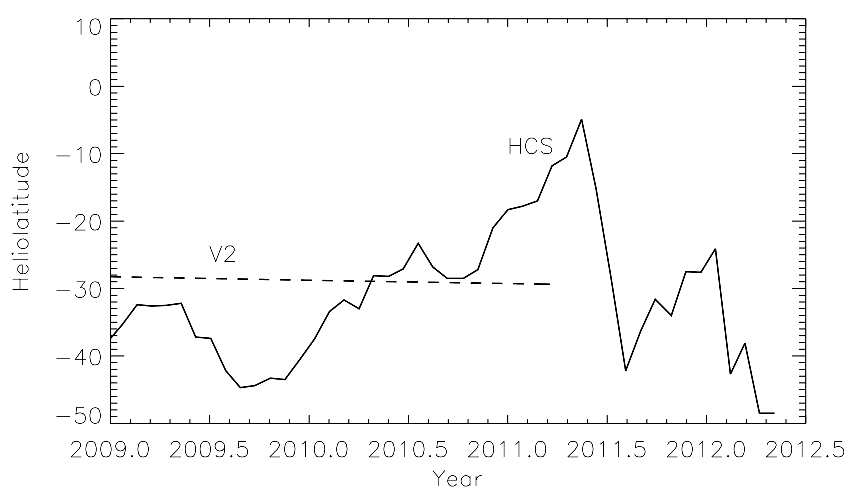

Figure 2. Latitude of the HCS predicted by the Wilcox Solar Observatory time-shifted forward 1.5 years and the heliolatitude of *V2*.

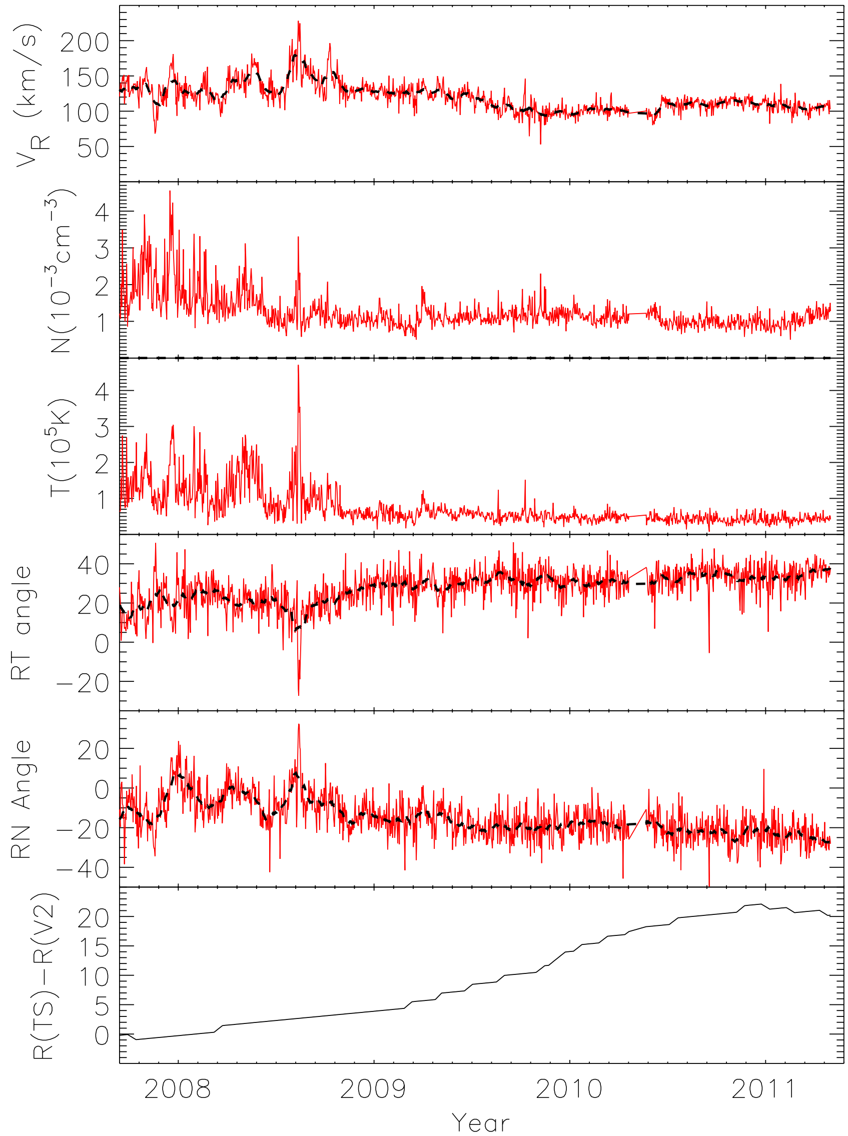

Figure 3. Daily averages and 25 day running averages (dashed lines) of the radial speed, density, temperature, and flow angles of the thermal protons and the distance of *V2* from the model TS.

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

the direction of the HSH flows (Bridge et al. 1977). The time resolution is 192 s in the HSH. The electrons in the HSH have energies below the 10 eV threshold of the instrument and are generally not observed. We select only spectra with currents measured in all three Earthward looking detectors and fit these data with convected isotropic Maxwellian distributions to determine the plasma velocity, density, and temperature; these distributions provide good fits to the observations. The peak currents observed are typically 10^{-14} to 10^{-13} A, with the lower values close to the noise level of the instrument. The uncertainties introduced by this noise contributes to 1σ error bars for the fit parameters of about 10% for V_R, 30% for N, and 40% for the thermal speed $W_{\rm th}$.

Figure 3 shows daily averages of the HSH data through 2011 March (solid lines) with 25 day running averages superposed (dashed lines). The average speed remained essentially constant at about 130 km s^{-1} until 2009.5, when it decreased to 100 km s^{-1}, then it increased to 115 km s^{-1} near 2010.4. The density fell by a factor of two from the TS to 2008.5 and since then has averaged about 0.001 cm^{-3}, with a small step-like increase at 2009.3 and a decrease at 2010.4. The temperature has decreased across the HSH. The character of the fluctuations changed at 2008.8, with fluctuations in the plasma parameters much less after this time. The flow angles increase across the HSH as the plasma turns toward the heliotail. The RT angle increased from about 20° near the TS to 33° in 2011 and the RN angle decreases from −12° near the TS to about −25° in 2011. 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 4 illustrates the long-term trends in the outer heliosphere and HSH, showing 1 AU averages of V_R, N, and T and the relative standard deviations σ_R (i.e., $\sigma_R(V_R)$ = standard deviation of V_R/average of V_R) for these periods. The radial speed slowly decreases across, but $\sigma_R(V_R)$ decreases by a factor of two. The density decreased quickly after the TS and has since remained fairly constant. $\sigma_R(N)$, however, decreased by more than a factor of two and is now smaller than in the solar wind. T also decreased rapidly after the TS and continues a monotonic

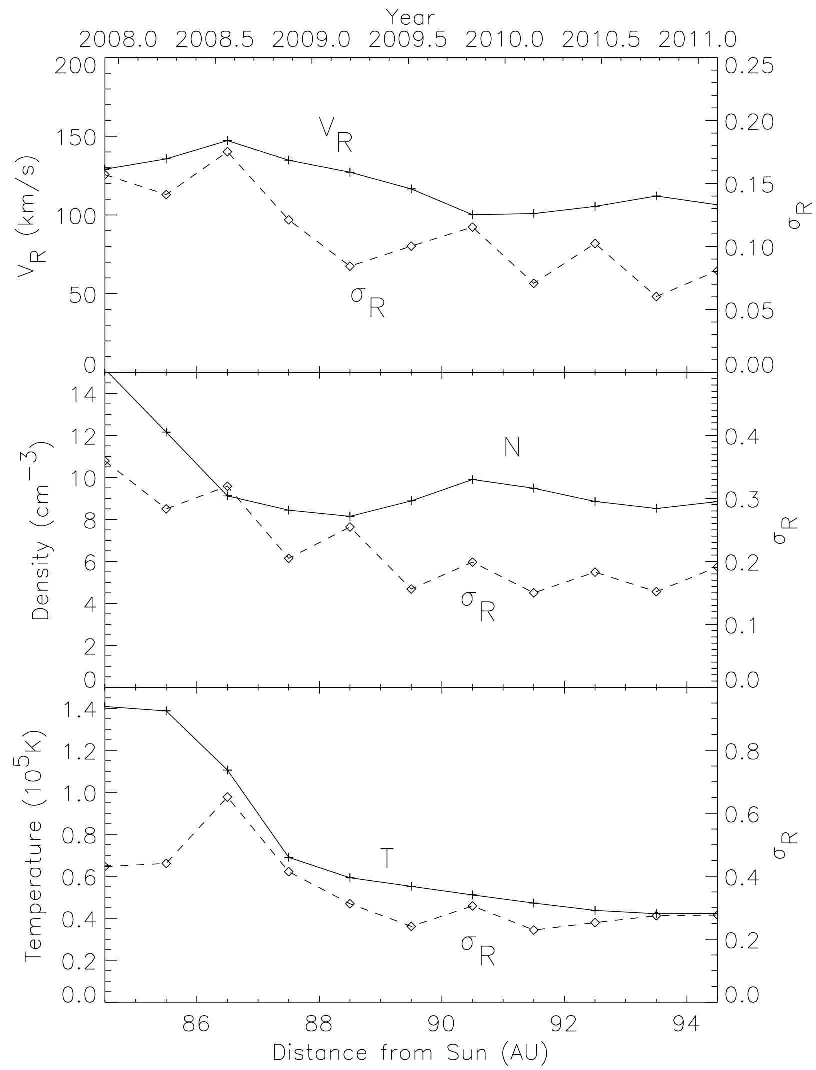

Figure 4. Averages and relative standard deviations for 1 AU intervals of the daily averages of the thermal proton radial speed, density, and temperature.

decrease. $\sigma_R(T)$ did not change across the TS, but outside 87 AU decreased by almost 50%.

5. DISCUSSION

We note above that the character of the HSH changes significantly at about 2008.8, with large fluctuations in the plasma before this time but not after. One possible explanation is that before 2008.8 the TS motions produce regions of compressed and rarefied plasma. Such compressions would give the positive correlation between N and T that is observed. The speed is also higher in the high N and T regions, again consistent with outward motion of the TS compressing the plasma. Roelof et al. (2010) suggest that coronal holes in the southern solar hemisphere may be driving these pressure changes. The bottom panel of Figure 3 shows the distance of *V2* from the TS using the model TS distance from Figure 1. *V2* stays within 5 AU of the TS until 2009; the region with large variability in the plasma is within about 3 AU of the TS. Thus, it is plausible that the variations inside 2008.8 are related to TS motions.

The data show little evidence that *V2* is entering the high-speed flow region as suggested by Figure 2. The increase in speed coincident with the density decrease at 2010.4 in Figure 3 is qualitatively consistent with observing a larger ratio of high-speed flow, but the changes are only 20%, not the factor of two expected for a change from pure low-speed to pure high-speed wind. The average value of V_N is -37 km s^{-1} in the HSH; thus the HCS should be carried poleward by the plasma flow about 30 AU in 3.5 years, or about 18° in latitude. This motion would place the HCS well above the *V2* location in Figure 2. Thus high-speed solar wind would not be expected at *V2*, consistent with observations.

We note that the flows observed at *V2* are very different than those reported at *V1*. The plasma instrument on *V2* does not work, so the *V1* flows are determined from ions measured by the Low Energy Charged Particle instrument in the tens of keV energy range using the Compton–Getting effect (Decker et al. 2005). The radial speeds observed by *V1* have been consistently well below those observed at *V2*; this difference is not understood. Recent *V1* observations from *V1* show that the radial component of the flow has gone to zero (Krimigis et al. 2011). The tangential component of flow at *V1* has remained constant at about 40 ± 20 km s^{-1}, in contrast to the increasing tangential flow observed at *V2*. The *V2* values are consistent with three-dimensional MHD model results (Borovikov et al. 2011).

The temperature decrease observed across the HSH was not predicted. The heating from pickup ions is likely less as the pickup ion energies are much less, so some amount of adiabatic cooling might be expected. But $E_\perp \propto B \propto R^{-1}$, so this should only be a 20% effect even including the inward motion of the TS, whereas Figure 3 shows that T decreases by a factor of three.

The decrease in variability observed in the HSH is not observed in other sheaths, but this difference in not surprising given the much larger size of the HSH. Much of the interior of the HSH should be insulated from the effects of boundary motions, unlike planetary magnetosheaths. Fluctuations in all plasma parameters do remain, consistent with our view of sheaths being turbulent regions and with the thermal plasma containing only a small amount of the thermal energy and thus not driving local plasma features.

6. SUMMARY

V2 has now been in the HSH for 3.5 years and our model calculation shows that it is 20 AU from the TS. For the first year in the HSH, the plasma had large variations, which we attribute to the proximity of the TS. Since then the relative standard deviations of the speed, density, and temperature have decreased. The radial speed is slowly decreasing across the HSH, much more slowly than reported at *V1*. The density has decreased, both in response to changes at the Sun and to plasma diverting toward the heliotail. The temperature has decreased by a factor of three and continues downward. The flow angles are increasing as expected for flow diversion toward the heliotail.

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