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VOYAGER 2 OBSERVES A LARGE DENSITY INCREASE IN THE HELIOSHEATH

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ABSTRACT

Voyager 2 (V2) entered the heliosheath in 2007 August at roughly the same time solar minimum conditions were reaching the outer heliosphere. Soon after crossing the termination shock the solar wind density at *Voyager* decreased by a factor of two and the temperature decreased by a factor of three. At the beginning of 2011 the plasma density in the heliosheath began to increase and in mid-2012 it was up by more than a factor of two. The temperature rose by about 50% and the speed remained constant, although the flow direction continues to turn tailward. These changes may signal the end of solar minimum conditions at V2 in the heliosheath, although we do not understand why the speed did not decrease. The increased dynamic pressure has led to an outward movement of the termination shock from its very compressed state at solar minimum.

Key words: solar wind – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

Voyager 2 (V2) has observed the shocked solar wind in the heliosphere since it crossed the termination shock (TS) in 2007 August. The plasma instrument on *Voyager 1* (V1) does not work, but the Compton–Getting effect can be used to derive the plasma speeds (Gleeson & Axford 1968; Decker et al. 2005). The speeds observed at V1 have decreased across the heliosheath and are now near zero, sparking the hypothesis that V1 is now in a boundary layer in front of the heliopause (HP; Krimigis et al. 2011; Decker et al. 2012). V2 has observed faster flow speeds throughout the heliosheath than V1 with the flow direction turning toward the heliotail (Richardson et al. 2009).

In the six months after the TS crossing, the density fell by a factor of two to about 0.001 cm^{-3} (Richardson et al. 2009). The temperature decreased by a factor of three. These decreases were interpreted as being due to a combination of solar cycle effects, including the observed reduction in the solar source and the effects of a varying admixture of hot solar wind as the heliospheric current sheet tilt and fast wind boundaries changed (Richardson et al. 2009). Effects unique to the heliosheath could also be important, such as the increased distance from the TS and the turning of the flow (and thus particle flux) tailward.

This paper describes the newest V2 plasma data. The density has increased by a factor of two and the temperature by 50% since the beginning of 2011. The radial speed is essentially constant in this time period and the non-radial speeds have increased so that the flow turns more tailward. The solar wind dynamic pressure has increased slightly causing the TS to move outward. We present the data and discuss the origin of these changes.

2. THE DATA

The plasma instrument on V2 simultaneously measures ions with energy/charge from 10 to 5950 V in four Faraday cup detectors (Bridges et al. 1977). Flows at large (roughly $>60^\circ$) angles to the cup normals cannot be observed. The spectra are fit with convected isotropic proton Maxwellian distributions to determine the plasma velocity, density, and temperature. A new

set of spectra is acquired every 192 s. However, V2 is only tracked by the Deep Space Network 25%–45% of the time and only about 10% of the spectra can be confidently fit because of noise and selection effects. This ratio is higher for the new data shown from 2011 and 2012, about 15%, because the higher densities improve the signal-to-noise ratio.

Figure 1 shows daily averages (points) and 11 day running averages of plasma radial speed V_R , density, and temperature in the heliosheath. Immediately after the TS V_R averaged 131 km s^{-1} . By the end of 2011 the average V_R had decreased to 100 km s^{-1} , then dropped to 80 km s^{-1} in early 2012 before recovering to near 100 km s^{-1} . Despite these variations, the average V_R has remained essentially constant since the end of 2009. The flow angles have consistently increased across the heliosheath as the plasma turns tailward.

The density in the heliosheath just inside the TS (from 2007.7 to 2008) was 0.0021, about twice the average in the solar wind before the TS. From mid-2008 to 2011, the average density was about half the value near the TS, 0.0010 cm^{-3} . In 2011 the density increased by a factor of two to the value just inside the TS, about 0.0020 cm^{-3} . In mid-2012 it increased again, to an average of 0.0025 cm^{-3} . The proton temperature T averaged 141,000 K from the TS until the end of 2008, then kept decreasing to an average of 42,000 K at the end of 2010. It started a slow increase when the density increase began in 2011, and was up 20% to 55,000 K at the end of 2011 and as high as 75,000 K in mid-2012.

Figure 2 shows the total speed V and flow angles in the RT and RN planes. (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.) One remarkable feature is the flatness of the speed profile. The speed profile in the heliosheath is nearly constant with an average speed of 146 km s^{-1} . Models predict a decrease across the heliosheath. At V1 the speed was normally $<100 \text{ km s}^{-1}$ and decreased with time (Krimigis et al. 2011; Decker et al. 2012).

The average angle in the RN plane has turned more southward, changing from about -10° after the TS to -25° in 2012. The average flow angle in the RN plane has increased from 20° near

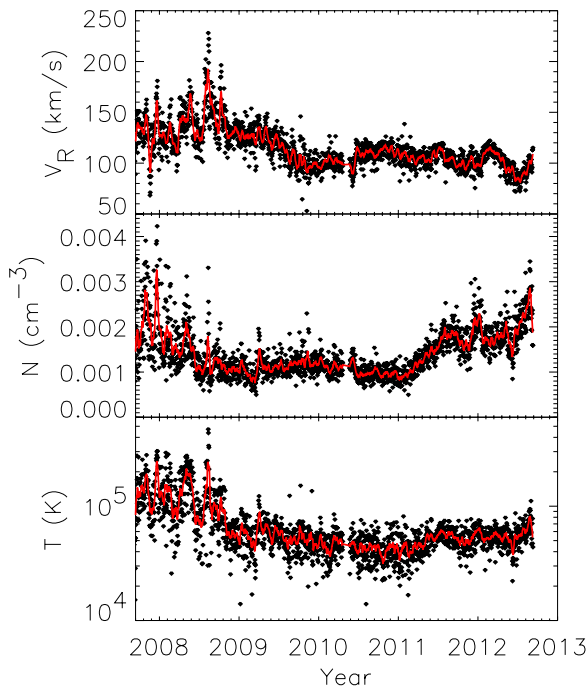


Figure 1. Daily (points) and 11 day running averages (lines) of the radial speed, density, and temperature observed at V2.

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

the TS to 43° in 2012, but this angle is biased to the low side because flow angles larger than about 50° cannot be observed by the instrument. However, since the variations in the angles are large and Gaussian, the distributions can be fit to find the unbiased flow angles (Richardson 2011). These are shown for each 0.5 year period by the diamonds and the corrected RN angle in 2012 is 55° .

3. DISCUSSION

The factor of two density increase observed in the heliosheath in 2011 which has persisted through 2012 September brought the heliosheath densities and flux up to levels observed near the TS before the decrease in 2008. With one spacecraft, spatial and temporal effects are difficult to separate, but *VI*, also in the heliosheath (130 AU away), and solar wind observations at 1 AU provide some constraints.

The easiest parameter to compare at V2 and 1 AU is the plasma flux NV , since the flux is conserved across the TS. Figure 3 shows the radial plasma fluxes observed near 1 AU by *Wind*, from 2 to 5 AU by *Ulysses*, and in the outer heliosphere by V2, all normalized to 1 AU by multiplying by R^2 . In the heliosheath, the flow is no longer radial but has a component away from the nose of the heliosphere, so a faster than R^2 falloff is expected (Richardson & Wang 2010). In the heliosheath, the plot shows both the V2 radial flux $V_R N R^2$ and the total plasma flux VNR^2 . The lower panel shows the spacecraft heliolatitudes. The *Wind* and *Ulysses* data are time-shifted forward 1 year to roughly compensate for the propagation time to V2.

The fluxes are very similar at all three spacecraft except near solar minima (1995–1999 and 2007–2011). At solar minima the solar wind has strong latitudinal gradients in speed, density, and also flux. The flux difference is illustrated a few different ways in Figure 2. *VI* and *Ulysses*, which are generally at higher latitudes, observe lower fluxes than *Wind*. Fluxes are about 50% higher at *Wind* than at V2 and *Ulysses* in the 1996–1999 solar minimum

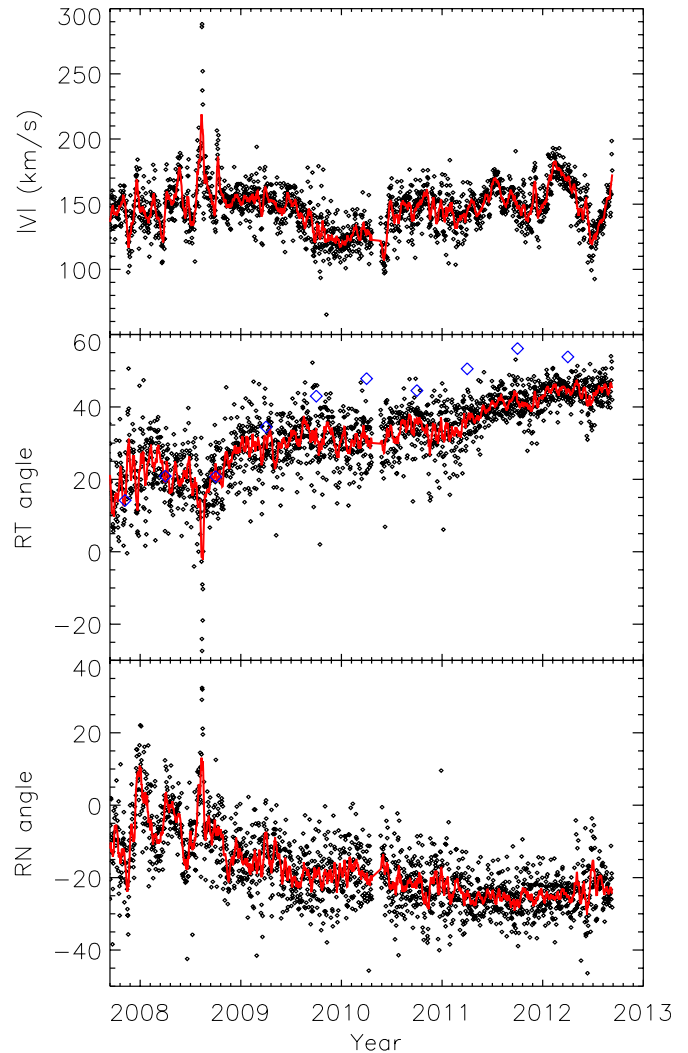


Figure 2. Daily (points) and 11 day running averages (lines) of the speed, RT angle, and RN angle observed at V2. The diamonds on the RT plot show the angles corrected for the instrument response.

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

and 50% higher than at *Ulysses* and 100% higher than at V2 in the 2007–2012 solar minimum. When *Ulysses* passes through the solar equator near solar minima (in 2008 in the time-shifted plot) the flux increases to a level comparable to that observed at 1 AU. Even though the total flux was much lower in the recent 2007–2012 solar minimum than in 1996–1999, the ratio of the fluxes observed at *Ulysses* and V2 to that observed in Earth orbit was about the same, with 50% more flux observed at *Wind*, which was nearer to the equator. Thus even though the solar plasma output has decreased significantly, the distribution with heliolatitude does not show evidence of change.

From 2011 to 2012 July the flux at V2 recovered to very near that observed at *Wind*, with the radial and total flux below and above the *Wind* values, respectively. The fluxes at *Wind* have remained at very low, nearly constant values even though the dynamic pressure increased starting in 2010.

The initial decrease in the solar wind flux was attributed to V2 encountering more high speed, lower-flux solar wind (Richardson & Wang 2010). The observed speed at that time did not increase, but neither did it decrease before the TS as observed at *VI*, so it was suggested that these effects offset, giving a constant speed. An increase in flux would then be

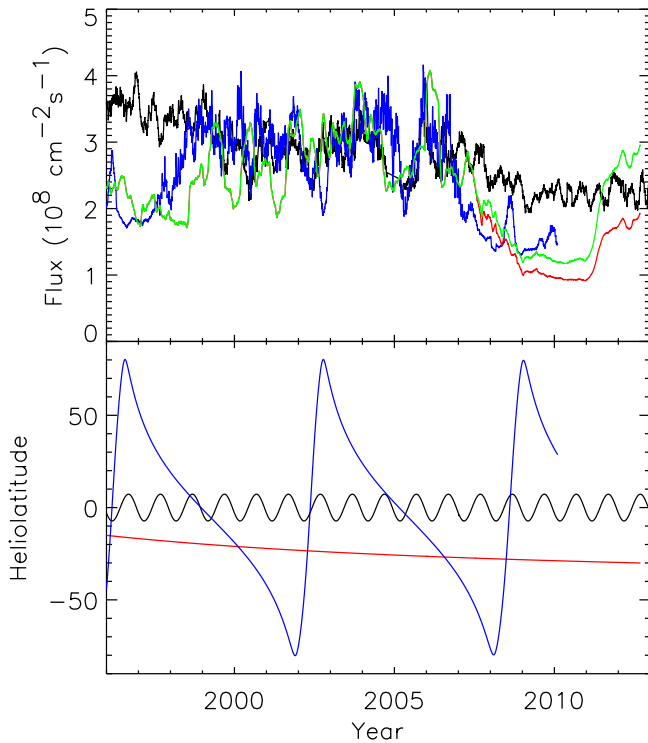


Figure 3. Plasma fluxes observed by *Wind* at 1 AU (black), *Ulysses* at 2–5 AU (blue), and the radial (red) and total (green) flux observed at V2. The bottom panel shows the heliolatitudes of these three spacecraft. (A color version of this figure is available in the online journal.)

expected when V2 left the high-speed wind, as observed. The speed, however, would also be expected to decrease and that is not observed. So although the changes in flux are consistent with V2 sampling, a larger percentage of low-speed, higher-flux solar wind as the solar cycle progresses the speed data do not seem to fit this picture.

The thickness of the heliosheath also changes with time; model results show substantial changes in the TS position over the solar cycle and much smaller motions of the HP, so the heliosheath thickness changes (Karmesin et al. 1995; Wang & Belcher 1999). Figure 4 shows the TS position calculated using the solar wind dynamic pressures observed by V2 until the TS crossing and at 1 AU after that. We propagate the *Wind* data out to 30 AU using a one-dimensional multifluid MHD model which includes pickup ions (Wang & Richardson 2001). Outside 30 AU a two-dimensional gasdynamic model which also includes pickup ions (Wang & Belcher 1999) is used to determine the TS location. The TS position profile is normalized to match the observed distance of the V2 TS crossing at 2007.7 at 84 AU. The bottom panel shows the dynamic pressure observed at V2 until the TS crossing at 2007.7 and the dynamic pressure at 1 AU time-shifted by 1 year after that. The top panel shows an outward movement of the TS location when V2 crossed the TS. The TS moved inward starting at 2009.2 due to the lower solar wind dynamic pressure. The average TS motion is small until 2009.2 (a 1 AU year⁻¹ change in the TS location gives a TS speed of 4.7 km s⁻¹). From 2009.2 until 2011.2 the TS moves inward 14 AU, for an average inward motion of 35 km s⁻¹. The thickness of the heliosheath is of order 35 AU, so the increase in heliosheath thickness due to the inward heliosheath motion may be substantial, which could slow the average heliosheath speed and may affect the outward flux. In early 2011 the inward TS motion stops, then it is outward in early 2012, which could lead

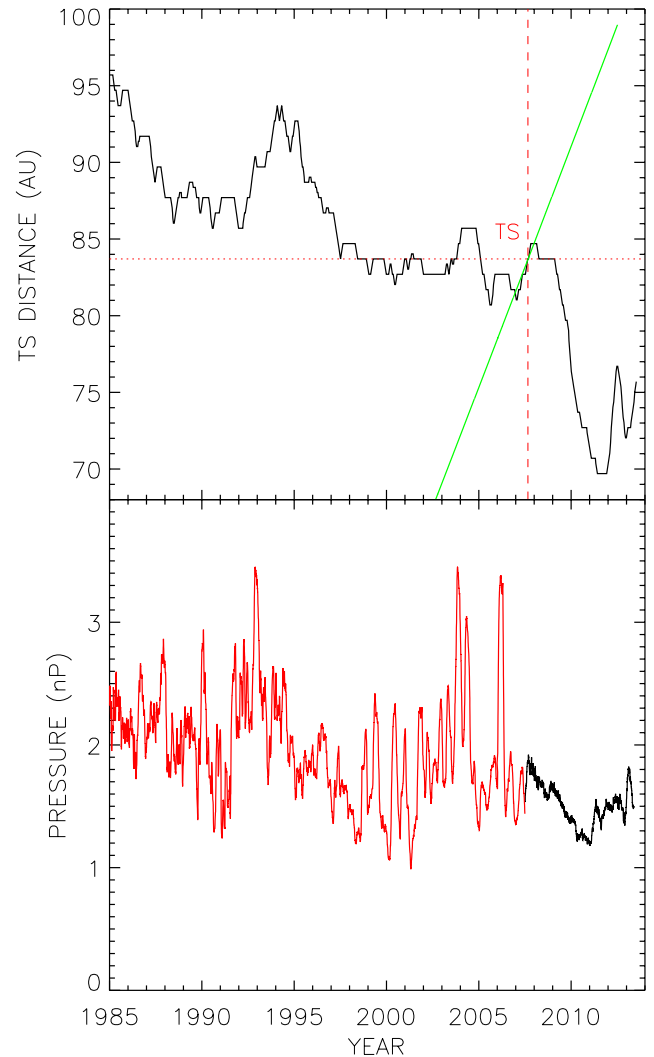


Figure 4. TS location derived from the model using the dynamic pressures in the bottom panel as input. The diagonal line shows the V2 location. (A color version of this figure is available in the online journal.)

to increased outward motion of the heliosheath. Thus calculating the expected flux through the heliosheath depends on many factors which are not well determined.

4. SUMMARY

V2 has observed a factor of two increase in the plasma density and plasma flux in 2011 which persists through 2012. This increase restores the density and flux levels to those observed just after the TS crossing and before a factor of two decrease observed in 2008. A possible explanation is that solar minimum conditions are ending in the outer heliosphere and V2 is observing more slow, higher-density, and higher-flux wind. The densities and fluctuations in density are comparable to those just after the TS, before the arrival of solar minimum in 2008. The fluxes at *Wind* and V2 are now comparable, whereas the *Wind* flux was 50% larger at solar minimum. The percentage difference between equatorial fluxes and higher-latitude fluxes was similar to the 1996–1999 solar minimum, even though the total flux was much lower in the recent solar minimum. The difficulty with this explanation is that the speed in the heliosheath has not changed significantly as might be expected for a return to low-speed wind.

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