Reconnection at the Heliopause: Predictions for Voyager 2

S. A. Fuselier$^{1,2}$ and I. H. Cairns$^3$

$^1$Space Science and Engineering Division, Southwest Research Institute, San Antonio, TX 78228, USA
$^2$Department of Physics and Astronomy, University of Texas at San Antonio, San Antonio, TX 78249, USA
$^3$School of Physics, University of Sydney, NSW 2006, Australia

sfuselier@swri.edu

Abstract. Predicted and observed properties of the inner and outer heliosheath were recently used to assess whether magnetic reconnection was occurring at the Voyager 1 crossing of the heliopause. It was concluded that reconnection may not have been occurring locally, but may have been occurring at a location remote from Voyager 1. Here observations of 37 to 70 keV electrons measured by the LECP instrument on Voyager 1 are interpreted as possible evidence for remote reconnection and the study is extended to the heliopause near the projected crossing location of Voyager 2, where the plasma depletion layer (PDL) should be significantly stronger. The predicted plasma properties are used to determine if local reconnection is possible at this projected heliopause crossing.

1. Introduction

Voyager 1 crossed the heliopause in August 2012 and was the first spacecraft to directly sample the outer heliosheath/local interstellar medium (LISM) near the boundary [1,2,3]. Over the course of almost a year, the plasma density increased and the magnetic field magnitude decreased (except during the passage of shocks in the LISM). These changes in the plasma parameters are characteristic of a plasma depletion layer [4]. The plasma depletion layer near the heliopause was predicted [5] and is analogous to the plasma depletion layer at the Earth’s magnetopause.

A plasma depletion layer forms because draping of the interstellar magnetic field against the heliopause increases the magnetic field magnitude and the perpendicular temperature of the plasma. These quantities increase until the perpendicular to parallel temperature anisotropy of the ions exceeds the threshold of the electromagnetic ion cyclotron (EMIC) instability. The waves grow rapidly to saturation and pitch-angle scatter ions into the parallel direction, reducing the temperature anisotropy. The scattered ions stream along the magnetic field and leave the region, resulting in a density decrease. The temperature anisotropy and the plasma density decrease are bounded throughout the plasma depletion layer by the marginal stability threshold of the EMIC instability [6,7]. The PDL is an example of a micro-kinetic process that has global-scale consequences in a plasma. Since this process is kinetic in nature, it is not captured in global, isotropic magnetohydrodynamic (MHD) computer simulations.
Magnetic reconnection is another inherently kinetic process that has global consequences at the Earth’s magnetopause. In particular, reconnection can mitigate the effect of magnetic field draping at the magnetopause. Reconnected field lines may convect north and south over the magnetic poles instead of slipping east or west around the flanks of the magnetopause. A similar effect may occur at the heliopause if there is reconnection at the boundary.

Reconnection at the Earth’s magnetopause is asymmetric and often involves a substantial guide field (i.e., component reconnection). The asymmetry occurs because there is a large change in density and a smaller change in magnetic field magnitude across the magnetopause. The magnetosheath density at the magnetopause is of the order of 20 cm$^{-3}$ while the outer magnetosphere density is of the order of 0.1 cm$^{-3}$, resulting in the density changing by a factor $\approx 200$ (e.g., [8]). The magnetic field magnitude in the magnetosheath is of the order of 56 nT while that in the outer magnetosphere is of the order of 25 nT, resulting in the magnetic field magnitude changing by a factor of $\approx 2$ at Earth’s magnetopause. Component (or guide field) reconnection with magnetic shear angles as small as $\sim 90^\circ$ may occur at the magnetopause (e.g., [9]).

Reconnection at the heliopause is also asymmetric and may involve a substantial guide field. The outer heliosheath/LISM density at the heliopause is approximately 0.05 cm$^{-3}$ [2] while the inner magnetosphere density is estimated to be approximately $2 \times 10^3$ cm$^{-3}$ (from Voyager 2 measurements, [10]), resulting in the density changing by a factor of 25. The outer heliosheath magnetic field magnitude, from Voyager 1 measurements is approximately 0.44 nT [3] while the outer magnetosphere magnitude is approximately 0.27 nT, resulting in the magnetic field magnitude changing by a factor of $\approx 2$. At the heliopause, the magnetic shear angle at the Voyager 1 crossing was only the order of $10^\circ$. Thus, the guide field (or non-reconnecting component of the magnetic field) may be very large.

A substantial electron diamagnetic drift occurs for asymmetric reconnection in the presence of a strong guide field [11]. If the electron drift speed is greater than the local Alfvén speed at the boundary, then reconnection is suppressed locally. This limiting velocity leads to conditions on the magnetic shear angle and the change in plasma beta across the boundary. Reconnection is suppressed when there is a large change in plasma beta and a small magnetic shear across the boundary [11]. However, although reconnection may be suppressed locally, it may be occurring remotely at a location where the diamagnetic drift velocity is less than the local Alfvén speed.

The suppression of reconnection at the heliopause has been investigated for the Voyager 1 crossing in two studies [11, 12]. The first study [11] was not limited to the location of the Voyager 1 crossing. It used global MHD simulations to determine the plasma properties over nearly the entire heliopause and concluded that reconnection occurs only where the magnetic shear angle is nearly $180^\circ$. The second study [12] used local measurements from Voyager 1 and 2, models for the pick up ions in the inner and outer heliosphere, and properties of the plasma depletion layer to determine the plasma properties at the heliopause at the Voyager 1 crossing. This study also concluded that reconnection was probably not occurring locally at the Voyager 1 heliopause location.

The purpose of this paper is to extend the second study [12] to 1) present observations that, by analogy with observations at Earth, suggest that reconnection was occurring at the heliopause remotely from the Voyager 1 location, and 2) determine if reconnection may be suppressed at the projected location of the Voyager 2 crossing of the heliopause. In particular, the effect of the plasma depletion layer (PDL) on predictions for reconnection is investigated because the PDL is predicted to be stronger at the Voyager 2 crossing than at the Voyager 1 crossing.

2. Reconnection at the Voyager 1 heliopause crossing

Table 1 summarizes the plasma parameters at the Voyager 1 crossing of the heliopause from [12]. The plasma density in the depletion layer is extrapolated from the Langmuir wave profile [2]. Over the course of the year following the heliopause crossing, this density increased by more than a factor of two as the spacecraft traversed the plasma depletion layer. A corresponding decrease in the magnetic field magnitude was not observed directly, due to the magnetic field increases caused by several
shocks propagating into the interstellar medium [3, 13] but can be discerned if the effects of the first shock is removed [4]. The ion temperature in the outer heliosheath was determined from the properties of the plasma depletion layer and an assumption that pick-up ions are 3% of the total ion density, consistent with pick-up ion models [14,15].

| Table 1: Plasma parameters at the heliopause along the Voyager 1 trajectory |
|---------------------------------|---------------------------|----------------------|
| Plasma parameter                | Value                     | Origin               |
| Density in the depletion layer adjacent to the heliopause | N = 0.047 cm⁻³ | Extrapolated from the Langmuir wave profile |
| Magnetic field magnitude in the depletion layer adjacent to the heliopause | B = 0.44 nT | Measured by the Voyager 1 magnetometer |
| Total temperature               | T = 1.5 x 10⁴ K           | Estimated from the plasma depletion layer properties and assuming 0.03% pick up ions |
| Density in the inner heliosheath adjacent to the heliopause | N = 2 x 10⁻³ cm⁻³ | Assumed, consistent with Voyager 2 observations |
| Magnetic field magnitude in the inner heliosheath at the heliopause | B = 0.25 nT | Measured by the Voyager 1 magnetometer |
| Total temperature in the inner heliosheath at the heliopause | T = 2 x 10⁶ K | Estimated from the assumption that there are 16.5% pick up ions |
| Plasma beta in the depletion layer | 0.13 | Computed from N, B, and T in the plasma depletion layer |
| Plasma beta in the inner heliosheath | 2.2 | Computed from N, B, and T in the inner heliosheath |
| Δβ across the heliopause = | | Δβ = 2.1 |

For the inner heliosheath, [12] used a mixture of Voyager 1 and Voyager 2 observations and some results from modeling. The density in the inner heliosheath at Voyager 2 was used for the inner heliosheath density at Voyager 1. Voyager 1 measured the magnetic field magnitude in the inner heliosheath just before the heliopause crossing [3]. The ion temperature was determined from the assumption that there are 16.5% pick-up ions relative to the total ion population [14, 16] and that pick-up ions dominate the overall plasma temperature.

Table 1 shows the plasma betas on both sides of the heliopause computed from these densities, ion temperatures, and magnetic fields and these betas. Also in Table 1 is the magnetic shear angle at the magnetopause measured by the Voyager 1 magnetometer. Figure 1 shows the test for suppression of reconnection from Swisdak et al. [11] for the Voyager 1 crossing (blue filled circle). For the measured magnetic shear and Δβ from Table 1, Figure 1 shows that reconnection is suppressed locally at the Voyager 1 crossing of the heliopause. The magnetic shear angle at the magnetopause would have had to be of the order of 90°, or about 15 times larger than the shear angle observed by Voyager 1, for reconnection to be possible.
3. Possible evidence for remote reconnection at the heliopause

At a basic level, the heliopause and magnetopause share many common characteristics. In this section, an analogy is drawn between the magnetopause and the heliopause to help interpret electron observations at the latter boundary.

For some interplanetary magnetic field orientations, there are large regions of the Earth’s magnetopause where reconnection is suppressed locally. When the IMF is northward, the region at low latitudes directly in the Earth-Sun line represents one such region. While reconnection is suppressed locally, there are locations at high latitudes where reconnection is not suppressed and is occurring essentially uninterrupted [17]. Often, spacecraft traversing the magnetopause at low latitudes are magnetically connected to reconnection sites at high latitudes. Electron observations during these crossings show two distinct characteristics that indicate that reconnection is occurring remote from the spacecraft location. First, there is a boundary layer inside the magnetosphere, called the low latitude boundary layer, where there is a loss of high-energy (several keV) electrons that are...
normally present in the magnetosphere. Second, on the sunward side of the magnetopause there is another boundary layer, often called the magnetosheath boundary layer, that contains moderately energized (100’s of eV to about 1 keV) electrons streaming along the magnetic field from the reconnection location.

Magnetospheric electrons are lost in the low latitude boundary layer because the magnetic field lines that thread the region are open or were open at one time. Electrons propagate very rapidly along magnetic field lines, so they can exit the magnetosphere along open field lines much faster than the ions. On the sunward side of the magnetopause, the magnetosheath boundary layer is formed by heating of the relatively cold magnetosheath electrons in or near the magnetopause current layer. They stream along reconnected field lines from the direction of the reconnection site and can propagate long distances (more than 60,000 km) from this site.

Voyager 1 did not have electron measurements in the appropriate energy range to observe the heated, streaming electrons in the boundary layer on the outer heliosheath side of the heliopause. However, it did have electron measurements in the appropriate energy range to observe the loss of inner heliosheath electrons in the boundary layer adjacent to the heliopause, equivalent to the low latitude boundary layer at Earth’s magnetopause. Figure 2 shows Voyager 1 observations that straddle the heliopause and show possible evidence of reconnection remote from the spacecraft location, as explained next.

Figure 2: LECP and Magnetometer data surrounding the Voyager 1 heliopause crossing. In the boundary layer, 37 – 70 keV electrons are lost, indicating that there was remote reconnection of the field lines that thread this region.
The heliopause (blue line) is placed at the steep gradient in the cosmic ray flux (not shown) and the equally steep gradient in the 3.4 – 17.6 MeV H+ in the top panel. As the heliopause is approached from the inner heliosphere side, the 37 – 70 keV electrons are lost prior to the heliopause crossing. This region where the 37 – 70 keV electrons are lost is analogous to the low latitude boundary layer at the magnetopause, where energetic magnetospheric electrons are lost [17]. Also in analogy with the Earth’s magnetopause, the 37 – 70 keV electrons are lost prior to the heliopause crossing because those field lines in the inner heliosheath were open to the LISM at one time or remained open throughout the traversal of the boundary layer.

The brief reappearance of the 37 – 70 keV electrons just before 2012.6 may indicate either transient remote reconnection or, more likely, simply the motion of the heliopause first further away from Voyager 1, then closer to the spacecraft. The dips in the 3.4 – 17.6 MeV H+ fluxes prior to the reappearance of the 37 – 70 keV electrons and after they went away for the last time suggest that the heliopause was in motion the entire time that Voyager 1 was in the boundary layer. The reappearance of energetic magnetospheric electrons because of boundary motion happens very frequently at the Earth’s magnetopause [17].

The observations in Figure 2 were also interpreted using global MHD simulations [18,19]. These studies place the heliopause crossing at the dashed line in Figure 2, which is identified here as the transition into the boundary layer. One of the studies [18] identifies the crossing of the outer boundary layer at the solid vertical line in Figure 2, which is identified here as the crossing of the heliopause. The conclusions from the MHD studies on the heliopause location are not consistent with observations at the Earth’s magnetopause, which show a loss of energetic electrons in the magnetospheric boundary layer before the magnetopause is encountered. One of the MHD studies [19] did not include reconnection at the heliopause boundary. However, the conclusion from the other study [18] is the same as the conclusion here: the electron observations in Figure 2 are consistent with a heliopause that was undergoing reconnection remote from the Voyager 1 location.

4. Reconnection at the projected Voyager 2 heliopause crossing
The same calculations that were used to investigate the possibility of reconnection at the Voyager 1 crossing of the heliopause are applicable to the projected Voyager 2 crossing of the heliopause. While the predicted date for the crossing is unknown, the conditions at the heliopause at the time of the crossing are predictable. Here, these conditions are determined from 1) the extrapolation of the current Voyager 2 plasma and magnetic field measurements to the heliopause using Voyager 1 observations as a guide, 2) an understanding of the plasma depletion layer process at the heliopause, and 3) a prediction of the magnetic shear angle at the projected crossing.

Table 2 shows the plasma parameters determined from this analysis. For the inner heliosheath, the magnetic field magnitude is assumed to be the same as that for Voyager 1. This magnitude is higher by about a factor of 2 from the magnitude currently measured on Voyager 2. However, the magnitude field magnitude increased as Voyager 1 approached the heliopause. The plasma density is assumed to be approximately equal to the currently measured density at Voyager 2 [10]. The temperature is the same as at Voyager 1 because it is estimated from the same model as that for the Voyager 1 crossing, using the same parameters (see, [12]).

For the outer heliosheath, the basic assumption is that Voyager 2 will cross the heliopause into a much stronger plasma depletion layer than was observed at Voyager 1. The predicted strong plasma depletion layer is consistent with the location of the crossing relative to the IBEX Ribbon and the nose of the heliosphere (see, [4]). The Voyager 1 and 2 measurements of a lower frequency cutoff of the heliospheric radio emissions measured in the 1980’s, 1990’s, and 2000’s (see, [20]) provide a lower bound on the density in the depletion layer adjacent to the heliopause (see [5]). Radio emissions were not observed below approximately 1.8 kHz, which corresponds to a plasma density of 0.04 cm-3. For the magnetic field magnitude in the strong depletion layer, a value of 0.8 nT is assumed. This magnitude is about a factor of 2 larger than the magnetic field magnitude observed by Voyager 1 at the
heliopause and is indicative of about a factor of 4 increase in the magnetic field in a strong plasma depletion layer [4].

The temperature anisotropy and temperature at the heliopause are computed using the assumption of an 0.03% pick up ion population and the anisotropy-beta relationship in the strong plasma depletion layer (see, [5]).

### Table 2: Plasma parameters at the projected heliopause crossing along the Voyager 2 trajectory

| Plasma parameter                                      | Value          | Origin                                                                 |
|-------------------------------------------------------|----------------|------------------------------------------------------------------------|
| Density in the depletion layer adjacent to the heliopause | $N = 0.04 \text{ cm}^{-3}$ | Minimum density in depletion layer from 1.8 kHz lower bound of radio wave emissions [Gurnett et al., 2003] |
| Magnetic field magnitude in the depletion layer adjacent to the heliopause | $B = 0.8 \text{ nT}$ | Assumed to be a stronger depletion layer than at the Voyager 1 location [Cairns and Fuselier, 2017] |
| Total temperature                                      | $T = 1.4 \times 10^4 \text{ K}$ | Estimated from the plasma depletion layer properties and assuming 0.03% pick up ions |
| Density in the inner heliosheath adjacent to the heliopause | $N = 2 \times 10^{-3} \text{ cm}^{-3}$ | Assumed, consistent with Voyager 2 observations [Richardson et al., 2017] |
| Magnetic field magnitude in the inner heliosheath at the heliopause | $B = 0.25 \text{ nT}$ | Assumed, measured by the Voyager 1 magnetometer at the heliopause |
| Total temperature in the inner heliosheath at the heliopause | $T = 2 \times 10^6 \text{ K}$ | Estimated from the assumption that there are 16.5% pick up ions |
| Plasma beta in the depletion layer                     | 0.03           | Computed from $N$, $B$, and $T$ in the plasma depletion layer |
| Plasma beta in the inner heliosheath                   | 2.2            | Computed from $N$, $B$, and $T$ in the inner heliosheath |
| $\Delta \beta$ across the heliopause = $|\beta_{\text{IHS}} - \beta_{\text{PDL}}|$ | $\Delta \beta = 2.2$ | Estimated for the projected Voyager 2 heliopause crossing |

Using the plasma parameters in Table 2, the plasma beta in the inner heliosheath is 2.2 (the same as that for Voyager 1 just before it crossed the heliopause) and the plasma beta in the outer heliosheath/plasma depletion layer is 0.03. Thus the predicted $\Delta \beta$ across the Voyager 2 heliopause location is approximately 2.2 because the plasma beta in the outer heliosheath is very low. This $\Delta \beta$ is very similar to the one at the Voyager 1 crossing (see Table 1) and is dominated by the plasma beta in the inner heliosheath.

The final quantity needed to determine if reconnection is suppressed at the projected Voyager 2 heliopause crossing is the magnetic shear angle. Voyager 2 may be crossing the heliopause at a location where the interstellar magnetic field has nearly the same orientation as the undraped field orientation far from the heliopause (see [4]). In RTN coordinates, the magnitude of the T and N components may be approximately equal, and therefore the angle in the T-N plane would be approximately $45^\circ$. In the inner heliosphere, the magnetic field orientation is approximately in either
the +T or –T direction, depending on the magnetic sector that the spacecraft is in. Thus, the magnetic shear angle at the heliopause is predicted to be either ~45° or ~135°.

Figure 1 shows \( \Delta \beta \) and the two magnetic shear angles from Table 2 for the projected Voyager 2 crossing. If the magnetic shear angle is ~135°, then reconnection may not be suppressed at the Voyager 2 crossing. Even for the smaller magnetic shear angle, the suppression of reconnection may be marginal.

5. Summary and Conclusions

Figure 1 shows that reconnection was likely suppressed locally at the Voyager 1 crossing. However, observations in Figure 2 of 37 to 70 keV electrons measured by LECP near the heliopause, specifically the loss of these electrons in a boundary layer on the inner heliosheath side of the heliopause, are closely analogous to similar observations of energetic electrons lost into the magnetosheath from remote reconnection sites on the Earth’s magnetopause. Figure 1’s result is in agreement with modeling of the conditions at the crossing [11] and the result inferred in Figure 2 is also not inconsistent with the conclusion of [18] that reconnection may occur at the heliopause away from Voyager 1’s location.

For the projected Voyager 2 crossing, Figure 1 shows that the suppression of reconnection will depend on \( \Delta \beta \) and the T component of the magnetic field direction at the time of the crossing. \( \Delta \beta \) is driven by the plasma beta in the inner heliosheath because the plasma beta in the outer heliosheath and plasma depletion layer is very small. The plasma beta in the inner heliosheath is driven strongly by the ion temperature. This temperature is determined by the percentage of pickup ions in the plasma, which is not directly measured by Voyager 2. Thus, \( \Delta \beta \) at the projected Voyager 2 crossing is strongly model dependent.

The magnetic shear angle at the projected Voyager 2 crossing is also strongly model dependent. This angle depends on the shape of the heliopause, which determines how the interstellar magnetic field drapes against the boundary. With a reasonable estimate of the draping (see, [4]), the magnetic shear angle depends on the sign of the T component of the field in the inner heliosheath. The most recently processed magnetic field data available on the CDAWeb site is more than a year out of date. These data indicate that, if Voyager 2 remains in that sector orientation up to the heliopause, then the magnetic shear angle will be approximately 45°. Figure 1 shows that reconnection is likely marginally suppressed for a magnetic shear angle of 45°. However, if Voyager 2 transitions to the opposite sector, then reconnection is possible.

The plasma instrument on Voyager 2 may observe the effects of local reconnection as an increase in the flow velocity and a change in the flow direction of the ions. Moreover, in analogy with observations of reconnection at the Earth’s magnetopause, these changes in the ion flow would be accompanied by a loss of the 37 to 70 keV electrons measured by LECP. Even if reconnection is suppressed locally, it is likely that these energetic electrons will be lost in the boundary layer because, like at the Voyager 1 crossing, reconnection is likely to be occurring remotely from the Voyager 2 location.

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7. References

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