Reconnection at the Heliopause: Comparing the Voyager 1 and 2 Heliopause Crossings

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1. Introduction

Voyager 1 crossed the heliopause in 2012 and made the first in situ observations of the boundary and of the local interstellar medium (LISM) adjacent to the heliopause [1, 2, 3]. Voyager 2 crossed the heliopause in 2018 at a very different location from Voyager 1, also made in situ observations of the boundary and the LISM, and became the second spacecraft to leave the heliosphere [4, 5, 6, 7]. Voyager 1 was in a boundary layer on the heliospheric side of the heliopause (i.e., in the inner heliosheath) for ~29 days. This boundary layer was thick and highly structured [3]. The top two panels of Figure 1 show observations from the Low Energy Charged Particle (LECP) instrument [1] and the magnetometer [3], respectively. The 3.4-17.3 MeV H+ are a mixture of heliospheric anomalous cosmic rays (ACRs) and low energy Galactic Cosmic Rays (GCRs). However, ACRs dominate the flux in the inner heliosheath and are accelerated out of the ion populations at the termination shock and in the inner heliosheath.
heliosheath. Fluxes of these ACRs and GCRs are relatively constant in the inner heliosheath, but have considerable structure in the relatively thick boundary layer. In the boundary layer, there are rapid flux and total magnetic field changes that are correlated. Across the heliopause, the ion flux decreases abruptly and there is some indication of a possible boundary layer in the outer heliosheath before the fluxes decrease to their GCR levels. The ACR gyroradius is \( \sim 10^9 \) m. Therefore, the ACR level should have decreased in 0.6 days at Voyager 1’s speed relative to the Sun, if the ACRs in the outer heliosheath were only due to scattering of large gyroradius ions at the boundary. In contrast, the smooth fall-off in flux lasted \( \sim 5-7 \) days beyond the heliopause. The bar at the top of the ion flux panel shows that 37-70 keV electrons (also of heliospheric origin) disappear somewhat abruptly at the inner edge of the boundary layer. In the boundary layer, there was a short interval when these fast-moving electrons returned.

One of the surprises from the Voyager 1 crossing was that the magnetic shear angle across the heliopause, between the inner and outer heliosheath (or LISM), was only \( \sim 6^\circ \) [3]. The angle between the solar wind magnetic field in the inner heliosheath and the direction of the interstellar magnetic field far from the heliopause, e.g., as deduced from the IBEX ribbon [8, 9], is at least \( \sim 45^\circ \) (e.g., [10]). Thus, the low-shear heliopause observed by Voyager 1 indicates that there is considerable draping of the interstellar magnetic field at the heliopause. Furthermore, these observations indicate that the heliopause is not a simple paraboloid of rotation about the direction of the Sun’s motion in interstellar space [10, 11].

The regions surrounding the Voyager 2 heliopause crossing had some similarities, but in general was very different from those observed by Voyager 1. The bottom two panels of Figure 1 show the same electron, ion, and total magnetic field data from the Voyager 2 crossing as in the top panels for the Voyager 1 crossing. Voyager 2 was in the boundary layer in the inner heliosheath for only \( \sim 3 \) days [4, 6] versus \( \sim 29 \) days for Voyager 1. While the magnetic field magnitude was enhanced in this thin layer, there was none of the structure seen in the thick boundary layer by Voyager 1. Similar to the Voyager 1 crossing, the Voyager 2 energetic electrons disappear somewhat abruptly at the inner edge of the boundary layer. Unlike the Voyager 1 electrons, the Voyager 2 energetic electrons did not reappear in the thin boundary layer. In the outer heliosheath, or LISM, beyond the heliopause, Voyager 2 observed a gradual decrease in the energetic ion flux. This decrease was much more gradual than that observed by Voyager 1. For the magnetic field, the major difference between the two crossings was that the total magnetic field was enhanced well before the Voyager 2 heliopause (see Figure 1). This enhanced total field lasted for 73 days and was called a “magnetic barrier” [4]. The persistence of this enhanced magnetic field has important implications for the heliopause structure, as described below.

The magnetic shear angle of 16.5° at the heliopause for the Voyager 2 crossing was a surprise. Based on the orientation of the solar wind magnetic field in the inner heliosheath and the interstellar magnetic field far from the heliopause, the shear angle was expected to be at least \( \sim 45^\circ \) and possibly as high as 135° [10, 12]. This lower-than-expected magnetic shear is again evidence of considerable draping of the interstellar magnetic field at the heliopause.

Observations of boundary layers in the inner heliosphere and energetic heliospheric ions in the outer heliosphere adjacent to the heliopause are evidence of plasma transfer processes at the boundary. In analogy with the Earth’s magnetopause, magnetic reconnection is a prime candidate for plasma transfer (e.g., [13]). Also, in analogy with the Earth’s magnetopause, magnetic reconnection at the heliopause is highly asymmetric (e.g., [13, 14]). The factor of \( \sim 100 \) difference in the densities in the inner and outer heliosheath [5, 7] is similar to the typical density difference between the Earth’s magnetosphere and magnetosheath (e.g., [13]). These large density differences make reconnection at the magnetopause and the heliopause highly asymmetric.
Figure 1. LECP and Magnetometer data surrounding the Voyager 1 and 2 heliopause crossing. The boundary layer in the inner heliosheath was much thicker for Voyager 1 than for Voyager 2. The energetic protons, predominantly ACRs, extend much farther into the outer heliosphere at the Voyager 2 crossing. In the boundary layers, 37-70 keV electrons are lost, indicating that reconnection on these field lines opened them at some time in the past and that they may or may not have remained open. The primary differences in the total magnetic field profiles at the two crossings is the magnetic barrier in the inner heliosphere for the Voyager 2 crossing.
Asymmetric reconnection is subject to special limitations, particularly in localized regions where the magnetic shear across the current layer is small or, equivalently, there is a strong guide field. Asymmetric reconnection may be suppressed locally for strong guide fields [15] because of a substantial electron diamagnetic drift. This suppression, called diamagnetic drift suppression, occurs if the electron drift is greater than the local Alfvén speed at the boundary. This limitation on the electron drift leads to conditions on the change in plasma beta and the magnetic shear angle across the boundary.

There have been several investigations of local suppression of reconnection at the heliopause for the Voyager 1 crossing [16, 17, 12]. These studies concluded that local reconnection was likely suppressed at the Voyager 1 crossing. However, reconnection far from Voyager 1 could have produced the relatively thick boundary layer seen in Figure 1. This conclusion is in analogy with the Earth’s subsolar magnetopause for northward interplanetary magnetic field conditions [17]. Locally at the Earth’s subsolar magnetopause, reconnection is suppressed because the magnetic shear is too small and the change in plasma beta is too large. However, reconnection occurring near the magnetospheric cusps and far from the subsolar point produces a relatively thick boundary layer with properties similar to that of the boundary layer observed by Voyager 1 at the heliopause.

Prior to the Voyager 2 heliopause crossing, there were also predictions for local reconnection at the heliopause [12, 14]. Based on predictions for the plasma and magnetic field at the heliopause, it was concluded that reconnection may occur locally depending on the magnetic shear at the boundary and that the associated plasma heating may be significant.

The purpose of this paper is to revisit the possibility of local asymmetric reconnection at the Voyager 2 heliopause crossing in light of the in situ observations at the boundary. The Voyager 1 and 2 crossings are compared and contrasted. It is shown that, despite the very low magnetic shear conditions at the Voyager 2 heliopause, magnetic reconnection is not suppressed locally. The primary reason why reconnection is not suppressed locally is that the magnetic barrier lowers the plasma beta in the inner heliosheath and thus reduces the change in plasma beta across the heliopause. Local reconnection may explain the relatively thin boundary layer observed at the Voyager 2 heliopause. ACRs in reconnected flux tubes may also explain the slow falloff in ACR flux beyond the heliopause for Voyager 2.

2. Plasma parameters and predictions for reconnection at the Voyager 1 and 2 heliopause crossings

Several plasma and magnetic field parameters at the heliopause are needed to determine if reconnection is suppressed locally at the Voyager 2 crossing. These include the temperature, density, and total magnetic field to determine the plasma beta and the magnetic field directions on either side of the boundary to determine the magnetic shear. For the heliopause crossings, Voyager 2 had a distinct advantage over Voyager 1 because it had an operating instrument that measured the thermal plasma in the inner heliosheath. Although this plasma instrument measured almost the entire density of the thermal plasma in the inner heliosheath [7], it could not measure the plasma temperature because it did not measure the pickup ions. Therefore, the temperature is estimated here from knowledge of the pickup ion population in the inner heliosheath. Table 1 shows the required plasma and field parameters, their values on either side of the Voyager 1 and 2 heliopause crossings, and how the parameters were obtained or estimated.

Draping of the interstellar magnetic field at the heliopause produces a plasma depletion layer (PDL) where the magnetic field increases and the plasma density decreases (Fuselier and Cairns, 2013; Cairns and Fuselier 2017). The magnetic field magnitude, the total plasma density, and the uncertainties in these quantities were directly measured by Voyagers 1 and 2 in the PDL. The higher magnetic field magnitude and the lower plasma density in the Voyager 2 depletion layer compared to that for Voyager 1 (see Table 1) indicates that the depletion effect was stronger at Voyager 2 than at Voyager 1, as predicted (Cairns and Fuselier, 2017; Fuselier and Cairns, 2017). The stronger depletion layer is the reason why the plasma beta is much lower in the PDL adjacent to the Voyager 2 crossing than in the Voyager 1 crossing (see Table 1).
**Table 1:** Plasma parameters at the heliopause along the Voyager 1 and 2 trajectories

| Plasma or magnetic field parameter | Value | Origin |
|-----------------------------------|-------|--------|
| Density in the depletion layer exterior to the heliopause | \(N = 0.047 \text{ cm}^{-3}\) | Voyager 1: Extrapolated from the Langmuir wave profile |
|                                    | \(\pm 0.01 \text{ cm}^{-3}\) | Voyager 2: Similar measurement close to the heliopause |
| Magnetic field magnitude in the depletion layer exterior to the heliopause | \(B = 0.44 \text{ nT}\) | Voyager 1 and 2: Measured by the magnetometers |
|                                    | \(\pm 0.03 \text{ nT}\) | |
| Total temperature exterior to the heliopause | \(T = 1.4 \times 10^4 \text{ K}\) | Voyager 1 and 2: Estimated from the plasma depletion layer properties and assuming 0.03% pick up ions |
|                                    | |
| Density in the inner heliosheath (Voyager 1) and magnetic barrier (Voyager 2) | \(N = 0.0023 \text{ cm}^{-3}\) | Voyager 1: Assumed the same as measured by Voyager 2 |
|                                    | \(\pm 0.001 \text{ cm}^{-3}\) | Voyager 2: measured by the plasma and plasma wave instruments |
| Magnetic field magnitude in the inner heliosheath (Voyager 1) and magnetic barrier (Voyager 2) | \(B = 0.25 \text{ nT}\) | Voyager 1 and 2: Measured by the magnetometers |
|                                    | \(\pm 0.03 \text{ nT}\) | |
| Total temperature in the inner heliosheath (Voyager 1) and magnetic barrier (Voyager 2) | \(T = 2 \times 10^6 \text{ K}\) | Voyager 1 and 2: Estimated from the assumption that there are 16.5% pick up ions |
|                                    | |
| Plasma beta in the depletion layer | 0.117 | Computed from \(N, B,\) and \(T\) in the plasma depletion layer |
| Plasma beta in the inner heliosheath (Voyager 1) and magnetic barrier (Voyager 2) | 2.56 | Computed from \(N, B,\) and \(T\) in the inner heliosheath (Voyager 1) and in the magnetic barrier (Voyager 2) |
| \(\Delta \beta\) across the heliopause = | \(\Delta \beta = 2.45\) | |
| \(\frac{\beta_{\text{HS or MB}} - \beta_{\text{PDL}}}{\beta_{\text{PDL}}}\) | \(\pm 1.27\) | Voyager 1 and 2: Measured by the magnetometers |
| Magnetic shear angle across the heliopause | \(6\degree \pm 2.2\degree\) | |

The magnetic field magnitudes and uncertainties in the magnitude in the inner heliosheath (Table 1) were measured directly by the Voyager 1 and 2 magnetometers. The magnetic field magnitude at Voyager 1 was a factor of 2 lower than that at Voyager 2, primarily because of the magnetic barrier adjacent to the Voyager 2 heliopause. Since the densities and temperatures in the inner heliosheath are assumed to be the same for Voyager 1 and Voyager 2, the higher magnetic field magnitude in the magnetic barrier is the reason why the plasma beta in the inner heliosheath for the Voyager 2 crossing is so much lower than that for the Voyager 1 crossing.
Figure 2. Regions in Δβ-magnetic shear of possible and suppressed reconnection. For the Voyager 1 heliopause crossing, reconnection was probably suppressed locally. For the Voyager 2 crossing, reconnection was marginally possible.

The assumption of identical densities and temperatures for the Voyager 1 and 2 inner heliosheaths requires some discussion. The density was measured directly by Voyager 2 (except for the pickup ion density), but there was no corresponding direct measure of the shocked solar wind density in the inner heliosheath for Voyager 1. Neither Voyager spacecraft could measure the pickup ion population, which dominates the pressure in the inner heliosheath. Therefore, the temperatures at Voyager 1 and 2 were estimated from the assumption that pickup ions represented 16.5% of the total density in the inner heliosheath. This assumption is consistent with models [18] and extrapolation of the pickup ion density in the heliosphere from New Horizons observations [19].

Figure 2 shows the test for suppression of reconnection from theory [15, 20] for the Voyager 1 crossing (dark blue filled circle) and the Voyager 2 crossing (brown filled circle) using the Δβ and magnetic shear angles in Table 1. For Voyager 1, Figure 2 shows that reconnection is suppressed locally at the heliopause crossing. The magnetic shear angle at the magnetopause would have had to be of the order of 90°, or about 15 times larger than the observed shear angle, for reconnection to be possible locally at the Voyager 1 crossing. Previous estimates of Δβ and magnetic shear at the Voyager 1 crossing resulted in similar conclusions [20, 12]. Even though local reconnection was suppressed, the boundary layer structure and particularly the loss of the energetic heliospheric electron in the boundary layer suggest that remote reconnection opened field lines in the boundary layer [12].

For Voyager 2, Figure 2 shows that reconnection is marginally possible locally at the heliopause crossing. The diamagnetic suppression test in Figure 2 is a necessary, but not a sufficient test for reconnection. Therefore, it does not prove that there was local reconnection shortly before or during the
Voyager 2 crossing. However, the loss of the energetic, heliospheric electrons in the thin boundary layer suggests that this region is, or was, on reconnected field lines. Also, it is well known that local reconnection produces thin boundary layers at Earth’s magnetopause (e.g., [21]). Finally, the presence of energetic, heliospheric ions in a relatively thick layer adjacent to the heliopause in the outer heliosheath is also a characteristic of open field lines (e.g., [22]).

3. Summary, Discussion, and conclusions

Voyager 1 and 2 observed very different boundary layers at their respective heliopause crossings (Figure 1). The boundary layer in the inner heliosheath for the Voyager 1 crossing was thick and highly structured. In contrast, the boundary layer in the inner heliosheath for Voyager 2 was considerably thinner.

Using observed and modelled properties of the plasma and magnetic field on the two sides of the heliopause (Table 1), the crossings were tested to determine if local reconnection could occur (Figure 2). For the Voyager 1 crossing, local reconnection was not possible because the magnetic shear was too small and the $\Delta B$ was too large. In contrast, for the Voyager 2 crossing, local reconnection was marginally possible. The possibility of local reconnection may explain why the Voyager 2 boundary layer was considerably thinner than that for Voyager 1 and why ACRs were observed considerably farther beyond the heliopause. It may also reduce the magnetic build-up and plasma depletion beyond the heliopause compared with the expectations based on the Voyager 1 observations.

Most of the plasma parameters for the two crossings were similar (or had to be assumed the same because of a lack of observations). Although the magnetic shear angle for the Voyager 2 crossing is almost three times that for Voyager 1, both shear angles are quite small (16.5°±2.2° versus 6°±2.2°, respectively). The primary reason for the difference in the predictions for local reconnection is the presence of a magnetic barrier in the inner heliosheath at the Voyager 2 heliopause crossing. The higher magnetic field magnitude reduces plasma beta in the inner heliosheath and therefore reduces $\Delta B$ across the heliopause. Thus the “magnetic barrier” facilitates local reconnection and plasma transfer across the heliopause.

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