

Plasma properties at the Voyager 1 crossing of the heliopause

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Abstract. In August 2012, Voyager 1 crossed the heliopause at a distance of 121.5 AU from the Sun. It is argued that the spacecraft entered a region in the outer heliosheath that had the characteristics of a plasma depletion layer. Observed plasma parameters at the heliopause, properties of plasma depletion layers, and some assumptions are used to derive a set of plasma parameters on both sides of the heliopause. Using the density, temperature, and magnetic field magnitude on each side, the corresponding plasma beta and Alfvén Mach number (in the outer heliosheath) are derived. These plasma parameters are used to demonstrate that the plasma depletion process is occurring in the outer heliosheath adjacent to the heliopause and these parameters are used to determine if lower hybrid waves are generated locally and if magnetic reconnection is occurring locally at the location of the Voyager 1 crossing. Reconnection may not be an effective source of superthermal electrons at the heliopause, based on the small Alfvén speeds there ($V_A < 100$ km/s) and an empirical connection between electron heating and Alfvén speed found in inner solar system studies.

1. Introduction

The heliopause is the location where the total pressures in the inner and outer heliosheath balance. This boundary is considered the outer limit of the solar wind plasma and magnetic field and the beginning of interstellar space. If the heliopause is in motion, then the pressures on the two sides of the boundary may not balance exactly. Recently, there are reports that the Voyager 1 spacecraft crossed this boundary at a distance of 123 AU from the Sun and entered interstellar space [1,2,3].

The density and magnetic field immediately upstream of the heliopause crossing are shown in Table 1. The density is derived from plasma wave instrument data. Specifically, occasional bursts of Langmuir waves in the outer heliosheath near the heliopause allow direct measurement of the density profile near the boundary. The value in Table 1 is determined by extrapolating back to the heliopause location using the density profile observed in the first ~250 days after the crossing on 25 August, 2012 [2]. The magnetic field is measured directly at the heliopause crossing by the Voyager 1 magnetometer. Across the heliopause, there was very little shear in the magnetic field [1].

After crossing the heliopause, the spacecraft entered a region of increasing plasma density and slightly decreasing magnetic field magnitude [1,3]. The density and magnetic field changes in this region are analogous to those observed in the plasma depletion layer upstream from the Earth's magnetopause. A plasma depletion layer [4] is produced by draping of magnetic field lines against a nearly impermeable obstacle, like a magnetosphere or heliosphere. At Earth, the formation and

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properties of the plasma depletion layer are well understood [e.g., 5,6,7], as follows: The magnetic field magnitude increases as the field drapes against the obstacle. This increase drives an increase in the perpendicular temperature of the ions (and electrons) and, according to double adiabatic theory [7,8], a dramatic decrease in the parallel temperature. Above a certain ion temperature anisotropy, the threshold of the electromagnetic ion cyclotron (EMIC) instability is exceeded. The EMIC waves grow rapidly, saturate, and pitch angle scatter ions into the parallel direction. The scattered ions are lost as they propagate along the draped magnetic field lines. Through this loss, the plasma density decreases and the temperature anisotropy increases. Further draping causes the instability to grow again and repeats the process of plasma loss. The temperature anisotropy remains close to the threshold of the EMIC instability throughout the plasma depletion layer. Another important result from this depletion process is a dramatic increase in the Alfvén speed and a similar dramatic decrease in the Alfvén Mach number.

In addition to temperature anisotropies that depend on plasma beta, opposite gradients in the density and magnetic fields are some of the defining features of a plasma depletion layer. The positive gradient in the density is evident in the Voyager 1 plasma wave data (see Figure 2 in [2]). However, the negative gradient in the magnetic field magnitude is not as evident because of transient increases in the total magnetic field resulting from shocks propagating past the spacecraft [1].

Table 1 shows the density and magnetic field in the “undisturbed” outer heliosheath upstream from the plasma depletion layer. The density was extrapolated from the plasma wave observations [2] while the magnetic field was estimated from the magnetic field observations [1,9] with the transient increases in the total magnetic field removed. The Alfvén speed in Table 1 was computed from these density and magnetic field values. The depletion factor in Table 1 quantifies the change in the Alfvén speed from the outer heliosheath to the plasma depletion layer adjacent to the heliopause.

The remainder of this paper uses the observed parameters in Table 1, the properties of the plasma depletion layer, and several assumptions to derive a set of plasma parameters for the local conditions at the Voyager 1 heliopause crossing. These parameters include the temperature and its anisotropy and the parallel and total plasma betas at the Voyager 1 crossing. The plasma conditions are then used to determine if certain plasma processes are active locally at the Voyager 1 heliopause crossing. The plasma processes considered here are the growth of lower hybrid waves in the plasma depletion layer and magnetic reconnection at the heliopause. Finally, the implications for a more extensive depletion layer and non-local effects are discussed.

Table 1: Plasma parameters in the outer heliosheath along the Voyager 1 trajectory

Plasma parameter	Value	Origin
Density in the depletion layer adjacent to the heliopause	$N = 0.047 \text{ cm}^{-3}$	Extrapolated from the Langmuir wave profile
Magnetic field magnitude in the depletion layer adjacent to the heliopause	$B = 0.44 \text{ nT}$	Measured by the magnetometer
Alfvén speed in the depletion layer adjacent to the heliopause	$V_A = 44 \text{ km/s}$	Derived from the density and magnetic field in the depletion layer
Density in the outer heliosheath upstream from the depletion layer	$N = 0.1 \text{ cm}^{-3}$	Extrapolated from the Langmuir wave profile
Magnetic field magnitude upstream from the depletion layer	$B = 0.3 \text{ nT}$	Estimated from the magnetic field measurements
Alfvén speed in the outer heliosheath upstream from the depletion layer	$V_A = 21 \text{ km/s}$	Derived from the density and magnetic field in the outer heliosheath
Degree of plasma depletion =	Depletion Factor = 2.1	Computed from the density and

$$B_{\text{PDL}}/B_{\text{OHS}} * \sqrt{(n_{\text{OH}}S/n_{\text{PDL}})}$$

magnetic field in the depletion
layer and outer heliosheath

2. Evidence of Plasma Depletion Layer Processes

The density decrease from the “undisturbed” outer heliosheath to the heliopause is certainly consistent with the plasma depletion process. However, there is additional evidence that the depletion process is active in the outer heliosheath adjacent to the heliopause. This evidence consists of the change in the Alfven speed and Alfven Mach number and an estimate of the changes in the ion temperature anisotropy with and without a plasma depletion layer.

The Alfven speed upstream from the plasma depletion layer is 21 km/s and is determined from the density and magnetic field in the region (Table 1). This speed is lower than the speed of approximately 26 km/s observed for the interstellar neutral Helium [10,11]. Assuming that the interstellar medium is in thermal and collisional equilibrium, the speeds and temperatures of all the neutral and ion species are the same. Thus, if there is no slowing of the ions in the outer heliosheath (i.e., either no shock or a weak shock in the interstellar medium upstream of the heliopause), then the Alfven Mach number is greater than 1 in the region. One of the known effects of a depletion layer is to reduce the Alfven Mach number of the flow past the obstacle [4,5]. The Alfven speed estimated in the depletion layer just beyond the heliopause is 44 km/s (Table 1), which is considerably higher than the bulk plasma flow speed in the outer heliosheath or the interstellar medium. Thus, near the heliopause, the flow is sub-Alfvenic. A similar effect occurs at the Earth’s magnetopause. The reduced Alfven Mach number allows magnetic reconnection at the Earth’s magnetopause over a wide range of latitudes [12,13], thereby affecting plasma entry into and escape from the magnetopause. This effect is potentially relevant to whether or not magnetic reconnection plays a major role at the heliopause, cf. [14,15].

Further evidence of the depletion process comes from estimates of the temperature anisotropy with and without a depletion layer. Double adiabatic theory [7,8] provides an estimate of the change in the temperatures as the density and magnetic field change, via

$$\frac{d}{dt} \left(T_{\parallel} \frac{B^2}{n^2} \right) = 0 \quad (1)$$

$$\frac{d}{dt} \left(\frac{T_{\perp}}{B} \right) = 0 \quad (2)$$

where $T_{\parallel}$ is the parallel ion temperature, $T_{\perp}$ is the perpendicular ion temperature, B is the magnetic field magnitude, and n is the density. To keep the quantities in the parentheses in Equation 1 and Equation 2 constant, $T_{\parallel}$ must decrease dramatically as the magnetic field increases and the density decreases while $T_{\perp}$ must increase as the magnetic field increases. Using Equation 1 and the change in the magnetic field magnitude and density from the outer heliosheath to the heliopause (see Table 1), $T_{\parallel}$ must decrease by a factor of 7.7 and $T_{\perp}$ must increase by a factor of 1.5. Therefore, under the assumption that the perpendicular and parallel temperatures are not coupled, $T_{\perp} / T_{\parallel}$ must increase by a factor of 11.6 from the outer heliosheath to the Voyager 1 location adjacent to the heliopause. This is a very large change in the ion temperature anisotropy and, as will be shown below, such a large change will not occur. Long before the ion distribution becomes this anisotropic, the EMIC instability will grow, saturate, and cause ions to pitch angle scatter from the perpendicular to the parallel direction. This pitch angle scattering effectively couples the parallel and perpendicular temperatures and negates the double adiabatic assumption.

3. Derivation of temperatures and plasma betas

The plasma depletion process is a kinetic process that couples the parallel and perpendicular temperatures through EMIC wave-particle interactions. It is driven by the draping process and the

plasma throughout the layer maintains marginal stability to EMIC waves. The marginal stability leads to a temperature anisotropy – plasma beta relationship that is maintained throughout the layer [5,6,7].

$$\frac{T_{\perp}}{T_{\parallel}} - 1 \approx \frac{0.715}{\beta_{\parallel}^{0.5}},$$

where $\beta_{\parallel}$ is the ion beta computed from the parallel ion temperature and the numerator and exponent on $\beta_{\parallel}$ are determined by the degree of marginal stability [6]. An exponent of 0.5 is chosen so that Equation 3 is solvable analytically. Solving Equation 3 for $T_{\perp}$ as a function of $T_{\parallel}$ yields a quadratic equation. The first root of the quadratic equation has $T_{\perp} / T_{\parallel} < 1$, which yields a negative $\beta_{\parallel}$, which is unphysical. The second root has $T_{\perp} / T_{\parallel} > 1$, which yields a positive $\beta_{\parallel}$ and so is physical. Table 2 shows the values for $T_{\perp}$, $T_{\parallel}$ (from the second root of the quadratic equation), $T_{\perp} / T_{\parallel}$, the total temperature $T_{\text{Total}} = (2 T_{\perp} + T_{\parallel})/3$, and plasma beta. The perpendicular temperature was estimated by considering charge-exchange of solar wind neutrals with interstellar protons and the resulting convection to the heliopause without energy losses:

$$T_{\perp} = 2 * T_{\text{ISN}}(1 - \text{PU}\%) + \frac{1}{2} \frac{m_p v_{\perp}^2}{k_B} (\text{PU}\%), \quad (4)$$

where T_{ISN} is the (isotropic) average temperature of interstellar neutral Helium measured by IBEX (= 8250 K) [11,16], PU% is the percent of pick up ions relative to the interstellar proton density in the outer heliosheath, and $v_{\perp}$ is the velocity of the pickup ion ring (= slow solar wind velocity of approximately 450 km/s). Equation 4 assumes thermal equilibrium between the bulk ions and neutrals in the outer heliosheath and assumes that the ion temperature increases by a factor of 2 from the interstellar value as the plasma approaches the heliopause. This increase is consistent with global MHD simulations of the heliosphere-interstellar medium interaction [e.g., 17,18].

Equation 4 assumes that pickup ions are generated beyond the heliopause by charge exchange between interstellar protons and secondary neutrals formed earlier by charge-exchange of solar wind protons with interstellar neutrals within the heliosphere. These “secondary” pickup ions form a ring that is perpendicular to the draped magnetic field against the heliopause. Theoretical estimates place the pickup ion percentage relative to the density in the outer heliosheath, PU%, at 0.03% (see, for example, [17,18]), which is the first entry in Table 2.

Table 2: Temperatures and plasma betas derived for various pickup ion fractions, using Equations 3 and 4 and the density and temperature in Table 1, for the depletion layer adjacent to the heliopause at the Voyager 1 crossing.

PU% (percent)	$T_{\perp}$ (K)	$T_{\parallel}$ (K)	$T_{\perp} / T_{\parallel}$	$\beta_{\parallel}$	T_{Total} (K)	β_{Total}
0.03	2.0×10^4	4.2×10^3	4.8	0.04	1.5×10^4	0.13
0.1	2.9×10^4	7.5×10^3	3.9	0.06	2.2×10^4	0.18
2	2.6×10^5	1.6×10^5	1.6	1.4	2.3×10^5	1.9

4. Plasma Processes in the Depletion Layer and at the Heliopause

Table 2 shows that the pickup ions in the outer heliosheath do not contribute significantly to the temperatures and betas unless they are a few percent of the total density. That is, their density needs to be almost 70 times higher than current theoretical predictions. Thus, because the cold interstellar temperature dominates the plasma energy, beta is very low in the plasma depletion layer. Based on

Equation 3, this low-beta plasma supports a very large temperature anisotropy of 4.8. However, this anisotropy is not nearly as large as the ratio $T_{\perp} / T_{\parallel} = 11.6$ predicted for double adiabatic theory. Therefore, the growth of EMIC waves and the coupling of the parallel and perpendicular temperatures through pitch angle scattering dominates the plasma depletion layer near the Voyager 1 crossing. This is a strong argument that the plasma depletion process is taking place locally along the Voyager 1 trajectory.

In addition to conditions conducive for the growth of EMIC waves, the plasma depletion layer has two other characteristics that relate to plasma processes at the heliopause. The first process is the growth of lower hybrid waves and the second process is magnetic reconnection at the heliopause.

4.1 Lower Hybrid Waves in the Plasma Depletion Layer:

Pickup ions in the outer heliosphere are a free energy source for lower hybrid waves. These waves, with wave vectors almost perpendicular to the local magnetic field, can accelerate electrons parallel to the magnetic field. This "lower hybrid drive" process [20] is believed to produce the seed population of suprathermal electrons that are further accelerated in the outer heliosphere by shocks propagating through the region [21,22]. The chain of wave-particle interactions ultimately results in the generation of Langmuir waves, which mode convert to electromagnetic radiation that propagates into the inner heliosheath and heliosphere. This electromagnetic radiation was observed in the 2-3 kHz range by spacecraft in the outer heliosphere beyond about 20 AU [e.g., 23].

Lower hybrid waves start this chain of wave-particle interactions. They are driven unstable primarily when the ring velocity of the pickup ions is less than five times the local Alfvén speed [20]. The ring velocity of the pickup ions is fixed at 450 km/s by the slow solar wind speed in the heliosphere. However, the Alfvén speed in the outer heliosphere increases in the plasma depletion layer [24]. Table 1 shows that the Alfvén speed increases from 20 km/s to 44 km/s near the heliopause. Unfortunately, the increase is only a factor of about 2.1 (the depletion factor in Table 1) and the resulting ratio of the ring velocity to the local Alfvén speed is 10.2. This ratio is a factor of two too large for growth of the lower hybrid instability. Therefore, it is concluded that, although the depletion layer improves the conditions for growth of the lower hybrid instability, it is not likely that these waves are driven unstable in the local depletion layer observed by Voyager 1. As a consequence, the seed population for further acceleration by shocks is probably not produced locally. Such electrons could, however, move along the magnetic field to Voyager 1 from a region of the depletion layer that has a stronger reduction in density and increase in magnetic field, where the lower hybrid drive process is able to proceed.

Langmuir waves are observed on two occasions during the ~250 days the Voyager 1 spacecraft spent in the plasma depletion layer [2]. They are associated with shocks propagating in the outer heliosphere [1]. These Langmuir waves may be produced by electron beams that have been accelerated at some distant location in the depletion layer or by the local shock. In particular, if the depletion factor is larger further away from the Voyager 1 location, then the conditions for generation of lower hybrid waves and the associated superthermal electrons would be improved. Petrinen et al. [13] concluded that the depletion factor at the Earth's magnetopause had to be at least 3.6 in order to explain the vast majority (95%) of certain observations in that depletion layer. There are several assumptions that go into this result. In particular, the value of 3.6 is a minimum. Higher depletion factors are possible, but not required for Earth. Thus, the value of 3.6 should be considered as what is generally required at Earth. If the depletion factor was 3.6 at a remote location in the outer heliosheath (i.e., not on the Voyager 1 trajectory), then the Alfvén speed would be about 75 km/s and the ratio of the pickup ion ring speed to the Alfvén speed would be 6. This ratio is much closer to the required ratio of 5 for the lower hybrid process. Thus, the Langmuir waves observed by Voyager 1 in the depletion layer probably originated from beams produced at the shock, either remotely or locally, from superthermal electrons that were produced at a distant location in the plasma depletion layer where the depletion factor was larger.

4.2 Magnetic reconnection at the Heliopause:

Magnetic reconnection converts magnetic energy into particle energy and changes the topology of field lines in the vicinity of a current sheet like the heliopause. This process has been invoked to explain observations in the inner heliosheath near the Voyager 1 heliopause crossing [e.g., 14]. Magnetic reconnection can occur over a range of shear angles that depends on the plasma betas on either side of the discontinuity. The plasma betas in Table 2, combined with an estimate of the plasma beta in the inner heliosheath at the heliopause and the observed shear angle at the heliopause provide enough information to determine if reconnection is possible locally where Voyager 1 crossed the heliopause.

Table 3 contains the information and assumptions used to compute the plasma beta in the inner heliosheath at the heliopause. By summing over the core ions and pickup ions, the ion temperature was computed as

$$T = T_{SW}(1 - PU\%_{IHS}) + \frac{1}{2} \frac{m_p v_{\perp}^2}{k_B} (PU\%_{IHS}), \quad (5)$$

where T_{SW} is the temperature of the (shocked) solar wind proton distribution in the inner heliosheath (assumed to be $= 2.3 \times 10^5$ K, or 20 eV), $PU\%_{IHS}$ is the percent of pick up ions relative to the solar wind proton density in the inner heliosheath (assumed to be 16.5% [17,19], and $v_{\perp}$ is the velocity of the pickup ion ring (= slow solar wind velocity of approximately 450 km/s). In contrast to the outer heliosheath, the ion temperature in the inner heliosheath is dominated by the pickup ion shell because the pickup ion density is so large compared to the cold solar wind proton density.

Table 3: Estimation of the plasma beta in the inner heliosheath just interior to the heliopause and the change in beta across the boundary, for Voyager 1's location.

Quantity	Value	Origin
Magnetic field magnitude in the inner heliosheath at the heliopause	$B = 0.25$ nT Range: 0.20 – 0.35 nT	Measured by Voyager 1 [Burlaga et al., 2013]
Density in the inner heliosheath at the heliopause	$N = 2 \times 10^{-3}$ cm ⁻³ Range: $(1 - 4) \times 10^{-3}$ cm ⁻³	Assumed, consistent with Voyager 2 observations
Total temperature in the inner heliosheath at the heliopause	$T = 2 \times 10^6$ K	Computed from Equation 5
Plasma beta in the inner heliosheath at the heliopause	$\beta = 2.2$ Range: 0.6 – 6.9	Computed from the magnetic field density and temperature in this table
$\Delta\beta$ across the heliopause = $ \beta_{IHS} - \beta_{PDL} $	$\Delta\beta = 2.1$ Range: 0.4 – 6.8	β_{IHS} from this table and β_{PDL} from Table 3 with 0.03 PU%

Using the estimate of plasma beta in the inner heliosheath from Table 3 and the estimate of plasma beta in the depletion layer from Table 2 (with the assumption that the pickup ion percentage is 0.03), the change in beta across the heliopause at the Voyager 1 crossing ($\Delta\beta$) is 2.1 (see the last entry in Table 3). This relatively large change across the heliopause has implications for local reconnection at the boundary. Variations in the density (measured by Voyager 2 in the inner heliosheath) and magnetic field (measured by Voyager 1 in the inner heliosheath near the heliopause) result in a range for $\Delta\beta$ of 0.4 to 6.8.

Swisdak et al. [25] developed a theoretical condition for reconnection onset that depends on the change in beta across a current sheet and the shear angle at the boundary. This condition has been successfully tested at current sheets in the solar wind [26] and has been investigated at the Earth's magnetopause [27] and Saturn's magnetopause [28,29]. Figure 1 shows how the onset of reconnection depends on $\Delta\beta$ and shear angle. Three curves separate $\Delta\beta$ -shear angle regions where reconnection is

possible and where it is “suppressed”. It is likely that there is no actual suppression of reconnection at the entire heliopause or any other current layer. Instead, what likely happens for high $\Delta\beta$ conditions is that reconnection is initiated at locations on the boundary where the shear angle is large. Thus, Figure 1 provides an estimate of the range of shear angles where reconnection is possible at the heliopause and whether this range includes the shear angle observed at the Voyager 1 crossing. The dark blue bar in Figure 1 shows $\Delta\beta = 2.1$ at the heliopause (from Table 3). Allowing for a range of thicknesses of the current layer from 0.5 to 2 ion inertial lengths (d_i), reconnection can occur at locations where the shear angle is greater than about 55° , with a range of possible minimum shears ranging from 55° to 127° . (For the extrema of the range $\Delta\beta = 0.4 - 6.8$, the shear angle must exceed 15° and 140° , respectively.) For $\Delta\beta = 2.1$, the range of possible minimum shears is broad, but it does not include the shear angle that was observed at the Voyager 1 crossing. One of the surprises from the Voyager 1 crossing was that the direction of the magnetic field changed very little across the heliopause. Burlaga et al. [1] report that, across the entire transition of the heliopause, the magnetic field deviates from the Parker spiral direction in elevation by about 14° and in azimuth by about 17° . Therefore, Figure 1 shows that $\Delta\beta = 2.1$ is too high to support reconnection locally at the Voyager 1 crossing. Given the extrema of the range of $\Delta\beta$ from Table 3, Figure 1 does indicate the possibility that reconnection could occur locally if the fluctuations in the density and magnetic field were at their limits.

Plasma beta is reduced in a depletion layer. At the Earth and other planets, the lower beta upstream of the magnetopause opens up the range of shear angles where reconnection is possible because the plasma beta inside the magnetosphere is typically less than 1. At the heliopause, the opposite is true. Plasma beta in the inner heliosphere is typically significantly greater than 1 and the plasma betas in the outer heliosphere and in the depletion layer are significantly less than 1. Thus, lowering plasma beta in the depletion layer further (through increased plasma depletion) has little effect on the $\Delta\beta$ across the heliopause. Instead, $\Delta\beta$ is dominated by the plasma beta in the inner heliosphere, which in turn is dominated by the number of ions in the pickup shell. Thus, Figure 1 with $\Delta\beta = 2.1$ is likely a good representation of the conditions across the entire section of the heliopause that faces the interstellar flow. It remains to be determined if there are locations on the heliopause where the shear angle is large enough to support reconnection. Finally, if the solar wind sector was in the opposite direction in the inner heliosphere at the Voyager 1 crossing, then the shear angle would have been close to 180° . For those conditions, reconnection could occur for almost any $\Delta\beta$.

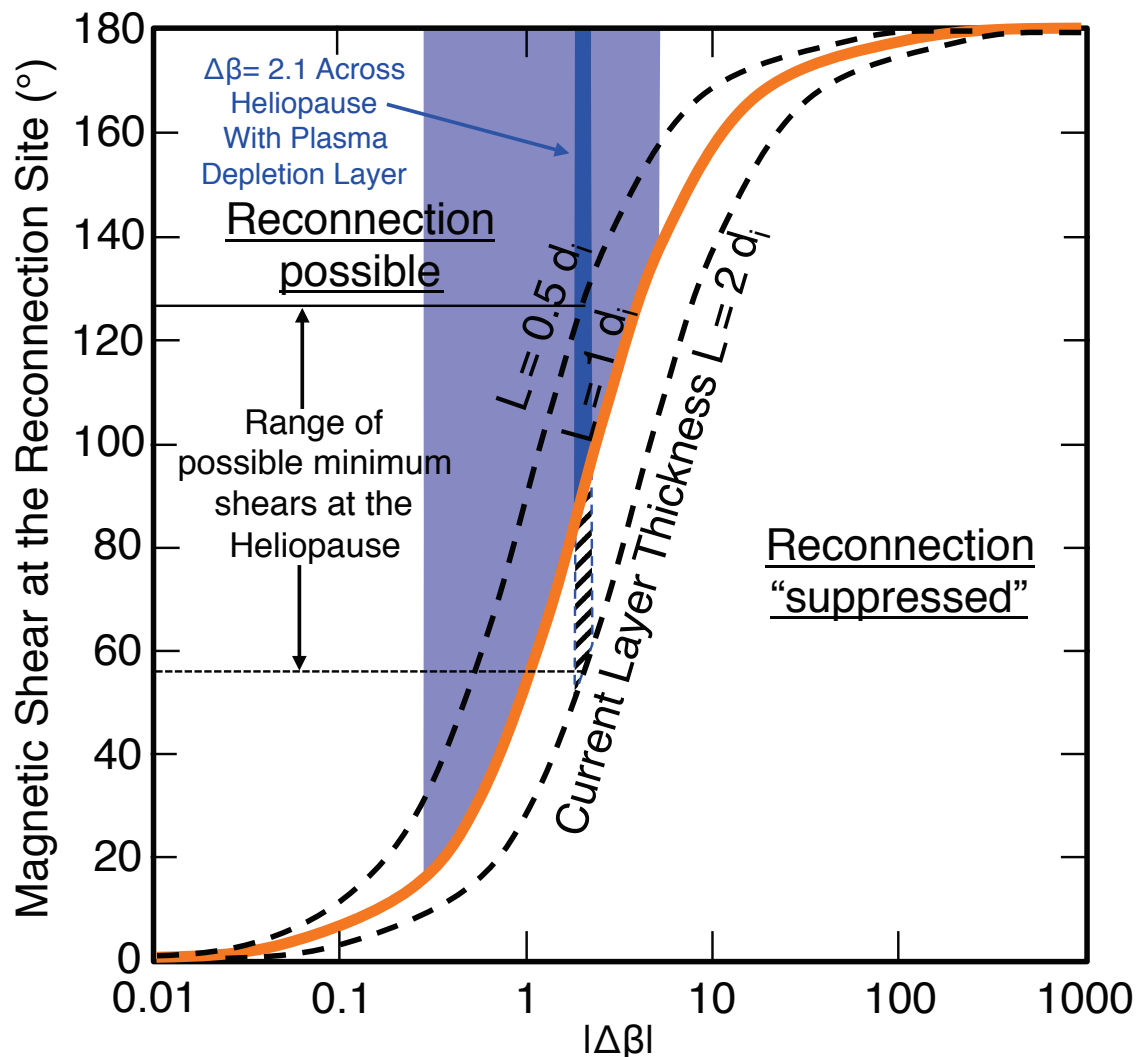


Figure 1: Regions in $\Delta\beta$ -magnetic shear of possible and suppressed reconnection. For the $\Delta\beta = 2.1$ (dark blue line) change across the heliopause at the Voyager 1 crossing, the range of possible magnetic shears that support reconnection is from 55° to 180° . The minimum shear angle of 55° is too large to support reconnection locally at the Voyager 1 crossing (where the shear angle was very small). The extrema of the range of $\Delta\beta$ (light blue shading) could support reconnection down to $<20^\circ$.

Even if reconnection occurred locally at the heliopause near the Voyager 1 crossing, it is not a source of significant electron heating at the boundary. The small ($V_A < 100$ km/s) Alfvén speeds in the plasma depletion layer should result in weak electron heating in the reconnection exhaust [30]. Thus, locally in the vicinity of Voyager 1, an electron seed particle population for further acceleration is created neither by reconnection nor by lower hybrid waves.

5. Conclusions

Using observations from Voyager 1, properties of plasma depletion layers, and some assumptions about the plasma in the outer and inner heliosheath, Tables 1 through 3 contain the plasma parameters near to the heliopause for the Voyager 1 crossing. The plasma in the depletion layer has Alfvén Mach number less than 1, is very low beta, is highly anisotropic and is moderately “depleted” compared to

the outer heliosheath upstream from the depletion layer (see the depletion factor of 2.1 in Table 1). Locally at the Voyager 1 crossing, the plasma is marginally stable to the Electromagnetic Ion Cyclotron instability, the conditions are not favorable for growth of lower hybrid waves (the ratio of the pickup ring speed to the Alfvén speed is too high) and the local shear at the heliopause is too small to support reconnection. Closer to the center of the draping region on the heliopause (away from the Voyager 1 crossing), the plasma depletion is likely greater and the conditions might be favorable for growth of lower hybrid waves. Similarly, away from the Voyager 1 crossing location, the change in plasma beta across the heliopause may be small enough and the local shear at the heliopause large enough to support reconnection. Everywhere on the heliopause, magnetic reconnection, if it occurs, is predicted to be ineffective at heating electrons, based on the small values of Alfvén speed ($V_A < 100$ km/s) in the depletion layer and an empirical relation between the Alfvén speed and electron heating observed in the solar wind and Earth's magnetosphere [30]. This ineffective electron heating persists even if the asymmetric form of the Alfvén speed [31, 32] is considered.

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