Limits on the interstellar magnetic field imposed by observational constraints indicate that Voyager 1 remains in the inner heliosheath

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Abstract. The unmeasured interstellar magnetic field strength is an essential parameter for models of the heliosphere moving relative to the Local Interstellar Cloud (LIC) that surrounds it. Here we use recent measurements of the differential energy spectra of energetic neutral hydrogen (ENH) combined with Voyager 1 (V1) measurements of energetic particles to calculate the total pressure and its 1-σ limit in the inner heliosheath, the region between the termination shock at ~90 AU and the heliopause that V1 presumably crossed at 122 AU. Balancing pressure across the heliopause, we find the magnetic pressure in the outer heliosheath at ~135 AU where V1 is currently located. From this magnetic pressure we find an extraordinarily large magnetic field strength of 0.84±0.08 nT compared to the 0.464±0.009 nT field strength currently measured by V1. We conclude that V1 is currently not measuring the interstellar field, but rather the solar magnetic field. Voyager 1 is thus not in interstellar space but still inside a new, unanticipated, and most unusual region of heliosphere that it entered in late August 2012. We recalculate total pressures in the ordinary heliosheath (~90–122 AU), in the new, co-called cold inner heliosheath (122–145 AU), in the outer heliosheath and in the unperturbed LIC. Pressure balance again requires that all these pressures must be equal. Constrained by the requirement of pressure equality between all regions and minimum reduced χ² fits to the ENH spectrum and the differential intensities of particles measured by V1 in the ordinary, co-called hot heliosheath, we find the common pressure to be (3.45±0.39)×10⁻¹² dyne-cm⁻². The magnetic field strength in the outer heliosheath is calculated to be 0.90±0.089 nT, and in the unperturbed LIC it is 0.86±0.11 nT. To achieve common pressure for all regions imposes firm limits on the LIC neutral hydrogen density, n(HI) = 0.10±0.02 cm⁻³. Pressure balance between the LIC and the hot cloud surrounding it places firm limit on the proton density in the unperturbed LIC, n(HII) = 0.036±0.012 cm⁻³.

1. Introduction
Currently, the Voyager 1 spacecraft, hereafter referred to as V1, is generally believed to be in interstellar space [1-3], in the outer heliosheath beyond the heliopause, which separates the heliosphere from the local interstellar medium. In this region, the putative outer heliosheath, particles that had been accelerated in the inner heliosphere have disappeared [2,3], galactic cosmic rays (GCRs) reached maximum intensity [2,3], suggesting easy escape of the former across the heliopause and entry of the latter. But has V1 actually crossed the heliopause and is it at this moment in the local interstellar medium? Here we provide conclusive evidence to the contrary. First, we compute the total average pressure in the inner heliosheath (between 94 AU when V1 crossed the termination
shock, and 122 AU, the assumed location of the heliopause [1-3]) using recently published differential intensity spectra of Energetic Neutral Hydrogen (ENH) at low [4] and high [5,6] energies, and direct observations of the magnetic field [8] and > 40 keV particles [3] by V1, and find it to be 3.45•10^{-12} dyne-cm^2. Most of this pressure (3.22•10^{-12} dyne-cm^2) comes from the thermal pressure of pickup ions, about half from locally created pickup ions and half from transmitted pickup ions that were produced in the supersonic solar wind, convected across the termination shock that heated and compressed them. The total pressure in the outer heliosheath just outside the heliopause is the sum of the particle (interstellar plasma and locally created pickup ions) thermal pressures and magnetic pressure due to the draped magnetic field. Pressure balance requires that the total pressure in the outer heliosheath near the heliopause must be the same as the total average pressure in the inner heliosheath. ENHs created in the outer heliosheath will also be detected by IBEX and thus contribute to the measured IBEX spectrum. Constrained by the IBEX observations, we compute the outer heliosheath particle pressure, finding it to be only 5.35•10^{-13} dyne-cm^2. A magnetic field strength of 0.84±0.08 nT is required to achieve pressure balance across the heliopause. However, V1 measures only 0.464±0.009 nT [7], a field strength that is lower than the 4-σ lower limit of the field required from pressure balance. Not only is the direction of the magnetic field observed by V1 [8] unchanged from the direction of the heliospheric magnetic field, which is in a substantially different direction from the expected direction of the interstellar magnetic field inferred from both IBEX observations of energetic neutral atoms (ENAs) [9,10, and references therein], as well as from observations of the polarization of interstellar grains [11], not only is the magnetic field strength unusually smooth and nonturbulent [7], but now we also find it to be far too weak. It must thus be concluded that V1 remains in the inner heliosheath.

Fisk and Gloeckler [12,13] have developed a detailed model for the nose region of the heliosphere, the region of the heliosphere in the direction of motion of the Sun through the local interstellar medium, the region that the Voyagers are exploring. Our model [12,13] is based on the assumption that the solar wind can be compressed. The high plasma densities measured by Gurnett et al. [1] are thus not interstellar densities but rather densities of the compressed solar wind. The model yields flow patterns for the solar wind that are consistent with the convective solar wind velocities inferred from >40 keV anisotropy observations, the technique used to determine the solar wind velocity in the absence of a working plasma detector on V1 [14,15]. The model also yields the likely distance to the heliopause, as well as the likely properties of the heliopause. For our purposes here, the details of the model of Fisk and Gloeckler [12,13] are not needed, other than to note that it is possible to construct a complete model for the nose region of the heliosheath in which the solar wind is compressed. V1 is currently in a most unusual region of the inner heliosheath, the so-called cold inner heliosheath, from which particles below ~40 keV accelerated in the hot inner heliosheath (between the termination shock and heliocliff at 122 AU) have disappeared and galactic cosmic rays (GCRs) have reached maximum intensity [2,3], suggesting easy escape of the former across the heliopause and entry of the latter.

IBEX, looking in the V1 direction, will detect ENHs created in (a) the hot, the ordinary inner heliosheath (~90 to 122 AU), (b) the cold inner heliosheath (122 AU to the heliopause at ~145 AU), and (c) the outer heliosheath (145 to roughly 175 AU). Three quite distinct charged particle populations, interacting with the neutral gas moving at ~26 km/s toward the Sun, produce Energetic Neutral Atoms and, in particular, ENHs: (i) the thermal population and their common tail [16], (ii) locally created pickup ions, and (iii) transmitted pickup ions, which are pickup ions created in the supersonic solar wind [17] upstream of the termination shock. Transmitted pickup ions are convected away from the Sun by the thermal plasma (solar wind), are compressed and heated as they cross the termination shock and enter the inner heliosheath. As detailed below, transmitted (population (iii)) together with local (population (ii)) pickup ions provide by far the mayor contribution (43% and 41%, respectively) of the total pressure (3.45•10^{-12} dyne-cm^2) in the inner hot heliosheath. The solar wind, ACRs, and magnetic field contribute only ~7, ~7, and ~2%, respectively.

In the hot heliosheath the distribution functions of each of the three populations will have strong common tails (-5 power laws with exponential rollovers at high speeds), e.g., ACR tails on the
transmitted pickup ion distribution, accelerated by the pump mechanism [16] in this highly turbulent [8] region.

In the cold heliosheath, where the measured magnetic field is incredibly smooth and the pump mechanism extremely inefficient, tails are not produced, and only the core distributions remain. Furthermore, particles with energy above ~ 30 keV (e.g. ACRs) have escaped [2,3], and, as we will show below, the transmitted pickup ion distribution rolls over sharply at 2.55•10^8 cm s^-1 (28.9 keV). In the cold heliosheath, the solar wind contributes 55%, the magnetic field 25%, transmitted pickup ions 17%, and locally created pickup ions only 3%.

In the outer heliosheath near the heliopause the total pressure must be the same as the average pressure in the hot inner heliosheath, which must be the same as in the cold inner heliosheath. The total pressure in the outer heliosheath is the sum of the unknown and as yet unmeasured magnetic pressure and the thermal pressures of the interstellar plasma (interstellar wind) and locally created pickup ions. The ram pressures are negligibly small because the radial component of the bulk speed of the interstellar plasma vanishes at the heliopause. As detailed below, we find that the particles contribute a small amount (6%) to the total pressure of 3.45•10^-12 dyne-cm^-2, 5.7% and 0.3% for locally produced pickup ions and the interstellar plasma, respectively. Magnetic pressure is the primary balancing force, providing 94% of the total pressure. The strength of the draped magnetic field in the outer heliosheath is 0.90 nT.

Next, we derive the magnetic field strength in the unperturbed LIC, again using pressure balance with respect to the heliosphere, and independently with respect to the hot cloud that surrounds the LIC. To achieve pressure balance with the heliosphere requires a magnetic pressure of 2.94•10^-12 dyne-cm^-2, or 85% of the total balancing pressure of 3.45•10^-12 dyne-cm^-2. The only particle population in the unperturbed LIC is the interstellar plasma with its common tail. The sum of the ram and thermal particle pressures (13% and 2%, respectively) accounts for 15% of the total pressure. The magnetic field strength in the unperturbed LIC is 0.86 nT.

The LIC thermal pressure is only a small fraction (2 to 4%) of the hot cloud pressure surrounding the LIC. Thus, to balance the measured [18] thermal pressure of 3•10^-12 dyne-cm^-2 in the hot cloud requires a LIC magnetic field of ~ 0.87 nT [19], which is remarkably close the value of we derive for the LIC magnetic field. To make the two values of the LIC field identical requires a LIC proton density of 0.036 cm^-3.

2. Computations of Pressures

At each location of the heliopause surface the total pressure just inside must be equal to that just outside the heliopause that separates the solar wind and magnetic field from the local interstellar field and plasma. In the subsonic inner heliosheath (between the termination shock, where the solar wind becomes subsonic, and the heliopause) the distribution between magnetic, thermal, and ram pressures will vary with heliocentric distance. For example, just downstream of the termination shock, where the radial speed component of the solar wind is large, the ram pressure of the solar wind will be relatively high, while the thermal pressure due to locally created pickup ions will be relatively small because so few are created just downstream of the shock. However, the sum of these separate pressures at any distance must be the same throughout the entire inner heliosheath, and the total average pressure of the entire inner heliosheath must thus be the same as the pressure in the inner heliosheath at the heliopause.

The average total pressure in the inner heliosheath is the sum of (a) the average thermal pressures, \( P_{th} \), of (1) thermal ions and electrons (e.g. bulk solar wind) and (2) pickup ions, (b) the average ram pressure of ions, \( P_{ram} \) (the ram pressures due to electrons are negligible), and (c) the average magnetic pressure, \( P_{mag} \). These pressures, as well as the number densities, \( n \), are computed using equation (1),

\[
n = 4\pi \int_0^\infty f(v) v^2 \, dv; \quad P_{th} = \frac{4\pi m_i}{3} \int_0^\infty f(v) v^4 \, dv; \quad P_{ram} = \rho U_r^2; \quad P_{mag} = \frac{B^2}{8\pi},
\]  

(1)
where \( f(v) \) is the phase space density (psd) as a function of \( v \), the particle speed in the solar wind or interstellar plasma reference frame, \( m_p \) is the proton mass, \( \rho \) the mass density, and \( U_r \) the radial component of the solar wind or interstellar plasma bulk speed.

In order to compute particle pressures we need to know the distribution functions, \( f_{i,k}(v) \), for each major particle population, where \( j \) designates the charged particle’s mass, (e.g. \( j = 1 \) for protons, \( j = 4 \) for He, etc.), and \( k \) refers to one of the three major particle populations in the inner heliosheath (solar wind, transmitted pickup ions [17], and locally created pickup ions), and the two most dominant particle populations (interstellar thermal plasma and locally created pickup ions) in the outer heliosheath where \( V1 \) now presumably resides. Above \( \sim 40 \) keV \( (2.8 \times 10^8 \) cm s\(^{-1}\)) \( V1 \) measures the distribution functions [3], and above \( \sim 8.8 \times 10^8 \) cm s\(^{-1}\) the composition [3] directly, and partial pressures above these high speeds are readily computed. Unfortunately, no direct particle measurements from \( V1 \) are available below 40 keV. Therefore we use the measured time-averaged velocity distribution function (psd versus particle speed, \( v_r \)) of energetic neutral hydrogen (ENH) measured by \textit{IBEX} [4], \textit{Cassini} [5], and \textit{SOHO} [6], shown as filled circles in figure 1, to determine the proton velocity distributions \( f_{1,k}(v) \) in the inner heliosheath for speeds below \( 2.8 \times 10^8 \) cm s\(^{-1}\), where most of the total particle pressure resides, mostly in pickup ions.

![Figure 1. Time-averaged phase space density of energetic neutral hydrogen (ENH), \( f_{\text{ENH}}(v_r) \), measured by \textit{IBEX} [4] from \( \sim 5 \times 10^6 \) to \( \sim 10^9 \) cm s\(^{-1}\), \textit{Cassini} [5] from \( \sim 1.1 \times 10^8 \) to \( \sim 3.1 \times 10^8 \) cm s\(^{-1}\), and \textit{SOHO} [6] from \( \sim 3.1 \times 10^8 \) to \( \sim 4.4 \times 10^8 \) cm s\(^{-1}\) (filled circles), versus the radial component of the speed, \( v_r \), of the hydrogen atoms. The sum of the five labeled curves (A, B, C, E, and F) ENH phase space density spectra of particle populations in the inner heliosheath and the outer heliosheath near the heliopause (\( \sim 122 \) to \( \sim 152 \) AU) yield the total spectrum (bold curve) of ENH below \( \sim 4.4 \times 10^8 \) cm s\(^{-1}\) from the emission region (inner and outer heliosheaths) where these ENH are created. Curve D is the low end of the ACR ENH spectrum derived from the directly measured [3] proton spectrum by \( V1 \) in the inner heliosheath. In the text we describe how the six spectra were computed. Curve A is the velocity distribution of ENH created by transmitted pickup protons. The transmitted pickup ion population is created in the supersonic solar wind upstream of the termination shock (TS), and convected with the solar wind across the TS. In crossing the TS transmitted pickup ions are compressed and heated. Convected through the highly turbulent [8] inner heliosheath, common spectrum [16] ACR suprathermal tails develop on these pickup ion distributions, and at the same time the cutoff speed of the pickup ion distribution is reduced.]
2.1. Standard Model of the Heliosphere

Here we use the standard model of the heliosphere with the standard inner heliosheath that extends from the termination shock to the heliopause, and the outer heliosheath beyond the heliopause. This is the model that is generally accepted [1-3,7] with the heliopause at a heliocentric distance of 122 AU that Voyager 1 presumably crossed in late August 2012. If one accepts this model then Voyager 2 is now in the outer heliosheath near the heliopause, exploring interstellar space for almost 4 years.

We begin by computing the distribution functions of protons \( f_{\alpha,k}(v) \) using equation (2).

\[
f_{\alpha,k}(v) = f_0 \exp\left\{-\left(\frac{v_{\text{low}}}{v}\right)^{\alpha_{\text{low}}} \left[1 + \frac{1}{\kappa} \left(\frac{v}{v_{\text{th}}^k}\right)^2\right] \right\} \exp\left(-\left(\frac{v}{v_0}\right)^{100}\right) \\
+ f_{\text{tail}} \exp\left(-\left(\frac{v_0}{v}\right)^{100}\right) \left(\frac{v}{v_0}\right)^{5} \exp\left(-\left(\frac{v}{v_{\text{high}}^k}\right)^{\alpha_{\text{high}}}\right)
\]

(2)

This single equation is used to model the phase space density of the (a) thermal solar wind or interstellar plasma (by setting \( v_{\text{low}} = 0 \) and \( \alpha_{\text{low}} = 1 \)) with a common tail or without \( f_{\text{tail}} = 0 \) and \( v_0 = 10^{10} \text{ cm s}^{-1} \) for no tail), (b) pickup ions with a common tail or without \( f_{\text{tail}} = 0 \) and \( v_0 = 10^{10} \text{ cm s}^{-1} \) and (c) common spectra above speed \( v_0 (f_0 = 0) \). Distribution functions observed [16] at 1 AU with ACE, and distribution functions of transmitted pickup ions measured [17] with Ulysses at ~5 AU, have been fit using equation (2).

Next, we convert the five proton distributions, \( f_{\alpha,k}(v) \), to the respective \( f_{\text{ENH},k}(v) \), the ENH phase space densities, using equation (3), which requires values for the neutral hydrogen gas density, \( n(\text{HI}) \),

\[
f_{\text{ENH},k}(v_r) = n(\text{HI}) L \sigma(v_{\text{rel}}) f_{\alpha,k}(v_r - U_r),
\]

(3)

for \( L \), the radial width of the respective emission regions (~92 to 122 AU for the inner heliosheath and 122 to ~152 AU for the outer heliosheath), for the H-p charge exchange cross section \( \sigma(v_{\text{rel}}) \) [20], which depends on \( v_{\text{rel}} \), the relative speed between the neutral gas and protons, with \( \alpha = 30^\circ \) and \( \beta = 5^\circ \),

\[
v_{\text{rel}} = \sqrt{\left(V_o \cos \alpha \cos \beta - v_r - U_r\right)^2 + \left(V_o \cos \alpha \sin \beta - U_r\right)^2 + \left(V_o \sin \alpha - v_r - U_r\right)^2},
\]

(4)

for the \( r \) direction, and \( V_o = 26 \text{ km s}^{-1} \), and finally for \( U_r \), the radial component of the bulk speed of the solar wind in the inner heliosheath, or of the plasma in the outer heliosheath. The values and errors we use for \( n(\text{HI}) \) are listed in row 3, column 2 of table 1, those for \( L \) are \( 30 \pm 2 \text{ AU and 30 AU in the inner and outer heliosheaths, respectively, and those for } U_r \) in the inner heliosheath are taken from row 2, column 2 of table 2. In the outer heliosheath near the heliopause \( U_r \approx 0 \).

The observed ENH spectrum (filled black circles of figure 1) must be matched by the sum (black solid curve) of the three spectra, curve \( A \) for transmitted pickup protons in the inner heliosheath, curve \( B \) for locally created pickup protons in the inner heliosheath and curve \( E \) for locally created pickup protons in the outer heliosheath near the heliopause. These three spectra make the dominant contribution to the total observed ENH spectrum above \( 5 \times 10^6 \text{ cm s}^{-1} \) in three different velocity intervals \( (a, b, \text{ and } e \text{ in figure 1)} \). The inner heliosheath solar wind spectrum (curve \( C \)), computed using Voyager 2 solar wind measurements [21], makes negligible contributions to the measured ENH spectrum.
Table 1. Values and 1-σ errors of key parameters in the outer heliosheath.

| LIC parameter          | Mean and standard error<sup>a</sup> | Value 1 and 1-σ error | Value 2 and 1-σ error | Value 3 and 1-σ error | Value 4 and 1-σ error |
|------------------------|--------------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Flow speed, $V_o$ (km s<sup>-1</sup>) | 26.12 ± 0.27 [24] | 25.4 ± 1.1 [25] | 26.7 ± 0.5 [26] | 26.08 ± 0.21 [26] | 26.3 ± 0.4 [27] |
| Neutral Hydrogen density, $n$(HI) (cm<sup>-3</sup>) | 0.125 ± 0.016 [28] | 0.09 ± 0.02 [29] | 0.115 ± 0.025 [30] | 0.165 ± 0.035 [31] | 0.13 ± 0.04 [32] |
| Temperature, $T_o$ (°K) | 7427 ± 423 [24] | 8000 ± 1300 [25] | 8150 ± 390 [26] | 7260 ± 270 [26] | 6300 ± 340 [27] |

<sup>a</sup>Mean values and standard error of respective parameters of columns 3 to 6.

Table 2. Mean values and errors of solar wind parameters and magnetic field strength in the inner heliosheath (94 to 122 AU) and the outer heliosheath (122 to 152 AU) measured by Voyager 1 and Voyager 2.

| Parameter                              | ~94 to ~122 AU       | ~122 to ~152 AU       |
|----------------------------------------|----------------------|-----------------------|
| Mean radial component of flow speed, $U_r$ (km s<sup>-1</sup>) | 34.0 ± 6.9 [14] | ~0                     |
| Number density of protons, $n_p$ (cm<sup>3</sup>) | 0.0019 ± 0.0007<sup>a</sup> | 0.085 ± 0.01 [1] |
| Thermal speed, $v_{th}$ (km s<sup>-1</sup>) | 29.2 ± 0.07<sup>a</sup> |                         |
| Magnetic field strength, (nT)           | 0.121±0.02 [8]       | 0.464 ± 0.009 [7]      |

<sup>a</sup>Voyager 2 solar wind measurements [21] in the inner heliosheath.

Next, we vary parameter values in equation (2) for each of the three populations, curves A and B in the inner heliosheath, and curve E in the outer heliosheath, to obtain the best fit (minimum reduced $\chi^2$) to the observed ENH spectrum. The final set of parameters that gave the minimum reduced $\chi^2 = 0.955$ is listed in rows 3 to 5, columns 3 to 11 in table 3. For the Anomalous Cosmic Ray (ACR) population [3] (curve D) the parameters in equation (2) are obtained from best fits to the directly measured [3] proton spectrum above 40 keV.

Using the three parent proton velocity distribution, $f_{1,k}(v)$, in the ENA emission regions that together give the best fit to the observed ENH spectrum (filled circles in figure 1), the proton spectrum [3] of ACRs and the magnetic field strength [8] in the inner heliosheath, both directly measured by VI, as well as the maxwellian solar wind proton spectrum observed [21] by Voyager 2 and assumed for the inner heliosheath, we find the total pressure in the inner heliosheath, $P_{HI}$, sum of magnetic pressure, $P_{HI,mag}$, and particle pressure, $P_{HI,particle}$, which in turn is the sum of thermal and ram pressures of protons, heavy particles, and electrons. In the outer heliosheath just beyond the presumed heliopause at 122 AU, the total pressure, $P_{OHI}$, is the sum of the unknown magnetic pressure, $P_{OHI,mag}$, of the draped magnetic field and the particle thermal pressures, $P_{OHI,particle}$, of the interstellar plasma and of pickup ions that are produced primarily in the nose region of the outer heliosheath near the heliopause. In that region the particle ram pressures are negligible because there the particle flow is nearly parallel to the heliopause.
Three of the five parent proton spectra are well constrained by the measured ENH spectrum. The two that are not are (a) the inner heliosheath solar wind spectrum (curve C, previously discussed) and (b) the distribution of the thermal interstellar plasma in the outer heliosheath (curve F). We model the later distribution as a maxwellian (very large $\kappa$ in equation (2)), with no suprathermal tail. This type of distribution is quite reasonable because the measured magnetic field [7] in that region is so exceptionally smooth (nonturbulent). In the absence of turbulence, maxwellian distributions without tails are generally observed [16]. For the interstellar plasma density we use the value of $0.085 \pm 0.1 \text{ cm}^{-3}$ measured [1] by the Plasma Wave System instrument on $V1$ in the presumed outer heliosheath where $V1$ is now located. For the interstellar protons thermal speed we use $11.0 \pm 2.6 \text{ km s}^{-1}$, assuming that the thermal speed of the plasma is the same as the measured thermal speed of the neutral gas in that region computed from the temperature listed in row 4 of column 2 of table 1. The total particle pressures in each of the two regions is the sum of values in columns 4 and 5 of rows 3 to 5 and of rows 6 and 7, respectively, of table 1. The ACR pressure, computed using the directly measured [3] proton spectrum above 40 keV and corrected for galactic cosmic ray contributions above ~5 MeV.

We used the standard propagation of errors procedure to compute 1-$\sigma$ errors of the total particle pressures, taking into account that some of the uncertainties are correlated.

Pressure balance across the heliopause requires that $P_{OH} = P_{HI}$. To achieve this pressure balance requires that $P_{OH,\text{req}} = P_{HI} - P_{OH,\text{particle}} = 3.59 \times 10^{12} - (0.20 \times 10^{12} + 0.34 \times 10^{15}) = 3.05 \times 10^{12} \text{ dyne cm}^{-2}$. From the fourth equation in equation (1), the strength of the draped magnetic field in the region where $V1$ currently resides is $0.876 \pm 0.088 \text{ nT}$. The 4-$\sigma$ lower limit is $0.521 \text{ nT}$, which is larger than $0.464 \pm 0.009 \text{ nT}$, the field strength currently measured [7] by $V1$.

### Table 3. Proton densities and parameter values for equation 2.

| Region | Type | $n_0 (p) (\text{cm}^{-3})$ | $v_{low} (\text{cm s}^{-1})$ | $\alpha_{low}$ | $v_{th} (\text{km s}^{-1})$ | $\kappa$ | $v_0 (\text{cm s}^{-1})$ | $f_{\text{tail}} (\text{s}^{-1} \text{ km}^{-6})$ | $v_{high} (\text{cm s}^{-1})$ | $\alpha_{high}$ |
|--------|------|------------------|-----------------|----------------|-----------------|------|-----------------|-------------------|-----------------|----------------|
| INNER  | Thermal | 0.002 | 0 | 1 | 30.0 | 100 | $10^{10}$ | 0 | $10^5$ | 1.8 |
| INNER  | Local | 0.008 | 5•10$^7$ | 1.17 | 42.0 | 100 | $1.35 \times 10^7$ | 2•10$^4$ | $5 \times 10^7$ | 1.8 |
| INNER  | Trans | 0.000362 | 10$^7$ | 1.0 | 400 | 6.01 | $2 \times 10^8$ | 0.03 | 4•10$^9$ | 1.2 |
| INNER  | ACRs | 4.1•10$^{10}$ | 10$^{10}$ | 1 | 1 | 100 | $2 \times 10^8$ | 2.5•10$^3$ | $10^{10}$ | 1.5 |
| HOT    | Thermal | 0.005 | 0 | 1 | 22.0 | 4.0 | $7.5 \times 10^6$ | 0.003 | $1 \times 10^5$ | 1.5 |
| HOT    | Local | 0.006 | 3•10$^7$ | 1 | 40.0 | 5.0 | $1.2 \times 10^7$ | 0.0005 | $5.5 \times 10^7$ | 6.89 |
| HOT    | Trans | 0.000351 | 7•10$^6$ | 1.0 | 394.5 | 6.11 | $1.8 \times 10^8$ | 8.1•10$^3$ | $1 \times 10^7$ | 2.00 |
| COLD   | Thermal | 0.09 | 0 | 1 | 22.0 | 100 | $10^{10}$ | 0 | $10^6$ | 1.5 |
| COLD   | Local | 0.002 | 6.9•10$^7$ | 1.35 | 6.0 | 17 | $10^{10}$ | 0 | $5 \times 10^7$ | 1.20 |
| COLD   | Trans | 0.000351 | 7•10$^6$ | 1.0 | 394.5 | 6.11 | $1.88 \times 10^8$ | 7.9•10$^3$ | $2.35 \times 10^5$ | 8.00 |
| OUTER  | Thermal | 0.09 | 0 | 1 | 11 | 10 | $5 \times 10^6$ | $10^5$ | $10^6$ | 1.5 |
| OUTER  | Local | 5•10$^{-5}$ | 4•10$^7$ | 1.3 | 26 | 8 | $2 \times 10^7$ | $3 \times 10^9$ | $10^8$ | 1.2 |
| LIC    | Thermal | 0.0357 | 0 | 1 | 8.08 | 10 | $4 \times 10^6$ | $3 \times 10^6$ | $10^9$ | 1.5 |

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$^a$INNER: standard inner heliosheath (94 to 122 AU); HOT: hot inner (standard) heliosheath (~90 to 122 AU); COLD: cold heliosheath (122 to ~145 AU); OUTER: outer heliosheath (~145 to ~175 AU); LIC: unperturbed local interstellar cloud (>2000 AU).

$^b$Thermal: solar wind or interstellar wind with or without tail; Local: locally created pickup ions with or without tails; Trans: transmitted pickup ions with or without tails.

$^c$Densities are computed using the first equation in equation (1).
Table 4. Pressures of thermal ions and electrons, locally created pickup ions, transmitted pickup ions and magnetic field in various regions of the outer heliosphere, the outer heliosheath, and the LIC.

| Region | Type | Protons and Thermal Pressure | All ions and electrons | Magnetic Field (nT) |
|--------|------|-------------------------------|------------------------|-------------------|
|        |      | Thermal Pressure | Ram Pressure | Total Pressure | Magnetic Pressure | Magnetic Field |
| Inner  | Thermal | 1.54×10^{-14} | (3.49±0.61)×10^{-14} | (5.58±1.87)×10^{-14} | (9.07±1.97)×10^{-14} | (5.83±1.93)×10^{-14} | 0.121±0.020 |
| Inner  | Local  | 8.94×10^{-13} | (1.38±0.24)×10^{-12} | (1.75±0.59)×10^{-13} | (1.56±0.25)×10^{-12} | 0.876±0.088 |
| Inner  | Trans  | 1.06×10^{-12} | (1.64±0.28)×10^{-12} | (7.93±0.26)×10^{-15} | (1.65±0.28)×10^{-12} | 0.876±0.088 |
| Outer  | Thermal | 8.66×10^{-14} | (1.96±0.34)×10^{-13} | ~0×10^{-13} | (1.96±0.34)×10^{-12} | 3.05±0.62×10^{-12} | 0.876±0.088 |
| Outer  | Local  | 2.19×10^{-13} | (3.39±0.59)×10^{-13} | ~0×10^{-13} | (3.39±0.59)×10^{-13} | 0.876±0.088 |

Fisk and Gloeckler Model

| Region | Type | Protons and Thermal Pressure | All ions and electrons | Magnetic Field (nT) |
|--------|------|-------------------------------|------------------------|-------------------|
|        |      | Thermal Pressure | Ram Pressure | Total Pressure | Magnetic Pressure | Magnetic Field |
| HOT    | Thermal | 4.34×10^{-14} | 1.40×10^{-13} | 1.83×10^{-14} | 5.83×10^{-14} | 0.121 |
| HOT    | Local  | 8.32×10^{-13} | 1.29×10^{-12} | 1.31×10^{-13} | 1.42×10^{-12} | 0.121 |
| HOT    | Trans  | 9.27×10^{-13} | 1.43×10^{-12} | 7.69×10^{-15} | 1.44×10^{-12} | 0.121 |
| HOT    | ACRs   | 1.62×10^{-13} | 2.51×10^{-13} | 9×10^{-18} | 2.51×10^{-13} | 0.121 |
| COLD   | Thermal | 8.23×10^{-13} | 1.86×10^{-12} | 7.84×10^{-14} | 1.86×10^{-12} | 0.464 |
| COLD   | Local  | 6.59×10^{-14} | 1.02×10^{-13} | 1.37×10^{-15} | 1.03×10^{-12} | 0.464 |
| COLD   | Trans  | 3.73×10^{-13} | 5.78×10^{-13} | 2.40×10^{-16} | 5.78×10^{-13} | 0.464 |
| Outer  | Thermal | 4.36×10^{-13} | 9.87×10^{-15} | ~0×10^{-15} | 3.24×10^{-12} | 0.902 |
| Outer  | Local  | 1.27×10^{-13} | 1.96×10^{-13} | ~0×10^{-13} | 1.96×10^{-13} | 0.902 |
| LIC    | Thermal | 2.71×10^{-14} | 6.12×10^{-14} | 4.42×10^{-13} | 5.03×10^{-13} | 0.859 |
| CLOUD  | Thermal | ~3×10^{-12} | 2.94×10^{-12} | 2.94×10^{-12} | 0.859 |

aInnen: standard inner heliosheath (94 to 122 AU); HOT: hot inner (standard) heliosheath (~90 to 122 AU); COLD: cold heliosheath (122 to ~145 AU); OUTER: outer heliosheath (~145 to ~175 AU); LIC: Unperturbed local interstellar cloud (>2000 AU); CLOUD: hot cloud surrounding the LIC.

bThermal: solar wind or interstellar wind with or without tail; Local: locally created pickup ions with or without tails; Trans: transmitted pickup ions with or without tails.

cIncludes contributions from protons, electrons, and heavy ions for the solar wind and interstellar thermal ion populations and protons as well as heavy ions for local and transmitted pickup ions and ACRs. Since the composition of the solar wind [30] is well known, as is the composition of transmitted pickup ions [17] and ACRs [3], the total particle pressures are readily computed. For locally accelerated pickup ions we use solar wind abundances [30].

dAll pressures in units of dyne cm^{-2}. Thermal pressures, ram pressures, and magnetic pressures are computed using the second, third, and fourth equations, respectively, in equation (1).

eAverage magnetic field strength measured by VI in the hot [8] and cold [7] inner heliosheaths.

fValue and 1-σ error of magnetic pressure or field strength in the outer heliosheath derived from pressure balance.

2.2. Fisk and Gloeckler Model of the Nose of the Heliosphere

The observations [7,8] that the magnetic field direction did not change to the much different direction of the interstellar field, and that the magnetic field was so incredibly smooth [7], unlike anything observed at magnetopauses of planets, already cast doubt that Voyager 1 entered interstellar space in
late August 2012. Now we find that there is a 99.99% certainty that the weak magnetic field strength currently measured by $V1$ is not the interstellar field in the outer heliosheath. It must therefore be concluded that Voyager 1 is currently not in the outer heliosheath, nor in the local interstellar medium. It is, however, certainly in a most unusual region of the heliosphere, a region never before explored. The Fisk and Gloeckler model [12,13] of the nose of the heliosphere describes the properties of this unusual region they called the cold inner heliosheath: The magnetic field is incredibly smooth [7] and its direction the same as it was in the hot or standard inner heliosheath [7,8]. Particles above 40 keV nuc$^{-1}$ are no longer observed above background [2,3], they disappeared. The solar wind in the cold inner heliosheath is highly compressed. Its density is, in fact, the $\sim 0.085 \text{ cm}^{-3}$ high density measured by $V1$ in that region [1].

We now use pressure balance (1) along the radial direction of the $V1$ trajectory and (2) between our LIC and the larger hot cloud that surrounds it to determine best values of key parameters in the unperturbed (by the heliosphere) LIC. Constrained by observations (the ENH differential intensities, the $>$40 keV energetic particle spectra and magnetic field by $V1$, solar wind bulk velocity by $V1$ and $V2$ and its density by $V2$), we find the best mean values and 1-$\sigma$ error limits for $B$, the strength of the magnetic field, for $n$(HI), the neutral hydrogen density, and for $n$(HII), the proton density.

Pressure balance along the radial direction of the $V1$ trajectory requires that the average pressure in the hot heliosheath is the same as the average pressure in the cold heliosheath, is the same as the pressure in the outer heliosheath near the heliopause, and finally, is the same as the pressure in the unperturbed LIC, thousands of AU from the sun. The values of average particle pressures in the hot and cold inner heliosheath are constrained by the measured averaged ENH spectrum and the measured average energetic particle differential intensities. Since in these two regions of the inner heliosheath the magnetic field is also measured, the total average pressure in each of the two regions is also known. In figure 2 we show the derived ENH velocity distributions from (a) transmitted pickup protons and their tails, (b) locally accelerated protons and their tails, and (c) thermal (solar wind) protons and their tails. Parameter values in equations (2) and (3) were adjusted to (1) make the pressures in the hot and the cold inner heliosheath the same, and (2) obtain best fit (minimum reduced $\chi^2$) of the sum (black curve) of the individual spectra to the measured spectrum (black circles). The final and observationally most constrained set of values for $B$, $n$(HI), and $n$(HII) are $0.86 \pm 0.11$ nT, $0.10 \pm 0.02 \text{ cm}^{-3}$, and $0.036 \pm 0.012 \text{ cm}^{-3}$, respectively. Our best mean values and 1-$\sigma$ uncertainties for the LIC densities of neutral hydrogen and protons and for the magnetic field strength are listed in row 2, columns 2, 3, and 5, respectively, along with other estimates of these quantities.

Table 5. Densities of neutral hydrogen, protons and electrons magnetic field strength in the unperturbed local interstellar cloud.

| Source            | $n$(HI) [neutral hydrogen density (cm$^{-3}$)] | $n$(HII) [proton density (cm$^{-3}$)] | $n$(e$^-$) [electron density (cm$^{-3}$)] | $B$ [Magnetic field strength (nT)] |
|-------------------|----------------------------------------------|--------------------------------------|------------------------------------------|----------------------------------|
| Present work      | $0.10 \pm 0.02$                              | $0.036 \pm 0.012$                    |                                           | $0.86 \pm 0.11$                  |
| Reference [28]    | $0.09 \pm 0.02$                              |                                      |                                           |                                  |
| Reference [23]    | $0.115 \pm 0.025$                            | $0.040 \pm 0.017$                    | $0.049 \pm 0.016$                        | $< 0.43^a$                      |
| Reference [6]     | $0.13 \pm 0.04$                              |                                      |                                           |                                  |
| Reference [29]    | $0.165 \pm 0.035$                            |                                      |                                           |                                  |

$^a$The sizeable pressure due to transmitted pickup ions was not included.
3. Concluding Remarks

The most far-reaching conclusion of this paper is the strength of the interstellar magnetic field. The ~0.9 nT field, required for pressure balance between our local interstellar cloud and the hot cloud surrounding it, we now confirmed using pressure balance between the LIC and the heliosphere moving relative to it. Because magnetic pressure exceeds dynamic pressure by almost an order of magnitude, the shape of the heliosphere is not comet-like as all of us believed, but of the type to be shaped in a strong surrounding magnetic field as shown by Parker [22]: essentially a sphere draped by the interstellar field. The motion of the heliosphere distorts the polar field lines, dragging them tailward into two lobes, as imaged by IBEX. As IBEX observations clearly show, the reason for the existence of the high LIC field is to balance the high pressure (~3.5 × 10⁻¹² dyne cm⁻²) of the inner heliosphere. The reason why this pressure is a factor of two higher than what we previously believed (e.g. Gloeckler et al. [23]) is because we grossly underestimated the thermal pressure from pickup ions. Pickup ions play a dominant role in the dynamics of the outer heliosphere and must be included along with the solar wind in any credible numerical model of the heliosphere, even though this presents an enormous challenge. These model must also use the realistic value of ~0.9 nT for the LIC magnetic field strength, neutral hydrogen density (~0.1 cm⁻³), and proton density (~0.035 cm⁻³).

The implications of the existence of this new region are also far-reaching and profound, and will require rethinking by our scientific community of the physics that applies to this highly unusual region. Our analysis of the measured ENH differential intensity shows that pickup ions, both transmitted and locally created, and their suprathermal tails (ACRs) account for 96% of the total inner heliosheath pressure and thus dominate the dynamics of the heliosphere. Unfortunately, current numerical models of the heliosphere ignore this fact and will thus require major revisions.

The near certainty that Voyager 1 has not yet reached interstellar space implies that the exciting exploration of the outer heliosheath is still ahead after VI crosses the heliopause several years from

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Figure 2. Same as figure 1 but here applied to the Fisk & Gloeckler model [12,13] for the nose of the heliosphere, which has the cold inner heliosheath. The sum of the eight ENH phase space density spectra of particle populations in the hot inner heliosheath (red curves A, B and C), the cold inner heliosheath (green curves G, H and K), and the outer heliosheath near the heliopause (~145 to ~175 AU, blue curves E and F) yield the total spectrum (bold curve) of ENH below ~4.4×10⁸ cm s⁻¹ from the emission region (hot inner, cold inner and outer heliosheaths) where these ENH are created. Curve D is the low end of the ACR ENH.
now. But even before this historic crossing, it is very likely that the predicted [12,13] field polarity reversal will be observed. Then we will know precisely just how slow the solar wind flows in the cold inner heliosheath of the heliosphere.

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