IBEX Observations provide strong Evidence that Voyager 1 is still in the Heliosheath

G Gloeckler and L A Fisk
Department of Atmospheric, Oceanic and Space Sciences
University of Michigan, Ann Arbor, Michigan 48109-2143, USA

E-mail: gglo@umich.edu

Abstract. After plasma wave measurements by Voyager 1 (V1) revealed a surprisingly high value for the plasma electron density, a value close to that expected in the local interstellar medium, all principal investigators of the Voyager mission currently exploring the heliosheath suddenly reversed their position on the location of V1. They concluded unanimously, and NASA announced that V1 has crossed the heliopause and is now in local interstellar space. We have disputed this conclusion, pointing out that to account for all the V1 observations, particularly of the magnetic field direction together with the density, it is necessary to conclude that the higher densities observed by V1 are due to compressed solar wind. In this paper we show that our model for the nose region of the heliosheath can account in detail for the spectral shapes and intensities of Energetic Neutral Hydrogen (ENH) observed by the Interstellar Boundary Explorer (IBEX) looking in the directions of V1 and Voyager 2 (V2). A key feature of our model is the existence of a region, the hot heliosheath, where the outward-moving solar wind is gradually compressed and thus heated, followed by a region, the cold heliosheath, where the solar wind is still compressed but now cold. It is the existence of this cold heliosheath, the region of cold but high-density solar wind, which provides a unique and simple explanation for the low-energy IBEX ENH differential intensities. Finally, since this cold heliosheath is the region where V1 must now reside, the low-energy IBEX observations provide strong evidence that V1 is still in the heliosphere.

1. Introduction
Differential intensities (spectra) of energetic neutral hydrogen (ENH) measured by the two main instruments on the Interstellar Boundary Explorer (IBEX) provide invaluable information about the proton velocity distribution throughout, and especially in, the nose region of the heliosheath currently being explored by the two Voyager spacecraft. As shown in figure 1, on Voyager 1 (V1) proton measurements are available only above ~40 keV, and on Voyager 2 (V2) the core of the solar wind protons (but not any tails) are measured as well. IBEX makes line-of-sight measurements, producing average spectra in most directions integrated over time and a small solid angle. The Voyagers, on the other hand, measure in situ proton spectra at each radial distance in the heliosheath they are exploring. Unfortunately, on V1 there are no proton measurements in the important energy range of pickup protons nor are there solar wind observations, and while on V2 the bulk properties of the core solar wind are available, no information is provided on any tails on the solar wind distributions.

1 To whom any correspondence should be addressed.

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.

Published under licence by IOP Publishing Ltd
Figure 1. Differential intensity versus inertial (sun) frame energy of (1) Energetic Neutral Hydrogen (ENH) measured by IBEX in the Voyager 1 direction (red symbols) and (2) greater than 40 keV protons measured in the heliosheath at ~115 AU by LECP and CRS on Voyager 1 (green symbols). No in situ particle are measured by V1 below 40 keV where solar wind protons, transmitted pickup ions and their suprathermal tails reside. On Voyager 2, in addition to greater than 40 keV particles, the core of the velocity distribution of solar wind protons is measure (blue curve) still leaving a gap between ~0.1 to 40 keV (shaded region). IBEX ENH measurements provide essential information about heliosheath proton populations in the energy ranges not covered by the Voyagers.

When at ~122 AU V1 crossed the heliocliff, greater than ~40 keV protons suddenly disappeared and the Galactic Cosmic Ray (GCR) intensity increased. Yet, because the direction of the magnetic showed no change in crossing this sharp boundary, it was generally believed that V1 remained in the heliosheath, although this new region of the heliosheath was clearly very different from that between the termination shock (TS) and the heliocliff. In this new region of the heliosheath energetic particles had easily escape to, and GCRs had easily entered from the local interstellar medium located beyond the heliopause. However, when Gurnett et al. [1] reported exceptionally high (compared to values observed by V2 nearer to TS) plasma densities at ~123 AU just beyond the heliocliff, the opinion of many, including all Voyager PIs, changed completely. They argued that these high (~0.1 cm⁻³) density protons had to be of interstellar origin not only because the high values were similar to rough estimates of interstellar proton density, but also because they believed that the heliosheath solar wind could not be compressed. The Voyager PIs voted unanimously that V1 has been in the local interstellar medium ever since it crossed the heliocliff, which in retrospect they claimed was really the heliopause. This historically important event was announced to the public in a NASA press conference.

We (Fisk and Gloeckler) have disputed the assertion that V1 has crossed the heliopause, pointing out that to account for all the V1 observations, particularly the lack of any change in the magnetic field direction [2] in crossing the heliocliff, it is necessary to conclude that the high densities observed by Gurnett et al. [1] are due to compressed solar wind. Indeed, by applying the mass conservation law to the solar wind velocity measurements (using energetic particle anisotropies) of Decker et al. [3] and Stone and Cummings [4], that showed a decrease in all three components of the solar wind bulk.

---

2 Even though the solar wind density is not measured directly on V1, measurements of the density of local thermal electrons are available from plasma wave observation under occasional favorable circumstances.
velocity, it must be concluded that the solar wind becomes compressed beyond \( \sim 110 \) AU along the trajectory of V1. Fisk and Gloeckler [5] developed a model for the nose of the heliosphere (hereinafter referred to as the F&G model) in which a new region (the cold heliosheath) between the heliocliff and heliopause contained a dense but cold (low temperature) solar wind (see figure 2). In the F&G model, sufficiently energetic (e.g. greater than \( \sim 40 \) keV) mobile particles could easily escape to the local interstellar medium and GCR could enter the cold heliosheath primarily at the flanks through a porous heliopause\(^3\) provided the heliosheath magnetic field had a favorable polarity. Thus, Gloeckler and Fisk [6] predict that with the higher densities (and hence lower speed) of the compressed solar wind, V1 will encounter another current sheet in the heliospheric magnetic field that results from the change in polarity of the solar magnetic field during the solar cycle. With the then latest estimates of the radial solar wind speed beyond 122 AU, they predicted that V1 should encounter the next current sheet by the end of 2016.

Figure 2. Schematic representation of the nose region of the heliosphere in the planes of constant latitude of V1 (~30\(^\circ\) north) and V2 (~30\(^\circ\) south). The sharp heliocliff (HC) boundary (red) separates the hot from the cold heliosheath, and is more blunt than either the steady-state termination shock (TS, blue) or the heliopause (HP, green). The brown curves represent two sample streamlines from the F&G model of the nose of the heliosheath. Best fits to the low-energy segment of the IBEX ENH spectra in the V1 and V2 directions respectively determine the widths of the cold heliosheath near the flanks (V2 direction) to be \( W_2 \approx 3 \) AU, and near the centerline (V1 direction) to be \( W_1 \approx 18 \) AU, as predicted in the F&G model.

The Interstellar Boundary Explorer (IBEX) has been observing Energetic Neutral Hydrogen (ENH), created beyond the termination shock (TS) [7]. In particular, IBEX measures line-of-sight ENH spectra in nearly all directions including those of V1 and V2 (e.g. [8]). Nearly all ENH seen by IBEX is produced in the heliosheath where interstellar neutral hydrogen gas flowing into the heliosphere charge-exchanges with solar wind and more energetic protons (suprathermal solar wind tails and pickup ions with their tails). The ENH spectra (differential intensities as a function of inertial or sun frame energy \( E \)), \( J_{\text{enh}}(E) \), is derived from the proton spectra, \( J_p(E,r) \), beyond 100 AU using the standard ENH production equation:

\[
J_{\text{enh}}(E,\theta,\phi) = \int_{100\text{AU}}^{\infty} J_p(E,\theta,\phi,r) N(r) \sigma(v_{\text{rel}}(r)) dr
\]

where \( N(r) \) is the density of the neutral gas, \( \sigma(v_{\text{rel}}(r)) \) is the H-p charge exchange cross section and \( v_{\text{rel}}(r) \) is the relative speed between the proton and the interstellar hydrogen gas with which it interacts. Thus, IBEX spectra in a given (\( \theta,\phi \)) pixel provide essential information on the proton spectra in the same (\( \theta,\phi \)) direction in the heliosheath. In particular, IBEX spectra in the V1 and V2 directions, combined with in situ measurements by V1 of the solar wind velocity and proton spectra above 40 keV from the TS to the heliocliff, and of solar wind bulk parameters as well as >40 keV proton spectra

\(^3\) The heliopause in the F&G model had to be a rotational discontinuity boundary.
by V2, provide, through equation 1, essential information on heliosheath proton spectra in the IBEX energy range (~0.005 to ~5 keV) as a function of heliocentric distance $r$.

While most of the attention was focused on explaining the IBEX ribbon$^4$ spectra, Gloeckler and Fisk [10] were among the first to offer an explanation of the then available IBEX non-ribbon spectrum in the V1 direction. They considered 4 proton populations in the heliosheath, among them the low density heliosheath solar wind that periodically would be moving radially inward. This inward moving solar wind would then create the ENH that was detected by IBEX. However, when Fuselier et al., [8] published updated IBEX spectra over the entire energy range of the IBEX-Lo and IBEX-Hi instruments in both the V1 as well as the V2 directions, the Gloeckler and Fisk [10] model predicted much lower fluxes below ~0.3 keV than those of the updated IBEX spectra of 2012 (see figure 7 of [8]). Model fits to the non-ribbon IBEX spectra by others (e.g. [10,11]), including the most recent one by Zirnstein et al. [12], assumed that pickup ion populations in the heliosheath were the dominant source of the ENH observed by IBEX.

In the most recent attempt to explain the IBEX non-ribbon spectra, Zirnstein et al. [12] considered the parent populations of IBEX ENH to be three forms of pickup ions (transmitted, reflected and injected). Contributions from the solar wind or its suprathermal tail were deemed to be insignificant, because after all, it was generally believed that the solar wind could not be compressed nor develop strong tails anywhere in the heliosheath. Summing up the three pickup proton populations in both the heliosheath (they called the "Inner Heliosheath" or IHS) and the local interstellar medium (they called the "Outer Heliosheath" or OHS) resulted in a complex spectrum that flattens and then bends down below 100 eV (see figure 4 of [12]). In particular, below ~0.15 keV their model flux was at least 10 times lower than fluxes measured by IBEX.

IBEX fluxes below ~0.1 keV were never explained. Nobody could find a plasma source for these very low energy ENHs. There is, however, a very simple explanation for the non-ribbon ENH differential intensities, $J_{\text{enh}}(E)$, measured by IBEX over its entire energy range. All that is necessary to fit these IBEX spectra, is to have a high density hot solar wind just upstream of the heliocliff and a high density but very cold solar wind in the cold heliosheath region between the heliocliff and the heliopause. It is in the cold heliosheath where the lowest energy ($< ~0.1$ keV) ENH is created.

2. The F&G model for the nose region of the heliosheath

The existence of a cold heliosheath between the heliocliff and the heliopause is an essential feature of the Fisk and Gloeckler [5] model for the nose of the heliosheath. We will briefly describe this model which in the hot heliosheath (between the termination shock and the heliocliff) also allows for the compression and heating of the solar wind and pickup ions, as well as formation of strong suprathermal tails on both the solar wind and pickup proton distributions. In the hot heliosheath the outward moving solar wind is gradually compressed and heated reaching densities of $\sim 0.05$ cm$^{-3}$ at the heliocliff.

Note in figure 2 that in the F&G model the shape of the heliocliff is more blunt than either the termination shock or the heliopause. This will result in a difference in the widths of the hot and cold heliosheaths in the directions of V1 and V2, which are also noted in figure 2. Figure 2 should be interpreted as an appropriate representation for both the heliographic latitude of V1 (34.6 north) and of

$^4$The ribbon is a relatively narrow region of enhanced ENHs, with energies $\sim$1 keV, superimposed on the nose-region spectrum, and stretching like a ribbon across the sky. There have been numerous explanations put forth for the IBEX ribbon, many of which are summarized in [Schwadron et al. (2014)], and most of which involve processes occurring beyond the heliopause
V2 (31.1 south). Note that the trajectory of V1 is close to the centerline at its latitude, and thus in this direction the hot heliosheath is relatively narrow and the cold heliosheath relatively wide. In contrast, the trajectory of V2 is closer to the flanks, where the hot heliosheath is relatively wide and the cold heliosheath relatively narrow. The general features of the F&G model [5] are illustrated in figure 2 that shows: (1) A region between the termination shock and the heliocliff (where there is a precipitous decrease in the ACRs). This region is the 'hot heliosheath' (HH) in which the solar wind is gradually compressed and heated as it drifts outward, attaining maximum thermal speed near the heliocliff. (2) A region between the heliocliff and the heliopause, where the solar wind continues to be compressed, but is very cold. This region is the 'cold heliosheath' (CH) from which ACRs, TSPs and the high-energy pickup ions as well as tail particles of the solar wind have escaped into the local interstellar medium. The escape of these mobile particles is primarily along the magnetic field that is lined up with the heliocliff and connects to the heliopause primarily at the flanks. To make this possible, the heliocliff must be more blunt than the heliopause.

The F&G model of the nose region of the heliosheath [5] is based on two Voyager observations: (1) In the HH, along a cone of constant heliographic latitude at radial distances along the V1 trajectory beyond ~110 AU the solar wind flow direction turns increasingly more from the radial to a transverse direction. (2) In the cold heliosheath, mobile particles such as pickup ions and ACRs, which contain the pressure, have escaped. Thus, these energetic, mobile particles that are free to move along the magnetic field to balance pressure, can be considered and treated as a separate gas from the solar wind. The solar wind inner core (but not its tail) contains the mass and is responding to local conditions.

The uncoupling from the bulk or inner core of solar wind of the its outer core and tail, and the subsequent escape of the solar wind outer core and tail as well as of the higher energy pickup ions, TSP protons and ACRs, combined with the observation that the solar wind flows primarily on a cone of constant heliographic latitude, makes it quite simple to calculate the streamlines of the solar wind, as is done in [5]. With the streamlines primarily radial and azimuthal downstream from the termination shock, there must be a centerline region, where the streamlines diverge, flowing to the right and to the left of the centerline. Furthermore, the centerline region must occur at all heliographic latitudes, defining a plane that is oriented roughly perpendicular to the heliographic equator. The centerline plane includes the direction of motion of the Sun through the local interstellar medium so that the flow of solar wind into the tail of the heliosheath forms a tail that is opposite to the direction of motion.

A vacuum is created on either side of the centerline by the divergence of the streamlines into which the solar wind can leak. The centerline region thus exerts a drag that reduces the outward flow speed of the solar wind. This decrease in speed results in an increase in solar wind density, converting solar wind ram pressure into thermal pressure. The region where the solar wind is gradually being compressed and heated is the hot heliosheath.

As the solar wind velocity decreases, the azimuthal speed goes to zero before the radial speed and the solar wind continues to flow radially outward to the heliopause, across which the solar wind and the magnetic field have to escape. In the F&G model the heliopause must thus be a rotational discontinuity, which can accommodate flows normal to the discontinuity. In the F&G model the heliopause is at 140 to 145 AU.

The escape of the solar wind across the heliopause will result primarily in the decrease of its pressure since the higher energy particles escape more easily than the lower energy ones. When this escape

5 See ref [5] for the details of the escape mechanism.
becomes possible, the ACRs, the high-energy pickup ions, and the high-energy tail of the solar wind disappear as is observed. This region is thus analogous to a balloon that is cooled. The balloon shrinks in size and the density increases to equal the densities observed by [1]. The region where escape across the heliopause occurs is the cold heliosheath, and the boundary between the hot and cold heliosheath is the heliocliff, marked by the sudden escape of the ACRs.

We emphasize again that in the F&G model the shape of the heliocliff is more blunt than the heliopause resulting in a difference in the widths of the hot and cold heliosheaths in the directions of V1 and V2, as noted in figure 2. Figure 2 is an appropriate representation for both the heliographic latitude of V1 (34.6 north) and of V2 (31.1 south). Note that the trajectory of V1 is close to the centerline at its latitude, and thus in this direction the HH is relatively narrow and the CH relatively wide. In contrast, the trajectory of V2 is closer to the flanks, where the HH is relatively wide and the CH relatively narrow.

3. The ENH Spectra in the Directions of Voyagers 1 and 2

Using the general features of the F&G model for the nose region of the heliosheath, we determine the proton velocity distributions as a function of heliocentric distance, \( r \), as well as the dimensions of the HH and CH that are required to fit the IBEX ENH spectra in the directions of V1 and of V2, respectively. We use the most recent IBEX spectra in both the V1 and V2 directions published by Fuselier et al. [8] who have extrapolated their measured spectra back to 100 AU (i.e. to the inner edge of the HH), correcting background and for the extinction that occurs from charge-exchange in the supersonic solar wind between 1 and 100 AU. These V1 and V2 pixel IBEX spectra cover the full energy range (~0.006 to ~4 keV) of the IBEX instruments and, while the error bars on the lowest four energy points of the spectra are large, they have sufficient accuracy to distinguish among models.

3.1. Proton velocity distributions in the heliosheath

The Energetic Neutral Hydrogen spectra observed by IBEX are directly related to the proton spectra in the heliosheath in the IBEX energy range through equation 1. In this range reside several important populations of particles. Among them the solar wind with its suprathermal tail, and transmitted pickup protons and their tails make the dominant contributions to the ENH spectra. Unfortunately, as shown in figure 1, energy spectra of protons are not measured on V1 in the IBEX energy range and, while on V2 solar wind distributions are measured, they are typically confined to energies below about 0.01 keV, and with V2 still in the hot heliosheath, are currently available only to distances not that far from the termination shock.

Lacking direct measurements of proton velocity distributions in the IBEX energy range we use three analytic functions, each with a minimum number of free parameters, that respectively fit velocity distribution of (a) the solar wind with its suprathermal tail, (b) interstellar pickup ions, and (c) suprathermal tails measured directly by ACE and Ulysses in local strong acceleration regions. Making the reasonable assumption that these spectral forms are also representative of the heliospheric proton populations, we use the same analytic function for proton distributions in the heliosheath and then adjust the few free parameters of these functions to match the IBEX spectra.

3.1.1. The solar wind proton distribution function in the hot heliosheath

The hot heliosheath (HH) is characterized as a region of high compressive turbulence [2], making it an ideal region for accelerating particles by the Fisk & Gloeckler [13] pump mechanism. Similar regions of high compressive turbulence are often observed downstream of strong propagating (CME) shocks at 1 AU. In figure 3 we show the solar-wind-frame phase space density spectrum of protons measured by ACE downstream of a strong shock [13]. The function (solid curve) that fits the entire spectrum has the simple form:
With \( f_{sw} = \frac{v}{v_{th,sw}} \left[ 1 + \left( \frac{v}{v_{th,sw}} \right)^2 \right]^{-2.5} \exp \left[ -\left( \frac{v}{v_{roll,sw}} \right)^2 \right] \) (2)

With \( f_{sw,0} = 4 \times 10^{11} \text{s}^3/\text{km}^6, v_{th} = 2.3 \times 10^6 \text{ cm/s} \) and \( v_{roll,sw} = 4.5 \times 10^8 \text{ cm/s} \), equation 2 provides an excellent fit to the observed spectrum (red filled circles). The number density derived from this distribution is 18 cm\(^{-3}\). The observed spectrum has a core segment that is reasonably well fit my a maxwellian distribution (dashed curve) with a density of 18 cm\(^{-3}\) and thermal of 2.3\( \times \)10\(^6\) cm/s, (the same values that were used in equation 2) and a suprathermal \(-5\) power law tail segment above 4 times the thermal speed (~1\( \times \)10\(^7\) cm/s) that rolls over at an e\(^{-}\)folding speed of 4.5\( \times \)10\(^8\) cm/s.

**Figure 3.** Distribution function of protons (red symbols) observed at 1 AU by ACE SWICS and ULEIS downstream of a strong shock [13]. The blue curve is a fit to the spectrum using equation 2 and parameters listed in the text. The dashed curve is a fit of a maxwellian distribution to the core phase space density (lowest two energies points).

It is reasonable to assume that similar spectra exist in the hot heliosheath, the region downstream of the termination shock. Allowing for the gradual compression of the solar wind as it propagates outward the three parameters in equation 2 will depend on heliocentric distance \( r \). However, the three parameters can be reduced to two by assuming adiabatic compression of the solar wind. The thermal speed is then related to the density by equation 3,

\[ v_{th} = v_{th,TS} \left\{ \frac{n_{sw}}{n_{TS}} \right\}^{1/3} \] (3)

Thus, equation 2 becomes

\[ f_{sw} (r) = f_{sw,0} \left( \frac{n_{sw}}{n_{TS}} (r) \right) \left[ 1 + \left\{ \frac{v}{v_{th,TS}} \right\} \left\{ \frac{n_{TS}}{n_{sw}} (r) \right\}^{1/3} \right]^{-2.5} \exp \left[ -\left( \frac{v}{v_{roll,sw}} \right)^2 \right] \] (4)

It has only 2 free parameters, the density and the rollover speed \( v_{roll,sw} \). The contribution of solar wind protons to the IBEX ENH spectra become progressively more important with increasing solar wind density which reaches its highest value (~0.05 cm\(^{-3}\)) in the hot heliosheath at the heliocliff.
3.1.2. The transmitted pickup proton and tail distribution functions in the hot heliosheath

Pickup protons (PP) created upstream of the termination shock are compressed and heated as they cross the TS and enter the HH. Convected across the TS, their density and pressure increase is given by the Rankin-Hugonion relations and will depend on the compression ratio of the TS (typically ~3). These pickup protons will make the dominant contribution to the IBEX ENH spectra near the TS. Unfortunately, these important populations are not measured by V1. However, Ulysses measured directly [14] pickup proton distributions and their suprathermal tails downstream of Jupiter’s bow shock (see figure 4). Because the heliosheath has many similarities to the region downstream of Jupiter’s shock we use the same analytic functions that best fit the Jupiter spectra for describing the pickup proton distributions and their tails in the heliosheath downstream of the termination shock.

The function (blue curve in figure 4) that fits to the pickup proton segment of the spectrum downstream of Jupiter’s bow shock has the form:

\[
f_{\text{PP}} = f_{\text{PP,0}} \left[ 1 + \left( \frac{v}{4v_{\text{upstrm}}} \right)^2 \right]^{-15} \exp \left[ -\left( \frac{v}{12v_{\text{upstrm}}} \right)^2 \right] \exp \left[ -\frac{3v_{\text{upstrm}}}{v} \right] \]

(5)

It has only two free parameters: the pickup proton density (that determines \(f_{\text{PP,0}}\)), and the solar wind speed upstream of the shock. With \(f_{\text{PP,0}} = 2.2 \cdot 10^5 \text{s}^3/\text{km}^6\) and \(v_{\text{upstrm}} = 4.2 \cdot 10^7 \text{cm/s}\), equation 5 provides an excellent fit to the observed spectrum (red symbols) below \(2 \cdot 10^8 \text{cm/s}\).

Ulysses HI-SCALE measured the -5 power law suprathermal tail (filled red squares). This segment of the spectrum is well fit by the analytic function:

\[
f_{\text{PP tail}} = f_{\text{PP tail,0}} \left( \frac{v}{4v_{\text{upstrm}}} \right)^{-5} \exp \left[ -\left( \frac{v}{v_{\text{roll,PP tail}}} \right)^5 \right] \exp \left[ -\left( \frac{2v_{\text{upstrm}}}{v} \right)^2 \right] \]

(6)

It also has only 2 free parameters: the tail density (that determines \(f_{\text{PP tail,0}}\)), and the rollover e-folding speed, \(v_{\text{roll,PP tail}}\). Setting \(f_{\text{PP tail,0}} = 2.2 \cdot 10^5 \text{s}^3/\text{km}^6\), \(v_{\text{roll,PP tail}} = 10^9 \text{cm/s}\), and using for \(v_{\text{upstrm}} = 4.2 \cdot 10^7 \text{cm/s}\) (same as in equation 5) yields an excellent fit to the suprathermal tail segment of the measured spectrum. Equation 6 has also only two free parameters, \(f_{\text{PP tail,0}}\) and \(v_{\text{roll,PP tail}}\).

It is reasonable to assume that in the hot heliosheath similar transmitted pickup proton distributions and pickup proton tail distributions exist. The free parameters would now be dependent on heliocentric distance \(r\), and we will adjust them to fit the upper energy segment of the IBEX ENH spectra.

**Figure 4.** Distribution function of protons (red symbols) observed [14] downstream of Jupiter’s bow shock. The blue curve is the analytic function from equation 5, and the filled red squares are the HI-SCALE measurements of the suprathermal tail.
shock by Ulysses SWICS and HI-SCALE. The blue and red curves are, respectively, fits to the pickup proton and the suprathermal tail segments of spectrum using equations 5 and 6 and parameters listed in the text.

3.1.3 The proton distribution function in the cold heliosheath
At the heliocliff the solar wind density is most compressed and its pressure has attained its highest value. The density and pressure of the pickup proton tail have also reached their maximum values. However, the pickup proton pressure has to gradually decreasing with increasing $r$, and at the heliocliff its pressure is at its lowest value. The reason for this is the transfer of energy from pickup protons to the tail. Pickup protons lose the energy they transfer to the tail. The pump acceleration mechanism, with its key assumption that the total energy of the system remains constant, produces the tail. In a system of constant energy the total pressure (sum of the PP and the PPtail pressures) must therefore remaining constant.

Crossing the heliocliff the proton distributions enter the cold heliosheath where the magnetic field lines intersect the heliopause at the flanks. When the heliosheath magnetic field direction is roughly aligned with the direction of the draped local interstellar field (as has been the case since V1 crossed the heliocliff) the highly mobile energetic particles will escape and enter the local interstellar medium. This is why V1 observes of the sudden disappearance of $> 40$ keV protons and heavier particles.

The velocity distribution of the remaining protons in the cold heliosheath, those that have not escaped, will be

$$f_{\text{cold, remain}} (r, v) = \left\{ f_{\text{sw}} (r, v) \exp \left[ - \left( \frac{v}{v_{\text{uncouple}}} \right)^4 \right] + f_{\text{PP, HC}} (v) + f_{\text{PPtail, HC}} (v) \right\} g(v)$$

The exponential term represents the speed-dependent uncoupling function of the solar wind tail. The function $g(v) = [1 - h(v)]$ with

$$h(v) = \left\{ 1 - \exp \left[ - \left( \frac{v}{v_{\text{cold}}} \right)^3 \right] \right\}$$

The function $h(v)$ is the particle escape probability. Few low speed particle escape, while hardly any particles having speeds several times the rollover speed, $v_{\text{cold}}$, remaining. The single free parameter in $h(v)$, $v_{\text{cold}}$, is strongly constrained by the disappearance of $>40$ keV particle observed by V1 after crossing the heliocliff, and by the requirement of pressure balance (some low energy pickup ions must remain in the cold heliosheath to compensate for the pressure lost due to the disappearance of $>40$ keV particles). The other free parameters in equation 7 (especially $v_{\text{uncouple}}$) are determined by matching the lowest energy segment of the IBEX spectra.

3.2. Radial dependence of the fit parameters
The IBEX V1 and V2 pixel ENH spectra along with in situ observations of the energy spectra of protons above 40 keV by V1 allow us to find the radial dependence of the few free fit parameter in equations 4 to 8.

The main free parameter in fitting the time averaged IBEX spectra is radial dependence of the time-averaged density of the solar wind in the heliosheath and, to a lesser degree, the density of pickup ions near the termination shock. The radial dependence of the solar wind density that provided the best fit to the middle energy segment of the IBEX V1 pixel spectrum is shown in figure 5a. Starting at 0.002 cm$^{-3}$, the solar wind density gradually ramps up to a value of $\sim 0.05$ cm$^{-3}$ at the heliocliff. The
density continues to increase rapidly beyond the heliocliff, reaching the local interstellar density about 4 AU downstream of the heliocliff at ~126 AU.

The other essential fit parameter is the time-averaged radial speed, \( u_r(r) \) of the solar wind. One needs to know \( u_r(r) \) for transforming from the solar wind frame of reference to the sun frame of reference of the IBEX measurements. The blue curve in figure 5b shows the dependence of \( u_r(r) \) on heliocentric radial distance. Starting near the termination shock, the time-averaged \( u_r(r) \) decreased matching the in situ measurement\(^6\) of Decker et al. [3]. At about 115 AU \( u_r(r) \) reaches its minimum value of only ~ 5 km/s. To fit the lowest energy segment of the IBEX V1 spectrum it is necessary to slowly increase \( u_r(r) \) to about 13 km/s near the heliopause\(^7\).

![Figure 5.](image)

**Figure 5.** Solar wind number density (upper panel) and radial component of the bulk velocity measured by Decker et al. [3] (lower panel) as a function of heliocentric radial distance. The smooth red and blue curves are respectively the time-averaged density and the radial speed profiles that give best fits to the IBEX ENH spectra. Snap-shot measurements of density by Gurnett et al. [1] (blue symbols) and of radial speed by Decker et al. [3] will deviate from the time-averaged values as discussed in the text.

The fit parameters used in equations 3 to 8 give us the radial dependence of the distribution functions of the various proton populations in the heliosheath. From these distribution functions we derive physical parameters (e.g. thermal speeds of the core spectrum and pressures) of each of these populations. In figure 6a we show the variation of the thermal speed of the core solar wind with heliocentric distance. As the solar wind is compressed, its thermal speed increase, reaching 115 km/s at the heliocliff. Upon entering the cold heliosheath the solar wind immediately cools considerably by shedding its strong suprathermal tail. The thermal speed of the solar wind in the CH is reduced to just ~20 km/s\(^8\).

---

\(^6\) *In situ* measurements of the solar wind radial speed and density by the Voyagers will fluctuate from the time-averaged values due to the dynamics of the system. These semi-periodic fluctuations over distances of several AU are evident in measurements of \( u_r(r) \) and are likely to occur in the solar wind density measurements as well.

\(^7\) The time-averaged speed \( u_r(r) \) derived from the IBEX measurements beyond the heliocliff is considerably higher than that used by Gloeckler and Fisk [6] to estimate the time of observation of the magnetic sector reversal. This higher radial speed implies that V1 should see the 180° change in the magnetic field direction several years later than estimated in ref [6].

\(^8\) An ideal plasma detector on V1 looking in all directions would easily have detected this solar wind. While V2 has a working (but not an ideal) plasma instrument with its field of view pointing primarily towards the sun, it is not clear that solar wind observations will be made once V2 enters the region of the heliosheath where \( u_r(r) \) is less than the speed of the spacecraft (~17 km/s).
IBEX ENH spectra combined with Voyager observations of magnetic field strength and energetic particle spectra above 40 keV allow us to obtain a good estimate of the total pressure ($2.5 \times 10^{-12}$ dyne/cm$^2$) in the heliosheath from the sum of pressures of the magnetic field and of the four proton populations (solar wind and its tail, transmitted pickup protons, suprathermal tails and ACRs). In figure 6b we show the radial dependence of the respective pressures. Just downstream of the termination shock transmitted pickup protons (PP) account for nearly all the pressure. According to the pump mechanism the tail pressure (tail) will gradually increase (due to the increase of the rollover speed of the tail) to its maximum value at the heliocliff. The pressure gained by the tails results in the loss of pressure of the pickup protons. At the heliocliff nearly all of the tail particles and most of the pickup protons vanish, and the pressure of remaining energetic particles drops precipitously.

The pressure resulting from the solar wind and its -5 tail (SW) is insignificant in the low-density solar wind. However, as the solar wind is compressed its pressure increased dramatically and at the heliocliff this is by far the dominant pressure (almost $2.5 \times 10^{-12}$ dyne/cm$^2$). When the solar wind enters the cold heliosheath it loses not only its tail but also much of the high-energy portion of its core. These solar wind particles detach from the solar wind inner core and escape. The solar wind in the cold heliosheath is dense because the remaining innermost core particles (which determine the density) have not escaped, but its thermal speed is low because of the loss of outer-core particles. While its pressure drops from $2.5 \times 10^{-12}$ dyne/cm$^2$ at the heliocliff to $1.5 \times 10^{-12}$ dyne/cm$^2$ in the cold heliosheath, it still carries most of the pressure.

![Figure 6](image)

**Figure 6.** Radial profiles of the thermal speed of the core solar wind (upper panel), and (lower panel) the pressures of the solar wind with its -5 tail (SW), pickup protons (PP), tail protons (often labeled TSPs), ACR protons and magnetic field (Mag). There is an abrupt decrease at the heliopause in the solar wind density and all the particle pressures because of escape of the more energetic, highly mobile particles (described in the text). At the same time there is a large increase in the magnetic pressure required to maintain pressure balance.

The magnetic field pressure is estimated from the magnetic field strength measured by V1 [2]. In the hot heliosheath the magnetic pressure (Mag, dashed curve) is small. In the cold heliosheath its pressure jumps to $\sim 10^{-12}$ dyne/cm$^2$. This large increase in magnetic pressure compensates for the
pressure loss from the disappearing ACRs, pickup protons and tails and pressure balance is maintained.

3.3. Fits to the V1 and V2 pixels IBEX Energetic Neutral Hydrogen spectrum

The solar wind frame velocity distributions of the various proton populations in the hot and cold heliosheaths as a function of heliocentric radial distance along either the V1 direction, \((\theta_{V1}, \phi_{V1})\) are computed using equations 3 to 8. The corresponding differential intensities in the sun frame are then given by

\[
J_p(E, r, \theta_{V1}, \phi_{V1}) = 1.83E_p \left( v_{p, \text{radial}} - u_{sw, \text{radial}} r, \theta_{V1}, \phi_{V1} \right)
\]

where \(E\), in units of keV, is \([2.283 \times 10^{-8} (v_{p, \text{radial}} - u_{sw, \text{radial}} r)]^2\), \(v_{p, \text{radial}}\) is the radial component of the particle velocity and \(u_{sw, \text{radial}}\) is the radial component of the solar wind bulk velocity, all in units of cm/s. Note that \(u_{sw, \text{radial}}\) is a function of \(r\) and its variation with \(r\) is shown in figure 5b. The ENH differential intensity in the sun frame is then computed using the summation form of equation 1:

\[
J_{\text{enh}}(E, \theta_{V1}, \phi_{V1}) = \sum_{k=1}^{\text{\# Jin}} \int J_p(E, r_k, \theta_{V1}, \phi_{V1}) \varnothing \sigma(v_{rel}(r_k)) \Delta r_k
\]

We use a constant value of 0.15 cm\(^{-3}\) for the neutral hydrogen density and for the p-H charge exchange cross section, \(\sigma\), we use the formula given by Lindsay and Stebbing [15]. Note that \(v_{rel}\), the relative speed between the interstellar gas and the proton with which it charge-exchanges will also depend on \(r\). Also note that \(J_p(E, r_k, \theta_{V1}, \phi_{V1})\) is the sum of the differential intensities of all proton populations in the IBEX energy range (i.e. solar wind, pickup protons and tail particles) at \(r_k\). The summation starts at \(r_1 = 100\) AU and ends at \(r_n = r_{\text{heliopause}} = 140\) AU, and the increments, \(\Delta r_k\), are variable, typically 2 AU when changes in the solar wind density are large and 5 AU when the changes in density are small. Summing over the entire heliosheath from 100 AU to 140 AU (the likely location of the heliopause at V1) produces the heavy black curve in figure 7a. This excellent fit to the V1 pixel ENH spectrum over the entire energy range of IBEX is obtained using the V1 solar wind density profile of figure 6a, the profile of the radial component of the solar wind bulk velocity for V1 shown in figure 6b, a pickup proton density of 0.0008 cm\(^{-3}\) and a cutoff speed ('upstream' speed, \(v_{\text{upstrm}}\), in equation 5) of 320 km/s just downstream of the termination shock. With increasing distance from the TS, the cutoff speed \((v_{\text{upstrm}})\) was gradually reduced to produce the decrease in the pickup proton pressure shown in figure 6b. Decreasing the PP cutoff speed reduced the pickup proton contribution to highest energy segment of the IBEX spectra. This effect can be seen by examining dashed red curve of equation 9 from 100 AU to 110 AU where the PP cutoff speed remained high. Lowering the cutoff speed will result in a more truncated dashed curve and thus a smaller contribution to the total high-energy segment of the ENH spectrum. Because of the low solar wind density in this co-called low-density hot heliosheath near the termination shock contributions from the solar wind (in the energy range from \(\sim 0.01\) to 0.1 keV) are small. The primary contribution to the mid energy segment of the IBEX spectrum, however, does come from the compressed and hot solar wind near the helioclliff (red curve in figure 7a). The high-density but very cold solar wind from cold heliosheath is the primary source of the lowest energy ENH. The ENH spectrum resulting from this dense but cold solar wind is the blue curve in figure 7a. This spectrum (blue curve) was obtained by summing from 122 to 140 AU, making an 18 AU wide cold heliosheath in the V1 direction.
Figure 7. Differential intensity spectra measured by Fuselier et al. [8] in the V1 (panel a, red symbols) and V2 (panel b, blue symbols) directions, and model spectra described in the text. Main contributions to the IBEX spectra come from the cold, high density solar wind (at the lowest energy, blue curve), from the hot, high density solar wind in the hot heliosheath (middle energies, red curve), and from the transmitted pickup protons in the hot, low density heliosheath (highest energies, dashed curve).

The only published V2 pixel ENH spectrum [8] is shown in figure 7b. Above ~0.1 keV the V2 (light blue symbols) and V1 (red symbols) spectra are nearly identical. Below 0.05 keV the V2 ENH fluxes fall more and more below those of V1 and at the lowest energy they are lower by about a factor of 5. Even though the statistical and systematic uncertainties are large, the difference in fluxes is real since the background subtraction and survival probability corrections are independent of the look direction of the IBEX instruments. The simplest way to account for the reduced V2 fluxes at the lowest energies is to decrease the size of the cold heliosheath in which these low energy ENHs are created. Indeed decreasing the width of the cold heliosheath in the V2 direction, which is further from the centerline, to ~3 AU while keeping all the other parameters the same as for V1 provides an excellent fit to the V2 pixel ENH spectrum.

4. Closing remarks
We have demonstrated that the IBEX ENH observations in the directions of V1 and V2 can be fully accounted for by the model of Fisk and Gloeckler [5] for the nose region of the heliosheath. To fit the ENH observations requires a region of compressed and hot solar wind (the hot heliosheath), with an extensive suprathermal tail, and a region of compressed but cold solar wind (the cold heliosheath), lying between the hot heliosheath and the heliopause.

We have also obtained from fits to the lowest energy segments of the IBEX spectra the widths of the cold heliosheaths in both the V1 direction (close to the centerline) and the V2 direction (near the flanks). Assuming that in the V2 direction the heliopause is somewhere between 140 and 145 AU, we predict that V2 will cross the heliocliff at 137 to 143 AU, just 3 AU from the heliopause. But even before reaching the heliocliff, the working V2 plasma detector should begin to see a ramp up in the density and thermal speed before reaching 118 AU.
It is important to emphasize that the cold heliosheath is essential for fitting the IBEX ENH observations below ~0.01 keV. These low-energy ENH observations cannot be accounted for by ENHs produced beyond the heliopause, as demonstrated by Zirnstein et al. [12]. Rather to account for these low-energy IBEX ENH observations we require the unique features of the cold heliosheath: a dense, cold region with a very slow outward flow in the sun frame of reference. Furthermore, IBEX observations indicate that the width of the cold heliosheath near the flanks is much smaller than near the centerline, as is requires in the F&G model. Thus, the low-energy IBEX ENH observations provide strong evidence of the existence of the cold heliosheath, which implies that Voyager 1 must be in the cold heliosheath, is still in the heliosphere and has not yet crossed the heliopause.

Finally, we note how powerful the IBEX observations of ENH spectra have been for determining the properties of the solar wind in the heliosheath. To date, only a handful of such spectra have been published. We are hopeful that in the very near future the IBEX team will remedy this by making publically available many more ENH spectra, down to the lowest energies and in many other direction than V1, V2, the ribbon and a few others that have been published. Still, IBEX, is a Small Explorer with limited energy resolution, sensitivity, and lifetime. The continuing exploration of the heliosheath, a relatively unexplored but highly scientifically significant region of the heliosphere, requires that we make these higher-resolution, more comprehensive ENH observations especially at the very lowest energies. We call on NASA to implement as soon as possible the high-priority IMAP mission that is designed to make these crucial observations.

Acknowledgments
This work was supported in part by NASA Grant NNX10AF23G and by NSF Grant AGS-1043012. We thank Nathan Schwadron for comments and suggestions.

References
[1] Gurnett, D. A., Kurth, W. S., Burlaga, L. F., & Ness, N. F. 2013, Sci, 341, 1489
[2] Burlaga, L. F., Ness, N. F., & Stone, E. C. 2013, Sci, 341, 147
[3] Decker, R. B., Krimigis, S. M., Roelof, E. C., & Hill, M. E. 2012, Nature, 489, 124
[4] Stone, E. C., and Cummings, A. C. 2011, in Proc. 32nd Int. Cosmic Ray Conf., Vol. 1 (Beijing: IUPAP), 29
[5] Fisk, L. A., and Gloeckler, G. 2014a, ApJ, 789, 41
[6] Gloeckler, G., and Fisk, L. A. 2014, GRL, 41, 5325
[7] McComas, D. J., Dayeh, M. A., Allegrini, F., et al. 2012, ApJS, 203, 1
[8] Fuselier, S. A., Allegrini, F., Bzowski, M., et al. 2012, ApJ, 754, 14
[9] Prested, C., Schwardon, N. A., Passuite, J., et al. (2008), JGR, 113, A06102
[10] Gloeckler, G. and Fisk, L. A. 2010, AIP CP1302, 110
[11] Desai, M. I., Allegrini, F. A., Browski, M., et al. 2014, ApJ, 780, 1
[12] Zirnstein, E. J., Heerikhuisen, J., Zank, G. P., et al. 2014, ApJ, 783, 129
[13] Fisk, L. A., & Gloeckler, G. 2014b, JGR, 119, 8733
[14] Gloeckler, G. and Fisk, L. A. 2007, AIP CP932, 264
[15] Lindsay, B. G., & Stebbings, R. F. 2005, JGR, 110, A12213