Global Structure and Dominant Particle Acceleration Mechanism of the Heliosheath: Definitive Conclusions

L. A. Fisk and G. Gloeckler

Department of Climate and Space Sciences and Engineering, University of Michigan, 2455 Hayward St., Ann Arbor, MI 48109-2143, USA; lafisk@umich.edu

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Abstract

During its exploration of the heliosheath, the region that lies between the termination shock of the solar wind and the heliopause that separates the solar wind from the local interstellar medium, the Voyager 1 spacecraft (V1) in 2012 encountered an apparent boundary where there was a precipitous decrease in energetic particles accelerated in the heliosheath, the so-called anomalous cosmic rays (ACRs), and from the occasional plasma density measurements on V1, a density comparable to the expected density in the interstellar medium. In 2013, the Voyager principal investigators announced that this apparent boundary was the heliopause and that V1 had entered the interstellar medium. In 2014, Fisk & Gloeckler presented a detailed model that demonstrated that the apparent boundary was simply an internal surface within the heliosheath, across which compressed solar wind flows and will continue to flow until it encounters the actual heliopause. There is compelling observational evidence that the model of Fisk & Gloeckler for the nose region of the heliosheath is correct: V1 did not cross the heliopause in 2012 and is not now in the interstellar medium. There is also compelling observational evidence that the ACRs are accelerated in the heliosheath by the pump acceleration mechanism of Fisk & Gloeckler. The success of the models of Fisk & Gloeckler confirms that the plasma in the nose region of the heliosheath consists of two separate components, the pickup ions and ACRs, and the thermal solar wind, and as a unique plasma is worthy of more study and, if possible, more exploration.

Unified Astronomy Thesaurus concepts: Heliosphere (711); Heliopause (707); Heliosheath (710); Termination shock (1690)

1. Introduction

The Voyager 1 spacecraft (hereinafter referred to as V1) crossed the termination shock of the solar wind, where the supersonic flow of the solar wind becomes subsonic, in 2004 December at 94 au from the Sun (Burlaga et al. 2005; Decker et al. 2005; Gurnett & Kurth 2005; Stone et al. 2005). Beyond the termination shock lies the heliosheath, the region between the termination shock and the heliopause, which separates the heliosphere from the local interstellar medium. En route through the heliosheath, V1 observed many interesting phenomena, including that the heliosheath is a prodigious accelerator of energetic particles, so-called anomalous cosmic rays (ACRs), which can reach energies of tens of MeV nucleon$^{-1}$. Then, in 2012 August, when V1 reached 121.6 au, it observed a precipitous decrease in the intensity of the ACRs (Krimigis et al. 2013; Stone et al. 2013).

The question in 2012 August was whether the precipitous decrease marked the heliopause, and thus whether having passed through this boundary, V1 entered the interstellar medium, the first human-made object to achieve this distinction. Initially, Burlaga et al. (2013) decided the boundary was not the heliopause, noting that the magnetic field did not change direction at the boundary, as might have been expected if beyond the boundary was the interstellar medium, with an independent magnetic field draped across the heliopause. Then, Gurnett et al. (2013) observed plasma waves, which are a direct measure of thermal electron density, the only plasma density measurements available on V1, which no longer has a working plasma detector. Gurnett et al. found the density to be $\sim 0.1$ cm$^{-3}$, a density comparable to the expected density in the interstellar medium. Gurnett was convinced that he was observing interstellar gas and that his measurement was proof that V1 had entered the interstellar medium. He persuaded other Voyager investigators, including Burlaga & Ness, who recanted their earlier position and joined Gurnett as coauthors on Gurnett et al. (2013).

There was a subsequent paper by Burlaga & Ness (2014) in which they determined the orientation of the last sector boundary separating regions of opposite magnetic polarity, which was observed just before the precipitous decrease in the ACR intensity, and found that it was oriented at $\sim 90^\circ$ to the solar equatorial plane. The heliosphere contains a single large current sheet separating two hemispheres of opposite magnetic polarity. This current sheet lies roughly parallel to the solar equatorial plane during solar minimum conditions and rotates through the solar poles at solar maximum, where it is oriented perpendicular to the solar equatorial plane. The current sheet is convected into the heliosheath and determines the orientation of the sector boundaries: at 90$^\circ$ during solar maximum conditions, whereas during solar minimum, when the tilt of the current sheet is below the heliographic latitude of V1, there are no sectors. Burlaga & Ness (2014) convinced themselves that V1 at 121.6 au was experiencing solar minimum conditions and thus the sector boundary they observed, orienting 90$^\circ$ to the solar equatorial plane, could not be due to the heliospheric current sheet, and thus must be the heliopause. Unfortunately, as pointed out in Gloeckler & Fisk (2014), Burlaga & Ness (2014) made a mistake and calculated the transit time of sector boundaries through the heliosheath using the average solar wind speed. Transit times depend on the inverse of the solar wind speed, and since the solar...
wind slows down drastically in the heliosheath, Burlaga & Ness (2014) miscalculated the transit time by 5 yr. V1 was observing solar maximum conditions, and the observed sector boundary, oriented 90° to the solar equatorial plane, was the result of the heliospheric current sheet.

Fisk & Gloeckler (2014a) published a detailed model, hereinafter referred to as the F&G model, for the heliosheath being explored by V1, which is the nose region of the heliosheath that lies in the direction of motion of the Sun through the local interstellar medium. The F&G model assumes, and for which there is supporting observational evidence, that the plasma in the nose region of the heliosheath consists of two separate components: (1) interstellar pickup ions plus ACRs, which have the dominant particle pressure inside where there is a precipitous decrease in the ACR intensity, and (2) the thermal solar wind. Each component has its own governing equations. The interstellar pickup ions and ACRs with their dominant pressure balance the pressure exerted on the heliosheath from the region beyond where the precipitous decrease in ACRs occurs. The solar wind flow is governed by the standard solar wind flow equations and depends only on the magnetic field being convected with the solar wind and the solar wind thermal pressure, not the pressure in the pickup ions and ACRs. The solar wind can be compressed, and thus Gurnett et al. (2013) did not observe interstellar gas but rather the compressed solar wind. The solar wind flows across what the Voyager investigators considered to be the heliopause, convecting the heliosheath magnetic field into a region where the magnetic field can connect to the actual heliopause, on the flanks of the heliosheath, far from the location of V1. With a connection to the heliopause, the ACRs can escape along the magnetic field, resulting in the observed precipitous decrease in the ACR intensity. Thus, the heliopause of the Voyager investigators is nothing more than a surface that separates the heliosheath magnetic field that spirals within the heliosheath from the heliosheath magnetic field that connects to the heliopause. Fisk & Gloeckler (2014a) labeled this surface the heliocliff, a descriptive term since the solar wind flows across this cliff, and the energetic particles flowing with it precipitously decrease. Beyond the heliocliff lies a region of the heliosheath with a lower pressure due to the escape of the pickup ions and ACRs, and with a continuous outflow of solar wind that continues until V1 encounters the actual heliopause.

During the development and publication of the F&G model, Fisk and Gloeckler argued with the Voyager investigators, pointing out that the observational evidence that V1 had crossed the heliopause was not conclusive, the F&G model was a very viable alternative, and thus no conclusive statement should be made that V1 had crossed the heliopause. The arguments made by Fisk & Gloeckler had no impact, and the Voyager investigators declared that V1 was the first human-made object to enter interstellar space. Fisk and Gloeckler went on to write a number of papers (e.g., Fisk & Gloeckler 2015, 2016) that expanded the F&G model and found supporting evidence of its validity; Gloeckler & Fisk (2015) used observations of Energetic Neutral Atoms (ENAs) to demonstrate that the solar wind is compressed, just as the F&G model predicted. All this, however, was to no avail. The Voyager investigators have continued to interpret their data and encouraged others to believe that since 2012, V1 has been in the interstellar medium.

Concurrent with their research on the global structure of the heliosheath, Fisk and Gloeckler also considered the acceleration of the ACRs. When V1 and Voyager 2 (hereinafter referred to as V2) crossed the termination shock, no evidence was found for ACR acceleration at the shock front, but downstream, low-energy ACRs were observed that have a unique differential intensity spectrum, a power law in energy with a spectral index of $-1.5$, or equivalently a distribution function in particle speed with a spectral index of $-5$ (Decker et al. 2006; Gloeckler et al. 2008). Fisk and Gloeckler noted that no known acceleration mechanism yields this unique spectral shape, and so proposed a new acceleration mechanism, a pump acceleration, in which pressure variations in the pickup ions pump the ACRs to higher energies (the best description of the pumps acceleration mechanism is in Fisk & Gloeckler 2014b). Despite being able to explain the observed spectral shape of the ACRs in the heliosheath, and the spectral shape of low-energy particles accelerated in the inner heliosphere, pump acceleration has not yet been widely used or applied. The preferred acceleration mechanism remains diffusive shock acceleration, a mechanism that has been widely applied since it was first introduced in 1978 (Krymsky 1977; Axford et al. 1977; Bell 1978; Blandford & Ostriker 1978). As for the acceleration of ACRs in the heliosheath, noting that the higher-energy ACRs are not accelerated at the termination shock where V1 and V2 crossed, the advocates of diffusive shock acceleration argue that the acceleration occurs elsewhere on the termination shock followed by propagation into the heliosheath to the locations of V1 and V2 (e.g., McComas & Schwadron 2006; Schwadron & McComas 2007; Schwadron et al. 2008).

It is the point of this paper to discuss and present new analyses of the V1 data, as well as previously unexplained mysteries in the V1 data, which we consider allows for definitive conclusions about the global structure and dominant acceleration mechanism of the heliosheath. The F&G model of the heliosheath is correct: V1 did not cross the heliopause in 2012 and is not now in the interstellar medium. The dominant particle acceleration mechanism is pump acceleration. The three observations on which we base these definitive conclusions are as follows.

1. Dialynas et al. (2021) analyzed data from the V1 Low-Energy Charged Particle (LECP) instrument (Krimigis et al. 1977) and discovered that at energies below $\sim 100$ keV there is radial outflow that is perpendicular to the magnetic field and extends from the heliopause of the Voyager investigators (the F&G heliocliff) at 121.6 au to the current location of V1 at close to 150 au. Moreover, the spectrum of the outflowing particles is the same as the spectrum of low-energy particles accelerated in the heliosheath inside 121.6 au, a differential intensity spectrum with a spectral index of $-1.5$. The only possible explanation for low-energy energetic particles to flow radially outward, perpendicular to the magnetic field, preserving the spectral shape, is that the magnetic field itself must be moving radially outward. Thus, Dialynas et al. (2021) provide compelling observations that the solar wind and its embedded magnetic field flows across the heliopause of the Voyager investigators, proving it is not the heliopause, but rather the F&G heliocliff. The flow continues throughout the heliosheath out to at least 150 au, providing compelling evidence that
V1 is not yet in the interstellar medium. Dialynas et al. acknowledge that Fisk & Gloeckler (2014a) predicted their observed radial outflow but note that “this explanation requires that V1 is still within the heliosheath, which contradicts previous interpretations of the V1 measurements (Burlaga et al. 2013; Krimigis et al. 2013; Stone et al. 2013)”; indeed, it does. The Dialynas et al. (2021) observations provide compelling evidence that Fisk & Gloeckler (2014a) were correct, while Gurnett et al. (2013), Burlaga & Ness (2014), Krimigis et al. (2013), and Stone et al. (2013) were not.

2. Without a working plasma detector on V1, the velocity of the solar wind inside the heliocliff can only be measured using the convective anisotropies of low-energy particles observed by the LECP instrument, the same technique that is used to measure the radial outflow beyond the heliocliff. The results inside the heliocliff provide some of the most important constraints on acceptable models of the heliosheath. The most challenging of these observations are summarized in Krimigis et al. (2019) who report that V1 observes that the solar wind flows inward for two years prior to crossing the heliocliff, a seemingly impossible situation since V1 observes the solar wind flowing outward beyond the heliocliff. As we will discuss in this paper, although not recognized in Fisk & Gloeckler (2014a), this unusual phenomenon is in fact an expected feature of the F&G model and is a further compelling observation that the F&G model is correct.

3. We have performed our own analysis of the publicly available V1 LECP data and determined the ACR differential intensity spectra at different locations in the heliosheath. The observed spectra, and particularly the spatial variations of the spectra, are wholly consistent with pump acceleration, not diffusive shock acceleration as the dominant acceleration mechanism in the heliosheath, and even more significant, provide observational confirmation that the plasma in the heliosheath inside the heliocliff consists of two separate components, the pickup ions and ACRs, and separately the thermal solar wind.

We begin this paper by reviewing the F&G model, demonstrating that it is wholly consistent with the observations of Dialynas et al. (2021) and can account for the inward motions of the solar wind summarized in Krimigis et al. (2019). In Section 3, we review the pump acceleration mechanism and demonstrate that it is wholly consistent with the observed ACR spectra and validates that the plasma inside the heliosheath consists of two separate components. In Section 4, we use the results of Sections 2 and 3 to calculate the speed of the solar wind beyond the heliocliff and estimate the likely distance to the actual heliopause. In Section 5 we find supporting evidence for the F&G model in the Voyager 2 observations. In Concluding Remarks, we discuss the implications for research on the heliosheath now that there is compelling evidence of the validity of the Fisk & Gloeckler models.

2. The F&G Model for the Nose Region of the Heliosheath

We begin this section by reviewing the properties of the nose region of the heliosheath and the step-by-step process by which Fisk & Gloeckler (2014a) developed a quantitative model that can account for all V1 observations.

1. The interstellar pickup ions and accelerated pickup ions, the ACRs, are a separate gas from the thermal solar wind. The dominant particle pressure in the heliosheath inside the heliocliff resides in interstellar pickup ions and accelerated pickup ions, the ACRs. Most of the pickup ions are created in the solar wind inside the termination shock where interstellar neutral gas is ionized by charge exchange and photoionization. The pickup ions are convected outward with the solar wind but do not assimilate into it; the pressure in the accumulated pickup ions becomes greater than the thermal pressure in the solar wind upstream of the termination shock; at the termination shock, the pickup ions are heated far more than the thermal solar wind (Richardson 2008). As is discussed in detail in Section 3, in the heliosheath the pickup ions are accelerated by pump acceleration, which pumps approximately half the pressure in the pickup ions into the ACRs. The spectrum of ACRs is such that the pressure in the ACRs resides primarily in the highest-energy particles, which in the relatively weak magnetic field in the heliosheath have large gyroradii, even comparable to the width of some narrow magnetic sectors in the heliosheath.

The ACRs are highly mobile along the magnetic field and not coupled to local conditions in the thermal solar wind, nor do the pickup ions assimilate into the solar wind. Pump acceleration pumps pressure from the pickup ions into the ACRs and thus at each location in the heliosheath the pressure in the pickup ions and ACRs are combined into a single pressure, distinct from and unrelated to the thermal pressure in the solar wind.

2. There is an external constraint on the pickup ions and ACRs.

The dominant pressure in the pickup ions and ACRs must balance the pressure exerted on the heliosheath from the region beyond the heliocliff, and thus the pickup ions and ACRs are in static equilibrium.

3. The solar wind and the pickup ions and ACRs experience and respond to different magnetic fields.

The solar wind convects an embedded magnetic field across the termination shock into the heliosheath. The solar wind responds to the embedded magnetic field through the Lorentz force. In the separate gas of pickup ions and ACRs, each pickup ion and ACR particle has a dipole moment which aligns to collectively form a magnetization that is proportional to the dominant pressure in the pickup ions and ACRs. Since the pickup ions and ACRs are in static equilibrium, balancing the pressure exerted from beyond the heliocliff, we can think of this region of the heliosheath as a medium with intrinsic dipole moments. Using the appropriate forms of Maxwell’s equations, the magnetic field in this region of the heliosheath, to which the pickup ions and ACRs respond, is not the embedded magnetic field of the solar wind but the embedded magnetic field offset by the magnetization. The offset magnetic field is the magnetic field that is observed in the heliosheath. (Fisk & Gloeckler 2014a) present observational evidence that confirms that the observed magnetic field is the embedded magnetic field offset by the magnetization of the pickup ions and ACRs. It should also be noted that the concept that a magnetization resulting from a separate
gas with substantial pressure is observed in the Earth’s magnetosphere. The ring current is a separate gas with substantial pressure that creates a magnetization that offsets the intrinsic magnetic field of the Earth.)

4. The governing equations.

For the pickup ions and ACRs: the sum of the pressure in the pickup ions and ACRs plus the pressure in the observed magnetic field, which includes the magnetization, must be a constant and balance the pressure exerted on the heliosheath from the region beyond the heliocliff, and thus,

$$P_{\text{psl, ACR}} + B_{\text{obs}}^2/8\pi = \text{constant.}$$ (1)

For the solar wind: the standard solar wind flow equations, with only the embedded magnetic field and the solar wind thermal pressure, not the pressure in the pickup ions and ACRs.

5. Constraints on the flow direction of the solar wind.

The dominant pressure in the pickup ions and ACRs forces the solar wind to flow in a plane that contains the magnetic field. The gradients in the pressure of the pickup ions and ACRs can be relieved only along the magnetic field. Thus, the solar wind cannot diverge in a direction perpendicular to the plane containing the magnetic field, since this would introduce unsustainable gradients in the dominant pickup ion and ACR pressure. The magnetic field in the heliosheath lies primarily in the azimuthal or T-direction of the Voyager R–T–N coordinate system (the +e_R axis points radially outward from the Sun, the +e_T axis is in the direction of rotation of the Sun, and e_N = e_R x e_T). It is possible that immediately downstream from the termination shock there can be polar flows introduced by the shape of the termination shock, but as the solar wind flows outward through the heliosheath it must be primarily in the R–T plane, and this is observed (Stone & Cummings 2011; Decker et al. 2012).

6. Requirements on acceptable solar wind solutions.

Solar wind flows governed by equations that only include the thermal pressure of the solar wind would normally be considered to be supersonic. However, the solar wind is flowing through a medium created by the pickup ions and ACRs in which the sound speed exceeds the flow speed, and thus acceptable solutions to the solar wind flow equations must satisfy subsonic boundary conditions. There must be a smooth reduction in the radial flow speed to a speed that satisfies the conditions at the boundary where the solar wind escapes the nose region.

Fisk & Gloeckler (2014a) solve analytically the required solar wind flow equations for the nose region of the heliosheath. The flow is in the R–T plane. The magnetic field is the magnetic field embedded in the solar wind. The pressure is only the solar wind thermal pressure. The solution is required to yield the observed radial flow speed of the solar wind, which is determined from the convective anisotropies of low-energy energetic particles (Krimigis et al. 2011; Decker et al. 2012), thus ensuring that the solution is a proper subsonic solution that will match the required boundary conditions.

Shown in Figure 1, which is taken directly from Fisk & Gloeckler (2014a), are the analytic solutions for the solar wind streamlines in the nose region of the heliosheath. The solar wind streamlines and magnetic field lines lie on a cone of constant heliographic latitude and thus have only radial and azimuthal components. In Figure 1 these radial and azimuthal components are plotted on a rectangular plane. The solar wind streamlines are in red, originating at the Sun, crossing the termination shock at 94 au, and then, to escape the heliosheath in the R–T plane, turning to flow in the azimuthal direction. There is a centerline, the axis of symmetry of the nose region, which should lie in the direction of motion of the Sun through the local interstellar medium. The solar wind flows azimuthally in opposite directions about the centerline, creating a centerline region that is a vacuum. The magnetic field lines shown in green in Figure 1 cross the centerline region, the solar wind from the surrounding streamlines fills in the centerline region, and the density of the solar wind is the same as the density of the surrounding streamlines.

The observed radial solar wind speed, which is used to determine the streamlines in Figure 1, becomes increasingly small with distance into the heliosheath. The magnetic field in the solar wind increases with the decreasing radial flow speed and decelerates the solar wind. The azimuthal flow speed goes to zero first, leaving only the small radial outflow of compressed solar wind. The point at which the radial outflow occurs, approximately 40° from the centerline in Figure 1, marks the edge of the centerline region.

The solar wind continues to flow outward beyond the point where it turns radial until it reaches the heliopause. The heliopause in this model is not a tangential discontinuity, but rather a rotational discontinuity, across which is a normal component of the magnetic field and a flow of solar wind. The polarity of the heliosheath and the draped interstellar magnetic field are assumed to be the same and thus the heliosheath field can readily merge into the draped interstellar field on the flanks of the heliosheath. With this connection, the higher-energy ACRs can escape across the heliopause, resulting in the precipitous decrease of ACRs observed by V1. This is the heliocliff, the location separating magnetic field lines that remain in the heliosheath from magnetic field lines that connect to the heliopause, with the resulting escape of higher-energy ACRs.

One of the properties of a rotational discontinuity is that the density is continuous across the discontinuity. Outside the heliopause is the interstellar medium. Thus, the density of the solar wind inside the heliopause must be the density of the interstellar plasma. This is the boundary condition that an acceptable subsonic solution to the solar wind flow equations must satisfy. The decrease in the radial solar wind speed must be such that the solar wind is compressed to a density equal to the interstellar density on any field line that connects to the heliopause. Such is the case for the streamlines shown in Figure 1.

When the F&G model of the nose region on the heliosheath was developed in 2014 there was a constraint. To be considered a valid model it had to explain all V1 observations known at that time, and it succeeded.

1. The model yields a plasma density at and beyond what the Voyager investigators were calling the heliopause that is comparable to the expected density in the interstellar medium. The density is due to the compressed solar wind, not interstellar gas, invalidating the claim of Gurnett et al. (2013) that the density they observed was conclusive evidence that V1 had entered the interstellar medium.
2. The model explains that the precipitous decrease in higher-energy ACRs occurs when the magnetic field being convected outward with the solar wind connects to the actual heliopause, far from the location of V1. The heliopause of the Voyager investigators is the heliocliff of the F&G model, a surface that separates the heliosheath magnetic field that spirals within the heliosheath from the heliosheath magnetic field that connects to the heliopause.

3. The model explains why the magnetic field does not change direction across what the Voyager investigators called the heliopause, as might have been expected (Burlaga et al. 2013). The magnetic field in the heliosheath is simply being convected across the heliocliff.

4. The model can account for the abrupt increase in the observed magnetic field at the heliocliff (Burlaga et al. 2013; Burlaga & Ness 2014). Inside the heliocliff the pickup ions and ACRs are in static equilibrium, resulting in a magnetization that offsets the magnetic field embedded in the solar wind. Outside the heliocliff, where the pickup ions and ACRs can escape, the pickup ions and ACRs are not in static equilibrium, there is no offsetting magnetization, and the observed magnetic field is the magnetic field that is convected across the heliocliff with the solar wind.

5. The model can account for the significant reduction in turbulence observed outside the heliocliff (Burlaga et al. 2013). Inside the heliocliff variations in the perpendicular pressure of the pickup ions and ACRs result in extensive compressive turbulence, which will be used in the next section to accelerate the ACRs by pump acceleration. Outside the heliocliff, where the pickup ions and ACRs can escape along the magnetic field, there should be a substantial reduction in perpendicular pressure.

The F&G model also explains the observations of Dialynas et al. (2021) that at energies below ~100 keV there is radial outflow that is perpendicular to the magnetic field and extends from the heliocliff at 121.6 au to the current location of V1 at close to 150 au. This outflow is simply the solar wind that is flowing across the heliocliff, convecting the heliosheath magnetic field out to the heliopause, which lies beyond 150 au.

The F&G model, with a small refinement, can also explain the V1 observations summarized in Krimigis et al. (2019) that the solar wind flows inward for two years prior to crossing the heliocliff, observations that were not evident in 2014 when the F&G model was developed. The trajectory of V1 is shown in Figure 1, and within two years before crossing the heliocliff, V1 is in the centerline region. The magnetic lines that cross the centerline region are shown as simply following the spiral pattern of the magnetic field outside the centerline region. This cannot be the case, since the field lines in the centerline are not moving outward on their own; rather they are being dragged outward by the solar wind streamlines on either side of the centerline region. There is then nothing to support the field lines in the centerline region, and they will tend to straighten. The solar wind on each field line is the solar wind that is provided to it by the streamline to which it is attached. As the solar wind in the streamlines flows radially outward to the heliocliff, the solar wind that V1 observes in the centerline region must flow radially inward to straighten the magnetic field lines. These are the inward motions of the solar wind reported by Krimigis et al. (2019).

The inward motions of the magnetic field in the centerline region will also straighten and flatten the heliocliff, which must be parallel to the magnetic field. In fact, Burlaga et al. (2013) observe that the magnetic field direction prior to the heliocliff crossing is at 17° relative to the $-T$ axis in the Voyager $R$–$T$–$N$ coordinate system. With the trajectory of V1 at a longitude of

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**Figure 1.** From Fisk & Gloeckler (2014a), the azimuthal and radial components of the solar wind streamlines (red curves) and magnetic field lines (green curves) on the cone of constant heliographic latitude observed by V1, plotted on a rectangular plane. As discussed in the text, the solar wind streamlines cross the termination shock at 94 au, then, to escape the heliosheath in the $R$–$T$ plane, turn to flow in the azimuthal direction, creating a centerline region, and then turn in the radial direction to flow across the heliocliff and radially outward to the heliopause.
17° from the centerline, a heliocliff at 17° relative to the –T axis will be perpendicular to the centerline. The observed orientation of the heliocliff provides confirmation that there is a centerline region, as depicted in Figure 1, and the heliocliff is flat due to the inward motions of the solar wind.

Finally, we note in Figure 1 that several magnetic sectors are depicted in the region between the heliocliff and the heliopause. The expectation in 2014 was that with the small outward flow of the solar wind beyond the heliocliff V1 would observe a sector boundary crossing, thereby confirming that V1 remained in the heliosheath. In Section 4 we will use the radial outflow observed by Dialynas et al. (2021) to determine the outward flow velocity of the solar wind along the V1 trajectory. We will demonstrate that with a heliocliff that is flat, V1 should not encounter a sector boundary, and so far, out to at least 150 au, it has not.

3. The Pump Acceleration Mechanism

In this section we review the pump acceleration mechanism of Fisk & Gloeckler, the best description of which is in Fisk & Gloeckler (2014b), and demonstrate that it is wholly consistent with the observed ACR spectra, it validates that the pickup ions and ACRs are a separate gas from the thermal solar wind and that diffusive shock acceleration at the termination shock cannot account for these observations.

The pump acceleration mechanism works on a very simple principle: a thermally isolated system of a constant volume containing a gas with irreversible particle–particle interactions will evolve toward a state of maximum entropy, which requires a distribution function with a high-energy tail. For example, a gas in a thermally isolated, fixed volume container, which lacked high-energy particles to complete a Maxwellian distribution, which is the state of maximum entropy, will create the needed high-energy tail by extracting energy from the lower-energy particles through particle–particle collisions. Total energy and number of particles are conserved in the system and the system accelerates some particles to higher energies without an external source of energy.

The heliosheath is an ideal setting in which to apply the pump acceleration mechanism. There is no adiabatic deceleration of energetic particles as in the supersonic solar wind, and thus the volume can be considered constant. The pressure in the pickup ions and ACRs is large compared to the magnetic pressure and thus, from Equation (1), essentially constant. There is thus no net inflow or outflow of energy, and the heliosheath can be considered thermally isolated.

There are of course no particle–particle collisions. There are, however, interactions between individual particles and the collective motions of other particles. Variations in the dominant pressure in the pickup ions and ACRs will result in regions where the magnetic field is compressed or expanded. Indeed, with an intertwined magnetic field, where the particle pressure seeks equilibrium both along and across the magnetic field, such variations in pressure must always be present, and with constant volume, compression regions must always be surrounded by expansion regions. An individual pickup ion or ACR interacts with the magnetic field that is being compressed or expanded due to the collective motions of other pickup ions and ACRs. These interactions are irreversible provided that a particle can diffuse across the magnetic field from a compression into a surrounding expansion region, an escape that is restricted to the higher-energy particles where the spatial variation between compression and expansion regions is largest. Energy is conserved in the system, and the pickup ions and ACRs evolve to a state of maximum entropy by accelerating the ACRs. The pump acceleration mechanism thus extracts the energy or pressure in the ACRs from the pressure in the pickup ions and satisfies Equation (1).

Fisk & Gloeckler (2014b) derived an equation for the time evolution of the spectral shape resulting from pump acceleration. It is a somewhat challenging calculation since it is necessary to properly describe the interaction of a single particle with the collective behavior of all other particles. The standard approach for calculating spectra, which is not appropriate here, is to treat each particle separately, as opposed to each particle interacting with the collective motion of all other particles and conserving energy in the process. The result of the Fisk & Gloeckler (2014b) derivation is an equation that describes the time evolution of the mean distribution function of particles being accelerated, f, which is defined here as the distribution function that determines the mean pressure:

\[
\frac{\partial}{\partial t} (v^2 f) = v \frac{\partial}{\partial v} \left( \frac{\delta u^2 / 9 \kappa^2}{v^2} \right). \quad (2)
\]

The diffusion coefficient normal to the magnetic field is \( \kappa \), which determines the rate at which higher-energy particles can escape from a compression region into a surrounding expansion region; \( \delta u^2 \) is the mean squared variation in motions of the magnetic field, and \( v \) is particle speed.

The solution to Equation (2) is

\[
f = f_0 v^{-5} \exp \left[ -9 \kappa / \left( (1 + \xi^2) \delta u^2 t \right) \right]. \quad (3)
\]

where the diffusion coefficient is taken to have the form, particle speed times a power law in particle rigidity, with exponent \( \xi \). Note that technically \( f \) is the distribution function that determines the mean pressure. Fisk & Gloeckler (2014b) show that \( f \) is indistinguishable from the observed mean distribution function in the portion of the spectrum that is a power law with a spectral index of –5 and differs only slightly at velocities above where the spectra decrease exponentially.

We assume that the perpendicular diffusion is due to gradient and curvature drifts in random magnetic fields, in which case \( \kappa = v r_g / 3 \), where \( r_g \) is particle gyroradius and \( \kappa \propto T \) where \( T \) is particle kinetic energy. For comparison with observations, we convert the distribution function in Equation (3) into particle differential intensity \( j \) as a function of \( T \), or

\[
j = j_0 T^{-1.5} \exp \left[ -T / T_{\text{roll}} \right]. \quad (4)
\]

Here, \( T \) is in units of MeV nuc\(^{-1} \), \( j_0 \) is evaluated at 1 MeV nuc\(^{-1} \), and \( T_{\text{roll}} \) is the energy at which the spectrum rolls over and is a function of time and the other parameters in the exponential in Equation (3).

Shown in Figure 2 are the ACR hydrogen (H) differential intensity spectra observed by V1, averaged over one calendar year at locations immediately downstream from the termination shock, at distances one-third and two-thirds the distance between the termination shock and the heliocliff, and during the last calendar year before V1 crossed the heliocliff. These spectra are determined by analyzing the publicly available V1 Low-Energy Charged Particle (LECP) data available on the University of Maryland website. The LECP data at the lowest energies do not distinguish between H and other elements (or

1 voyager-mac.umd.edu
background), making it difficult to determine in detail the H spectrum at these energies. The spectral shape is well established to be a power law with a spectral index of $-1.5$, the spectral form in Equation (4), and found by, e.g., Decker et al. (2006) and Dialynas et al. (2019). Thus, the H spectra in Figure 2 can be determined (the red points) by doing a best fit of the spectral form in Equation (4) to the LECP H observations at energies above $\sim 400$ keV nuc$^{-1}$ (the blue points), an energy range where LECP can readily distinguish H from other elements. The 2005 V1 spectrum in panel (a) of Figure 2 shows that the spectral form in Equation (4) is an excellent fit at all observed energies. In 2007 (panel (b)), galactic cosmic rays (GCRs) are beginning to be observed at the highest observed energies and the blue points deviate upward from the ACR spectra. This trend continues with increasing distance into the heliosheath, but in all cases where the ACRs are clearly observed, the spectral form in Equation (4) is an excellent fit. There is no reason to assume that pump acceleration stops accelerating the ACRs in the presence of GCRs and so the ACR spectra shown in the red dots in panels (c) and (d) should be correct to the highest energies.

Shown in Table 1 are the parameters ($j_0$ and $T_{rol}$) used to fit the spectra in Figure 2. As is evident from Figure 2 and Table 1, the ACR H spectra are remarkably spatially uniform in the heliosheath observed by V1. The maximum energy to which the ACRs are accelerated is approximately the same independent of distance into the heliosheath. This uniformity can be understood by examining the pressure in the ACR H, which can be calculated by integrating the spectra in Figure 2 over all ACR energies. A spectrum with a spectral index of $-1.5$ results in a pressure that is logarithmically divergent in energy and so almost all the pressure resides in the observed ACRs and the pressure integral is insensitive to the threshold between pickup ions and ACRs. The resulting pressure in ACR H is listed in Table 1, in units of $10^{-12}$ dynes cm$^{-2}$. Gloeckler & Fisk (2015) estimate from ENA observations that the average pressure in pickup and ACR H between the termination shock and the heliocliff

![Figure 2](image-url)
is \( \sim 0.3 \times 10^{-12} \) dynes cm\(^{-2}\) and thus the ACR H pressure in 2005 and 2007 is approximately half of the total pressure in pickup ions and ACRs. Pump acceleration is a first-order acceleration mechanism that pumps energy from the pickup ions into the ACRs to maximize entropy. It follows then that the pumping can continue only until the remaining pressure in the pickup ions equals the pressure in the ACRs. The spatial uniformity in the 2005 and 2007 ACR H spectra results because pump acceleration is a sufficiently efficient process that pumps all available energy out of the pickup ions, and from Equation (1) the combined pressure in the pickup ions and ACRs must be approximately constant.

Equation (1) requires that the pressure in all pickup ions and ACRs, not just the H pickup ions and ACRs, plus the pressure in the observed magnetic field, is a constant. If we assume that the ACRs include a little less than 10% He and a small amount of O, values consistent with the analysis of Fisk & Gloeckler (2009), then the total pressure in ACRs is approximately a factor of 1.4 times the pressure in ACR H in Table 1. With the pressure in the pickup ions equal to the pressure in the ACRs, the total pressure in pickup ions and ACRs is an additional factor of 2 higher, yielding the values listed in Table 1. The pressure in the observed magnetic field can be determined from the published data from the V1 MAG instrument and is also listed in Table 1 in the same units as the pickup ion and ACR pressure \( (10^{-12} \) dynes cm\(^{-2}\)). The magnetic field strength used to calculate the magnetic pressure is an approximate average over one year of the observed field strength. In 2005 and 2007, the observed field strength remains approximately constant at 0.1 nT or 1 \( \mu \)G. In 2009 there is a slight increase to approximately 1.5 \( \mu \)G and then in 2011 a further increase to approximately 2.4 \( \mu \)G. The sum of the pickup ion and ACR pressure plus the pressure in the observed magnetic field, listed in the final column of Table 1, is constant and Equation (1) is satisfied.

There are two important conclusions to draw from this analysis of the observed ACR spectra. First, the observed spectra are exactly the spectra that are expected from the pickup acceleration mechanism, the differential intensity spectrum in Equation (4). Second, and of equal importance, the pressure in the pickup ions and ACRs satisfies Equation (1), and thus provides further confirmation that the pickup ions and ACRs are a separate gas from the solar wind.

Finally, the observed ACR spectra categorically eliminate diffusive shock acceleration at the termination shock as a viable mechanism for accelerating ACRs in the heliosheath. Acceleration at a location on the termination shock different from where V1 crossed and subsequent propagation to the location of V1, as proposed by, e.g., McComas & Schwadron (2006), Schwadron et al. (2008), Schwadron & McComas (2007), cannot possibly yield the ACR spectra in Figure 2, a specific spectral shape and no spatial variations. Moreover, there is a problem with the pressure. The pickup ions are heated at the termination shock and convected radially outward. In pump acceleration the ACRs are accelerated out of the pickup ions and together the pickup ion and ACR pressure remain constant. If the ACRs were accelerated elsewhere in the heliosheath and propagated to the location of V1, they would add pressure to the pickup ions being convected radially outward from the termination shock and violate the requirement that the total particle pressure in the heliosheath must be approximately constant.

### 4. The Speed of the Solar Wind Beyond the Helioclipf and the Location of the Heliopause

In Section 3 we determined the ACR H differential intensity spectrum inside the heliocliff. Recognizing that the ACRs are convected across the heliocliff with the solar wind, we can use the radial outflow observed by Dialynas et al. (2021) with the V1 LECP instrument to determine the radial solar wind speed in the region between the heliocliff and the heliopause. With this radial solar wind speed and recognizing, as discussed in Section 2, that the heliocliff is flat where V1 crossed it, we can constrain the likely location of the heliopause.

Dialynas et al. (2021) express the radial outflow as an intensity, as opposed to a flux or streaming, and find that in the energy range 46–109 keV,

\[
J_{\text{outflow}} = 0.00233(46/T)^{1.5}(\text{cm}^2 \text{s st keV})^{-1},
\]

where energy \( T \) is in units of keV. We use the spectral index of \(-1.5\), which is the spectral index of the ACRs being convected across the heliocliff and well within the errors on the spectral index found by Dialynas et al. of \(-1.4 \pm 0.4\).

As noted in Section 3, the LECP low-energy measurements do not distinguish between different elements and measure all elements observed in a given keV range. To compare with observed H spectra in Section 3, we need to determine the portion of the outflow that is due to H. Fisk & Gloeckler (2009) found that the differential intensity spectrum of ACR H is a power law in energy per nucleon with a spectral index of \(-1.5\) and approximately 10% of the H spectrum. Thus, in the energy ranges observed by Dialynas et al. (2021), 

\[0.001165(46/T)^{1.5}(\text{cm}^2 \text{s st keV})^{-1}.\]

The spectrum of ACR H in 2011, the full calendar year before V1 crossed the heliocliff, is shown in Figure 2(d), and the accompanying parameters used to fit this spectrum, \( j_o \) and \( T_{\text{roll}} \), are listed in Table 1. V1 crossed the heliocliff in 2012 August and thus we need to make an adjustment in the 2011 spectrum to determine the ACR spectrum closer to the heliocliff. Recall that the total pressure in the pickup ions and ACRs plus the pressure in the observed magnetic field is a constant. In early 2012 the observed magnetic field increased from the average value in 2011 assumed in Table 1 of 2.4 \( \mu \)G to an average value for the full year immediately inside the heliocliff of approximately 2.7 \( \mu \)G. As a result, the pressure in the pickup ions and ACRs decreases from 0.2 to 0.14 in the

### Table 1

| Year | \( J_o \) | \( T_{\text{roll}} \) | \( P_{\text{ACR, H}} \) | \( P_{\text{total}} \) | \( B_{\text{obs}}/8\pi \) | \( P_{\text{total}} + B^2/8\pi \) |
|------|--------|---------|----------------|----------------|----------------|------------------------|
| 2005 | 2.3    | 14      | 0.14           | 0.39           | 0.04           | 0.43                   |
| 2007 | 2.3    | 13.95   | 0.14           | 0.39           | 0.04           | 0.43                   |
| 2009 | 2.1    | 14.1    | 0.12           | 0.34           | 0.09           | 0.43                   |
| 2011 | 1.15   | 14.8    | 0.07           | 0.2            | 0.23           | 0.43                   |

**Note.** Listed for each spectrum in Figure 1 are the parameters used to fit the spectra, the ACR’s H pressure, the total pressure in pickup ions and ACRs, and the pressure in the observed magnetic field.
units of pressure in Table 1 (10^{-12} \text{ dynes cm}^{-2}) and $j_0$ decreases from 1.15 to 0.8.

After crossing the heliocliff, the high-energy particles escape, leaving only the low-energy particles. There is a resulting decrease in the pressure to 0.05 10^{-12} \text{ dynes cm}^{-2} since much of the pressure in the ACRs resides in the higher-energy particles. However, the heliocliff is a stationary structure and the pressure in the ACRs and pickup ions must be constant across the heliocliff, which requires that the value of $j_0$ must increase to 2.24.

Thus, the differential intensity spectrum of the low-energy ACR H that is convected with the solar wind between the heliocliff and heliopause, in the same units as Equation (6), is

$$J_{\text{convect},H} = 0.227(46/T)^{1.5}(\text{cm}^2 \text{ st s keV})^{-1}.$$  (7)

To determine the radial outflow that results when $J_{\text{convect}}$ is convected by the solar wind at speed $u$, we first convert the differential intensity in Equation (7) into differential number density:

$$U = 4\pi(0.227/\nu)(46/T)^{1.5} = 4\pi(0.227/\nu)(46/T)^2$$  (8)

where $\nu$ is the speed of a 46 keV particle, 2970 km s^{-1}. We then apply the Compton–Getting equation (Gleeson & Axford 1967) and determine the differential radial flux, or streaming $S$:

$$S = uU - (u/3) \frac{\partial}{\partial T}(2TU) = 4\pi(5u/3)(0.227/\nu)(46/T)^2.$$  (9)

We then convert the differential streaming to differential intensity to compare with the results of Dialynas et al. (2021), and Equation (9) becomes

$$J_{\text{outflow},H} = 277(5u/3\nu)(46/T)^{1.5}.$$  (10)

Finally, comparing Equation (10) with the observed radial outflow of H in Equation (6), we find that the radial solar wind speed beyond the heliocliff is

$$u = 1780(0.001165 / 0.227) = 9.14 \text{ km s}^{-1}.$$  (11)

We can use the radial outflow speed at V1 in Equation (11), and our model for the nose region of the heliosheath depicted in Figure 1 to estimate the distance to the heliopause. In Figure 1, the solar wind streamline on the edge of the centerline region, which is dragging the magnetic field and the solar wind in the centerline region across the heliocliff, is located approximately 40° from the centerline. The heliocliff is flat in the centerline region and located at 121.6 au along the trajectory of V1, which makes an angle of 178° with the centerline. With this geometry, the streamline at the edge of the centerline region crosses the heliocliff at a radial distance of 151.8 au. Using the parameters that determine the streamlines in Figure 1 and requiring that the solar wind density where the streamline crosses the heliocliff is 0.1 cm^{-3}, matching the expected density in the local interstellar medium, the speed of the solar wind crossing the heliocliff is 1.15 km s^{-1}. If we then assume that the heliopause is spherical at a fixed radial distance, and of course that the solar wind that is dragged outward with the streamlines fills the volume inside the heliopause, then with the radial outflow speed along the trajectory of V1 of 9.14 km s^{-1} and the radial outflow speed of the solar wind streamline of 1.15 km s^{-1}, the heliopause is located at 156.2 au.

Clearly, this should not be considered a precise prediction. There are many simplicities and assumptions in this calculation of the distance to the heliopause. Nonetheless, it is not surprising that V1 has not yet crossed the heliopause, nor should we be surprised if V1 crosses the heliopause in the next few years.

Questions of course are what will the heliopause look like, and what should we be looking for? The heliopause is a rotational discontinuity and thus a rotation in the magnetic field should be expected. However, the rotation depends on the tangential velocities of the solar wind on either side to the discontinuity and, given the trajectory of V1, very near the nose of the heliosheath, these tangential velocities may be small, resulting in a small rotation. Certainly, the outward flow velocities observed by Dialynas et al. (2021) will be disrupted, perhaps even change direction. The region beyond the heliopause is likely to be turbulent. Whatever is the actual structure of the heliopause, it is unlikely to be simple, probably not stable, but very interesting.

5. The Observations of Voyager 2

The F&G model for the nose region of the heliosheath can account in detail for the observations of V1, the trajectory of which is at a northern heliographic latitude of 34.5°, essentially straight into the nose of the heliosheath. In this section we show that the F&G model can also account for the observations of Voyager 2 (V2), the trajectory of which is at a southern heliographic latitude of 32.2° and a longitude of 218°, or 43° east of the longitude of V1 and on the flanks of the nose region of the heliosheath. We begin by reviewing some of the key observations of V2 and then proceed to show how the F&G model can account for these observations.

There is a working plasma detector on V2, PLS, which in principle can measure solar wind flow velocities (Richardson et al. 2019). However, at large radial distances the orientations of the PLS detectors are such that there are limited measurements of the solar wind angular distribution. The measurements of the flow along the magnetic field, which lies in the azimuthal direction (the $T$-direction of the Voyager $R$–$T$–$N$ coordinate system), are considered to be accurate, but the measurements perpendicular to the magnetic field in the radial or polar directions, less so. There are also measurements of the solar wind flow velocities using the convective anisotropies of low-energy energetic particles observed by LECP, the same technique as was used to determine the solar wind velocities observed by V1 (Krimigis et al. 2011, 2019; Decker et al. 2012). The convective anisotropy measurements have the opposite problem from the PLS measurements. The radial flow velocity is considered to be accurate because LECP can measure the angular distribution of energetic particles. The azimuthal flow velocity is suspect because energetic particles can flow freely along the magnetic field, resulting in anisotropies in the azimuthal direction from other than the flow of the solar wind.

Krimigis et al. (2019) find that the V2 radial flow speed decreases with radial distance and becomes small at 119 au, a boundary where there is a decrease in the intensity of energetic particles. The radial speed does not go to zero inside 119 au, nor does the solar wind appear to flow inward in advance of 119 au, as was observed on V1. Richardson et al. (2019) find that the azimuthal speeds have their lowest values in the region just beyond the termination shock, which for V2 is at 84 au,
and in the region just inside 119 au. In between these two regions, the azimuthal flow becomes large and at ~110 au reaches ~100 km s\(^{-1}\) in the positive \(T\)-direction. 

In 2019, the Voyager principal investigators declared that V2 had crossed the heliopause at 119 au (Burlaga et al. 2019; Gurnett & Kurth 2019; Krimigis et al. 2019; Richardson et al. 2019; Stone et al. 2019). However, the case for the heliopause at V2 to be at 119 au was even less convincing than was the case for the heliopause at V1 to be at 121.6 au, and for both V1 and V2, the claimed heliopause is the heliocliff. At V2, there is clear observational evidence that the solar wind is flowing beyond 119 au and creating a region that contains heliosheath plasma. The magnetic field does not change direction at 119 au, consistent with the solar wind convecting the magnetic field across the heliocliff. The ACRs are observed beyond the heliocliff on magnetic field lines that are clearly heliosheath magnetic fields. The plasma density, to the extent that PLS can accurately determine the plasma density, is observed to increase as the radial flow speed of the solar wind decreases, demonstrating that the solar wind can be compressed to the densities observed by Gurnett & Kurth (2019) beyond the heliocliff.

There is also information on the heliosheath being explored by V2 in the spectra of ACRs, just as there is in the ACR spectra observed by V1, shown in Figure 2 and Table 1, and discussed in detail in Section 3. The ACR H differential intensity spectra observed by V2, averaged over one calendar year at locations immediately downstream from the termination shock (2008), at distances one-third (2011) and two-thirds (2014) the distance between the termination shock and the heliocliff, and during the last calendar year before V2 crossed the heliocliff (2017), are well fit by Equation (4), the spectrum that results from pump acceleration. The parameters used to fit these spectra are listed in Table 2. Note that the rollover energies are large. The ACRs achieve the maximum possible acceleration and thus, as discussed in Section 3, the pressure in the ACRs equals the pressure remaining in the pickup ions.

Listed in Table 2 are the pressures in ACR H and the total pressures in all pickup ions and ACRs, which, as in Table 1, is 2.8 times the ACR H pressure. The units of pressure in Tables 1 and 2 are \(10^{-12}\) dynes cm\(^{-2}\). There are very little published data on the magnetic field observed by V2. Consulting the magnetic field data that are available, the magnetic field magnitudes average about 0.1 nT and the magnetic pressure that results from a field of 0.1 nT is listed in Table 2 for 2008, 2011, and 2014. The magnetic field magnitude is slightly higher in 2017 and the magnetic field pressure listed in Table 2 for 2017 is the pressure that results from a magnetic field of 0.13 nT. (Note: Burlaga et al. 2019 observed a dramatic increase in the magnetic field before and at the heliocliff, but this occurred in 2018.) The sum of the pressures in the ACRs and pickup ions plus the magnetic field pressure in 2008 and 2017 is \(0.43 \times 10^{-12}\) dynes cm\(^{-2}\), the total pressure in the centerline region shown in Table 1 that satisfies Equation (1) and balances the pressure exerted on the heliosheath from the region beyond the heliocliff. The total pressures in 2011 and 2014 at radial distances one-third and two-thirds of the distance between the termination shock and the heliocliff are lower than \(0.43 \times 10^{-12}\) dynes cm\(^{-2}\).

Figure 1 illustrates the configuration of the solar wind streamlines of the F&G model, and the resulting heliocliff and heliopause, at a northern heliographic latitude of 34°5. We assume that the configuration of streamlines is the same at a southern heliographic latitude of 32°2, the latitude of the V2 trajectory. In Section 4 we found that at the latitude of V1, the heliocliff on the flanks is at 151.8 au, whereas at the latitude of V2, the heliocliff on the flanks is at 119 au, and all distances at southern latitudes, including the width of the centerline region, will scale accordingly. With the proviso that distances in the southern hemisphere are smaller, we can use the general configuration of the streamlines in Figure 1 to illustrate that the F&G model can account for the V2 observations.

1. The trajectory of V2, on the flank of the nose region of the heliosheath, will be to the left of the centerline region in Figure 1, and thus, as observed, the radial flow speeds decrease with radial distance becoming small at the heliocliff. The radial speed does not go to zero inside the heliocliff, nor does the solar wind appear to flow inward in advance of the heliocliff.

2. Although not shown in Figure 1, the solar wind streamlines that V2 crosses at intermediate distances between the termination shock and the heliocliff cannot reach the heliocliff and must turn and flow into the tail region of the heliosheath. Thus, as observed, there are flows at a large speed in the positive \(T\)-direction.

3. The acceleration of the ACRs should be the same over a wide range of longitudes in the region immediately beyond the termination shock. The pickup ions are heated crossing the termination shock and then immediately accelerated by pump acceleration and achieve their maximum possible pressure. Thus, as observed, the total pressure in ACRs and pickup ions immediately beyond the termination shock is the same as the total pressure in the centerline region.

4. At intermediate radial distances between the termination shock and the heliocliff, the ACRs and pickup ions can escape into the tail region following the spiral magnetic field. Thus, as observed, the total pressure in the ACRs and pickup ions is lower than the total pressure in the centerline region.

5. In the region immediately inside the heliocliff, the magnetic field will be convected across the heliocliff before the pickup ions and ACRs can escape into the tail region. Thus, as observed, the total pressure in pickup ions and ACRs is the same as the total pressure in the centerline region.

| Year | \(j_0\) | \(T_{eci}\) | \(P_{ACR,H}\) | \(P_{total}\) | \(B_{den}/8\pi\) | \(P_{total} + B_{den}/8\pi\) |
|------|--------|------------|-------------|-------------|----------------|-----------------|
| 2008 | 2.4    | 10         | 0.14        | 0.39        | 0.04           | 0.43            |
| 2011 | 1.5    | 100        | 0.12        | 0.34        | 0.04           | 0.37            |
| 2014 | 0.98   | 100        | 0.08        | 0.22        | 0.04           | 0.26            |
| 2017 | 1.685  | 100        | 0.13        | 0.36        | 0.07           | 0.43            |

Note. Listed for each V2 spectrum observed at locations described in the text are the parameters used to fit the spectra, the ACR’s H pressure, the total pressure in pickup ions and ACRs, and the pressure in the observed magnetic field.
6. Concluding Remarks

There is compelling observational evidence that the model of Fisk & Gloeckler (2014a) for the nose region of the heliosheath is correct: V1 did not cross the heliopause in 2012 and is not now in the interstellar medium. There is compelling observational evidence that the ACRs are correctly modelled in the heliosheath by the pump acceleration mechanism of Fisk & Gloeckler (2014b). The success of the models of Fisk & Gloeckler confirms that the plasma in the nose region of the heliosheath consists of two separate components, the pickup ions plus ACRs and the thermal solar wind. Each component has its own governing equations. The pickup ions and ACRs respond to a magnetic field that includes the magnetization resulting from the dipole moments of the pickup ions and ACRs. The solar wind responds only to its embedded magnetic field.

The premature announcement that V1 crossed the heliopause and entered the interstellar medium in 2012 stifled any serious consideration of the models of Fisk & Gloeckler and had the consequence of ensuring that all efforts to model the heliosheath have been based on an incorrect understanding of the governing physics. There is not a single numerical model that correctly describes the plasma in the nose region of the heliosheath. Many models are single fluid models in which there is a single equation of state that couples the density of the solar wind with the pressure in the pickup ions and ACRs. The recent paper by Ofer et al. (2020), which attempted to treat pickup ions as a separate gas, did not recognize that pickup ions respond to the magnetic field that includes the magnetization and not the magnetic field embedded in the solar wind.

Rather than lament our lack of progress in understanding the heliosheath, we should view this as an exciting time. There is much to do. Models need to be rebuilt to be consistent with the reality of the heliosheath. Observations that were interpreted as if V1 were in the interstellar medium need to be reconsidered. We should recognize also that the heliosheath of Fisk & Gloeckler is a more interesting place than the heliosheath of the Voyager investigators or those who have attempted to model it. There are physical processes unlike any we have been able to study, with implications for other astrophysical plasmas. Indeed, the heliosheath is sufficiently interesting that it merits revisiting with modern instrumentation with Interstellar Probe, a mission currently under study.

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ORCID iDs

L. A. Fisk @ https://orcid.org/0000-0002-0646-2279
G. Gloeckler @ https://orcid.org/0000-0002-5497-9758

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