

A model for the nose region of the heliosheath

L A Fisk and G Gloeckler

Department of Atmospheric, Oceanic and Space Sciences, University of Michigan,
2455 Hayward St, Ann Arbor, MI 48109-2143,

E-mail: lafisk@umich.edu

Abstract. The *Voyager 1* spacecraft is currently in the vicinity of the heliopause, which separates the heliosphere from the local interstellar medium. There has been a precipitous decrease in particles accelerated in the heliosphere, and a substantial increase in galactic cosmic rays (GCRs), suggesting easy escape of the former across the heliopause, and entry of the latter. The question is, has *Voyager 1* actually crossed the heliopause and is it now in the interstellar medium? Here the evidence is inconclusive. The direction of the magnetic field observed by *Voyager 1* is essentially unchanged from the direction of the heliospheric magnetic field. However, the plasma density, which is measured from observations of plasma waves, is similar to the expected higher density of interstellar plasma. In this paper, the principal results of an analytic model are presented demonstrating that the higher plasma densities measured by *Voyager 1* are likely to be compressed solar wind. Thus both the magnetic field and the plasma density observations are consistent with *Voyager 1* still remaining well within the heliosheath. The model has a simple test: *Voyager 1* should encounter a current sheet crossing, where the behavior of particles accelerated in the heliosphere and the GCRs will be different from what *Voyager 1* is now observing.

1. Introduction

The *Voyager 1* spacecraft, hereafter referred to as *V1*, is currently in the vicinity of the heliopause, which separates the heliosphere from the local interstellar medium. There has been a precipitous decrease in particles accelerated in the heliosphere, and a substantial increase in galactic cosmic rays (GCRs) [1,2], suggesting easy escape of the former across the heliopause, and entry of the latter. The question is, has *V1* actually crossed the heliopause and is it now in the interstellar medium? Here the evidence is inconclusive. The direction of the magnetic field observed by *V1* is unchanged from the direction of the heliospheric magnetic field [3], and is in a substantially different direction from the expected direction of the interstellar magnetic field inferred from both *IBEX* observations of energetic neutral atoms (ENAs) [4,5 and references therein] as well as from observations of the polarization of interstellar grains [6]. However, Gurnett et al. [7] observe plasma oscillations at 122.2 AU, 122.5 AU, and 123.9 AU, which are a direct measure of the plasma electron density, and finds densities of 0.055 cm^{-3} , 0.058 cm^{-3} , and 0.083 cm^{-3} , respectively. These densities are comparable to densities expected in the local interstellar medium, and are much larger than the plasma densities observed by the *Voyager 2* (hereafter referred to as *V2*) plasma detector closer to the termination shock [8].

In this conference paper, we present the main arguments and conclusions of a model for the nose region of the heliosheath, which is described in Fisk and Gloeckler [9]. This analytic model is based upon and is consistent with all *Voyager* observations, and demonstrates that



the higher plasma densities measured by *V1* are likely due to compressed solar wind. Thus, in the interpretation presented here, both the magnetic field and the plasma density observations are consistent with *V1* still remaining well within the heliosheath, and, as we shall show, *V1* is years away from crossing the heliopause.

We begin with a detailed discussion of the unusual properties and unusual physical processes that occur in the nose region of the heliosheath. We then use these properties and physical processes to develop an analytic model for the flow of the solar wind through the nose region of the heliosheath, demonstrating that the solar wind will be compressed to values equal to those observed by Gurnett et al. [7]. The model allows us to make specific predictions about the distance to the heliopause, and provides a test for the validity of the model: we predict, as discussed in detail in Gloeckler and Fisk [10], that *V1* will soon encounter a current sheet in which the polarity of the magnetic field reverses, clearly indicating that *V1* remains within the heliosheath.

2. The unusual properties of the nose region of the heliosheath

There are two properties of the nose region of the heliosheath on which our model is based: (1) the dominant pressure in the pickup ions and ACRs; and (2) the flow direction of the solar wind.

(1) The particle pressure in the nose region of the heliosheath is primarily the result of the mobile interstellar pickup ions and particles accelerated in the heliosheath (usually referred to as anomalous cosmic rays, ACRs), and is readily modeled and/or observed: (a) The pickup process in the supersonic solar wind is readily modeled and yields the pressure in pickup ions upstream of the termination shock. Observations by the working plasma detector on *V2* find that it is the pickup ions, not the solar wind, that are heated at the termination shock, satisfying the Rankine-Hugoniot relationship, which determines the pickup ion pressure in the heliosheath [8]. This pickup-ion pressure is validated by the *IBEX* observations of energetic neutral atoms resulting from the pickup ions [11]. (b) As for the energetic particles observed in the nose region of the heliosheath, at ~ 120 AU the differential intensity spectrum of ACRs has a spectral index of -1.5 , with an exponential rollover, as is expected from the pump acceleration mechanism of Fisk and Gloeckler [12]. For such a spectrum, the pressure is due primarily to particles with energies that are measured by the Cosmic Ray Subsystem (CRS) detector on *V1* [2], and thus the ACR pressure is readily determined. The combined pressure in the pickup ions (deduced from *IBEX* observations), and in the ACRs (measured by *V1* at distances of ~ 120 AU) is $\sim 1.2 \times 10^{-12}$ dyne cm^{-2} [11].

The pressure in the pickup ions and ACRs is the dominant pressure in the nose region of the heliosheath. The plasma detector on *V2*, which is closer to the termination shock than *V1*, measures both the ram pressure and the thermal pressure of the solar wind [8]. The pressure in the pickup ions and ACRs is a factor of ~ 3 larger than the ram pressure, and is a factor of ~ 150 larger than the thermal pressure of the solar wind. The solar wind is not heated crossing the termination shock, and relative to itself, it remains supersonic in the heliosheath.

(2) Although *V1* does not have a functional plasma detector, Krimigis et al. [13] and Decker et al. [14] have been able to infer the solar wind flow velocity from the convective anisotropy of ~ 50 -keV ions. Their instrument, the Low-Energy Charged Particle (LECP) detector, normally rotates approximately in an R-T plane of the *Voyager* R-T-N coordinate system, where the $+\mathbf{e}_R$ axis points radially outward from the Sun, the $+\mathbf{e}_T$ axis is in the direction of the rotation of the Sun, and $\mathbf{e}_N = \mathbf{e}_R \times \mathbf{e}_T$. From measurements that have been made continuously since *V1* crossed the termination shock, Krimigis et al. [13] and Decker et

al. [14] find that the inferred radial flow speed decreases systematically to essentially zero beyond ~ 113 AU, with a small azimuthal speed persisting. At distances between ~ 116 AU and ~ 120 AU from the Sun, *V1* was rotated at a number of short time intervals to observe the anisotropies of low-energy ions in approximately the \mathbf{e}_N direction [14]. At these distances the anisotropies, and thus the inferred convective flow speed in the polar direction, were found to be small, essentially zero [14]. This result is consistent with that of Stone and Cummings [15], who observe, using the Cosmic Ray Subsystem (CRS) detector that measures somewhat higher energy particles, that the anisotropies in the polar direction become increasingly small with distance into the heliosheath.

3. Implications of the dominant pressure in the pickup ions and ACRs

The hot pickup ions, and particularly the energetic ACRs, have average speeds very much larger than the thermal speeds of the solar wind. The pickup ions and ACRs should flow freely along the magnetic field, and seek to maintain pressure equilibrium in the nose region of the heliosheath, independent of the local conditions in the solar wind.

Thus, in the nose region of the heliosheath we have two distinct, and basically uncoupled gases: the mobile pickup ions and ACRs, which contain the pressure, and the relatively cold thermal solar wind, which contains the mass. The pickup ions and ACRs are responding to the global conditions in the heliosheath as they attempt to maintain pressure equilibrium. The solar wind is flowing into the heliosheath across the termination shock, and its density is responding to local conditions. The solar wind by itself has an equation of state that relates pressure and density, and the same is true for the pickup ions and ACRs. However, it is inappropriate to consider the combined gas of pickup ions, ACRs, and solar wind as having an equation of state since the pressure is determined by global conditions and the density by local conditions.

The need to treat the pickup ions and ACRs separately from the solar wind has important implications for the magnetic field in the nose region of the heliosheath: Consider first the magnetic field associated with the pickup ions and the ACRs. Each pickup ion and ACR particle has a dipole moment, which collectively align to form a magnetization that is proportional to the dominant pressure in the pickup ions and ACRs. Since the pickup ions and ACRs are in pressure equilibrium in the nose region of the heliosheath, we can think of the nose region as a substance with intrinsic dipole moments. The appropriate form for Ampere's Law (in a steady state) is then

$$\mathbf{J} = \frac{c}{4\pi} \nabla \times \mathbf{H}. \quad (1)$$

Here, \mathbf{H} is the magnetic field that includes the magnetization and c is the speed of light.

The current \mathbf{J} in Equation (1) is due to the perpendicular pressure of the pickup ions and ACRs, and including the magnetization and all gradient and curvature drifts, is given by (e.g. [16])

$$\mathbf{J} = \frac{c\mathbf{H} \times \nabla P_{\perp}}{H^2}. \quad (2)$$

Crossing \mathbf{H} into Equation (2) yields the equation for static equilibrium for the pickup ions and ACRs:

$$-\nabla P_{\perp} + \frac{1}{4\pi}(\nabla \times \mathbf{H}) \times \mathbf{H} = 0. \quad (3)$$

Note that the \mathbf{H} -field is entirely determined by the pressure of the pickup ions and ACRs, and does not depend on the solar wind.

It is important to realize in this paper that we use the symbol \mathbf{H} to denote the magnetic field in the nose region of the heliosheath that is determined by the pickup ions and ACRs, independent of the solar wind. This is standard notation in any basic E&M book (e.g. [17]); the macroscopic magnetic field of an object with intrinsic magnetic dipoles is denoted by \mathbf{H} . This notation is not standard in conventional plasma physics, where either no distinction is made between an \mathbf{H} -field and a \mathbf{B} -field, or the magnetization is considered to be wholly contained in the \mathbf{B} -field. We reserve the symbol \mathbf{B} to describe the magnetic field that is convected into the heliosheath and controlled by the solar wind.

The solar wind convects the heliospheric magnetic field across the termination shock and into the heliosheath. The solar wind is coupled to the magnetic field through the Lorentz force, which depends upon \mathbf{B} . The momentum equation for the solar wind (again in a steady state) is then

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\nabla P_{sw} + \frac{1}{4\pi}(\nabla \times \mathbf{B}) \times \mathbf{B}. \quad (4)$$

Here, \mathbf{u} is the solar wind velocity; ρ is the solar wind mass density, and P_{sw} is the solar wind thermal pressure, which remains small compared to the pressure in the pickup ions and ACRs. Similarly, Faraday's Law requires that, in a steady state,

$$\nabla \times (\mathbf{u} \times \mathbf{B}) = 0, \quad (5)$$

where the electric field has been set equal to the convective electric field, $\mathbf{E} = -(\mathbf{u} \times \mathbf{B})/c$.

In a conventional plasma, where pressure and density are directly related, \mathbf{H} and \mathbf{B} are the same. The pressure in Equation (3) is the same as the pressure in Equation (4) and directly related to the density in Equation (4). In the nose region of the heliosheath \mathbf{H} and \mathbf{B} are not the same. The dominant pressure in the pickup ions and ACRs in Equation (3) is determined by the global properties of the nose region and is unrelated to the solar wind pressure or density in Equation (4), which is determined by the local flow properties of the solar wind.

The magnetic field at ~ 120 AU is observed by *V1* to be primarily in the azimuthal direction [3]. As discussed in Section 2, the radial flow speed of the solar wind is inferred to decrease to near zero in the radial and polar directions. If the heliosheath were a conventional plasma, then from Equation (5) we should expect that the magnetic field strength would increase dramatically to very large values, and yet no such significant change is observed in the field magnitude [3].

The resolution of this contradiction is provided by noting that the *V1* magnetometer observes the \mathbf{H} -field, which is determined by the pressure in the pickup ions and ACRs, not the \mathbf{B} -field, which is determined by Equation (5). Indeed, the observed decrease in the radial and polar solar wind flows without a major increase in the observed magnetic field strength is strong evidence for the validity of the approach taken in this paper: the pickup ions and ACRs

are a separate gas, responding to global conditions and determining the **H**-field; the solar wind is responding to local conditions and determining the **B**-field.

4. The flow of the solar wind in the nose region of the heliosheath

With the unusual properties and physical conditions in the nose region of the heliosheath described in Section 2, and a few straightforward simplifications, it is possible to calculate the flow of the solar wind analytically, without resorting to a numerical model. The solar wind is treated as a separate gas from the pickup ions and ACRs, coupled to the magnetic field **B**, and governed by standard continuity equations, such as the momentum equation in Equation (4). For our purposes, we use the energy continuity equation,

$$\nabla \cdot \left(\rho \mathbf{u} \left(\frac{u^2}{2} + \frac{5}{2} \frac{P_{sw}}{\rho} \right) - \frac{1}{4\pi} (\mathbf{u} \times \mathbf{B}) \times \mathbf{B} \right) = 0, \quad (6)$$

where again, **u** is the solar wind velocity; ρ is the solar wind mass density, and P_{sw} is the solar wind thermal pressure. We take the solar wind to be adiabatic, $P_{sw} \propto \rho^{5/3}$.

The solar wind velocity **u** is taken to lie on a cone of constant heliographic latitude, consistent with the observations of energetic particle anisotropies from *V1* discussed in Section 2 that show that the polar flow of the solar wind becomes diminishingly small [14,15]. This simplification is not strictly valid immediately downstream from the termination shock, where polar flows occur, but it is valid beyond about 110 AU, which is the main concern of this paper. The magnetic field is taken to lie in the azimuthal direction. Burlaga et al. [3] observe small deviations of the magnetic field direction from azimuthal, which also do not affect the main conclusions of this paper.

With the flow of the solar wind in the nose region of the heliosheath in the radial and azimuthal directions only, there must be a centerline region, where the flow of the solar wind diverges, one streamline flowing in the positive azimuthal direction and the streamline on the other side of the centerline in the negative azimuthal direction. The actual location of the centerline is unknown. We take the centerline to be offset by $\sim 15^\circ$ in azimuthal angle from the trajectory of *V1*, which is moving in the direction of motion of the Sun through the local interstellar medium. Such a location of the centerline is consistent with numerical models such as those by Opher et al. [18] in which pressure of the interstellar magnetic field distorts the shape of the heliopause.

As is illustrated in figure 1, the streamlines in the heliosheath on either side of the centerline (the first streamlines) originate from essentially the same location on the termination shock. They create a region that is a vacuum as the two streamlines diverge, each flowing in an opposite direction. However, the magnetic field is azimuthal and crosses the vacuum region. The pickup ions and ACRs will flow easily into the vacuum, along the magnetic field, but so must the solar wind. Thus, the streamlines that are adjacent to the centerline will leak particles as they flow outward, and these particles will fill in the centerline region, making the solar wind density azimuthally independent in the nose region of the heliosheath.

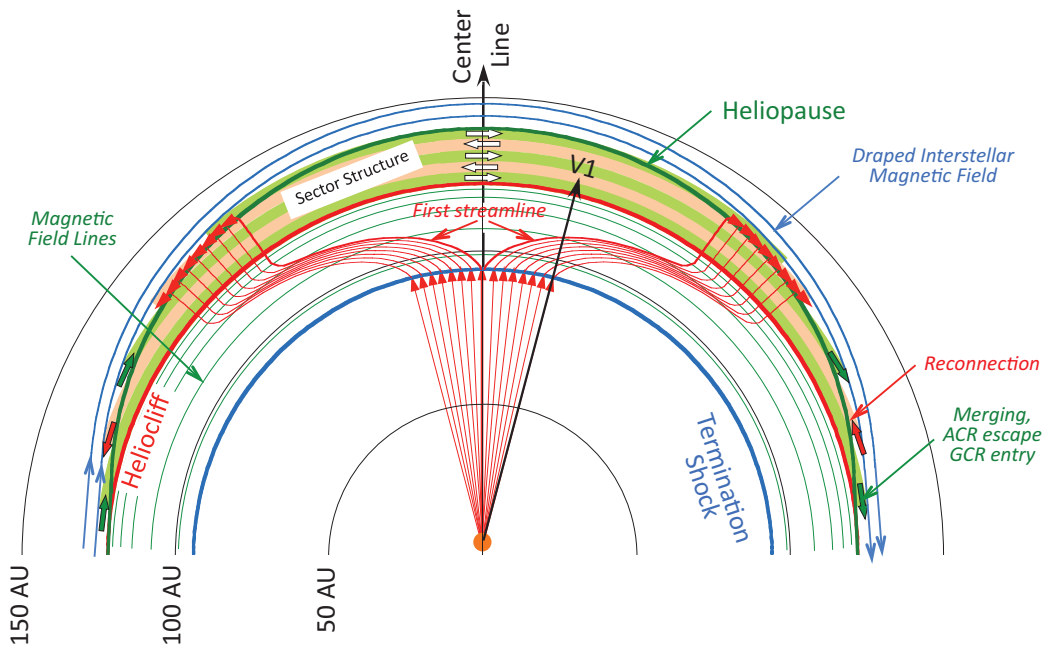


Figure 1. The solar wind streamlines (red curves) and the magnetic field lines (green and blue curves) on a cone of constant heliographic latitude projected onto a rectangular plane (after Fisk and Gloeckler [9]). At the centerline, which is slightly offset from the trajectory of *Voyager 1*, the flow of the solar wind diverges, with one streamline flowing in the positive azimuthal direction and the streamline on the other side of the centerline in the negative azimuthal direction. The two ‘first streamlines’ and the heliopause define the boundaries of the centerline region. The streamline regions lie to the left and right of the centerline region. Between the heliocliff and the heliopause lies a high-density region where the solar wind flow is highly compressed, reaching the density of the interstellar plasma ($\sim 0.1 \text{ cm}^{-3}$), and flows radially outward at a few km s^{-1} toward the heliopause. The azimuthal magnetic field in this high-density region is expected to reverse polarity several times, providing a test of our model. See text.

There can be no mass flow along the magnetic field connecting streamlines on either side of the centerline. By definition, the azimuthal velocity is zero at the centerline. So as streamlines leak particles along the magnetic field, they will create a region with no azimuthal flow, and in a steady state, with density equal to the density on the streamlines. With the magnetic field in the azimuthal direction there is no dependence of the density on azimuthal angle in the vicinity of the centerline region, and the density will increase with radial distance according to

$$\rho u_r r^2 = \rho_{ts} u_{ts} r_{ts}^2, \quad (7)$$

where u_r is the radial flow speed of the solar wind and ts denotes ‘evaluated at the termination shock’.

In figure 1 we present the results of our solution to Equation (6), and its consequences for the region beyond the current location of *V1*, and for the location and properties of the heliopause. The calculations for these streamlines are presented in detail in Fisk and Gloeckler [9]. The solar wind streamlines and the magnetic field all lie on a cone of constant heliographic latitude. Figure 1 is the projection of this cone onto a rectangular plane. The solar wind streamlines are in red, originating at the Sun, crossing the termination shock at 94 AU, and then flowing through the heliosheath to the heliopause.

The streamlines shown in figure 1 result from an analytic model. It would clearly be useful to calculate these streamlines in a full numerical simulation of the nose region of the heliosheath. In some ways, the required numerical simulation is simpler than many of the numerical simulations now in use (e.g., [19-22]). In the model presented in this paper, the solar wind is treated as a separate fluid from the pickup ions and ACRs, and simply needs to be modeled so as to have the correct flow directions in the nose region of the heliosheath. Although the pressure in the pickup ions and ACRs does not influence the solar wind flow directly, it can be expected to resist the flow of the solar wind in the polar direction, since such flow would introduce strong pressure gradients in the pickup ions and ACRs, which cannot be relieved along the primarily azimuthal magnetic field. We have then a two-dimensional flow of the solar wind, which is initially supersonic downstream of the termination shock, which is expected to create a centerline region where the solar wind flow diverges; which suffers mass loss from the escape of the solar wind into the centerline region; and which can be cooled by the escape of the thermal energy when the embedded magnetic field crosses the heliopause.

5. Implications of the model of the flow of the solar wind

As is illustrated in figure 1, after the solar wind crosses the termination shock, it first turns in the azimuthal direction, and then turns back into the radial direction, and flows outward to the heliopause, which results in a flow velocity normal to the heliopause. The heliopause can thus not be a tangential discontinuity, but rather must be a rotational discontinuity, since rotational discontinuities have a normal component of the magnetic field and can accommodate flows normal to the discontinuity.

Rotational discontinuities, unlike tangential discontinuities, propagate. The heliopause, however, is stationary relative to the Sun. Thus, to maintain the heliopause stationary in the frame moving with the Sun, the rotation discontinuity must propagate into the interstellar medium at a speed equal to the velocity of the Sun through the local interstellar medium.

The solar wind flow across the heliopause will result primarily in a decrease in temperature, not in mass, since it is the higher energy particles, including the pickup ions, that will most readily escape. The resulting decrease in pressure will not balance the interstellar medium, with the result that the heliosheath will shrink in size with a resulting increase in the solar wind density. The region between where the solar wind flow turns radial and the heliopause is analogous to a balloon that is cooled; the balloon shrinks in size and the density increases.

At the same time the solar wind is escaping, cold dense interstellar gas is entering across the heliopause. The solar wind density should increase only to where the density equals the interstellar density, which we take to be $\sim 0.1 \text{ cm}^{-3}$. In a steady state, then, the density of the solar wind increases to equal the interstellar density, and the pressure in the heliosheath is able to balance the interstellar pressure since no further shrinkage is occurring.

Note that the increased density is not accompanied by an increased pressure, as occurs on the adiabatic streamlines. Rather, the region beyond where the streamlines turn radial is not adiabatic since there is an escape of thermal energy across the heliopause, which cools this region of the heliosheath to achieve the required pressure with an increased density. We have then two separate and distinct regions in the nose region of the heliosheath: a region where the solar wind flow is controlled by the flow parameters at the termination shock and is adiabatic, and a separate region where the solar wind flow properties are determined by the escape of thermal energy across the heliopause and the solar wind flow is not adiabatic.

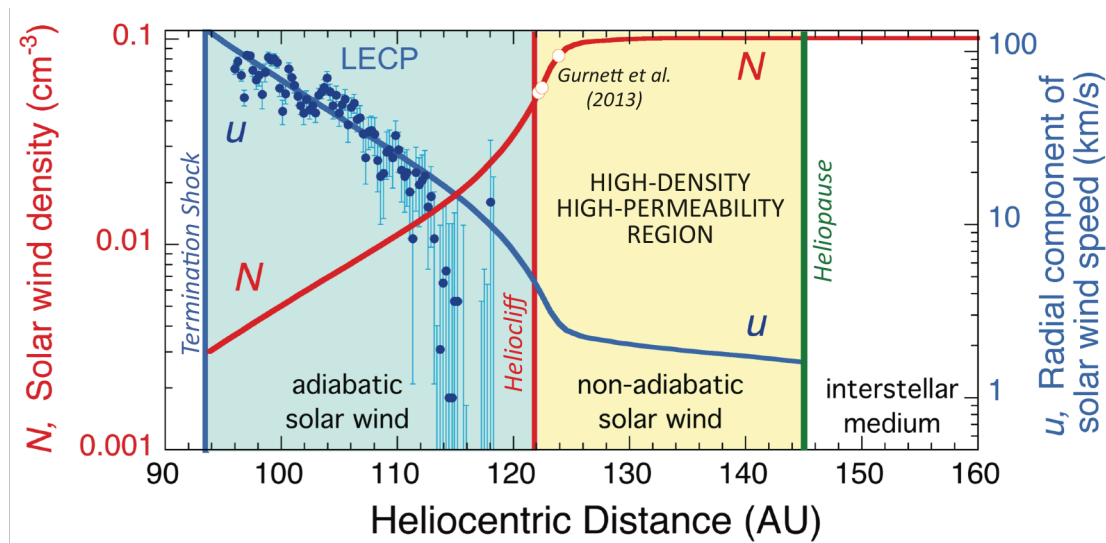


Figure 2. Variations of the radial component of the solar wind speed (blue curve) and solar wind number density (red curve) with heliocentric distance (after Fisk and Gloeckler [9]). *V1* is currently at about 127 AU. The speed profile (blue curve) was chosen to match the average radial speeds deduced from anisotropy measurement of ~ 50 -keV ions [13,14] between ~ 96 AU and ~ 112 AU (filled blue circles). Plasma densities measured by Gurnett et al. [7] at ~ 123 AU to 124 AU (red circles), an interstellar plasma density of 0.1 cm^{-3} and a solar wind density at the termination shock of 0.003 cm^{-3} were used in Equation (7), to obtain the speed profile beyond ~ 122 AU. The two speed profiles were then smoothly connected between 112 AU and 122 AU. This speed profile was used in Equation (11) to calculate the streamlines shown in figure 1. The solar wind is compressed to densities measured by Gurnett et al. [7]. See text for further discussion.

Shown in figure 2 is the radial profile of the solar wind density predicted in the model. The predicted density is consistent with the radial flow speed inferred from the anisotropy observations, which is also shown and yields the densities, and the gradient in the density observed by Gurnett et al. [7]. In this model the density equal to the interstellar density observed by Gurnett et al. [7] results because the solar wind is compressed to where it equals this density. The flow of thermal energy along the field lines that cross the heliopause maintains the solar wind density equal to the interstellar density.

Equation (7) still describes the relationship between the solar wind density and the radial flow speed of the solar wind and can be used to determine u_r in the nonadiabatic region. The radial flow speed becomes small, and is now only a few km s^{-1} , as shown in figure 2.

6. A test of the model

The precipitous decrease in the ACRs, often referred to as the ‘heliocliff’, should occur where the magnetic field is directly connected to the heliopause. In this model, there is a normal component of the magnetic field across the heliopause, which is a rotational discontinuity. However, we should expect a difference in the nature of the heliocliff, depending on the orientation of the heliosheath magnetic field relative to the interstellar magnetic field. In the case where the orientation is such that the heliosheath and interstellar magnetic fields merge, ACRs and GCRs should flow freely along the magnetic field, the former escaping and the latter entering. In the case where the orientation of the heliosheath field is opposite to the interstellar field, reconnection islands should occur which could limit the escape of ACRs and prohibit the entry of GCRs.

We note that the heliocliff observed by *VI* was marked by the escape of the ACRs, the entry of GCRs, and a sector boundary crossing [3]. There was evidence of increased magnetic field before the heliocliff, but the full escape of the ACRs and entry of GCRs occurred roughly coincident with a sector boundary, which suggests that at this boundary *VI* entered a region where the magnetic field was aligned with the interstellar magnetic field, providing for the abrupt escape of ACRs and entry of GCRs.

The calculations, described in detail in Fisk and Gloeckler [9] and illustrated in figure 1, predict that *VI* is currently about 18 AU from the heliopause. As discussed in Section 5, the solar wind flow speed is very slow beyond the location of *VI*, such that it will take *VI* more than two magnetic field reversals of the Sun to reach the heliopause. Thus, *VI* is certain to encounter another current sheet, where the magnetic field reverses polarity and we should expect reduced escape of ACRs, and certainly limited entry of GCRs.

Thus, there is a very clear test of the model presented in this paper. If *VI* encounters another current sheet, with different behavior of the ACRs and GCRs, it is clear that *VI* remains in the heliosheath and that *VI* is still years away from crossing the heliopause.

In Gloeckler and Fisk [10] we use *Voyager* observations to estimate when *VI* should encounter the next sector boundary, and find that it could well be within the next 2 years.

When *VI* finally reaches the heliopause there will be no change in the plasma density, which is simply the interstellar density, but the magnetic field should rotate to be more closely parallel or antiparallel to the interstellar magnetic field. There will then be a boundary layer beyond the heliopause, where the magnetic field is still the heliosheath magnetic field, followed by a region of merging or reconnecting magnetic fields. It may well be beyond the lifetimes of the *Voyager* spacecraft before they reach a region that can be said to be truly in the interstellar medium.

7. Concluding remarks

When *VI* passes out of the heliosphere into interstellar space, it will be an event of historical importance, the first human-made object to leave the domain of the Sun. At present the evidence as to whether *VI* is in interstellar space is unclear. There is no doubt that, with the observed precipitous decreases in particles accelerated in the heliosheath, *VI* is in the vicinity of the heliopause. The unchanged magnetic field direction suggests that *VI* remains within the heliosheath [3], whereas the observed plasma densities equal to expected interstellar density suggests that *VI* is in the interstellar medium [7]. Clearly, considering the historical importance of *VI* crossing the heliopause, we need a higher degree of certainty as to whether the crossing has occurred or not.

In this paper, we present an analytic model that is based upon and is consistent with all *Voyager* observations, and in which the higher plasma densities inferred by *VI* are due simply to compressed solar wind. Thus, in the interpretation presented here, both the magnetic field and the plasma density observations are consistent with *VI* still remaining well within the heliosheath, and, as we showed, *VI* is years away from crossing the heliopause. Of most importance, the model presented here has a simple test: We predict that *Voyager 1* will encounter a current sheet crossing, where the behavior of ACRs and GCRs will be different from what *VI* is now observing. Should such a current sheet crossing occur there should be no doubt that *VI* remains within the heliosheath.

Acknowledgements

This work was supported in part by NASA Grant NNX10AF23G and by NSF Grant AGS-1043012. We acknowledge and are very appreciative of the *Voyager 1* and *2* teams, who provided us with an opportunity to examine their data.

References

- [1] Krimigis S M, Decker R B, Roelof E C, Hill M E, Armstrong T P, Gloeckler G, Hamilton D C and Lanzerotti L J 2013 *Sci.* **341** 144
- [2] Stone E C, Cummings A C, McDonald F B, Heikkila B C, Lal N and Webber W R 2013 *Sci.* **341** 150
- [3] Burlaga L F, Ness N F and Stone E C 2013 *Sci.* **341** 147
- [4] McComas D J, et al. 2009 *Sci.* **326** 959
- [5] McComas D J, et al. 2012 *ApJS* **203** 1
- [6] Frisch P C 2011 *AIP Conf. Proc.* **1436**, *Physics of the Heliosphere: A 10 Year Retrospective* ed J Heerikhuisen, G Li, N Pogorelov and G Zank (NY: AIP) p 295
- [7] Gurnett D A, Kurth W S, Burlaga L F, and Ness N F 2013 *Sci.* **341** 1489
- [8] Richardson J D 2008 *GRL* **35** L23104 doi:10.1029/2008GL036168
- [9] Fisk L A and Gloeckler G 2014 *ApJ* **789** 41
- [10] Gloeckler G, and Fisk L A 2014 *GRL* in press
- [11] Gloeckler G, and Fisk L A 2010 *AIP Conf. Proc.* **1302**, *Pickup Ions Throughout the Heliosphere and Beyond* ed J A le Roux, V Florinksi, G P Zank, and A J Coates (NY: AIP) p 110
- [12] Fisk L A and Gloeckler G 2013 *ApJ* **776** 79
- [13] Krimigis S M, Roelof E C, Decker R B, and Hill M E 2011 *Nature* **474** 359
- [14] Decker R B, Krimigis S M, Roelof E C, and Hill M E 2012 *Nature* **489** 124
- [15] Stone E C, and Cummings A C 2011 *Proc. of the 32nd Intl. Cosmic Ray Conference* (vol 12) (Beijing: IUPAP) p 29
- [16] Gurnett D A, and Bhattacharjee A 2005 *Introduction to Plasma Physics* (Cambridge: Cambridge Univ Press)
- [17] Jackson J D 1999 *Classical Electromagnetics* (New York: John Wiley and Sons Inc)
- [18] Opher M, Stone E C, and Gombosi T 2007 *Sci.* **316** 875
- [19] Pogorelov N V, Borovikov S N, Zank G P, and Ogino T 2009 *ApJ* **696** 1478
- [20] Izmodenov V V, Malama Y G, Ruderman M S, Chalov S V, Alexashov D B, Katushkina O A, and Provornikova E A 2009 *Space Sci. Rev.* **146** 329
- [21] Washimi H, Zank G P, Hu O, Tanaka T, Munakata K and Shinagawa H 2011 *MNRAS* **416** 1475
- [22] Opher M, Drake J, Swisdak M, Schoeffler K M, Richardson J D, Decker R B and Toth G 2011, *ApJ* **734**