Has Voyager 1 really crossed the heliopause?

G Gloeckler and L A Fisk
Department of Atmospheric, Oceanic and Space Sciences, University of Michigan, 2455 Hayward St, Ann Arbor, MI 48109-2143 USA
gglo@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). The evidence is unclear, however, as to whether Voyager 1 has crossed the heliopause into the local interstellar medium, or remains within the heliosheath. In this paper we propose a test that will determine whether Voyager 1 has crossed the heliopause: If Voyager 1 remains in the heliosheath, the high plasma densities must be due to compressed solar wind, with the consequence that Voyager 1 will encounter another current sheet, where the polarity of the magnetic field reverses. Voyager 1 observations can be used to predict that the next current sheet crossing is likely to occur during 2015. A prediction is also provided as to what the Voyager 2 plasma detector will measure in the next few years.

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. Particles accelerated in the heliosphere have disappeared, while galactic cosmic rays (GCRs) have reached maximum intensity \cite{1,2}, suggesting easy escape of the former across the heliopause and entry of the latter. But 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 \cite{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) \cite{4,5,6}, and references therein], as well as from observations of the polarization of interstellar grains \cite{6}. However, Gurnett et al. \cite{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 find 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 working plasma detector on Voyager 2 (hereafter referred to as V2) closer to the termination shock \cite{8}.

A simple test will determine whether V1 remains in the heliosheath or has already crossed the heliopause into the local interstellar medium. The test is based on two principles:

(i) One of the most observable features of the heliosphere, which would clearly identify that V1 remains in the heliosheath, is a current sheet crossing. The heliosphere contains a single large current sheet, which separates two hemispheres of opposite magnetic polarity. As the solar cycle evolves, the current sheet becomes highly tilted relative to the solar equatorial plane, and appears to rotate through the poles of the Sun, accomplishing the polarity reversal of the dipole component.
of the solar magnetic field. Warps in the current sheet will be compressed as the current sheet is convected into the distant heliosheath, where the radial solar wind speed becomes very small, as is inferred from observations of particle anisotropies [9,10]. Magnetic reconnection will then occur, resulting in two regions of opposite polarity, with reduced magnetic strength due to the reconnection. The single current sheet that separates these two regions marks the time where the field reversal of the Sun occurred at the heliographic latitude and radius of \( V_1 \).

(ii) If \( V_1 \) remains in the heliosheath, the large densities observed by Gurnett et al. [7] must be the result of compressed solar wind. If the solar wind is compressed, it must be the result of a reduced flow velocity of the solar wind, particularly a reduced radial flow velocity. \( V_1 \) is thus moving faster than the outward flow of the solar wind, and will encounter additional current sheets, where the polarity of the magnetic field reverses.

The likely distance at which \( V_1 \) will encounter the next current sheet can be estimated from \( V_1 \) observations, and thus provides a clear test for whether \( V_1 \) remains in the heliosheath.

Fisk and Gloeckler [11] have developed a detailed model for the nose region of the heliosheath, the region of the heliosheath in the direction of motion of the Sun through the local interstellar medium, the regions that the Voyagers are exploring. The model is based on the assumption that the solar wind can be compressed. The model yields flow patterns for the solar wind that are consistent with the convective solar wind velocities inferred from >40 keV anisotropy observations, the technique used to determine the solar wind velocity in the absence of a working plasma detector on \( V_1 \). The model also yields the likely distance to the heliopause, as well as the likely properties of the heliopause. For our purposes here, the details of the model of Fisk and Gloeckler [11] are not needed, other than to note that it is possible to construct a complete model for the nose region of the heliosheath in which the solar wind is compressed.

We begin by presenting the arguments for why it is both possible and indeed to be expected that the solar wind is compressed at the current location of \( V_1 \). We then use Voyager observations to predict when \( V_1 \) is likely to encounter another current sheet. Guided by \( V_1 \) observations and drawing on the work of Fisk and Gloeckler [11] we also predict what the Voyager 2 (V2) plasma detector should measure during the next few years. In Concluding Remarks we discuss the different behavior of energetic particles that should be expected when \( V_1 \) enters a region of opposite magnetic polarity.

2. The argument for compressed solar wind

The nose region of the heliosheath is a subsonic region, and thus the sum of the particle and magnetic pressure is expected to be constant. It is sometimes argued that since particle density and pressure are related to each other through an equation of state, the solar wind density should also be constant in the nose region of the heliosheath, i.e. the solar wind cannot be compressed.

However, the nose region of the heliosheath is not a conventional plasma. The particle pressure in the nose region of the heliosheath is the result of the mobile suprathermal particles, such as interstellar pickup ions, and particles accelerated in the heliosheath (usually referred to as anomalous cosmic rays (ACRs)). The velocity distributions of these mobile particles are readily observed and/or modeled: (1) The pressure in pickup ions in the supersonic solar wind upstream of the termination is easily determined using standard models of the pickup ion process. Observations by the working plasma detector on V2 find that it is the pickup ions and halo solar wind [12], not the bulk solar wind, that are heated at the termination shock, satisfying the Rankine-Hugoniot relationship, which determines the pickup ion and halo pressure in the heliosheath [13]. This component of the ion pressure is validated by the IBEX observations of energetic neutral atoms resulting from the pickup ions [14]. (2) Energetic particles (e.g. ACR oxygen) observed in the nose region of the heliosheath at ~117 AU have a power law differential intensity spectrum with a spectral index of -1.5, with an exponential rollover, as is expected from the pump acceleration mechanism of Fisk and Gloeckler [15]. For such a spectrum, the pressure is due primarily to particles with energies that are measured by the Cosmic Ray Subsystem (CRS) detector on \( V_1 \) [2], and thus the ACR pressure is readily determined. The combined perpendicular pressure in the halo solar wind, pickup ions (deduced from IBEX observations) and in
the ACRs (measured by V1 at distances of ~117 AU) plus magnetic field and bulk solar wind pressure is estimated to be $1.47 \times 10^{-12}$ dyne cm$^{-2}$, close to our earlier value of $\sim 1.2 \times 10^{-12}$ dyne cm$^{-2}$ [14].

The pressure in the halo solar wind, 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 ~350 larger than the thermal pressure of the solar wind. The bulk solar wind is not heated crossing the termination shock, and relative to itself, it remains supersonic in the heliosheath.

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 halo particles, pickup ions and ACRs, which contain the dominant pressure, and the relatively cold bulk solar wind, which contains most of the mass. The pickup ions and ACRs are responding to the global conditions in the heliosheath as they attempt to maintain pressure equilibrium. The bulk solar wind is flowing into the heliosheath across the termination shock, and its density is responding to local conditions. The bulk solar wind by itself has an equation of state that relates pressure and density, and the same is true for the gas of halo particles, pickup ions and ACRs. However, it is inappropriate to consider a single gas of halo particles, pickup ions, ACRs, and the bulk solar wind as having an equation of state since the pressure is determined primarily by global conditions and the density primarily by local conditions. There is thus no restriction on compressing the bulk solar wind.

We should in fact expect that the bulk solar wind must be compressed at distances at least out to ~122 AU, simply from the solar wind velocity measurements. Although V1 does not have a functional plasma detector, Krimigis et al. [9] and Decker et al. [10] have been able to infer the solar wind flow velocity from the convective anisotropy of >40 keV ions, and find with their Low-Energy Charged Particle (LECP) detector that the inferred radial flow speed decreases systematically to a very small value 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 a direction normal to the usual azimuthal rotation of LECP [10]. At these distances the anisotropies, and thus the inferred convective flow speed in the polar direction, were found to be small, with an average of essentially zero [10]. This result is consistent with that of Stone and Cummings [16], 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.

The V1 solar wind observations can only be made when there are low-energy energetic particles present, from which the convective anisotropies can be determined. The measurements cease at ~122 AU, when the particles accelerated in the heliosheath escape. However, inside this distance, where the solar wind flow velocity becomes small in all directions, the continuity of mass equation requires that the solar wind is compressed, and increases substantially. Beyond 122 AU there are no solar wind measurements on V1, but it is reasonable to assume that however small, the solar wind continues to flow radially outward, since otherwise the solar wind density would increase without bound.

3. Prediction of when V1 will encounter another current sheet
In this section we present our prediction as to when V1 will encounter another current sheet crossing. Our prediction is based primarily on the radial dependence of the average radial component of the solar wind speed, $\langle u_r(r) \rangle$, for which no direct measurements exist on V1. We determine $\langle u_r(r) \rangle$ from several indirect measurements, which taken together highly constrain when V1 should encounter the next current sheet.
3.1. The average radial speed of the solar wind from 1 AU to ~113 AU

Starting at 1 AU, \( <u_r(r)> \) gradually decreases [17,18,19], due to the process of picking up recently ionized interstellar neutral gas, to a somewhat smaller value immediately upstream of the termination shock at \( r_s \), the distance at which the solar wind ram pressure (determined by the upstream speed) roughly balances the component of the pressure of the Local Interstellar Cloud (LIC) normal to the heliopause (e.g. [18]).

Upon crossing the termination shock at \( r_s \), \( <u_r(r)> \) decreases by the termination shock compression ratio, which is measured to be ~3 by both \( V_1 \) and \( V_2 \). The compression ratio will likely be somewhat lower at solar maximum (a lower upstream speed) and somewhat higher at solar minimum (a higher upstream speed).

Further downstream of \( r_s \), out to ~118 AU, \( <u_r(r)> \) can be reliably estimated from the LECP observations [9,10]. The radial component of the solar wind speed is inferred from anisotropy measurements of \( >40 \) keV ions and, as shown in figure 1, shows quasi-periodic variations, \( \delta u_r(t,r) \), with time of about \( \pm 20 \) km/s over distance scales of several AU around a decreasing value of \( <u_r(r)> \). Thus, \( V_1 \) measures \( <u_r(r)> \pm \delta u_r(t,r) \).

Note that \( <u_r(r)> \) decreases linearly in figure 1 to where the variations, \( \delta u_r(t,r) \), are larger than \( <u_r(r)> \), and can even result in negative radial solar wind flows. In this region, beyond ~113 AU, where the variations exceed the mean, we cannot use LECP observations directly and require another technique to infer \( <u_r(r)> \). For \( <u_r(r)> \) between 105 and 112.5 AU we can reliably use a linear fit to the LECP data.

![Figure 1. Variation of the average radial speed component, \( <u_r(r)> \), and the associated average number density, \( <n(r)> \), of the solar wind with heliocentric distance \( r \). The termination shock is at heliocentric distance \( r_s \), which depends on and will vary with the solar wind speed upstream of the shock. Equation (2), with \( n_{ts} \), the density just downstream to the termination shock, relates \( <n(r)> \) to \( <u_r(r)> \). A smooth variation of \( <u_r(r)> \) with \( r \) (no abrupt changes) is achieved using a cubic spline fit through point \( a \) just downstream of the TS, line segment \( b \) (the linear fit to the LECP data from 105 AU to 112.5 AU), point \( c \) at ~117 AU (in the prime acceleration region), points \( d, f, \) and \( g \) (speeds derived from plasma densities measured by Gurnett et al. [7]), and points \( h \) and \( k \) (speeds derived from Local Interstellar Medium densities). The speed at \( c \) is adjusted until the CS0 trajectory goes through point \( X* (r*,t*) \), shown in Figure 2 (bottom panel). The dashed, solid, and dotted curves correspond to values of \( n_{ts} \) of 0.005, 0.004, and 0.003 cm\(^{-3} \), respectively. The distance, \( r* \) and time \( t* \) of the last current sheet crossed by \( V_1 \) were reported and labeled CS0 by Burlaga et al. [3]. It is worth remarking that the solar wind is already highly compressed in the heliosheath, reaching a very high density at ~117 AU. At the heliocliff the density has a local minimum, about a factor of two below the Local Interstellar Medium density.](image-url)
3.2. The average radial speed of the solar wind from ~113 to 121.31 AU

As the current sheet responsible for the reversal in the magnetic field polarity is convected outward with the solar wind, it will encounter \( V_I \) twice. First, in the supersonic solar wind, where the current sheet is moving faster than \( V_I \), the current sheet overtakes \( V_I \) at time \( t \) and distance \( r \). Then, since \( \langle u_r(r) \rangle \) decreases with \( r \) (see figure 1) to values below the speed of \( V_I \) (~ 17 km/s), \( V_I \) will overtake the same current sheet at a later time \( t^* \) and further distance \( r^* \). Fitting the related current sheet crossings observed by \( V_I \) places strong constraints on the radial dependence of \( \langle u_r(r) \rangle \) and can be used to determine \( \langle u_r(r) \rangle \) in the region beyond 113 AU.

We use the last current sheet crossing observed by \( V_I \), labeled CS0 by Burlaga et al. [3], which occurred at \( t^*_{CS0} = 2012.57 \) and \( r^*_{CS0} = 121.31 \) AU. This is the current sheet crossing that occurred just before the ‘helioclip’, where there was a precipitous decrease in the ACRs. We have identified the first crossing of CS0, when it overtook \( V_I \), to have occurred on DOY 135 in 2000 (14 May 2000, \( t_{CS0} = 2000.367 \)) when \( V_I \) was at 77.48 AU. As can be seen in figure 2 (top panel), the first crossing occurred when the current sheet rotated through the latitude of \( V_I \) and the dominant polarity changed; a close examination of the daily averages of the magnetic field direction showed an abrupt change in direction at hour 19 of 14 May 2000 (http://vgrmag.gsfc.nasa.gov/data.html).

![Figure 2](image-url)

**Figure 2.** (top) Variations with time of the maximum extent of the tilt angle in the northern hemisphere [20] during a Carrington rotation (step curve) and the 28% weighted average of the azimuthal angle, \( \lambda \), (in the RTN coordinate system) of the magnetic field (dashed curve) observed by MAG on *Voyager 1*. The solid curve is the 5% weighted average of the step curve. The dotted curve is an extrapolation of the average azimuthal magnetic angle beyond 2009. The dominant polarity reverses when \( \lambda \) (dashed or dotted curve) crosses zero. This reversal should coincide with the rotation of the current sheet past 90° observed at 1 AU. It should be noted that estimates of large tilt angles have large uncertainties, making it difficult to find the exact time when rotation past 90° occurred. The times of the next current sheet crossing by \( V_I \) are indicated by the vertical lines labeled 10% (probability), 50% and 90%. (bottom) Trajectories of current sheet crossings CS0 (observed) and CS1 (predicted). Even though numerous current sheet crossings were observed by \( V_I \) from 1991 to 2012.57 (between points \( Y \) and \( X^* \)), none were seen after the CS0 crossing at \( X^* \). The most plausible explanation is that magnetic reconnection occurs beyond ~122 AU, where the solar wind speed is very small, as discussed in the text.
The trajectory (distance versus time) of CS0 is calculated using the following simple equation:

\[ t(r) = t_0 + \int_{r_0}^{r} \frac{dr}{u_r(r)}. \]  

(1)

We assume that the solar wind speed at 1 AU is 455 km/s, an appropriate solar maximum value, consistent with the 453 km/s speed measured by Ulysses at the V1 latitude at approximately the same time (2 December 1999) (http://omniweb.gsfc.nasa.gov/coho/). We assume that out to 112.5 AU \( \langle u_r(r) \rangle \) is determined as described in section 3.1. Then, by requiring that the trajectory must pass through both \( (t_{CS0}, r_{CS0}) \) and \( (t^*_{CS0}, r^*_{CS0}) \), we find a mean radial speed of \( \langle u_r(r) \rangle = 4.3 \) km/s in the region from ~113 to 121.31 AU. Note that this calculation is particularly sensitive to values of \( \langle u_r(r) \rangle \) between 113 and 121 AU since with this slow speed, the dwell time of the current sheet in this region is long.

It is unlikely that \( \langle u_r(r) \rangle \) is constant at 4.3 km/s from ~113 to 121.31 AU, since this would result in an abrupt change in \( \langle u_r(r) \rangle \) at ~113 AU. In subsequent calculations we will make the transition of \( \langle u_r(r) \rangle \) smooth across ~113 AU (see caption to figure 1). The trajectory of CS0 is shown in figure 2 (bottom panel). As required, it goes through points \( X(t_{CS0}, r_{CS0}) \) and \( X^*(t^*_{CS0}, r^*_{CS0}) \).

3.3. The average radial speed of the solar wind beyond 121.31 AU

Using observations of plasma oscillations, Gurnett et al. [7] report very accurate measurements of the plasma electron density during three short time intervals when V1 was at 122.155, 122.465 and 123.910 AU, respectively. The measured densities are shown in figure 1. The corresponding radial solar wind speed, assuming that the density, \( n \), measured by Gurnett et al. [7] is due to compressed solar wind, can be found from the continuity of mass equation,

\[ \langle u_r(r) \rangle = \frac{n_r r^2 u_r}{n(r) r^2}. \]  

(2)

In the model of Fisk and Gloeckler [11], the density of the solar wind at radial distances beyond where Gurnett et al. [7] observed is assumed to have a value equal to the interstellar density. The solar wind density is maintained at this value due to the nature of the heliopause and the pressure in the LIC. We take the solar wind density beyond ~124 AU to be constant at ~0.1 cm\(^{-3}\) [e.g. 18], in which case, in this region, \( \langle u_r(r) \rangle \) decreases as \( r^{-2} \).

3.4. The profile of the average radial speed of the solar wind

Taking the results of sections 3.1-3.3 together, and providing smooth transitions across the boundaries between the regions considered, yields the profile of the average radial speed of the solar wind shown in figure 1, out to 130 AU. The parameters used in determining this profile can be varied, but only within fairly narrow limits, as we consider below. Also shown in figure 1 is the density profile calculated from equation (2). Note that there is a region just inside the heliocliff where the density reaches a maximum. It is interesting to note that the density maximum occurs at the location of prime acceleration of ACRs, where they reach their maximum energies [2].

3.5. The prediction of when V1 will encounter the next current sheet

As discussed in section 3.2, current sheet CS0, which V1 observed at \( t^*_{CS0} = 2012.57 \) and \( r^*_{CS0} = 121.31 \) AU, was the same current sheet that overtook V1 about 12 years earlier at \( t_{CS0} = 2000.367 \) and \( r_{CS0} = 77.48 \) AU. It follows then that the next current sheet that V1 should encounter is the current sheet that overtook V1 during the previous change in the polarity of the solar magnetic field, which, as can be seen in figure 2 (top panel), occurred at \( t_{CS1} = 1990.996 \) when V1 was at \( r_{CS1} = 43.54 \) AU.

Using the date and location of this initial encounter of V1 with CS1, and the average radial speed of the solar wind in figure 1 (to which we can make small adjustments in the parameters, particularly in the density at the termination shock, \( n_r \)), we can estimate when V1 will next encounter CS1. A lower limit on when the encounter will occur is obtained by noting that V1 has not yet overtaken CS1, and
thus $t^*_{CS1} > ~2014.4$, which implies that $\langle u(r) \rangle$ at 122.155 AU is greater than $\sim 4.65$ km/s. This speed condition is satisfied with a solar wind density just downstream of the termination shock of $n_s = 0.003$ cm$^{-3}$, which is reasonable for solar maximum conditions. To estimate the upper limit on $\langle u(r) \rangle$ we take the solar wind density just downstream of the termination shock to be 0.005 cm$^{-3}$ which yields $\langle u(r) \rangle$ at 122.155 AU of 7.85 km/s. Finally, a density just downstream of the termination shock of 0.004 cm$^{-3}$ (a reasonable value for solar maximum conditions) yields $\langle u(r) \rangle$ at 122.155 AU of 6.13 km/s.

Shown in figure 2 (bottom panel) are three trajectories of CS1 with values for $n_s$ of 0.003, 0.004, and 0.005 cm$^{-3}$, the dashed, solid, and dotted curves, respectively. The times when the trajectories of $V1$ and CS1 cross are 2014.43, 2015.07, and 2015.87, respectively.

Based on our analysis, the probability of $V1$ overtaking CS1 on 26 January 2015, and 14 November 2015 is 50% and 90% respectively.

### 3.6. Future solar wind measurements by the Voyager 2 plasma instrument

In the Fisk & Gloeckler [11] model of the nose region of the heliosheath the flow of the solar wind is primarily in the radial and azimuthal directions. There is a centerline where the solar wind flow must split, streamlines going to the left and to the right of the centerline. $Voyager 1$ is relatively close to the centerline, but $V2$ is exploring the heliosheath further away from the centerline. With its working plasma instrument, solar wind parameters will be measured directly in the nose region of the heliosheath at distances comparable to those $V1$ has now traversed. It is interesting to anticipate what type of plasma $V2$ will see as it approaches and then passes the heliocliff boundary. In particular, we will likely have definitive information on whether or not the heliocliff is the heliopause.

![Figure 3](image.png)

**Figure 3.** Variations with $Voyager 2$ heliocentric distance of the RTN components of the bulk solar wind speed (top to bottom: $V_R$, $V_T$, and $V_N$). The pink curves are $V1$ estimates of the speed components [9,10,16] plotted at the $V1$ distance plus 15 AU. The plasma instrument should be able to measure the N (polar) and T (azimuthal) components of the solar wind, especially during the periodic roll maneuvers of the spacecraft. The radial speed component should be well measured up to ~125 AU at which point the radial speed will be comparable to the speed of $V2$. Beyond that only a portion of the distribution will be observable, making evaluation of the radial speed more problematic. See text for additional discussion. ($V2$ plasma data (blue curves) courtesy of John Richardson).

In figure 3 we show the likely variations (dashed red curves) of the three RTN components of the solar wind speed with the $V2$ heliocentric distance. Our estimates are based on three assumptions: (1)
the heliocliff boundary is blunt, which pushes the heliocliff out to ~137 AU in the V2 direction, (2) at a given heliocentric distance the azimuthal speed increases with the angle from the centerline, and (3) the interstellar medium takes control of the general trend of the speed as it decreases at an upstream distance of ~20 AU from the heliocliff, allowing us to use the V1 speed measurements in determining how the three components will decrease beyond ~117 AU in the V2 direction.

Measurements that are not available from V1 are the density and temperature or thermal speed of the solar wind in the various regions of the heliosheath. If we had such direct measurements on V1 we would not be debating whether or not V1 is now in interstellar space. We use estimates of pressure and density of the bulk solar wind, halo particles, pickup ions and ACR as a function of the V1 heliocentric distance to deduce variations of the solar wind density and its thermal speed with V2 distance. The results are summarized in figure 4. We anticipate that the bulk solar wind will be compressed (its density will increase) as it slows down, and its thermal speed (temperature) will start also to gradually increase beyond ~110 AU. Maximum density and temperature will be reached near the heliocliff. The sudden drop in temperature is the result of the disappearance of mobile particles, leaving only the dense solar wind.

![Figure 4. Variations with Voyager 2 heliocentric distance of the number density (top panel) and thermal speed (bottom panel) of the solar wind. The red dashed curves are predicted future measurements by the plasma instrument on V2. See text for additional discussion. (V2 plasma data (blue curves) courtesy of John Richardson).](image)

4. Concluding remarks
In this paper we have provided a test of whether V1 has crossed the heliopause or still remains in the heliosheath. If V1 remains in the heliosheath, the high density measurements of Gurnett et al. [7] must be due to compressed solar wind, which should result from a very slow outward radial flow speed, from which it is possible to predict that V1 will most likely encounter another current sheet crossing during 2015.

The approach taken in this paper, that it is possible to compress the solar wind, is based upon the detailed model of Fisk and Gloeckler [11]. In this model there is also a prediction that ACRs and GCRs will behave differently when the magnetic field polarity reverses. The model predicts that when the heliosheath magnetic field is oriented in the same general direction as the interstellar magnetic field, the two fields can merge beyond the heliopause, yielding easy escape of ACRs and easy entry of GCRs. This is apparently the case with the magnetic polarity that V1 is now observing. When the heliosheath magnetic field is oriented generally opposite to the interstellar magnetic field,
reconnection should occur beyond the heliopause, reconnection islands will form, and escape of the ACRs, and certainly entry of GCRs will be restricted.

Thus, if V1 encounters another current sheet, it will provide strong observation evidence that the heliopause has not yet been crossed. If the region beyond the current sheet, with opposite magnetic polarity, is accompanied by less escape of ACRs and restricted entry of GCRs, it will be strong observational evidence for the model of Fisk and Gloeckler [11].

Finally, we made predictions of what the V2 plasma instrument should be seeing as V2 approaches and passes the heliocliff. If these direct measurements of plasma parameters by Voyager 2 turn out to be as predicted in figures 3 and 4, then these observations will lend further credence to the heliosheath model of Fisk and Gloeckler [11].

Acknowledgments
This work was supported in part by NASA Grant NNX10AF23G and by NSF Grant AGS-1043012. We thank John Richardson for proving up-to-date Voyager 2 plasma data through their web address: http://web.mit.edu/space/www/voyager.html

References
[1] Krimigis S M, Decker R M, Roelof E C, Hill M E, Armstrong T P, Gloeckler G, Hamilton D C and Lanzeroit L J 2013 Search for the exit: Voyager 1 at Heliosphere’s border with the galaxy Sci. 341 144–147
[2] Stone, E C, Cummings A C, McDonald F B, Heikkila B C, Lal N and Webber W R 2013 Voyager 1 observes low-energy galactic cosmic rays in a region depleted of interstellar ions Sci 341 150–153
[3] Burlaga L F, Ness N F and Stone E C 2013 Magnetic field observations of Voyager 1 entered the heliosheath depletion region Sci. 341 147–150
[4] McComas D J, et al. 2009 Global observations of the interstellar interaction from the Interstellar Boundary Explorer (IBEX) Sci. 326 959–962
[5] McComas D J, et al. 2012 The first three years of IBEX observations and our evolving heliosphere Astrophys. J. Supp. 203 doi:10.1088/0067-0049/203/1/1
[6] Frisch,P C 2011 How local is the local interstellar magnetic field Physics of the Heliosphere: A 10 Year Retrospective (AIP Conf. Proc. vol. 1436) ed J Heerikhuisen et al. (New York: AIP) pp 295–301
[7] Gurnett D A, Kurth W S, Burlaga L F and Ness N F 2013 In situ observations of interstellar plasma with Voyager 1 Sci. 341 1489–1492
[8] Richardson J D 2008 Plasma temperature distributions in the heliosheath GRL 35 L23104 doi:10.1029/2008GL036168
[9] Krimigis S M, Roelof E C, Decker R B and Hill M E 2011 Zero outward flow velocity for plasma in a heliosheath transition layer Nature 474 359–361
[10] Decker R B, Krimigis S M, Roelof E C and Hill M E 2012 No meridional plasma flow in the heliosheath transition region Nature 489 124–127
[11] Fisk L A and Gloeckler G 2014 On whether or not Voyager 1 has crossed the heliopause Astrophys. J. 789 doi:10.1088/0004-637X/789/1/41
[12] Gloeckler G, Fisk L A, Mason G M, Roelof E C and Stone E C 2012 Analysis of suprathermal tails using hourly averaged proton velocity distributions at 1 AU Physics of the Heliosphere: A 10 Year Retrospective (AIP Conf. Proc. vol. 1436) ed J Heerikhuisen et al. (New York: AIP) pp 136-143
[13] Richardson J D 2008 Plasma temperature distributions in the heliosheath GRL 35 L23104 doi:10.1029/2008GL036168
[14] Gloeckler G and Fisk L A 2010 Proton velocity distributions in the inner heliosheath derived...
from energetic hydrogen atoms measured with Cassini and IBEX. *Pickup Ions Throughout the Heliosphere and Beyond* (AIP Conf. Proc. vol. 1302) ed J A le Roux et al. (New York: AIP) pp 110–116

[15] Fisk L A and Gloeckler G 2013 The global configuration of the heliosheath inferred from recent Voyager 1 observations *Astrophys. J.* **776** doi:10.1088/0004-637X/776/2/79

[16] Stone E C and Cummings A C 2011 Voyager observations in the heliosheath: A quasi-stagnation region beyond 113 AU *Proc. of the 32nd Intl. Cosmic Ray Conf.*. vol 12 (Beijing: IUPAP) p 29

[17] Richardson J D, Liu Y, Wang C and McComas D J 2008 Determining the LIC H density from the solar wind slowdown *Astron. Astrophys.* **491**(1) 1–5

[18] Gloeckler G, Fisk L A and Geiss J 1997 Anomalously small magnetic field in the local interstellar cloud *Nature* **386** 374–377

[19] Lee M A 1997 Effects of cosmic rays and interstellar gas on the dynamics of a wind *Cosmic Winds and the Heliosphere* ed J R Jokippi et al. (Tucson: University of Arizona Press) p 857

[20] Hoeksema J T 1995 The large-scale structure of the heliosheath current sheet during the Ulysses epoch *Space Sci. Revs.* **72** 137–148 [http://wso.stanford.edu/Tilts.html](http://wso.stanford.edu/Tilts.html)