# The Fisk & Gloeckler model for the nose region of the heliosheath: Another model for Ed Stone to test

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**Abstract**. Ed Stone has always been receptive to new ideas, including controversial ones, provided that the idea can be tested by observations. This paper will discuss the latest controversial idea for Ed to test: the Fisk & Gloeckler model for the nose region of the heliosheath, which concludes that *Voyager* 1 remains in the heliosphere and is not in the local interstellar medium, and that the nose region of the heliosheath is a very different place from what others have considered, and it can be argued, a more interesting place than others have imagined. The test of the model is that within this year, *Voyager* 1 should encounter another current sheet, due to the reversal of the magnetic field of the Sun, thereby establishing conclusively that *Voyager* 1 remains in the heliosphere. If/when the current sheet is crossed, it will be appropriate to extend the Fisk & Gloeckler model. A preview will be provided of these extensions and the interesting properties and physical properties that result for: (1) the region inside the *Heliocliff*; (2) the *Heliocliff*; (3) the region between the *Heliocliff* and the actual *Heliopause*; and (4) the *Heliopause*.

## 1. Introduction

Ed Stone has always been receptive to a new thought. That is a talent that in others can diminish with age. With Ed, however, the approach has always been the same. Give him something that he can test. How can he use his data to test your idea, however outlandish? That is the right partnership between theory and observation. Ed's talent for what is the proper scientific method should be a model for all of us, and for all generations of scientists.

With this attribute of Ed Stone in mind, this paper will present our latest controversial idea: that *Voyager 1* remains in the heliosheath and is not in the local interstellar medium. Thus, the nose region of the heliosheath is a very different place from what others have considered, and frankly, in our judgment, a more interesting place than others have imagined.

We do assume that Ed approves of our approach. We are putting forth a new and interesting model, and most important we have a definitive test of whether our model is correct. We can all let the data decide.

The model of Fisk & Gloeckler for the nose region of the heliosheath has been presented and published numerous times, including at previous meetings of this conference [1-5]. Thus, in this paper we will simply summarize the basic concepts of the model. Also, as is well known, the test of our model is that we predict that *Voyager 1* will encounter another current sheet, due to the magnetic field reversal of the Sun, within the next few months, and since changes in magnetic polarity are a feature of the solar magnetic field, not the local interstellar magnetic field, if this current sheet is observed, as predicted, we will establish that *Voyager 1* is still inside the *Heliopause*.

We have not been idle waiting for the current sheet crossing. Rather we have developed many other aspects and predictions of our model, which we will preview in this paper. You should conclude that if the current sheet is crossed, and our model for the nose region of the heliosheath is correct, there are numerous additional consequences, which will have to be fully developed, and we will have a treasure of interesting physics to talk about.

## 2. The basics of the Fisk & Gloeckler model

We begin by reviewing briefly the essence of our model for the nose region of the heliosheath, which is illustrated in Figure 1, a simplified version of the detailed calculations presented in Fisk and Gloeckler [1]. The model is based upon the observed solar wind flow, as determined from the particle anisotropy observations [6-8], which need to be used to determine the solar wind flow in the absence of a working plasma detector on *Voyager 1*. The solar wind flow is observed to be primarily in the radial and azimuthal directions, particularly with increasing distance into the heliosheath, and to become small in all directions as it approaches what we call the *Heliocliff,* where the ACRs are observed to escape [9,10]. The *Heliocliff* is the location the *Voyager* investigators consider to be the *Heliopause*.

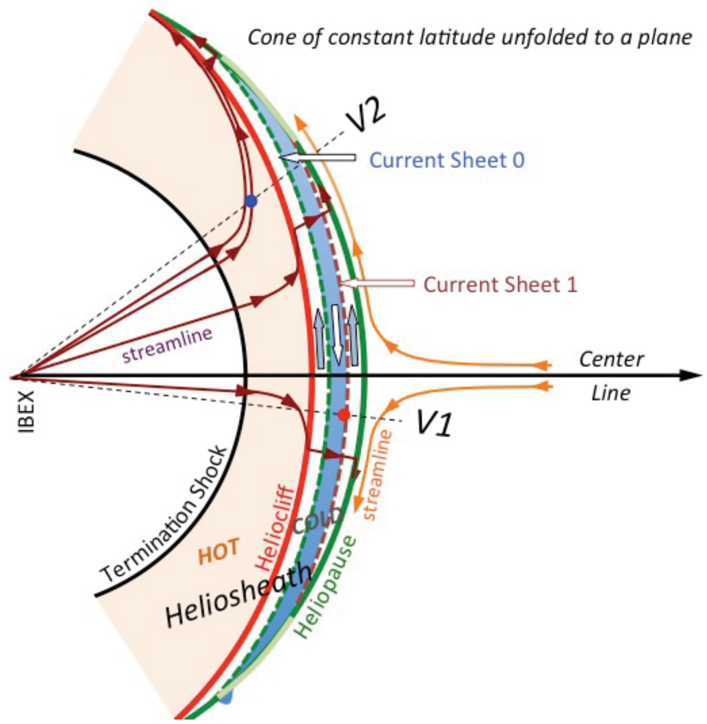


**Figure 1.** A schematics of the basic features of the Fisk & Gloeckler model for the nose region of the heliosheath (after Fisk and Gloeckler [1]).

As can be seen in Figure 1, the streamlines of the solar wind cross the termination shock, and then turn initially azimuthal, so the solar wind can flow out of the nose region of the heliosheath. The azimuthal flow creates a centerline region, which as is demonstrated in Fisk and Gloeckler [1] causes the flow speed to decrease. The azimuthal speed goes to zero first, and then the streamlines flow radially outward at a very low speed, across the *Heliocliff*, out to the actual *Heliopause*, which is beyond where *Voyager 1* is now located. The solar wind flows across the *Heliopause*, which is a rotational discontinuity.

The model naturally yields the so-called stagnation region, identified by the *Voyager 1* investigators (e.g. [11]), where the solar wind flow becomes very small. In this region, the solar wind is compressed and heated in our model. We refer to the region where the solar wind is compressed and heated as the *Hot Heliosheath*. Beyond the *Heliocliff*, where the solar wind and more energetic particles can escape across the actual *Heliopause*, the solar wind is cold and dense, and we call this the *Cold Heliosheath*. Gloeckler and Fisk [12] demonstrate that *Hot* and *Cold Heliosheaths* are necessary to explain the full spectrum of the *IBEX* ENA observations.

## 3. The *Hot Heliosheath*

As is discussed in detail in Fisk & Gloeckler [1], an essential feature of our model is that the pickup ions and ACRs, which are the mobile particles, are decoupled from the solar wind. The pressure in the pickup ions and ACRs is essentially constant, balancing the pressure of the local interstellar medium. If the pickup ions and ACRs are coupled to the solar wind, then the solar wind density must also be constant and cannot be compressed. However, if we decouple the pickup ions and ACRs from the solar wind, that constraint no longer applies, and the solar wind can be compressed, yielding the observed stagnation region and the *Hot Heliosheath*.

There is a known problem with the behavior of the magnetic field in the stagnation region, where the solar wind slows down in all directions, particularly in directions normal to the magnetic field. Even assuming a reasonable amount of reconnection, we should expect by Faraday's law that the magnetic field strength will increase dramatically. Yet it is observed by Burlaga and Ness [11] not to.

We can resolve this discrepancy by assuming that the pickup ions and ACRs are decoupled from the solar wind, thus providing corroborating evidence for the decoupling. If the pickup ions and ACRs are decoupled they can be considered mobile energetic particles, with a large pressure, little mass, and a ram pressure that can be ignored, and thus by using standard plasma physics, the pickup ions and ACRs create a current:

$$\mathbf{J}_{ep} = c\frac{\mathbf{B}\times\nabla_{\perp}P_{ep,\perp}}{B^2}\,. \tag{1}$$

Here, $\mathbf{B}$ is the magnetic field convected into the heliosheath across the termination shock; $P_{ep}$ is the pressure in the pickup ions and ACRs; $c$ is the speed of light.

The current in equation (1) is a magnetization current — the response of the pickup ions and ACRs to the application of **B**. The magnetization current creates a magnetic field that offsets the applied **B**-field and creates the observed magnetic field, which we refer to as **H**, which is standard notation in E&M textbooks. Thus, the current in equation (1), and **B** and **H** are related by

$$\frac{c}{4\pi}\nabla\times\mathbf{B} = \frac{c}{4\pi}\nabla\times\mathbf{H} + c\frac{\mathbf{B}\times\nabla_{\perp}P_{ep,\perp}}{B^2}\,. \tag{2}$$

Then, ignoring the curvature of the magnetic field, and noting from pressure equilibrium that

$$\nabla P_{ep,\perp} = -\nabla\left(H^2/8\pi\right), \tag{3}$$

we find that

$$\nabla H = \frac{\nabla B}{\left(1+H/B\right)}\,. \tag{4}$$

Note that the current in equation (1) is identical to the current of modulated galactic cosmic rays. In the cosmic ray case, the pressure in the cosmic rays is small, and thus this current is usually ignored. Also, the physics here is exactly the same as the physics of the ring current of the Earth. The ring current is a separate particle population with a current that alters the intrinsic magnetic field of the

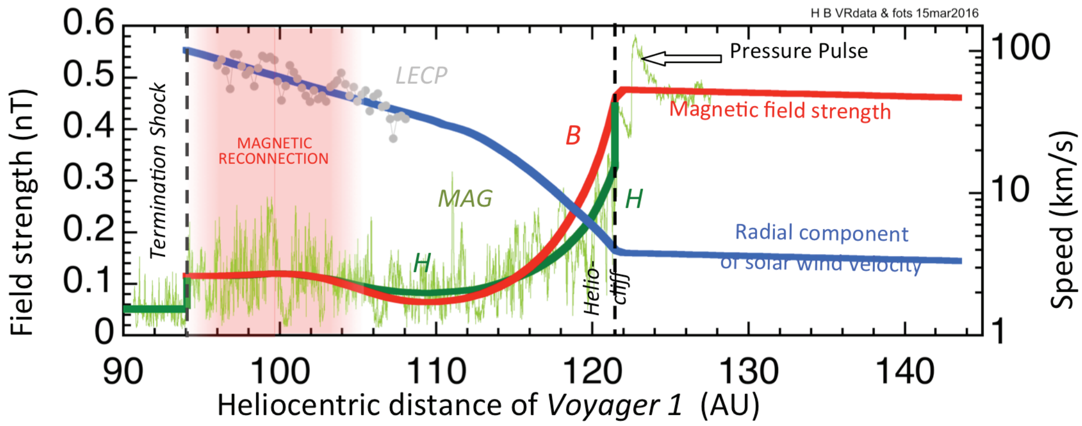


**Figure 2.** The underlying magnetic field that is convected into the *Hot Heliosheath* by the solar wind (B, shown in red), as determined from the observed magnetic field (H, shown in green). Also shown is the observed and predicted radial component of the solar wind velocity (shown in blue). See text for details.

Earth, just as the current in the pickup ions and ACRs alters the intrinsic, frozen-in magnetic field convected into the heliosheath with the solar wind.

We can then use equation (4) and the observed magnetic field $H$ in the *Hot Heliosheath* to determine the underlying value of $B$. Shown in Figure 2, in green, is the observed magnetic field, $H$, smoothed to remove short-period fluctuations. Then from equation (4), we determine $B$, shown in red. Note that the calculated $B$ is much larger than the observed $H$ in the stagnation region inside the *Heliocliff*, consistent with the expectation, from Faraday's Law, that $B$ should be larger than the observed field. Note also that $B=H$ beyond the *Heliocliff*. The pickup ions and ACRs escape beyond the *Heliocliff* and thus there is no magnetization current or difference between $B$ and $H$.

Finally, if we know the underlying solar wind magnetic field, which obeys Faraday's law, and use the data to make a reasonable assumption about the amount of reconnection, we can constrain the solar wind speed across the *Heliocliff*, and into the *Cold Heliosheath*, to around 5 $\text{kms}^{-1}$. This is the solar wind speed that we have used to estimate when the next current sheet should be observed by *Voyager 1* sometime this year.

It is worth emphasizing how many features of our model are interdependent and verifiable by observations. In order to create the *Hot Heliosheath*, the existence of which is verified by *IBEX* ENA observations [12], we need to decouple the pickup ions and ACRs from the solar wind, which permits us to explain the observations of the magnetic field magnitude in the *Hot Heliosheath* and to predict when the current sheet crossing should occur in the *Cold Heliosheath*.

## 4. The *Heliocliff*

Consider next the controlling physics of the *Heliocliff*, which can be seen in the simplified illustration of the nose region of the heliosheath in Figure 3. Immediately outside the *Heliocliff,* the magnetic field intersects the actual *Heliopause*, on the flanks, which provides for escape of the ACRs, and entry of GCRs, as is observed at the *Heliocliff*. In our model the entry of the GCRs is facilitated because the heliosheath magnetic field is oriented in approximately the general direction of the draped interstellar magnetic field. The fields merge and provide easy access to the GCRs. This should not be the case when we cross the next current sheet into a region of opposite magnetic polarity.

Consider a magnetic field line in the *Hot Heliosheath* just inside the *Heliocliff*. This field line remains in the heliosheath, executing the spiral pattern through the tail region of the heliosheath. This field line is then convected across the *Heliocliff*, and intersects the *Heliopause* on the flanks. Note, however, that in our model the *Heliocliff* is blunt. The bluntness results from the centerline region created by the diverging azimuthal flows illustrated in Figure 1. The bluntness is confirmed by the *IBEX* ENA observations [4].

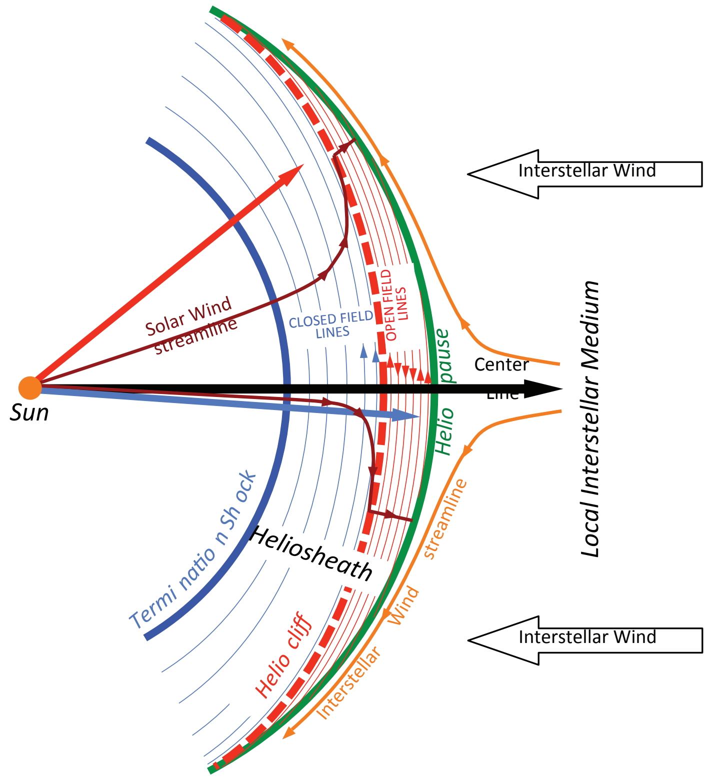


**Figure 3.** A simplified schematic of the nose region of the heliosheath.

Consider the length of a magnetic field line in the *Cold Heliosheath*, between its two *Heliopause* crossings. Because the *Heliocliff* is blunt, the length of the field line is rapidly reduced as the field line is convected outward with the radial flow speed of the solar wind. Since the density of the interstellar gas is larger than the initial density of the solar wind in the *Cold Heliosheath*, the shortening of the field line is the equivalent of a piston that rapidly compresses the density of the solar wind to equal the density of the interstellar medium.

The rapid increase in solar wind density will result in a rapid increase in the solar wind pressure. The mobile particles will perform their function of maintaining constant pressure by escaping across the *Heliopause*, to which the magnetic field is now attached. The pressure increase is rapid and the *Heliopause* is a long distance away, in which case only the higher energy mobile particles can reduce the pressure by escaping. Any particle previously considered a mobile particle, e.g., the pickup ions and ACRs, that cannot escape can no longer be considered a mobile particle that maintains pressure equilibrium. Since all the actual mobile particles escape, without the mobile particles, the observed magnetic field is simply the **B**-field of the solar wind, as seen in Figure 2.

## 5. The *Cold Heliosheath*

Now consider the *Cold Heliosheath*, which is bounded by the *Heliocliff* and the *Heliopause*. The higher energy particles, including the higher energy solar wind thermal particles, have escaped. The solar wind is compressed, but now cold, hence the term *Cold Heliosheath*. Also, the magnetic field is observed to be roughly constant, ignoring for the moment pressure waves, in which case the solar wind flow speed must decrease like $1/r$ from its estimated value at the *Heliocliff* out to the *Heliopause*.

The *Cold Heliosheath* is where *Voyager 1* should encounter the next current sheet resulting from the magnetic field reversal of the Sun, which, using the predicted solar wind velocity at the *Heliocliff*, should occur sometime in 2016. We can speculate on what conditions we will find in the region beyond the next current sheet.

In our model for the nose region of the heliosheath, mobile particles readily escape across the *Heliopause*, and GCRs readily enter when the heliosheath magnetic field is aligned with and merges with the interstellar magnetic field. This is the present situation observed by *Voyager 1*, which has been in a single sector since before crossing the *Heliocliff*; the mobile particles escape and the GCRs have entered. At the next current sheet crossing, the magnetic field will reverse direction, and thus it has been argued that the escape of the mobile particles and entry of GCRs will be restricted.

Consider what happened to the last current sheet when it crossed the *Heliocliff*, ~11 years ago. The same physical process should occur at the *Heliocliff* as with the sector *Voyager 1* is now in. There will be a compression of the solar wind along the magnetic field due to the blunt *Heliocliff* versus the spherical *Heliopause*, as described in the previous section, and the mobile particles need to escape in order that the pressure equals the interstellar pressure along the magnetic field lines, which now intersect the *Heliopause*. The escape may not be as easy as in the current sector, but will certainly have occurred by the time *Voyager 1* encounters the next current sheet. Thus, we should not expect to see ACRs at the next current sheet. What could be different, modified by the different escape, is the spectrum of the remaining particles that have not escaped. Also, the GCRs should not be as enhanced as they are in the current sector. Unlike the mobile particles, which simply have to escape across the *Heliopause*, for the GCRs to enter they need to penetrate through the region beyond the *Heliopause*, where there is reconnection and magnetic islands formed between the draped interstellar magnetic field and the oppositely directed heliosheath magnetic field.

Another interesting feature of the *Cold Heliosheath* is the striking lack of turbulence. Burlaga et al. [13] observe a very low level of compressive turbulence, much reduced compared to the compressive turbulence upstream of the *Heliocliff*. This reduction in compressive turbulence is to be expected because the *Cold Heliosheath* no longer contains mobile energetic particles, the pickup ions and ACRs that yield a magnetization current that determines the observed magnetic field (equations 1-4). In the *Hot Heliosheath*, the observed magnetic field, $H$, is determined by the perpendicular pressure of the mobile particles. The mobile particles are continuously attempting to maintain pressure isotropy, and pressure equilibrium along and across the magnetic field, i.e. the mobile particles are attempting to maintain pressure equilibrium both locally and remotely with one value for the pressure. Since the magnetic field does not have a uniform direction, but rather is entwined and random walking, pressure equilibrium on the scale of the entwining is not possible, and extensive compressive turbulence will result. In the *Cold Heliosheath*, the mobile particles are absent, and pressure equilibrium can be established locally, greatly reducing the compressive turbulence.

Another interesting feature of the *Cold Heliosheath* is pressure waves. Burlaga et al. [14] observe pressure waves beyond the *Heliocliff*; also in Burlaga et al. [13], the paper on turbulence beyond the *Heliocliff*, there is evidence of pressure waves. In some cases, these pressure waves are associated with the plasma waves observed by Gurnett et al. [15], which are observed preceding the pressure waves. Gurnett et al. and Burlaga et al. interpret the pressure wave as propagating into the interstellar medium (since they consider the *Heliocliff* to be the *Heliopause*), preceded by a shock, and thus the plasma waves are generated by electrons propagating upstream from a shock, as is observed in the supersonic solar wind.

Pressure waves can certainly propagate into the *Cold Heliosheath* of our model for the nose region of the heliosheath. Indeed, it is easier to propagate pressure waves into the *Cold Heliosheath* than into the interstellar medium since the solar wind flows outward in the *Cold Heliosheath* as opposed to the interstellar medium where the plasma flows inward.

A pressure wave in the *Cold Heliosheath* will be subject to pressure loss along the magnetic field, due to escaping mobile particles, just as in the underlying solar wind. Since most of the mobile particles have escaped, balancing the pressure in the underlying solar wind, the dissipation of the

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pressure wave will not be immediate, but should occur, reducing the outward speed of the pressure wave so that it basically moves with the outward radial speed of the solar wind. The loss of pressure along the magnetic field does not change the magnetic field, and a region of enhanced magnetic field, moving with the solar wind, is created in the *Cold Heliosheath*. *Voyager 1*, which is moving faster than the solar wind, will overtake the region of enhanced magnetic field, as opposed to the Burlaga et al. [14] interpretation that the wave overtakes *Voyager 1*.

The loss of pressure from the pressure wave is faster closer to the *Heliopause* than at the centerline in Figure 3, where *Voyager 1* is located. The disturbance thus moves faster along the centerline than it does closer to the flanks and develops a curved shape relative to the magnetic field direction, which is parallel to the *Heliocliff*. The magnetic field lines that *Voyager 1* observes in advance of the pressure wave thus intersect the pressure wave closer to the flanks. Mobile particles, in particular electrons, can propagate along the magnetic field lines that intersect the pressure wave, exciting the plasma waves observed by Gurnett et al. [15].

## 6. The *Heliopause*

The *Heliopause* is a rotational discontinuity at which the heliosheath magnetic field rotates and then merges or reconnects with the draped interstellar magnetic field. Thus, beyond the *Heliopause* there should be a turbulent boundary layer. Thus, we should know when we have crossed the actual *Heliopause*.

We can estimate the distance to the *Heliopause* by using our knowledge of the *Cold Heliosheath* and a property of a rotational discontinuity: it propagates relative to the plasma with a normal speed equal to the Alfven speed. Thus, the normal component of the escaping solar wind, $u_n$, must equal

$$u_n = \frac{B_n}{\sqrt{4\pi\rho_{\text{int}}}} . \tag{5}$$

Here, $B_n$ is the normal component of the magnetic field across the *Heliopause*, and $\rho_{\text{int}}$ is the mass density at the *Heliopause*, which is the interstellar mass density.

Referring to Figure 3, we can see that all of the magnetic flux in the *Cold Heliosheath* that passes through the centerline between the *Heliocliff* and the *Heliopause* must escape across the *Heliopause*. Thus, we can calculate the distance to the *Heliopause* by requiring that

$$B_{CH}\left(r_{hp} - r_{hc}\right) = \left(\sqrt{4\pi\rho_{\text{int}}}\right) u_n r_{hp} \Delta\phi . \tag{6}$$

Here, $B_{CH}$ is the magnetic field in the *Cold Heliosheath*; '*hp*' denotes *Heliopause*; '*hc*' denotes *Heliocliff*; and $\Delta\phi$ is the angle along the *Heliopause* on one side of the centerline, where the magnetic field escapes.

We take $B_{CH}$ to be the magnetic field at the *Heliocliff*, or 0.46 nT, and constant with radial distance. With a constant magnetic field, the product of the radial solar wind speed, and the radius is also constant, and thus we can evaluate $u_n r_{hp}$ at the *Heliocliff*, or $u_n r_{hp}$ =5.3 kms$^{-1}$*122 AU. We take $\Delta\phi$ to be 1 radian and the interstellar number density to be 0.08 cm$^{-3}$, in which case equation (6) becomes

$$r_{hp} = 122 + \frac{1}{.46}(0.013)(5.3)(122) = 140 \text{ AU} . \tag{7}$$

It should be noted that *Voyager 1* will cross a *Heliopause* at 140 AU within the next two years.

## 7. Concluding remarks

In summary, there are several conclusions to draw from this paper: The Fisk & Gloeckler model is a comprehensive model for the nose region of the heliosheath. It provides explanations for the governing physics of the *Hot Heliosheath*, the *Heliocliff*, the *Cold Heliosheath*, and the *Heliopause*. The various features of the model are interdependent and verifiable by observations. In some cases, the explanations contained in the model need further development to be sure they are correct. In all cases the model describes a heliosheath that is a very different place from what others have considered, and it can be argued, a more interesting place than others have imagined.

Thus, if we can establish through observations of the upcoming current sheet that *Voyager 1* has not crossed the *Heliopause*, and is still in the *Cold Heliosheath*, and that the *Heliopause* still lies ahead, we will have a treasure of interesting physics to talk about. We will have made one of the most interesting and profound discoveries of the space program. All brought to you by *Voyager*, the mission that Ed Stone has so ably led these many years.

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