Voyager observations of the magnetic field in the heliosheath and the local interstellar medium

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Abstract. This paper reviews observations of the magnetic field \( B \) in the heliosheath by Voyager 1 (V1) and Voyager 2 (V2) and the recent observations of the LISM by V1. The heliosheath is the region between the termination shock (TS) and the heliopause (HP). The TS was identified by both V1 and V2, and the internal structure of the TS was determined by V2. The radial distance of the TS was 94 AU at V1 and 84 AU at V2, suggesting a global asymmetry of the heliosphere. The average direction of \( B \) in the heliosheath is that of the Parker spiral magnetic field, and non-periodic magnetic sectors were observed by V1 and V2. The heliosheath is disturbed and turbulent, particularly just behind the TS, and it is described by the multifractal spectrum, the \( q \)-correlation function and the \( q \)-Gaussian distribution. The multifractal spectrum in the heliosheath also varies with the solar cycle. Voyager 1 has been in the LISM since at least August 25, 2012, but the nature of the HP and the time of the HP crossing not been determined. The magnetic field direction is close to, but distinguishable from the Parker spiral magnetic field, and its departure from the Parker spiral magnetic field is slowly increasing with distance from the sun. A large pressure pulse and two shocks or pressure waves have been identified in the LISM, presumably generated inside the heliosphere and transmitted through the heliosheath and heliopause. The interstellar magnetic field lines are draped across the heliopause, and \( B \) is approximately 0.5 nT. The fluctuations of \( B \) are very small but turbulent on scales 1 day to 468 days, with a Kolmogorov spectrum and an injection scale of approximately 10 pc.

1. Introduction
This paper discusses the magnetic field observations of the heliosheath observed by Voyager 1 (V1) and Voyager 2 (V2) and the recent observations of the interstellar magnetic fields originating in the local interstellar medium (LISM). Earlier reviews of the heliosheath and its interaction with the LISM were published by Seuss [1990], Axford [1990] and Zank [1999]. A recent comprehensive discussion of this topic is given by Zank [2015].

Voyager 1 is currently observing interstellar magnetic fields that are disturbed by the interaction between the heliosphere and the LISM in a region that may extend tens of AU beyond the current position of V1. Although the term LISM is used in many of the papers discussing observations and corresponding theories of the interstellar magnetic fields observed by V1, it is becoming
increasingly clear that one must distinguish between 1) the LISM referred to in astronomical literature on the local Galactic magnetic field [Frisch et al. 2011] and 2) the interaction region between the LISM and the heliosheath on the other. If there is a bow shock in front of the heliosphere this disturbed region could be called the “outer heliosheath”. However, McComas et al. [2012] conclude that a bow shock does not exist, and a number of authors refer to the interaction region as the “Very Local Interstellar Medium” (VLISM). In either case, the interstellar magnetic field is draped across the heliosphere and compressed by the interaction, and the LISM is disturbed by shock waves (and possibly other disturbances) produced by the sun and solar wind. This paper uses the term LISM for both the disturbed region near the heliopause and the distant undisturbed region. The magnetic fields and plasmas that are discussed in this brief overview are those observed by V1 and V2 in the heliosheath and by V1 in the LISM.

It is not universally accepted that V1 has entered the LISM. Fisk and Gloeckler [2014] suggests that the current data are consistent with V1 still being in the heliosheath, based on a model that they developed. In this model, the properties of the outermost region of the heliosheath are distinctly different from the properties described by the observations of the heliosheath discussed in this paper. In the model of Fisk and Gloeckler [2014], the high densities that are inferred from electron plasma oscillations at the largest distances that V1 has explored are considered to be a property of the inner heliosheath, and the strong magnetic fields that are currently observed are solar magnetic fields that result from a diamagnetic effect. Their model predicts that a sector boundary crossing will be observed during 2015 [Gloeckler and Fisk, 2014].

This paper shows that the magnetic field observations made by V1 since mid-2012 are consistent with the known properties of the interstellar medium and current models of the draping of the interstellar magnetic field about the heliosphere as it moves through the LISM.

2. Heliosheath
The supersonic solar wind emanating from the sun terminates at the termination shock (TS), which is the inner boundary of the heliosheath. At least five crossings of the TS were observed by Voyager 2 [Burlaga et al. 2008, Krimigis et al. 2008, and Stone et al. 2008], but only one crossing had a

![Termination Shock 3; Voyager 2](Image)

**Figure 1.** The third crossing of the termination shock by Voyager 2. The magnetic field strength $B$, the azimuthal angle $\lambda$, and the elevation angle $\delta$ are shown in the top three panels, and the radial component of the solar wind velocity $V_r$ is shown in the lowest panel.
relatively simple structure. The others were complex, because the shock was forming and dissipating on a scale of the order of a few days. Voyager 1 crossed the termination shock [Burlaga et al. 2005, Krimigis et al. 2005, and Stone et al. 2005] did not observe it because V1 moved past the TS during a data gap. Figure 1 shows the termination shock as observed by V2 during 2007. This is a classic supercritical perpendicular shock with a foot, a ramp in which most of the dissipation occurs, an overshoot, and undershoot [Mellott 1985]. The direction of the magnetic field $\mathbf{B}$ changed very little across the shock.

![Termination shock 3; Voyager 2](image)

Figure 2 shows a high-resolution view of the third crossing of the termination shock by V2, showing the foot, ramp, and overshoot. The ramp contains quasi-periodic fluctuations in $\mathbf{B}$ with a period of 12.6 seconds, corresponding to a wavelength of approximately 1000 km. The ramp moved past V2 in 90 seconds corresponding to a length scale of approximately 7000 km, which is the ion inertial length $c/\omega_p$, where $c$ is the speed of light and $\omega_p$ is the proton gyro-frequency.

An overview of the magnetic field observations in the heliosheath is shown in Figure 3. V1 was in the heliosheath from the time that it crossed the TS [Burlaga et al., 2005 Krimigis et al. 2004, Stone et al. 2015] to the time that it crossed the heliopause (sometime in the middle of 2012), implying that V1 was in the heliosheath for approximately 7.5 years. The magnetic field strength behind the TS was 2-3 times that in the supersonic solar wind prior to the TS crossing. During the first three years after crossing the TS, $\mathbf{B}$ fluctuated around a constant value, because the tendency for $\mathbf{B}$ to decrease with increasing distance was balanced by the tendency for $\mathbf{B}$ to increase with increasing solar activity. As solar activity declined, $\mathbf{B}$ decreased and declined until the historically low values were observed at solar minimum, which occurred during 2010-2011 at 1 AU. The magnetic field strength began to increase in 2011 at V1, partly because of the increasing solar activity but also because of the declining solar wind speed observed by Krimigis et al. [2013] between late 2010 and 2012.

Voyager 1 entered the heliosheath in December, 2004. The transition from the heliosheath to the local interstellar medium during 2014 is complex [Burlaga & Ness 2014a]. There does not appear to be a single “discontinuous” change in the magnetic field that can be identified as the heliopause. There is a growing number of theoretical papers that attempt to describe the nature of the transition (e.g., Swisdack et al. [2013], and Strumik 2013, 2014]). Based on the magnetic field and energetic particle observations, it appears that V1 was observing the LISM during 2012 shortly after it crossed a current sheet CS0 that looks like a sector boundary. After crossing this current sheet, the magnetic field differed from the Parker spiral direction by about 20° in the elevation and azimuthal angles as predicted by Pogorelov et al. [2009] as a consequence of the draping of magnetic field lines across the
heliopause. The magnetic field strength at this time was larger than observed anywhere in the heliosheath, and the magnetic strength fluctuations were very small.

The cosmic ray intensity increased as V1 moved through the heliosheath toward the source of the cosmic rays (Figure 3d), and then it showed a 2-step structure which is not understood [Webber and McDonald 2013]. The cosmic ray counting rate reached a plateau on August 25, 2012, after which V1 appears to be observing particles and fields in the LISM, as discussed below.

**Figure 3.** An overview of the magnetic fields and cosmic rays observed by Voyager 1 in the heliosheath. Panel (a) shows the magnetic field strength profile, while (b) and (c) are the azimuthal angle $\lambda$ and elevation angle $\delta$, respectively. The termination shock, the sunward boundary of the heliosheath, is labelled “T”. Panel (d) shows the profile of the >70 MeV/nucleon cosmic rays.

Large-scale features called “GMIRs” are observed in the heliosheath on a scale of one year, particularly near solar maximum [Burlaga, Ness & McDonald 1993]. GMIR’s are observed in the supersonic solar wind beyond approximately 15 AU and in the heliosheath. A GMIR in the supersonic solar wind can be preceded by a strong shock, which results from the coalescence of many forward shocks produced by solar activity [Burlaga et al. 2003]. An example of a GMIR produced in the heliosheath observed by V2 is shown in Figure 4 [Burlaga et al. 2011] In this case, the magnetic field strength in the GMIR is twice that in the ambient heliosheath, and it moved past V2 during an interval of 40 days. There is an indication that the GMIR was preceded by a fast-forward shock, but this occurred in a data gap. The strong magnetic fields produced a depression in the cosmic ray intensity, shown in Figure 4b, which is followed by a recovery during the next 200 days. Such a cosmic ray profile is called a long-lasting Forbush decrease. The red curve and Figure 4b is derived from the CR-B relation [Burlaga et al. 2011] that has been observed in the heliosphere that distances greater than or equal to 10 AU.

Burlaga et al. [1993] found that long-lasting Forbush decreases were associated with sustained enhanced solar activity for 1-3 solar rotations which introduce strong fields carried by coronal mass ejection and magnetic clouds as well as shocks associated with faster streams associated with these ejecta Burlaga et al. [2003] showed that such activity could produce organized structures (expanding shells of disturbed magnetic fields and shocks) in the heliosphere at approximately 15 AU.
characterized by an interval of strong magnetic fields moving past V1 and V2 for 1-3 solar rotations, and persisting out to at least 90 AU.

\[\text{Figure 4. A GMIR observed by Voyager 2 during 2006. The GMIR may have been preceded by a shock wave. The strong magnetic fields in the GMIR produced a depression in the cosmic ray counting rate, after which the cosmic ray intensity recovered in about 200 days, giving a long-lasting Forbush decrease.}\]

The upper left panel in Figure 5 shows typical spiral magnetic field the Parker field which is observed during declining solar activity when the predominant structures are corotating streams near solar maximum. There are times when the sun becomes particularly active for at least a solar rotation

\[\text{Figure 5. Schematic illustrating the formation and evolution of a Global Merged Interaction Region (GMIR).}\]
or even up to three solar rotations. During this time one observes a number of flares and erupting filaments. The associated coronal mass ejecta and magnetic fields move away from the sun carrying strong magnetic fields with them, as indicated by the shaded circle. This system of transient flows is observed continuously for a few solar rotations and then the activity dies off and a shell containing strong disordered magnetic fields is carried away from the sun to larger distances. Such shells were discussed many years ago in the context of cosmic ray modulation. The shells were originally thought to be shells of enhanced turbulence which produce decreases in the cosmic ray intensity on a time scale of a few solar rotations, but B is the primary factor, as shown in Figure 4.

On smaller scales smaller scales (from 1 to approximately 25 days) three types of features, associated with the multifractal structure of the magnetic field in the heliosheath, are observed throughout the heliosheath. These features are illustrated in Figure 6.

![Heliosheath: V2, 2010 (1 – 20 day scales): q-triplet](image)

The top left panel is a plot of increments of daily averages of B. The distribution of these daily increments of B is shown in the top-right panel. The core of the distribution is Gaussian, but the tail is significantly different from a Gaussian distribution. The curve in this figure is a fit to the data to a q-Gaussian distribution. The q-Gaussian distribution appears in a generalized central limit theorem [Umarov, 2009, 2008]. This distribution is known in non-extensive statistical mechanics as the Tsallis distribution [Tsallis 1988, 2004, 2009], which is derived from an entropy principle, and it appears as one form of the distributions used to fit the observations of nonthermal particle distributions in space physics. The width of the q-distribution is characterized by a number that Tsallis calls $q_{stat}$. This number would be equal to 1 if the distribution were Gaussian. However, the observed value in the heliosheath is $q_{stat} = 1.6$, indicating these fluctuations are significantly different than Gaussian distributions. The q-Gaussian distributions of increments of B or a general feature of the fluctuations in the heliosheath [e.g. Burlaga et al. 2006d,e, Burlaga et al. 2007, Burlaga and Ness 2009, Burlaga, Ness and Acuña 2009 d, and Burlaga and Ness, 2012a]

A second feature of the fluctuations in the heliosheath on scales from 1 to 25 days is more difficult to explain. It is associated with the multifractal structure of the fluctuations [see Burlaga, 1995]. The lower left panel of Figure 6 shows what is called “the multifractal distribution function”. The multifractal distribution function would be a delta function for a Kolmogorov spectrum.
associated with turbulence. However there are jumps and filaments in the magnetic field strength profile (See Figure 3) which give rise to a multifractal distribution. One way to think of this is to think of a power law distribution as associated with a structure function with an exponent to corresponding to a fractal or a straight line with a certain slope. One can generalize that concept by considering generalized structure functions with exponents different from 2, greater than less than 2. These correspond to increasing the width of the multifractal distribution. The multifractal distribution function gives a number called “\(q_{\text{stat}}\)”, which is related to the difference between the maximum and minimum value of the parameter \(\alpha\) [Tsallis 2004 ]. A multifractal distribution has been observed in the Heliosphere and during by every year that Voyager 1 has been in the heliosheath [e.g., Burlaga et al. [2006], Burlaga and Ness 2012 a, Burlaga & Ness 2013]. These observations were confirmed by Macek [2012, 2013 ], who also showed that the is the multifractality measure varies with the solar cycle.

A third feature describing the fluctuations in the heliosheath is the correlation function. The lower right panel in Figure 6 shows that the correlation function from V2 during 2010 was a power law, as opposed to the exponential correlation functions that are commonly observed in the laboratory. From the slope of the correlation function of this plot one can derive another parameter “\(q_{\text{rel}}\)” called the q- relaxation parameter. For the observations by V2 during 2010, \(q_{\text{rel}} = 3.9\), indicating long non-Gaussian tails on the distribution. Similar structures have been seen every year by V1 and V2 in the heliosheath and in the solar wind. The universality of these structures appears to be associated with the non-extensive statistical mechanics that governs the solar wind and heliosheath.

The familiar Boltzmann-Gibbs statistical mechanics deals with equilibrium systems that are usually closed boxes in which the phase space is uniform, there are no correlations, and the distribution functions are Gaussian. Tsallis non-extensive statistical mechanics was designed to describe quasi-stationary or metastable systems that are open, have a hierarchical structure which is described by a multifractal phase space, and contain correlations. Gell-Mann and Tsallis proposed that the \(q_{\text{sen}} < 1 < q_{\text{stat}} \leq q_{\text{rel}}\) [Tsallis 2009] This relationship is found in the observations shown in Figure 6, where the numbers are \(q_{\text{sen}} = -0.6 < 1 < q_{\text{stat}} = 1.6 \leq q_{\text{rel}} = 3.9\). Essentially the same numbers are obtained in the supersonic solar wind. In fact, this relationship for the q-triplet was first demonstrated using V1 solar wind data [Burlaga & Viñas, 2005, and confirmed by Burlaga and Ness 2013].

### 3. Transition between the heliosheath and the LISM

We now consider another topic, the transition between the heliosheath and the region of the local interstellar medium that is disturbed by the interaction between the LISM and the heliosphere. During
2012 there was great excitement in the energetic particle community based on the observations of cosmic rays [Stone et al., 2013] and energetic particles >0.5 MeV/nuc shown in Figure 7 [Krimigis et al., 2013]. Note the dropouts in >0.5 MeV/nuc particles on day 210 and near day 230 and the corresponding recoveries on day 226 and day 238. It was widely thought that these dropouts and recoveries corresponded to crossings of the heliopause, which implies that there were five crossings of the heliopause into and out of the LISM. Later, it was confirmed that there was an increase (decrease) in the magnetic field strength corresponding to each dropout (recovery) in the energetic particles [Burlaga et al., 2013], as shown in Figure 7.

There is a problem with interpreting these dropouts as crossings of the heliopause and entry into the LISM. The solar magnetic field is generated in the sun, and the solar wind magnetic field has a spiral geometry owing to the rotation of the sun and the convection of the magnetic field by the radially following plasma [Parker 1958, 1963]. The interstellar magnetic field on the other is produced by supernovae [Ferriere 1992] and the galactic dynamo [Parker 1971a, b]. One expects the magnetic field direction to change at the heliopause. However this is not what is seen in the observations shown in Figure 7. Neither $\lambda$ nor $\delta$ have any of the discontinuities, except perhaps one that might be that is obscured by noise. The change in the direction in the magnetic field across the discontinuities is < 2°, which is essentially no change that can be detected by the magnetometer. Thus, it is very unlikely that these discontinuities represent crossings of the heliopause.

The magnetic polarity that has been observed by V1 until at least day 271, 2014 was first observed when V1 crossed a current sheet labelled CS0 in Figure 7. The direction of B rotated within CS0 during the interval from approximately day 207.2271 - 209.7087, 2012. Burlaga & Ness [2014a] examined the boundary associated with CS0 whose normal n is given by the elevation angle $\delta = 23.9^\circ$ and the azimuthal angle $\lambda = 177.1^\circ$. They analyzed the structure of this rotation using the minimum

![Figure 7](image_url)
variance method, and found that minimum variance direction was \( \mathbf{n} = (-0.91, 0.05, 0.415) \) in the RTN coordinate system whose origin is at V1. The observed value of the component of \( \mathbf{B} \) in the minimum variance direction is \( < B_{\text{min}} > = 0.095 \) nT with a standard deviation of 0.057 nT. The current sheet is consistent with a tangential discontinuity within the uncertainties, although we cannot exclude a nonzero component. The minimum variance analysis of the current sheet CS that the minimum variance plane is inclined by an angle \( \theta = 100.6^\circ \) with respect to the solar equatorial plane. The projection of a plane with the normal \( \mathbf{n} \) on a meridional plane passing through the position of V1 at the time that CS0 was observed is shown in Figure 8. This figure has been interpreted as indicating that CS0 is the heliopause. However, two other current sheets (the one prior to CS0 in Figure 7, and another earlier) have been observed with a similar orientation, so that the orientation of the current sheet is not necessarily unique to the heliopause. We regard the nature and location of the heliopause as undetermined and a subject of current research.

There are several theoretical models of the transition between the heliosheath and LISM. Swisdack [2013] and Strumik [2013, 2014] suggested that CS0 is the site of magnetic reconnection which produces magnetic islands, giving rise to a broad and complicated heliopause structure. Indeed, CS0 and the sector boundary before it have a form of a “D-sheet” that Burlaga et al. [1968a,b] suggested might be a site of magnetic reconnection. Smaller events in the solar wind plasma and magnetic field with the same characteristics as a signature as a D-sheets were identified by Gosling [2007] as magnetic reconnection signatures. Opher and Drake [2012, 2013] suggested that magnetic reconnection commonly occurs within the heliosheath. Krimigis et al. [2013] proposed that an interchange instability occurs at the heliopause, allowing interstellar magnetic flux tube to enter the heliosheath. Florinski et al. [2015] suggested that such an instability can account for the dropouts discussed in reference to Figure 7. Liewer [1995] and Zank [1995] suggested that a Rayleigh-Taylor

Figure 8. Schematic of the heliopause interacting with interstellar plasma flow. The tangent to the heliopause at the position of V1 is qualitatively consistent with the orientation of CS0.
Figure 9. One frame from the model of Borovikov and Pogorelov [2014] showing the result of an instability on the heliopause as a result of the Rayleigh-Taylor instability and possibly also the Kelvin Helmholtz instability. The white line in the figure illustrates a hypothetical Voyager 1 trajectory which passes through three regions of strong magnetic fields which could correspond to the dropouts and >0.5 MeV/nuc particles shown in Figure 7.

4. Observations in the LISM.

Strong magnetic fields (>0.4 nT to 0.6 nT) were first observed shortly after the passage of CS0, during the first dropout in >0.5 MeV/nuc particles. They were observed again in association with the second dropout of energetic particles, and they have been observed continually since August 25, 2012 [Burlaga and Ness 2014a; Burlaga and Ness 2014b, Burlaga et al. 2015]. The counting rate of cosmic rays reached a plateau at the expected interstellar value [Stone et al. 2013, Krimigis et al. 2013] as shown in Figure 3. The plasma density reached 0.06 nT, which is characteristic of interstellar values, in October-November, 2012 [Gurnett at al, 2013]. Thus, it appears that V1 has been in the LISM since at least August 25, 2012.

Figure 10 shows observations of the magnetic field observed in the LISM from 2012.65 2 2014.74 [Burlaga and Ness, 2014b]. We shall show that these magnetic field observations throughout this interval, as well as plasma observations observed within the interval, indicate that that V1 is in the LISM, measuring interstellar magnetic fields that are draped across the heliopause and are compressed by the interaction of the heliosphere with the ambient LISM.
Let us first consider the direction of the magnetic field. The most obvious thing is there are no sector boundaries during this two-year interval, which suggests that V1 was not in the heliosheath. A remarkable feature, which has not been observed in the heliosheath, is the steadiness of the magnetic field direction during the entire interval; there are no visible fluctuations in Figure 10. A third important feature is that the average azimuthal angle $\lambda$ and the average elevation angle $\delta$ are very nearly constant throughout most of the interval, indicated by the red lines in Figure, namely $<\lambda> = 293.0^\circ \pm 1.5^\circ$ and $<\delta> = 21.5^\circ \pm 1.5^\circ$, respectively. These angles are about 21° and 23° from the Parker spiral direction within the uncertainty of ± 1.5°. These numbers were actually predicted as a consequence of magnetic draping by Pogorelov et al. [2009] before these observations were made. These directions are consistent with a interstellar magnetic field that passes through the center of the ribbon observed by IBEX [Grygorczuk et al. 2014]. The ecliptic longitude and latitude ($\lambda$, $\beta$) of the interstellar magnetic field is (221.9°, 38.4°).

Figure 10 shows that the average magnetic field strength B is 0.5 nT, and it ranges from 0.4 nT to 0.6 nT. YC Whang’s model [2010] of the draping of interstellar magnetic field lines across the heliopause predicts that the interstellar magnetic field strength at the nose of the heliopause should be 1.6 times the strength of the interstellar magnetic field at “infinity”. This implies an interstellar magnetic field strength about 0.3 nT or 3 micro-Gauss, which is consistent values for the interstellar magnetic field that are often quoted in the literature.

Compelling evidence that V1 was in the LISM during the interval shown in Figure 11 was published by Gurnett et al. [2015] based on observations from the plasma wave experiment on V1. These observations are shown in Figure 9, which shows three episodes plasma observations as a function of time. The ordinate is the frequency of these fluctuations, which is related to the ambient density of the plasma which is plotted on the ordinate on the right-hand side of Figure 9. From these data, density is found to vary between 0.06 cm$^{-3}$ and 0.11 cm$^{-3}$. These densities are characteristic of the interstellar medium and are at least 50 times greater than the densities of the heliosheath described above. On the other hand, Fisk & Gloeckler [2014 ] constructed a model that gives such densities for
the distant heliosheath. The model predicts that V1 will cross a sector boundary during 2015 (Gloeckler and Fisk 2014).

Now let us consider the jumps in B labeled “FS” in Figure 10a. Figure 12 from Burlaga et al. [2013a] shows the first jump in B which is associated with electron plasma oscillations observed by Gurnett et al [2013] during 2012. Gurnett found electron plasma oscillations beginning on day 290 and ending on approximately day 320, 2012, which corresponds to the jump in B. These observations are consistent with the widely accepted view that electron plasma oscillations are accelerated a beam of particles produced by a bump on tail instability [Filbert and Kellogg 1979, Fitzenreiter et al., 1984, Gurnett 1982] generated at the electronic foreshock boundary of a shock wave. There was a small to change in the direction (a few degrees) across this jump, consistent with a present perpendicular shock. By means of the co-polarity theorem Burlaga et al. [2013a] calculated the shock normal.

Figure 11. Observations of three bursts of electron plasma oscillations by Voyager 1 between mid-2012 and 2015.0. The densities inferred from these oscillations are shown on the ordinate of the right side of the figure. These densities are characteristic of interstellar densities reported in the astrophysical literature.
which is about 27° from the radial direction. The angle between the upstream magnetic field direction and the shock normal is 85°, indicating that the shock is quasi-perpendicular. The jump in $B$ at the shock is relatively small, 1.4, indicating a relatively weak shock. The upstream density was measured by the plasma oscillations to be 0.06 $\text{cm}^{-3}$ from which one calculates an Alfvén speed $V_A = 38 \text{ km/s}$. Assuming an interstellar temperature of 27,000° near the heliopause, one obtains a sound speed of $V_s = 17 \text{ km/s}$, so that the medium is magnetically dominated $(V_A/V_s)^2 = 5)$. The corresponding magnetoacoustic speed is 40 km/s, indicating that if the jump is associated with a shock, then the shock is propagating at greater than 40 km/s. Such shock speeds have been calculated by Whang and Burlaga [1994] and Washimi [2011]. There is no internal structure of the shock, indicating that it is a laminar shock, in contrast to the highly structured supercritical termination shock discussed in relation to Figures 1 and 2. The thickness of this interstellar shock is very large ($>10^9 \text{ c}/\omega_p$ or $>1000 \text{ ion inertial lengths}$) compared to that of the termination shock, whose thickness was of the order of several ion inertial lengths. The reason for the large difference in thickness is not known, but it may be related to the fact that the interstellar shock in Figure 12 is a resistive, laminar shock in a medium in which the interstellar pickup protons contribute the dominant pressure.

Gurnett et al. [1993] observed radio waves when V1 was in the supersonic solar wind, and they proposed that the radio waves were generated by a shock located beyond the heliopause, in the LISM, by mode conversion of the electron plasma oscillations upstream of the shock. Shortly afterward, Whang & Burlaga [1994] used V2 observations of a strong GMIR shock generated in the supersonic solar wind (similar to that indicated in Figure 4) as input to a calculation based on the method of characteristics. They found that the GMIR shock could propagate through the heliosheath and into the LISM. This process is illustrated in Figure 13, where the trajectory of the shock was computed by the method of characteristics. The panel on the left of Figure 13 shows the termination shock moving slowly inward from 70 AU and the heliopause at 100 AU. We now know that these initial conditions incorrect, but they serve to illustrate the basic process. The GMIR shock enters from the lower left and propagates outward through the heliosheath until it encounters the termination shock, whereupon it decelerates but continues to move outward to the heliopause. The termination shock,
shock becomes weaker as a result of the interaction, and it moves slowly outward. When the GMIR shock interacts with the heliopause, it is transmitted into the LISM as a weak slowly moving shock.

An inward propagating reverse shock is also generated during this process, and the heliopause is accelerated outward. The result of the interaction with the heliopause is a lenticular region shown on the right panel of Figure 13, which expands as the transmitted shock moves outward and the reflected shock moves inward. The existence of this process was confirmed by an MHD calculation of Washimi et al. [2011].

On smaller scales, Figure 10 shows no evidence of large-scale fluctuations in the LISM like those that are characteristic of the heliosheath. There is no indication of filaments and jumps in B that

Figure 13. Propagation of a shock from the supersonic solar wind through the termination shock, continuing through the heliosheath, and passing through the heliopause.

Figure 14. The top panel shows daily increments of the magnetic field strength. The bottom panel shows the distribution function. A q-Gaussian provides a good fit to the observations, which gives $q = 1$, corresponding to an ordinary Gaussian distribution, which is very different from what was observed in the heliosheath.
might be associated with a multifractal structure in the LISM. Macek et al. [2014] found no multifractal structure in B in the LISM after August 25, 2012. The 468 day interval from 213.36 - 214.64 shows a nearly uniform B and consequently a lack of correlations, unlike the heliosheath. The increments of daily averages of B at one day intervals are plotted at the top panel of Figure 14, and the distribution of these increments is shown in the bottom panel of Figure 14. The distribution can be described as a q-Gaussian distribution, but the parameter \( q_{cor} = 1 \) (characteristic of a Gaussian distribution) is distinctly different than the value \( q_{cor} = 1.6 \) characteristic of the heliosheath.

The preceding results show that the large-scale fluctuations observed by V1 after August 25, 2014 are not characteristic of fluctuations in the heliosheath. This is consistent with the view that the latter observations shown in Figure 10 are properties of the LISM.

Finally, we consider the possibility that the very small fluctuations in B observed by V1 from 2013.36-2014.64 might be interstellar turbulence. This question was answered by Burlaga et al. [2015]. After subtracting the trends in B from the observations during the 468 day interval a power spectrum of the IMS magnetic field was computed. The result is shown by the red curve in Figure 15, which is a plot of power spectral density versus wave number k. At the shortest wave numbers, the spectrum levels off to a constant value, which is at the noise level as discussed by Burlaga et al. [2014b]. At the longer wavelengths (smaller wave numbers, corresponding to larger frequencies) the spectrum has the slope of \( k^{-5/3} \), consistent with Kolmogorov turbulence.

![Figure 15](image)

**Figure 15.** The spectrum of the fluctuations observed by Voyager 1 from 2013.36 to 2014.64 is shown by the red curve. The tail levels out at the largest wave numbers as a result of instrument noise. The three curves are based on a model of Kolmogorov turbulence, with a \( k^{-5/3} \) spectrum which levels out at a scale \( L_c \).

Kolmogorov turbulence in the magnetic field of the interstellar medium has been observed with remote-sensing instruments by Minter and Spangler [1996]. Burlaga et al. [2015] considered the
relationship between the Voyager 1 observations of the spectrum of magnetic fluctuations and various estimates of the interstellar magnetic turbulence. Three model spectra are plotted in Figure 15 for an outer scale length (stirring scale) of $L_c = 100$ pc, 10 pc, and 1 pc, based on the assumption that $<\delta B>^2 = B_m^2$. In order to convert from time to wave number, it was assumed that Voyager 1 moved past the fluctuations and 20 km/s. Figure 15 shows that the Voyager 1 spectra are inconsistent with stirring scales of 100 pc and 1 pc, but they are consistent with $L_c = 10$ pc. In other words, the Voyager 1 spectra measured during 2013 and 2014 are consistent with the interstellar spectra. This supports the view that Voyager 1 is in the LISM.

The preceding discussion assumes that to first order there is only one scale involved in the turbulence, and that the effects of the interaction of the magnetosphere with LISM tend to enhance the turbulence by only a factor of the order of two or three, which would not change our conclusion. Voyager 1 that was observing interstellar turbulence. The discussion also neglects turbulence that might be generated by the fluctuations in the heliosheath acting on the heliopause. However, these fluctuations are known to be very weak [Burlaga et al. 2014, 2015] and they are expected to be attenuated by the heliopause, so that their contribution to the turbulence might be small. Further studies are needed to confirm the validity of these assumptions.

5. Conclusions
This paper has described and compared the magnetic properties of the heliosheath with those of the LISM in the region close to the heliosheath. It is clear that the properties of these two regions are very distinct in every respect. The simplest explanation of the magnetic field observations after August 25, 2012 is that Voyager 1 has been observing the draped interstellar magnetic field. The Voyager 1 observations of the magnetic field can be explained by generally accepted concepts and numbers for the local interstellar magnetic field. Nevertheless, the model of Fisk and Gloeckler [2014] has not been shown to be invalid up to this time; a definitive observation is predicted to occur during 2015.

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