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## TRIANGULATION OF THE INTERSTELLAR MAGNETIC FIELD

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### ABSTRACT

Determining the direction of the local interstellar magnetic field (LISMF) is important for understanding the heliosphere's global structure, the properties of the interstellar medium, and the propagation of cosmic rays in the local galactic medium. Measurements of interstellar neutral atoms by *Ulysses* for He and by *SOHO/SWAN* for H provided some of the first observational insights into the LISMF direction. Because secondary neutral H is partially deflected by the interstellar flow in the outer heliosheath and this deflection is influenced by the LISMF, the relative deflection of H versus He provides a plane—the so-called *B–V* plane in which the LISMF direction should lie. *Interstellar Boundary Explorer (IBEX)* subsequently discovered a ribbon, the center of which is conjectured to be the LISMF direction. The most recent He velocity measurements from *IBEX* and those from *Ulysses* yield a *B–V* plane with uncertainty limits that contain the centers of the *IBEX* ribbon at 0.7–2.7 keV. The possibility that *Voyager 1* has moved into the outer heliosheath now suggests that *Voyager 1*'s direct observations provide another independent determination of the LISMF. We show that LISMF direction measured by *Voyager 1* is  $>40^\circ$  off from the *IBEX* ribbon center and the *B–V* plane. Taking into account the temporal gradient of the field direction measured by *Voyager 1*, we extrapolate to a field direction that passes directly through the *IBEX* ribbon center (0.7–2.7 keV) and the *B–V* plane, allowing us to triangulate the LISMF direction and estimate the gradient scale size of the magnetic field.

*Key words:* ISM: magnetic fields – local interstellar matter

### 1. INTRODUCTION

The local interstellar magnetic field (LISMF) potentially has strong influences on the global heliosphere (e.g., Opher et al. 2006; Pogorelov et al. 2007, 2009; Ratkiewicz et al. 2012). However, for many years, the direction and strength of the LISMF has remained an enigma.

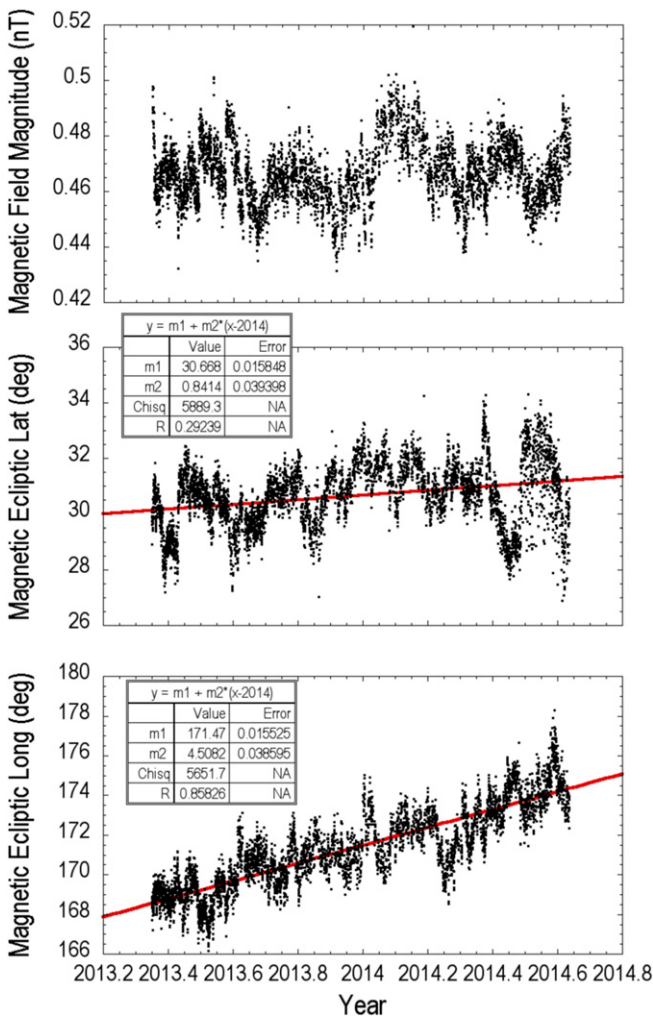
One of the first observational insights that constrained the direction of the interstellar magnetic field direction to a plane (Lallement et al. 2005) came from comparison of the velocities of interstellar He (Witte et al. 1996, 2004; Witte 2004; Lallement et al. 2005; Bzowski et al. 2014; Leonard et al. 2015; McComas et al. 2015; Möbius et al. 2015; Schwadron et al. 2015) and interstellar H (Wood et al. 2007; Lallement et al. 2010) measured in the heliosphere. The H inflow direction is more strongly affected by secondary interactions in the heliosheath than the He inflow. As a result, the difference between the H and He velocity vectors specifies a plane that breaks the symmetry of plasma deflection in the outer heliosheath due to the influences of the LISMF. Therefore, the plane containing both the neutral H and He velocity vectors inside the heliosphere should contain the LISMF direction (Lallement et al. 2005).

*Voyager 1* observations shortly after it crossed the termination shock showed the presence of ions streaming from the shock (Decker et al. 2005; Stone et al. 2005) indicating asymmetries of the heliosphere possibly induced by the interstellar magnetic field (Opher et al. 2006). Subsequent observations from *Voyager 2* confirmed an asymmetric termination shock (Stone et al. 2008) also consistent with the influence from a relatively strong ( $>3 \mu\text{G}$ ) interstellar magnetic field tilted well out of the ecliptic plane (Opher et al. 2009).

Further insight into the LISMF direction came with new discoveries by the *Interstellar Boundary Explorer Mission (IBEX)*, launched 2008 October, with the objective to discover the global interaction between the solar wind and the local interstellar medium (LISM) (McComas et al. 2009b). *IBEX* measures neutral atoms in the energy range of  $\sim 0.01$ –6 keV. In the keV energy range, the hydrogen energetic neutral atoms (ENAs) detected by *IBEX* are created predominantly from charge-exchange between neutral interstellar hydrogen and plasma protons in the heliosheath (McComas et al. 2009b, 2011). The *IBEX-Lo* sensor also measures neutral atoms including oxygen, helium and hydrogen coming directly from the LISM (Möbius et al. 2009).

One of the first key discoveries by *IBEX* was the existence of a narrow ribbon of higher flux ENA emissions (Funsten et al. 2009; Fuselier et al. 2009; McComas et al. 2009a). The ribbon is nearly circular with its center varying by  $\sim 11^\circ$  over the measured energy range (Funsten et al. 2013). An informed conjecture was made shortly after the ribbon's discovery that the center of the *IBEX* ribbon defines the direction of the LISMF (Schwadron et al. 2009). In fact, the direction roughly perpendicular to the LISMF derived from a pre-existing heliosphere model (Pogorelov et al. 2009) showed remarkably good qualitative correlation with the directions of strongest ribbon flux enhancements. The model (Pogorelov et al. 2009) on which this correlation was based was designed specifically to account for heliospheric asymmetries observed by *Voyager 1/2* and 2–3 kHz Radio Emission in the limit of a strong LISMF ( $>3 \mu\text{G}$ ).

The physical mechanism for the ribbon remains an area of active research (McComas et al. 2014). Until the physics of the ribbon generation is understood, it will be difficult to know



**Figure 1.** Interstellar magnetic field observed by *Voyager 1* over a period from 2013/130.6 to 2014/232.3 when the magnetic field magnitude (upper panel) remained roughly constant and the field direction changed steadily. We show the field direction in heliocentric (J2000) ecliptic coordinates and find the best linear fit to the data to infer the change in direction over time.

how the LISMF direction is related in detail to the *IBEX* ribbon. A number of heliospheric models have been devised with the property that the ribbon is highly sensitive to the LISMF direction (Frisch et al. 2010; Heerikhuisen et al. 2010; Ratkiewicz et al. 2012; Schwadron & McComas 2013b; Heerikhuisen et al. 2014).

Another part of the puzzle concerning the LISMF should, at least in principle, be deciphered from *Voyager 1* observations and eventually from *Voyager 2* observations. The *Voyager 1* and 2 spacecraft continue to move outward from the Sun into the outermost reaches of our heliosphere. There is believed to be a boundary separating the solar wind from the interstellar plasma called the heliopause, which was expected to be marked by a large increase in plasma density, from  $\sim 0.002 \text{ cm}^3$  in the inner heliosheath inside the heliopause, to  $\sim 0.1 \text{ cm}^3$  in the interstellar medium beyond the heliopause. On 2013 April 9, *Voyager 1*'s plasma wave instrument detected electron plasma oscillations at a frequency of  $\sim 2.6 \text{ kHz}$ . These oscillations are created relatively close to the spacecraft and have a frequency that can be used to determine the electron density of the nearby plasma. This electron density was found to be  $\sim 0.08 \text{ cm}^3$ , orders of magnitude larger than typical densities in the inner

heliosheath, and quite similar to the expected interstellar density. These observations provide evidence that *Voyager 1* had crossed the heliopause into the nearby interstellar medium (Gurnett et al. 2013).

The first indications that *Voyager 1* may have crossed the heliopause were observations made on 2012 July 28 at 121 by the Low Energy Charged Particle and Cosmic Ray (CRS) instruments, which showed abrupt decreases in the fluxes of energetic particles (EPs, termed “termination shock particles,” TSPs). In addition, anomalous cosmic rays (ACRs; Krimigis et al. 2013; Stone et al. 2013; Webber & McDonald 2013) also showed sharp decreases. The decreases in TSPs and ACRs were correlated with prompt increases in the galactic cosmic ray (GCR) intensities (Stone et al. 2013; Webber & McDonald 2013), which again suggested that the spacecraft had entered interstellar space where GCR intensities are strongest since GCRs are accelerated in the galactic medium and leak into the heliosphere as they scatter through the solar wind's magnetic field. Five similar crossings of the boundary were observed by *Voyager 1* between 2012 July 28 and August 25.

The *Voyager 1* magnetometer (MAG) observations (e.g., Burlaga et al. 2005; Burlaga & Ness 2013), however, have, at least initially, complicated the interpretation that *Voyager 1* had crossed back and forth across the heliopause and eventually entered interstellar space outside the solar wind. Although these boundary crossings showed sharp changes in observed magnetic field strength, the magnetic field direction remained relatively constant and roughly consistent with the spiral magnetic structure observed throughout the inner heliosheath. The magnetic field in the LISM (Lallement et al. 2005; Opher et al. 2006; Pogorelov et al. 2009; Frisch et al. 2012; Frisch & Schwadron 2014) is expected to be different than the inner heliosheath's magnetic field. It was therefore predicted that the crossing of the heliopause should be accompanied by both abrupt changes in the magnetic field magnitude and a strong rotation in the magnetic field direction.

The puzzling lack of a magnetic field rotation at the heliopause led to a number of alternative interpretations of the *Voyager 1* boundary crossings. Schwadron & McComas (2013a) suggested that *Voyager 1* had moved through “interstellar flux transfer events” (IFTEs), which are analogous to flux transfer events observed at the magnetosphere and associated with magnetic reconnection at the magnetopause (e.g., Russell & Elphic 1979; Fuselier & Lewis 2011; Tkachenko et al. 2011; Zhang et al. 2011; Fear et al. 2012). IFTEs are magnetically reconnected flux tubes, which *Voyager 1* may have passed through as it approached the heliopause. IFTEs provide magnetic connection to the interstellar medium, while maintaining a similar magnetic structure to that inside the heliopause. The magnetic connection would cause dropouts in ACRs and EPs. The magnetic connection also allows access to the interstellar medium leading to enhancements in GCRs. Another interpretation offered by Gloeckler & Fisk (2015) is that the boundary crossings of *Voyager 1* indicated passage into an outer envelope of the inner heliosheath inside the heliopause. Within this envelope pressure balance is maintained by the bulk solar wind, while suprathermal and EPs have escaped.

*Voyager 1* has continued to observe the magnetic configuration observed near the initial boundary crossings, and the EPs and ACRs remain suppressed while GCRs remain

enhanced. In fact, the magnetic field has shown some steady changes, which Burlaga & Ness (2014) argue is associated with draping of the interstellar magnetic field about the heliopause. If correct, the interpretation suggests that the *Voyager 1* spacecraft should observe the most strongly draped field configuration shortly after the crossing of the heliopause. Then, as *Voyager 1* moves outward further away from the heliopause, it should observe the draped field relax to the undisturbed interstellar field configuration, as recently indicated through a simple analytic flow model for the heliosphere (Isenberg et al. 2015) and with global heliospheric modeling (Zirnstein et al. 2015).

The purpose of our paper is simply to place the four different observations from *Ulysses*, *IBEX*, *SOHO/SWAN*, and *Voyager 1* into the same context to test our understanding of the interstellar magnetic field direction. Section 2 shows how these observations can be used to triangulate the direction of the LISMF. Section 3 discusses the implications of these observations for our understanding of the source of the ribbon and the properties of the LISM.

## 2. TRIANGULATION OF MAGNETIC FIELD OBSERVATIONS

We begin by examining the *Voyager 1* observations of the interstellar magnetic field, assuming that *Voyager 1* did in fact move beyond the heliopause in 2012. Burlaga & Ness (2014) examined the magnetic field data carefully and found an interval between 2013/130.6 and 2013/365.3 when the field strength remained relatively steady and the direction of the field underwent steady change. In subsequent work, Burlaga et al. (2015) studied a longer period of relatively quiet field conditions to determine the interstellar turbulence spectrum. We have used this extended interval from 2013/130.6 to 2014/232.3 over which period the interstellar magnetic field strength remained quite steady and the direction of the field continued to change steadily. Figure 1 shows the field direction in heliocentric (J2000) ecliptic coordinates. We have fit a straight line to the data using minimization of the  $\chi^2$  deviation between observations and the straight line:

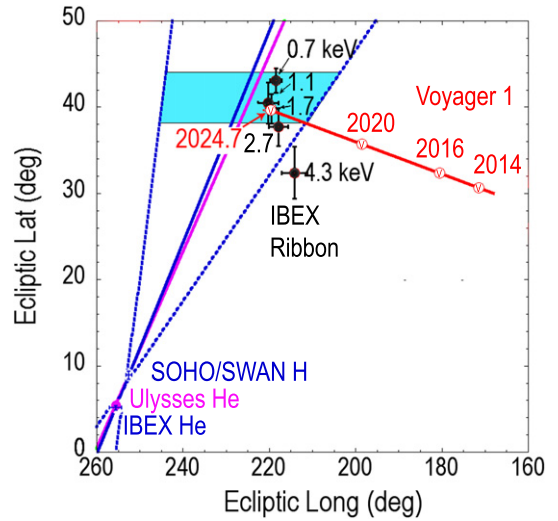
$$\ell(t) = \ell_0 + \ell'(t - t_0) \quad (1)$$

$$b(t) = b_0 + b'(t - t_0). \quad (2)$$

Here,  $\ell(t)$  is the ecliptic longitude field direction at time  $t$  and  $\ell_0 = 171^\circ:47 \pm 0^\circ:02$  is the ecliptic longitude field direction at time  $t_0 = 2014$ . The change in ecliptic longitude field direction over time is  $\ell' = 4^\circ:51 \pm 0^\circ:04 \text{ yr}^{-1}$ . The quantity  $b(t)$  is the ecliptic latitude field direction at time  $t$ ,  $b_0 = 30^\circ:67 \pm 0^\circ:02$  at time  $t_0 = 2014$ , and the change in ecliptic latitude over time is  $b' = 0^\circ:84 \pm 0^\circ:04 \text{ yr}^{-1}$ .

We test the significance of derived slopes by running a  $t$ -test for the “null” hypothesis—the probability of the existence of a zero slope. For the zero slope in longitude, we find a  $t$ -value of 116.8 with 4879 degrees of freedom. The probability of the zero slope is vanishingly small ( $< 1.0 \times 10^{-300}$ ). In the case of the zero slope in latitude, the  $t$ -value is 21.6 and the degrees of freedom remain at 4879. The probability of the zero latitude slope is also vanishingly small ( $< 6 \times 10^{-99}$ ). Therefore, both the slopes in longitude and latitude are extremely statistically significant.

We show these straight line fits to the *Voyager 1* magnetic field observations together with the  $B$ - $V$  plane limits, the



**Figure 2.** We combine four different sets of observations to determine the direction of the interstellar magnetic field. The red line shows the linear fit to *Voyager 1* observations of the interstellar magnetic field. This linear fit is projected forward in time (the red circles surrounding a “V” show discrete points in time along the *Voyager 1* trajectory). The H flow direction from *SOHO/SWAN* (Lallement et al. 2005, 2010) is shown with the He flow direction derived by Schwadron et al. (2015) in blue. The H inflow is more strongly deflected by secondary interactions in the heliosheath than the He inflow. Therefore, the  $B_{\text{ISM}}-V_{\text{ISM}}$  plane contains the deflection of H relative to He (Lallement et al. 2005). The region bounded by the dark blue dashed curves shows the limits of the  $B_{\text{ISM}}-V_{\text{ISM}}$  plane, which contains the orientation of the *IBEX* ribbon (Funsten et al. 2013) from 0.7 to 2.7 keV. The purple closed circle shows the He inflow direction based on the most recent analysis of *Ulysses* ISN flow observations (Wood et al. 2015). The purple line shows the corresponding  $B$ - $V$  plane connecting the *Ulysses* He and *SOHO/SWAN* H observations. The center (closed black circles) of the *IBEX* ribbon is shown at separate energy steps observed by the Hi sensor on *IBEX*. The projected interstellar field direction from *Voyager 1* converges with the 1.7 keV *IBEX* ribbon center on the date of 2024.7. The light blue region shows the extent of the intersections between the  $B$ - $V$  plane and the *Voyager 1* projection. This region of intersection contains the *IBEX* ribbon centers from 0.7 to 2.7 keV, demonstrating the successful triangulation of these distinct data sets.

directions and uncertainties of the *IBEX* ribbon centers in hydrogen ENAs (Figure 2). These directions are all shown in heliocentric (J2000) ecliptic coordinates. The straight line fits to *Voyager 1* data are projected forward in time and converge with the *IBEX* ribbon center at 0.7–2.7 keV on the date of 2024.7 when *Voyager 1* will be at  $\sim 164.6$  AU from the Sun.

Notably, the center of the *IBEX* ribbon at 4.3 keV is quite different from the ribbon centers at 2.7 keV and below. This is partially the result of significant broadening of the ribbon at 4.3 keV (Schwadron et al. 2014). Another important factor is simply that the ribbon fails to remain a coherent structure at this energy.

The *IBEX* He observations (in blue) used in Figure 2 from Schwadron et al. (2015) are derived from an extended analysis over the mission’s first five years. These results are consistent with other complimentary *IBEX* studies performed recently (Bzowski et al. 2015; Leonard et al. 2015; McComas et al. 2015). Collectively, this work provides a significant improvement in our understanding of interstellar He parameters from *IBEX* data (e.g., Bzowski et al. 2012; Möbius et al. 2012). According to the most recent analyses of *IBEX* and *Ulysses* ISN flow observations (Wood et al. 2015) the resulting velocity vectors agree within the uncertainties, but the interstellar temperature is now substantially higher than given by Witte (2004). For the triangulation in Figure 2, the velocity vector of



*Ulysses* (purple closed circle) provides a  $B-V$  plane (purple line) that almost matches the  $B-V$  plane from *IBEX* (blue line).

The light blue shaded region in Figure 2 shows the region of intersection between the *Voyager 1* projected field direction and the  $B-V$  plane. These projections extend to points in time from 2022.8 to 2030 when *Voyager 1* will be between 158 and 184 AU. These results suggest that field draping in the outer heliosheath extends across a region (along the *Voyager 1* trajectory) in the range of 37–63 AU. If the convergence of the *Voyager 1* projection to the 1.7 keV *IBEX* ribbon center holds, this would indicate the draping region is 43.6 AU along the *Voyager 1* trajectory. However, these extents of the draping region are only approximate as they neglect the effect of time variations and the possibility that the projection of the field direction is not linear.

The convergence of the extent of the  $B-V$  plane, the directions of the *IBEX* ribbon center at 0.7–2.7 keV, and the projection of the *Voyager 1* field direction represents a triangulation of the field direction. The data sets used to derive the triangulation are quite distinct. This strengthens the conclusion that the triangulated field direction is in fact an accurate representation of the true interstellar field direction.

### 3. SUMMARY AND CONCLUSIONS

We have examined the direction of the interstellar magnetic field from three distinct observational vantage points: (1) inflowing interstellar H is more strongly affected by secondary interactions in the outer heliosheath than interstellar He. Interstellar H is therefore deflected relative to He and the deflection vector should lie within a plane (the  $B-V$  plane) that contains the interstellar magnetic field vector (Lallement et al. 2005); (2) the center of the *IBEX* ribbon, which is believed to be oriented parallel to the interstellar magnetic field; and (3) the observations by *Voyager 1* of the steady undraping of the magnetic field after it crossed the heliopause late in 2012. We have used these independent observations to triangulate a unique orientation for the undisturbed interstellar magnetic field.

The triangulated field direction appears very consistent with the direction at the center of the *IBEX* ribbon, and is particularly close to the ribbon center at 0.7–2.7 keV. There are large inherent uncertainties. For example, the extrapolation of the field direction from *Voyager 1* observations is linear. However, *Voyager 1* has remained within the outer heliosheath over a relatively short observational period. It is therefore unclear whether a linear extrapolation will continue to hold. The linear projection suggests that *Voyager 1* could observe a field direction at the *IBEX* ribbon center by  $\sim 2025$  when the spacecraft is at  $\sim 165$  AU from the Sun. These predictions warrant careful further analysis of *Voyager 1* data in coming years. In addition, when *Voyager 2* crosses the heliopause, we may be able to add a fourth observational vantage point from which to compare projections of the interstellar field direction.

Thus, our triangulation of the interstellar magnetic field provides new support indicating both that *Voyager 1* is currently in the outer heliosheath beyond the heliopause and that the interstellar magnetic field direction is at the center of the *IBEX* ribbon. This analysis strongly supports the conclusion of Burlaga & Ness (2014) that the steady changes in magnetic field orientation observed by *Voyager 1* during quiet periods after it crossed the heliopause were in fact indications of the undraping of the interstellar magnetic field, as modeled by

Zirnstein et al. (2015). The *IBEX* ribbon center as the direction of the LISMF is consistent with the interstellar field direction obtained from locally, polarized starlight (Frisch et al. 2015). This implies that the ordering of the interstellar field persists over much larger spatial scales than that of the heliosphere. Further, these results strengthen the conclusion that the anisotropies in TeV cosmic rays are organized by this field direction over many parsecs in the local galactic environment (Schwadron et al. 2014).

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