The Local Interstellar Magnetic Field Observed by Voyager 1 and IBEX

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Abstract. Observations by the Interstellar Boundary Explorer (IBEX) have revealed the presence of the IBEX Ribbon, an almost circular band of increased ENA emissions that is believed to be centered on the direction of the interstellar magnetic field. IBEX measures a range of interstellar species including H, He, and O. IBEX has been able to distinguish primary He coming directly from the interstellar medium from secondary He that is created through neutralization of He$^+$ atoms in the heliosheath. Together with the observations of Lyman-α radiation from SOHO/SWAN, which is resonantly absorbed and re-emitted from interstellar H atoms that move into the heliosphere, the directions of interstellar flow for each of the observed interstellar species (H, primary He, secondary He, and primary O) line-up along a symmetry plane — the interstellar B–V plane — that should contain the interstellar magnetic field direction (B) and the interstellar flow direction (V). The B–V plane also contains the center of the IBEX Ribbon, which supports the concept that the Ribbon center is close to the direction of the interstellar magnetic field. Further, the deflection of the various interstellar species along the B–V plane are consistent with the compression of the heliosheath by the interstellar magnetic field pressure. Lastly, the interstellar magnetic field in the outer heliosheath is directly observed by Voyager 1 (V1). The direction of the interstellar magnetic field observed by V1 is offset from the Ribbon center, consistent with draping around the heliopause, and time variations in the interstellar magnetic field are consistent with the effects of large-scale compression and rarefaction in the outer heliosheath. Thus, we summarize the array of observations that suggest a consistent direction of the interstellar magnetic field, and the effects of the interstellar magnetic field on the structure and time variations in the heliosheath.
1. Introduction

The heliosphere is defined by the Sun’s solar wind expansion and its interaction with the local interstellar plasma. The solar wind transmits the plasma from the Sun to beyond the termination shock (TS) prior to being diverted back toward the heliotail. The heliopause (HP) separates the local the solar wind from the local interstellar medium (LISM).

Neutral interstellar atoms move on direct trajectories 100’s of astronomical units (AU) through the heliosphere, affected only by solar gravitation and radiation pressure (in the case of H) prior to ionization. Interstellar neutral atoms are critical for supplying information about the interstellar flow. Interstellar He atoms supply the best available information on the local interstellar flow direction, speed and temperature [1–6].

The direction and strength of the local interstellar magnetic field (LISMF) has remained an enigma for many years due to a lack of direct observations in the outer heliosheath and LISM. The Interstellar Boundary Explorer (IBEX) mission provided new information about the LISMF. With the discovery of the existence of the Ribbon, a narrow semi-circular band of high flux energetic neutral atom (ENA) emissions [7–10], it was believed that the IBEX Ribbon center is near the direction of the LISMF [7, 9]. The strength of the LISMF was also estimated to be $\sim 3\mu G$ from IBEX observations based on pressure balance [11] and modeling of the IBEX Ribbon [12].

This paper summarizes recent observations of interstellar neutral atom species, the IBEX observations of the Ribbon, and Voyager 1 (V1) observations of time variations in the outer heliosheath. Together these observations indicate a consistent direction and strength of the interstellar magnetic field and effects of the LISMF on the global heliosheath.

The paper is structured as follows. Observations that are used to define the B–V plane containing the interstellar magnetic field direction and the interstellar flow direction are discussed in §2. §3 describes observations made by V1 indicating compression and rarefaction regions in the outer heliosheath, which affect the observed draping of the interstellar magnetic field around the heliopause. Concluding remarks are made in §4.

2. The Interstellar B–V plane

The B–V symmetry plane is defined to contain both the direction of the LISMF and the local interstellar flow vector [13]. Observational studies defined the B–V plane by comparing the velocities of interstellar He [1–6, 13–15] and interstellar H [16, 17] measured in the heliosphere. The H flow direction is determined from observations of the Lyman-α radiation scattered from interstellar hydrogen that moves into the heliosphere. Therefore, the H-direction contains influences from both primary H atoms from the LISM and secondary H atoms generated through charge-exchange interactions in the heliosheath, which on average deflects the LISM H flow vector along the B–V plane, slows the H LISM flow, and increases its temperature. In contrast, LISM He undergoes very little charge-exchange in the heliosheath and has a flow vector that more accurately reflects the LISM conditions far from the heliosphere. The He and H velocity vectors uniquely define the B–V plane (Figure 1).

In addition to measurements of LISM H and He that define the B–V plane, more recent LISM measurements by IBEX include primary LISM O [18] and secondary He [19], which have improved the definition of the B–V plane. The separation of secondary He and primary He provide one of the best measures of the B–V plane (Figure 1, 2, grey curve).

In Figure 1, we also show recent magnetic field measurements of V1 [21]. Over the period from May 10, 2013 to Aug. 20, 2014, the LISMF shows steady undraping in the outer heliosheath. However, later, from May 26, 2015 to Aug 25, 2016 the LISMF is affected by a rarefaction region in the outer heliosheath, as detailed by [21] and summarized in the next section.

Figure 2 shows expanded ranges of the B–V plane (left) to better resolve the velocity directions of LISM species. Primary and secondary species show systematic deflections along the B–V
Figure 1. The LISM B–V symmetry plane (black, magenta and grey curves) is defined by the directions of LISM neutral O, He, and H from IBEX, Ulysses and SOHO/SWAN. The deflection of LISM H compared to LISM He provides a way to measure the B–V plane (black curve) [13, 17–19]. Dashed black curves show uncertainty limits of the LISM B–V plane. [19] provided an analysis of secondary He, which was compared to primary He both measured by IBEX to provide another important determination of the LISM B–V plane (grey curve). A third estimate of the LISM B–V plane (magenta curve) from measurements from SOHO/SWAN for H and Ulysses for He. Also shown are measurements of the LISMF direction from Voyager 1 (grey, blue and red data points) that shows departures from the IBEX ribbon center (black points) and the LISM B–V plane. The black points from the Ribbon center are defined by fitting the ribbon [20]. A model-based fit (yellow star) was provided by [12]. The direction of the LISMF measured by Voyager 1 changes with time: from May 10, 2013 to Aug. 20, 2014 (blue arrow fit to blue points) the LISMF tends toward the B-V plane and the IBEX ribbon center, consistent with undraping of the LISMF; LISMF directions from May 26, 2015 to Aug 25, 2016 (red points) show the opposite trend (red arrow fit to red data points) away from B-V plane and away from the IBEX Ribbon center. Figure taken from [21].

plane. LISM primary He represents the most definitive direction for the LISM flow far from the heliosphere. Secondary He, and H, which contains a secondary component, are both shifted northward with respect to primary He. Primary O is shifted southward with respect to primary He due to stronger filtration north of the nose. These directional deviations of primary and secondary components are caused by the heliospheric asymmetry due to stronger LISMF pressure south of the nose (Figure 2, right).
3. Voyager 1 observations in the outer heliosheath
The direction of the LISMF measured by V1 in the outer heliosheath shows deviation from the LISM B–V plane. This deviation is consistent with draping of the LISMF around the heliopause [23]. Draping of the LISMF around the heliopause creates a significant difference between the field direction measured by V1 and the direction of the ribbon center, as shown in Figure 1. [21] compared V1’s measurements of the LISMF with measurements of the solar wind made at 1 AU. Solar events in 2012 and 2013 create merged interaction regions that drive pressure changes. These variations are transmitted though the heliopause to drive compression and rarefaction within the outer heliosheath. The effect of the rarefaction region at V1 causes the expansion of the magnetic field (Figure 3), which leads to stronger draping of the LISMF near V1.

The magnetic observations of V1 provide direct evidence of the draping of the LISMF. The deflection of the magnetic field around the heliopause increases the magnetic tension, and is balanced by enhanced magnetic pressure. The deflection of the magnetic field measured by V1 has a direct connection to the magnetic pressure that drives asymmetries in the heliosphere (Figure 2, right) and, in turn, the deflections of primary and secondary neutral atom components (He, H, and O) that are used to determine the LISM B–V plane.

4. Conclusions
Neutral atoms and Lyman-α observations from Ulysses, SOHO/SWAN, and IBEX were used to determine the LISM B–V plane. This symmetry plane intersects the center of the IBEX Ribbon, showing the consistency of the concept that the center of the IBEX Ribbon is near the direction of the LISMF.

Voyager 1 provides direct observations of the LISMF in the outer heliosheath. The deflection of the magnetic field direction measured by V1 is consistent with the draping of the LISMF around the heliopause. Time variations measured by Voyager 1 indicate the presence of compressions and rarefactions driven by pressure variations transmitted through the heliopause.
Figure 3. Global Merged Interaction Regions from solar events in the 2012-2013 peak activity period of solar cycle 24 create pressure changes that are transmitted into the outer heliosheath. The compression and rarefaction regions cause further changes in the draped LISMF. Figure from [21].

Datasets from Ulysses, IBEX, SOHO/SWAN, and Voyager are now allowing determination of the direction and strength of the local interstellar magnetic field. The draping of the local interstellar magnetic field around the heliopause is associated with increased magnetic pressure in the outer heliosheath that drives asymmetries in heliosheath structure.

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