ON THE ROTATION OF THE MAGNETIC FIELD ACROSS THE HELIOPAUSE

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ABSTRACT

Based on the difference between the orientation of the interstellar and the solar magnetic fields, there was an expectation by the community that the magnetic field direction will rotate dramatically across the heliopause (HP). Recently, the Voyager team concluded that Voyager 1 (V1) crossed into interstellar space last year. The question is then why there was no significant rotation in the direction of the magnetic field across the HP. Here we present simulations that reveal that strong rotations in the direction of the magnetic field at the HP at the location of V1 (and Voyager 2) are not expected. The solar magnetic field strongly affects the draping of the interstellar magnetic field (B_{ISM}) around the HP. B_{ISM} twists as it approaches the HP and acquires a strong T component (East–West). The strong increase in the T component occurs where the interstellar flow stagnates in front of the HP. At this same location the N component B_N is significantly reduced. Above and below, the neighboring B_{ISM} lines also twist into the T direction. This behavior occurs for a wide range of orientations of B_{ISM}. The angle \( \delta = a \sin(B_T/B) \) is small (around \( 10^{-20^\circ} \)), as seen in the observations. Only after some significant distance outside the HP is the direction of the interstellar field distinguishably different from that of the Parker spiral.

Key words: ISM: magnetic fields – magnetohydrodynamics (MHD) – solar neighborhood – Sun: heliosphere

Online-only material: color figures

1. INTRODUCTION

Voyager 1 (V1) is at 125 AU from Earth, traveling toward the nose of the heliosphere in the Northern Hemisphere. Voyager 2 (V2) is trailing behind at 102 AU traveling in the Southern Hemisphere.

Within the heliosheath (HS) the solar magnetic field B_{SW} is the Parker spiral with a dominant East–West orientation. The interstellar magnetic field (B_{ISM}) is expected to have a component in the North–South direction to account for the asymmetries in the heliosphere (Opher et al. 2006, 2007, 2009; Izmodenov et al. 2009; Pogorelov et al. 2009). Consequently, there is an expectation that the magnetic field direction will rotate dramatically across the heliopause (HP), which is the boundary that separates the plasma domain of the Sun from that of the interstellar medium (ISM). This rotation was used as one of the criteria to determine if V1 had already crossed the HP. Based on this fact, the absence of a significant rotation in the direction of the magnetic field at the times of dropouts of energetic particles produced within the heliosphere were interpreted as indicating that V1 was still in the HS (Burlaga et al. 2013; Krimigis et al. 2013; Stone et al. 2013). However, simulations suggested a more complex HP, with magnetic islands that would produce dropouts in the intensity of HS particles with essentially no local magnetic field rotation (Swisdak et al. 2013). In such a picture, V1 might have already crossed the HP just before the dropouts. Recently, the Voyager team indeed concluded that V1 was in interstellar space, based on the elevated plasma density inferred from plasma wave measurements (Gurnett et al. 2013). The crossing was conjectured to have happened around the time of the dropouts in 2012 August. On the other hand, others have suggested that V1 remains in the HS (Fisk & Gloeckler 2013; McComas & Schwadron 2012; Schwadron & McComas 2013). In any case, if V1 is in interstellar space, the important question is why V1 has not revealed a significant rotation in the direction of the magnetic field outside the HP (Burlaga et al. 2013).

In this Letter, we present magnetohydrodynamic (MHD) simulations of the global heliosphere which reveal that strong rotations in the direction of the magnetic field at the HP at the location of V1 (and V2) are not expected. Only after some significant distance outside the HP is the direction of the field distinguishably different from a Parker spiral. This result implies that the magnetic field orientation cannot be used as a marker for the crossing of the HP for the Voyager spacecrafts.

In the next section we describe the twist of the interstellar magnetic field as it approaches the HP and then make some concluding remarks.

2. TWIST OF THE INTERSTELLAR MAGNETIC FIELD

To study the twist of the interstellar magnetic field we use our three-dimensional (3D) MHD model (Opher et al. 2009), which is based on a multi-fluid description that includes adaptive mesh refinement as well as the magnetic field of the Sun and the interstellar magnetic field (B_{ISM}). It possesses five fluids, one ionized and four neutral H fluids. The multi-fluid approach for the neutrals (Alexashov & Izmodenov 2005; Zank 1999) captures the main features of the kinetic model (Izmodenov 2009). Atoms of interstellar origin represent population 4. Population 1 appears in the region behind the bow shock (or slow shock), depending on the intensity of B_{ISM} (Ziegler et al. 2013). Populations 3 and 2 appear in the supersonic solar wind and in the compressed region behind the termination shock, respectively. All four populations are described by separate systems of the Euler equations, with corresponding source terms describing neutral-ion charge exchange.

The inner boundary of our domain is a sphere at 30 AU and the outer boundary is at \( x = \pm 1000 \) AU, \( y = \pm 1000 \) AU, \( z = \pm 10000 \) AU. Parameters of the solar wind at the inner boundary were chosen to match the values obtained by Izmodenov (2009) at 30 AU: \( V_{SW} = 417 \text{ km s}^{-1} \), \( n_{SW} = 8.74 \times 10^{-3} \text{ cm}^{-3} \), \( T_{SW} = 1.087 \times 10^5 \text{ K} \), and the Parker spiral magnetic field \( B_{SW} = 7.17 \times 10^{-3} \text{ nT} \) at the equator. In our simulation, we
assume that the magnetic axis is aligned with the solar rotation axis. The solar wind flow at the inner boundary is assumed to be spherically symmetric. For the interstellar plasma we assume: \( v_{\text{ISM}} = 26.4 \text{ km s}^{-1} \), \( n_{\text{ISM}} = 0.06 \text{ cm}^{-3} \), \( T_{\text{ISM}} = 6519 \text{ K} \). The number density of H atoms in the ISM is \( n_{\text{H}} = 0.18 \text{ cm}^{-3} \), the velocity and temperature are the same as for the interstellar plasma. The coordinate system is such that the \( Z \)-axis is parallel to the solar rotation axis, the \( X \)-axis is \( 5^\circ \) above the direction of interstellar flow, with \( Y \) completing the right-handed coordinate system (a schematic figure can be found in Alouani-Bibi et al. 2011). The grid domain has 14 million cells ranging from scales of 0.24 AU at the inner boundary and 1.0 AU (for cases (a) and (b) in Figure 1) and 2.0 AU (for case (c) in Figure 1) at the HP.

The strength of the \( B_{\text{ISM}} \) in the model is 4.4 \( \mu \text{G} \). The orientation of \( B_{\text{ISM}} \) continues to be debated in the literature. The orientation of \( B_{\text{ISM}} \) is defined by two angles, \( \alpha_{\beta BV} \) and \( \beta_{BV} \). \( \alpha_{\beta BV} \) is the angle between the interstellar magnetic field and the velocity vector \( \beta_{BV} \) is the angle between the ISM plane and the solar heliographic equator. In studies such as Opher et al. (2009) and Izmudov et al. (2009), small values of \( \alpha_{\beta BV} \approx 10^\circ\text{ to } 20^\circ \) were required to account for the heliospheric asymmetries, such as the different crossing distances of the termination shock by \( \text{V1 and V2} \) (Stone et al. 2008). Others (McComas et al. 2009; Heerikhuizen & Pogorelov 2011; Chalov et al. 2010) have used the observed shape and location of the IBEX ribbon to constrain the magnitude and orientation of \( B_{\text{ISM}} \). However, such constraints are sensitive to the specific model of the IBEX ribbon, which continues to be uncertain. Because of the uncertainties associated with the modeling of the IBEX ribbon, we take a strong \( B_{\text{ISM}} \) (4.4 \( \mu \text{G} \)) and an orientation that accounts for the heliospheric asymmetries (Opher et al. 2009). In any case, as we show that the twist of the interstellar magnetic field just outside of the HP is insensitive to its original orientation.

As illustrated in Figure 1, there is a pile-up of the tangential component of the interstellar magnetic field, \( B_T \), outside the HP that is independent of the original orientation of \( B_{\text{ISM}} \). (Here we use the \( R-T-N \) coordinate system as the local Cartesian system centered in the Sun. \( R \) is radially outward from the Sun, \( T \) is in the plane of the solar equator and positive in the direction of solar rotation, and \( N \) completes a right-handed system. A color version of this figure is available in the online journal.)

First, the HP becomes distinctly elongated in the direction of the solar spiral magnetic field direction. As a consequence the HP becomes distinctly elongated in the \( B_T \) plane much more easily in the absence of \( B_{\text{SW}} \) than in the case with \( B_{\text{SW}} \). This is documented in Figure 4 where the magnetic fields and flow streams are compared with and without \( B_{\text{SW}} \).
strongly with $B_{SW}$ than without $B_{SW}$. The peak values of $B_T$ are three times larger in Figure 4(a) compared with Figure 4(d). Third, the flows $V_N$ (Figures 4(c) and (f)) are essentially discontinuous across the HP in the case without $B_{SW}$ while they are essentially continuous with $B_{SW}$. With $B_{SW}$ the $B_{ISM}$ therefore twists in the direction of $B_{SW}$ at the stagnation region. The field lines get hung up in the stagnation region so that the magnetic field strength increases and exerts more pressure on the heliosphere than without $B_{SW}$, resulting in a smaller heliosphere. The normal flows $V_N$ just outside of the HP are also reduced as the magnetic field gets hung up in the stagnation region (Figures 4(c) and (f)). The neighboring interstellar magnetic field lines above and below the stagnation region also twist in response to the magnetic field pile-up near the stagnation region. There is therefore a layer of strong $B_T$ and small $B_N$ outside of the HP with a finite latitudinal extent. In this region the angle $\delta$ is reduced (Figures 2 and 5(c)).

Both $V_1$ and $V_2$ are close enough to the stagnation point so that for both spacecraft there is a region outside of the HP where the angle $\delta$ remains small. This result is insensitive to the original orientation of $B_{ISM}$. Only far outside of the HP does the $B_{ISM}$ twist away from the Parker-like field direction.

Far from the region of small $\delta$, how much of a twist of the magnetic field will $V_1$ measure? Far from the HP, $B_N$ and the angle $\delta$ are zero at a certain angle from the solar equator. This angle is given by the orientation of $B_{ISM}$ as $\theta_0 = 90^\circ - \tan^{-1}(1/(\sin B_0 \tan \alpha))$, where $\alpha$ is the angle between the $B_{ISM}$ and the X-axis (approximately $\alpha_{BV}$) and $\beta$ is the angle between the solar equator and the $BV$ plane. As shown by Zieger et al. (2013), a slow bow shock can form ahead of the HP. As the interstellar magnetic field goes through a slow bow shock, the angle $\delta$ slightly changes. But, in any case this angle will be close to $\alpha_{BV}$. As argued in Opher et al. (2009) and Izmodenov et al. (2009) $\alpha_{BV}$ should be between $10^\circ$–$30^\circ$. This angle is very similar to the latitude of $V_1$ ($30^\circ$ above the solar equator).

3. CONCLUDING REMARKS

These results suggest that the solar magnetic field plays a crucial role in controlling the draping of the interstellar magnetic field outside of the HP. It is the increased friction between the $B_{ISM}$ and $B_{SW}$ at the stagnation region that influences the draping of $B_{ISM}$ around the HP and creates the layer of strong $B_T$ in front of the HP.

Regardless of the orientation of $B_{ISM}$, the magnetic field twists to a Parker-like orientation just outside of the HP. The implication is that for neither $V_1$ nor $V_2$ can a strong magnetic field rotation out of the plane of the Parker spiral be used as a marker for the crossing of the HP. On the other hand, we do expect some rotation in the field direction (or a change in the angle $\delta$) across the HP. Therefore, the several particle intensity dropouts detected by $V_1$ from days 210 to 270, 2012, where there was no significant change in the direction of the magnetic field (Burlaga et al. 2013), cannot correspond to HP crossings. Our interpretation (Swisdak et al. 2013) is that the dropouts correspond to the separatrices of large-scale magnetic islands that form on the HP where the flux of heliospheric particles from the HS to the local interstellar medium is suppressed. In this interpretation $V_1$ crossed the HP on day 209 (when a current layer was crossed) and it has been...
measuring $B_{\text{ISM}}$ since that time. The angle $\delta$ reported during the subsequent period (Burlaga et al. 2013) is steady and around $14^\circ$; which is consistent with the results of our simulations in the region outside of the HP. Only after some distance from the HP will the spacecraft measure a substantial twist in the field, although in the case of V1 this twist is expected to be modest.

In reality the HP could be more complex because of processes not included in the ideal MHD simulations performed here. Particle-in-cell simulations (Swisdak et al. 2013) suggest that reconnection between the interstellar and solar fields might take place as suggested earlier (Fahr et al. 1986).

The simulations presented here demonstrate the influence of the solar magnetic field on the draping of $B_{\text{ISM}}$ outside the HP. The value of the magnetic field inside the HS in these simulations is much higher than seen in observations (Burlaga et al. 2011). Observations such as the loss of magnetic flux (Richardson et al. 2013) suggest that reconnection is taking place within the HS (Drake et al. 2010; Opher et al. 2011). A reduced magnetic field inside the HS might affect the exact value of pile-up magnetic field ahead of the HP. However, as long as the large-scale magnetic field in the HS remains in the $T$ direction (as the measurements by Voyager suggest, e.g., Burlaga et al. 2013), the effects discussed in the Letter will remain: the interstellar magnetic field gets hung-up in the stagnation region, causing the interstellar magnetic field lines in a wide latitudinal band to twist into the $T$ direction.

The IBEX ribbon, the band of increased intensity of energetic neutral atoms at 1 keV in the outer heliosphere, was originally believed to be aligned with the $B_{\text{ISM}} \cdot r = 0$ just outside the HP (Figure 4 of McComas et al. 2009; Figure 3 of Funsten et al. 2009; and Figure 3 in Schwadron et al. 2009). This idea will have to be revised. The centroid of $B_{\text{ISM}} \cdot r = 0$ just outside the HP is displaced from the position based on the direction of $B_{\text{ISM}}$ further outside of the HP. The thickness of the layer of strong $B_T$, as indicated in Figure 2, is around 10 AU. Only beyond $\approx 10$ AU outside the HP is the centroid of the band of $B_{\text{ISM}} \cdot r = 0$ aligned with the original $B_{\text{ISM}}$ direction. It is also in that region where the $B_{\text{ISM}}$ is mostly compressed.

There have been several proposed mechanisms for the generation of the IBEX ribbon (e.g., Heerikhuisen et al. 2010; Chalov et al. 2010). Chalov et al. (2010) proposes a model that depends on the regions of strong magnetic field outside the HP. They used a simulation that did not include the solar magnetic field. As shown in this Letter, the solar magnetic field affects the pile-up and the ribbon location.
Figure 4. Behavior of $B_{\text{ISM}}$ and plasma flows near the stagnation point. $B_T$ and $B_N$ (nT) components in the $V_1-z$ plane, as projected to the $xz$ plane (panels (a) and (b)) $\beta_{BV} = 51.5^\circ$; $\alpha_{BV} = 15.9^\circ$; with a monopole $B_{SW}$. Panels (d) and (e) are the same orientation of $B_{\text{ISM}}$ as in panels (a) and b) but for a simulation with no $B_{SW}$. Panels (c) and (f) show $V_N$ (km s$^{-1}$). It can be seen that the normal flows $V_N$ outside in the interstellar medium, outside the HP are much reduced at the stagnation region for the case with $B_{SW}$.

(A color version of this figure is available in the online journal.)

Figure 5. Same as Figure 1 but with a varying latitudinal solar wind as in Provornikova et al. (2013).

(A color version of this figure is available in the online journal.)

It is still possible that the IBEX ribbon is formed just outside the HP but the orientation of the $B_{\text{ISM}}$ cannot be inferred directly from the IBEX ribbon. It is crucial to know where the ribbon originates and take into account the strong variation of $B_{\text{ISM}} \cdot r = 0$ between the HP and at least 10 AU ahead of it.

The $B_{\text{ISM}}$ directions and intensity used in our simulations (Figures 1(a) and (c)) do reproduce the heliospheric asymmetries detected by Voyager (Opher et al. 2009; Izmodenov et al. 2009). The heliospheric asymmetries (even taking into account time dependence variations; Richardson et al. 2008) require a strong magnetic field $\approx 4 \mu$G and small angles between $B_{\text{ISM}}$ and the interstellar velocity, $V_{\text{ISM}}$ ($10^\circ$–$20^\circ$). There have been several studies by fitting a proposed model to the IBEX ribbon to constrain the direction and intensity of the $B_{\text{ISM}}$.

Heerikhuisen & Pogorelov (2011) used the Heerikhuisen et al. (2010) mechanism and look for large regions beyond to the HP. Some of these studies (Ratkiewicz et al. 2012; Grygorczuk et al. 2011) did not include the solar magnetic field while trying to look for regions of pile-up (as in Chalov et al. 2010). These studies tend to favor weaker fields with large angle $B_{\text{ISM}} - V_{\text{ISM}}$.

It is possible that by accounting for the effects in this Letter there will be a convergence between the $B_{\text{ISM}}$ intensity and $B_{\text{ISM}} - V_{\text{ISM}}$ angles suggested by the Voyager asymmetries (Opher et al. 2009; Izmodenov et al. 2009).

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