RevMexAA (Serie de Conferencias), **36**, 60–66 (2009)

SHOCKS AND MAGNETIZED WINDS: LEARNING FROM THE INTERACTION OF THE SOLAR SYSTEM WITH THE INTERSTELLAR MEDIUM

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RESUMEN

Se puede aprender mucho de choques y vientos magnetizados mediante el estudio de la interacción del sistema solar con el medio interestelar. La sonda Voyager 1 cruzó en diciembre de 2004 el choque de terminación y se encuentra ahora en la magneto-funda. El 30 de agosto de 2007, la sonda Voyager 2 cruzó el choque de terminación, proviéndonos con las primeras mediciones in-situ del viento solar subsónico en la magneto-funda. Nuestros resultados recientes indican que efectos magnéticos, en particular el campo magnético interestelar, son muy importantes en la interacción entre el sistema solar y el medio interestelar. Aquí hacemos un resumen de nuestro trabajo reciente que muestra que el campo magnético interestelar afecta la simetría de la heliosfera que puede ser detectada por diferentes mediciones. Combinamos mediciones de emisión de radio y de partículas a la deriva de las Voyager 1 y 2 con un extensivo modelaje MHD de vanguardia, para restringir la orientación del campo magnético interestalar en la localidad. La orientación obtenida es de un plano a unos $\approx 60° - 90°$ del plano galáctico. Como consecuencia del campo campo magnético interestelar, el sistema solar es asimétrico, siendo empujado en la direccón sur.

ABSTRACT

Through the interaction of the solar system with the interstellar medium we can learn about shocks and magnetized winds. Voyager 1 crossed, in Dec 2004, the termination shock and is now in the heliosheath. On August 30, 2007 Voyager 2 crossed the termination shock, providing us for the first time in-situ measurements of the subsonic solar wind in the heliosheath. Our recent results indicate that magnetic effects, in particular the interstellar magnetic field, are very important in the interaction between the solar system and the interstellar medium. We summarize here our recent work that shows that the interstellar magnetic field affects the symmetry of the heliosphere that can be detected by different measurements. We combined radio emission and energetic particle streaming measurements from Voyager 1 and 2 with extensive state-of-the art 3D MHD modeling, to constrain the direction of the local interstellar magnetic field. The orientation derived is a plane $\approx 60° - 90°$ from the galactic plane. As a result of the interstellar magnetic field the solar system is asymmetric being pushed in the southern direction.

Key Words: Sun: magnetic fields — solar system: general

1. INTRODUCTION

The solar system moves through the interstellar medium with a velocity of 25.5 km/s. As it moves, the solar wind is deflected by the interstellar wind producing a comet-like shape with an extended tail. We observe the collision of winds in astrophysical media via remote sensing, such as the bow shocks formed ahead of Epsilon Eridani. By learning in details about the interaction of the solar system and the interstellar medium, with in-situ data, we can learn on how two magnetized wind collide. In addition we can learn how magnetized shocks behave. With the Voyager spacecrafts, we have now the unique opportunity to have two spacecrafts sending back in-situ data from the farthest shock in the solar system, the termination shock.

The termination shock is the location where the solar wind becomes subsonic as it approaches the interstellar medium. Beyond the termination shock, the solar wind is gradually deflected tailward. The solar wind and the interstellar wind are both magnetized winds. As the Sun rotates, the solar magnetic field is carried by the solar wind and forms a spiral.

The interaction of the solar system with the interstellar medium is a highly complex system. Not only are the two winds ionized winds, and carry magnetic fields, but they also carry neutral H atoms, neutral He atoms; cosmic rays and pickup ions. Another complication is the solar cycle. The solar cycle af-

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fects the solar wind and the magnetic field embedded in it. The heliospheric current sheet (HCS) is known to change its inclination with respect to the solar rotation axis as the solar cycle progresses. The flows produced by the HCS and the solar cycle in the heliosheath have not yet been studied in detail. Also, with the solar cycle there will be more global merger interaction regions (that result of coronal mass ejections) that will affect this interaction as well.

We are fortunate to have the twin spacecrafts Voyager 1 (V1) and 2 (V2) probing in-situ the northern and southern hemisphere. V1 crossed the termination shock in December 2004 (Decker et al. 2005; Burlaga et al. 2005; Stone et al. 2005). V2 is the only spacecraft that has the capability to measure in-situ the plasma flows. In August 2007 V2 crossed the Termination Shock (TS) providing us for the first time with in-situ measurements of the subsonic flows in the heiosheath.

There are few previous modeling studies that include both the solar magnetic field and the interstellar magnetic field (Linde et al. 1998; Linde 1998; Pogorelov et al. 1998, 2004, 2006; McNutt et al. 1999; Washimi et al. 2001; Linde et al. 1998a,b) included the effects of neutral hydrogen atoms along with the solar magnetic field and an interstellar magnetic field either parallel or perpendicular to the interstellar wind velocity. Pogorelov et al. (2006, 2008) investigated models with inclined magnetic fields with neutral atoms treated as a separate fluid, while the model by Izmodenov et al. (2005) included neutrals with a kinetic treatment, but did not include the solar magnetic field. Previous models have shown qualitatively that if the interstellar magnetic field is not oriented parallel or perpendicular to the interstellar velocity, it can produce a lateral or north-south asymmetry in the heliospheric shape (Pogorelov & Matsuda 1998; Pogorelov et al. 2006; Zank, 1999). There are several recent observational evidence from V1 and 2 that there are asymmetries of the solar system. The observational evidence comes from different instruments and locations (termination shock, heliopause, and heliosheath), which indicates that V1 and 2 are detecting the signs of a global distortion of the heliosphere.

Among the several physical quantities that describe the interaction of the solar system with the interstellar medium, the least known are the direction and intensity of the local interstellar magnetic field (BISM). Models suggest that the strength of BISM is around few G (Cox & Helenius 2003). Based on the polarization of light from nearby stars, Frisch (1990) suggested that the magnetic field direction is parallel to the galactic plane (and directed toward l $\approx 70°$) (GAL). Voyager 3kHz radio emission data also show preferred source locations in a plane parallel to the galactic plane (Kurth & Gurnett 2003). On the other hand, Lallement et al. (2005), mapping the solar Lyman-α radiation that is resonantly backscattered by interstellar hydrogen atoms, found that the neutral hydrogen flow direction differs from the helium flow direction by 4°. The plane of the H deflection is tilted from the ecliptic plane by $\approx 60°$ and is consistent with an interstellar magnetic field parallel to the H-deflection plane (Izmodenov et al. 2005). We refer to this plane as the H-deflection plane (HDP). However, Gurnett et al. (2006) recently pointed out that at the Earths bow shock and interplanetary shocks, the radio emission occurs where the magnetic field lines are tangential to the shock surface and suggested that heliospheric radio emissions occur where the local interstellar magnetic field is tangential to the surface of the shock that excites the plasma. They concluded that the observed source location by Voyager spacecrafts implies that the local interstellar magnetic field is perpendicular to the galactic plane. This direction differs from the earlier suggestion (Gurnett & Kurth 1995) and is within 16° of the HDP plane.

In several recent papers (Opher, Stone, & Liewer 2006; Opher, Stone, & Gombosi, 2007; Opher et al. 2008) we proposed that the asymmetries are due to a global factor distorting the solar system that is the interstellar magnetic field. We analyzed the effect that the interstellar magnetic field direction has in the termination shock, in the heliopause, and in the heliosheath. We found that the orientation of the interstellar magnetic field that matches the observations is in a plane $60° - 90°$ from the galactic plane. This direction differs from the direction in large scale of the magnetic field that is the plane of the galaxy.

In § 2, we discuss the observational evidences for asymmetries. In § 3, we discuss the 3D MHD model and results. In § 4, we have the discussion and conclusion.

2. ASYMMETRIES

There have been observational evidence for asymmetries in the solar system. The first one is the *Position of the Termination Shock.* V1 crossed the termination shock in 2004 at a distance of 94AU. V2 on August 30, 2007 crossed the shock at 83.7AU, indicating that the termination shock is $10AU$ closer to the Sun in the southern hemisphere. The second one is the *Anisotropic streaming of Low Energy Particles.* In mid 2002, V1 began observing strong beams of energetic termination shock particles (TSPs) streaming outward along the spiral magnetic field. The strong upstream TSP beams were observed much of the time until V1 crossed the shock at 94 AU in December 2004. Jokipii et al. (2005) and Stone et al. (2005) suggested that the upstream beaming resulted from a non-spherical shock. For a spherical shock, V1 would have observed upstream TSPs streaming inward along the magnetic field. With a non-spherical shock, V1 could be connected to the termination shock along magnetic field lines that crossed the termination shock (the source of TSPs) and then crossed back into the supersonic solar wind. The north-south asymmetry was also seen by the observations (Stone et al. 2005), where V2 started detecting TSPs 10 AU before V1 started. V2 observed TSPs streaming inward (Cummings et al. 2005). There is also the distance of the spacecrafts to the shock when starting to detect the low-energy particles from the shock. Although there was no direct indication how distant V1 was from the shock when the upstream episodes of TSPs were observed, MHD models based on V2 solar wind pressure measurements (Richardson & Wang 2005) indicate that the distance was less than 3 to 4 AU; and at the time when V2 (was at 75 AU) started measuring the TSPs it was at a distance 5–7AU from the shock (Washimi et al. 2007), indicating that the termination shock is further pushed in, in the southern hemisphere, by 9AU; and unrolling of the energetic particle spectra, where there is indication that the point of magnetic connectivity is furter away from V2 than for V1.

There is also the *radio emission at the heliopause* where in the last 20 years, V1 and V2 have been detecting radio emissions in the outer heliosphere at frequencies from 2 to 3 kHz (Kurth et al. 1984; Gurnett et al. 1993, Gurnett, Kurth, & Stone 2003). The radio emissions were detected each solar cycle: first in 1983–84 during the solar cycle 21 (Kurth et al. 1984), second in 1992-94 during solar cycle 22 (Gurnett et al. 1993), and most recently in solar cycle 23 (Gurnett, Kurth, & Stone 2003). The currently accepted scenario is that the radio emissions are generated when a strong interplanetary shock produced by a period of intense solar activity reaches the vicinity of the heliopause and move into the interstellar plasma beyond (Gurnett, Kurth, & Stone 2003; Gurnett & Kurth 1995). Radio direction-finding measurements from V1 and V2 have been used to determine the positions near the heliopause at which the radio emission are generated (Kurth & Gurnett 2003). The sources lie along a line that passes near the nose of the heliosphere, roughly parallels the galactic plane. The GAL plane is 120° from the ecliptic plane. Based on the fact that the galactic magnetic field is oriented nearly parallel to the galactic plane, Kurth & Gurnett (2003) suggested the local interstellar magnetic field (in the local neighborhood of the Sun) was also parallel to the galactic plane.

Finally the *Flows in the Heliosheath* also indicate asymmetries. The termination shock separates the supersonic solar wind from the subsonic solar wind. Subsonic flows are sensitive to the obstacle ahead. Therefore, beyond the termination shock the flows will immediately be sensitive to the shape of the heliopause and start deflecting in response. The shape of the heliopause is affected by the pressure of the local interstellar magnetic field. The measured flows by V2 can probe additional asymmetries.

3. 3D MHD SIMULATIONS RESULTS

The model that we used in Opher et al. (2006, 2007, 2008) is based on the BATS-R-US code, a three-dimensional magnetohydrodynamic (MHD) parallel, adaptive grid code developed by University of Michigan (Gombosi et al. 1999) and adapted by Opher et al. (2003, 2004) for the outer heliosphere problem. Since we were interested in the global properties of the heliosphere, we used a coarse grid with cells sizes ranging from 1.5AU to 20AU. The inner boundary was set at 30 AU and the outer boundary was from −1500 AU to 1500 AU in the y and z direction; and from −800 AU to 800 AU in the x direction. The solar magnetic field axis was aligned with the solar rotation axis with a 26 days solar rotation period. The solar wind was taken as uniform at 450 km/s; only the ionized component was included. The parameters of the solar wind at the inner boundary (30AU) are $n = 7.8 \times 10^{-3}$ cm^{-3}, $T = 1.6 \times 10^3 K$ and a Parker spiral magnetic field with $B = 2\mu G$ at the equator. For the interstellar wind, we used $n = 0.07$ cm^{-3}, and $T = 10^4 K$ (Frisch 1996). The interstellar magnetic field (BISM) magnitude is taken to be BISM $=1.8\mu G$ (with the y component of BISM less than 0). The coordinate system has the z-axis as the solar rotation axis of the sun, the interstellar velocity direction in the x direction, with y completing the right handed coordinate system. In this coordinate system β is the angle between the interstellar magnetic field and the solar equator and α is the angle between the interstellar magnetic field and interstellar wind velocity. In this coordinate system, V1 is at 29.1° in latitude and 178.4° in longitude and V2 is at −31.2° and 213.4° in longitude, which ignores the 7.25° tilt of the solar equator with respect to the ecliptic plane.

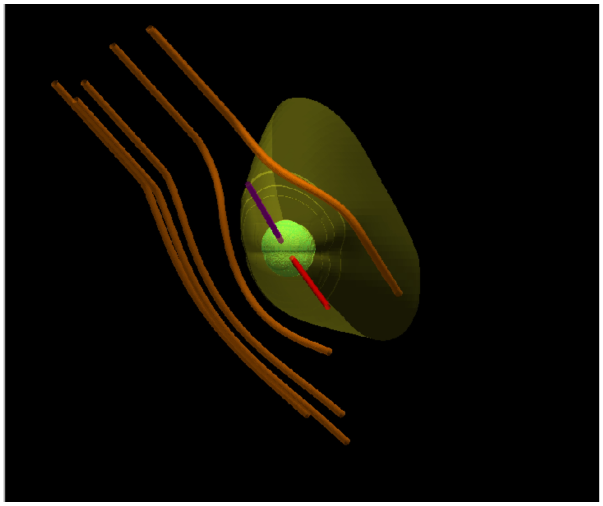

Fig. 1. Iso-surface of the Heliopause at log T=11.5 (yellow). The green iso-surface is the termination shock and the pink and red are, respectively the trajectory of V1 and V2. The orange field lines are the interstellar magnetic field in the HDP plane.

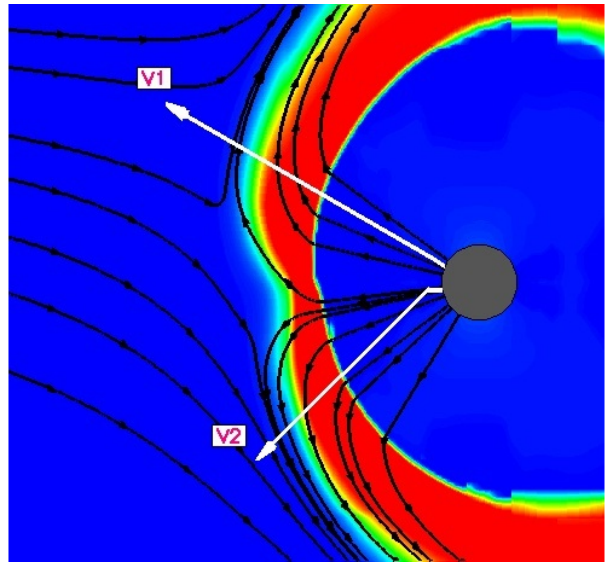

Fig. 2. Meridional cut showing the contours of the temperature. The black streamlines are the flow streamlines.

The interstellar magnetic field is frozen into the interstellar plasma that is deflected around the heliopause, causing the field to drape over the heliopause. If the plane of the interstellar magnetic field is not in the meridional plane of the Sun, and the angle between the interstellar magnetic field and interstellar velocity is non zero, it should break the symmetry of the heliosphere. This should be seen in the distortion of the heliopause and the termination shock. The shape of the heliopause is distorted by the pressure of the local interstellar magnetic field. For intensities around a few microgauss, the ambient interstellar magnetic pressure is comparable to the gas pressure, with the magnetic pressure increasing further in those regions where the interstellar flow decreases as it approaches the heliopause. The heliopause surface will vary with the orientation and strength of the local interstellar magnetic field.

Figure 1 indicates that the heliopause is strongly influenced by the interstellar magnetic field direction; the heliopause is asymmetric both north/south and east/west and has a plane of symmetry approximately parallel to the plane of the local interstellar magnetic field. The orange field lines are the interstellar magnetic field lines. The yellow surface is the heliopause and the green iso-surface is the termination shock. The trajectory of V1 and 2 are shown in magenta and red, respectively. At the heliopause due to the slow down of the plasma flow and piling up of the interstellar magnetic field the intensity of the magnetic field outside the heliopause is larger at the southern hemisphere than that at the northern hemisphere (Figure 2).

With our model (Opher et al. 2006, 2007, 2008) we have shown that the presence of an interstellar magnetic field is able to explain the different asymmetric signals as described above (in § 2). Additionally, we were able to constraint the direction of the interstellar magnetic field since we showed that the asymmetries both in the heliopause and in the terminarion shock are strongly dependent on the plane of the interstellar magnetic field. We considered several directions of interstellar magnetic field: the hydrogen deflection plane (HDP) that is 60° counterclockwise from the solar equatorial plane; the galactic plane (GAL) that is 120° counterclockwise from the solar equatorial plane; and the plane perpendicular to the galactic plane (PPG) that is 44° counterclockwise from the solar equatorial plane. The orientation of the magnetic field is also constrained by the angle between the interstellar magnetic field and interstellar velocity. We varied this angle as well (between $0 - 90°$).

The direction that can explain the different observations, indicating that there is a global asymmetry, is that the orientation of the local interstellar magnetic field in a plane inclined $60° - 90°$ from the large scale plane of the interstellar magnetic field (with $\alpha = 30° - 45°$). We investigated both the magnitude of 1.8 nT and 2.4 nT. All the orientations assumed the y component of the magnetic field as negative. This can have influence on the reconnection rate at the heliopause (between different solar cycles).

We showed that a field in the HDP-PPG plane will distort the TS such that the TSPs will stream inward at V2; which was later confirmed (Cummings et al. 2005; Decker et al. 2008; Stone et al. 2008). The model explained the outward streaming of the TSPs at V1. It also predicted the distance of the TS as being closer in the southern hemisphere by 10 AU (see Figure 3). We show (Opher et al. 2007) that for an interstellar magnetic field in the GAL the TS is distorted in the opposite direction, such that the TSPs stream inward towards V1 opposite to what was observed (Cummings et al. 2005). Additionally the model also predicted that V1 will be 2–3 AU from the shock and V2 will be 7–10 AU. The model also explained the difference in unrolling of the energetic particles and the location of the radio sources. Assuming a spherical interplanetary shock, the tangential field condition for the radio sources translates to $Br = 0$ with Br being the radial component of the interstellar magnetic field. For each modeled direction of the interstellar magnetic field, we compared the expected location of the radio sources (Br=0 at the heliopause) with the observed location of the radio sources detected by V1 and 2. With BISM parallel to GAL (with $\alpha = 45°$), the region where $Br = 0$ is almost perpendicular to the galactic plane, which is inconsistent with the radio observations. An interstellar magnetic field perpendicular to the galactic plane (PPG plane, with $\alpha = 30°$) produces the best agreement with the radio observations by Voyager. The HDP orientation differs from PPG by only 16° and is also in general agreement. The offset of $\approx 15°$ between the observations and the region with $Br = 0$ for the model in best agreement indicates that the accuracy of the model is not adequate to distinguish between the PPG and HDP field orientations (see Figure 4). Finally, the model is also in agreement with the heliosheath flows. We used the heliosheath flows from days 277–320 of 2007, when the heliosheath flows were relatively quiet before a transient arrived on day 320. The flows are mainly radial with the ratios $VN/VR = -0.30$ and $VT/VR = 0.35$. (RTN system is a local cartesian system centered at the spacecraft with unit vector $\mathbf{R}$ radially outward from the Sun, $\mathbf{T}$ is $\mathbf{Z} \times \mathbf{R}$, where $\mathbf{Z}$ is the rotation axis of the Sun and $\mathbf{N} = \mathbf{R} \times \mathbf{T}$. We perform an unweighted average calculation so as to equally weigh each day. The mean angle $\theta = \tan^{-1}(VN/VT)$ for the period is $-38.7°$ and an uncertainty of 2.1°. For BISM parallel to PPG or HDP and small $\alpha(30° - 45°)$, the

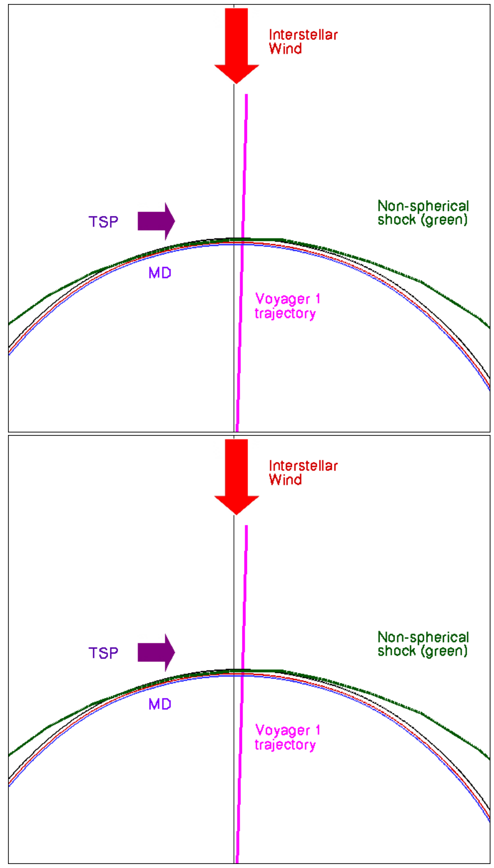

Fig. 3. Streaming of termination shock particles (TSPs) (magenta arrows) from the minimum distance of the termination shock to the Sun (MD) to Voyager 1 (V1) and 2 (V2), for the interstellar magnetic field in the a) hydrogen deflection plane (with $\alpha = 45°$). The interplanetary magnetic field is carried radially outward by the solar wind, forming a spiral on a conical surface. The conical surfaces coinciding with the V1 and V2 trajectories are shown. V1 and V2 are first connected to the shock along the spiral magnetic field lines that contact the shock at the point of its minimum distance from the Sun (labeled MD). The green line indicates the non-spherical termination shock. Upper panel shows the solar magnetic field lines that intersect Voyager 1; the field line intersecting the shock where V1 crosses the shock is labeled 0 AU (black) with red and blue indicating, respectively, magnetic field lines 2.0 AU and 3.0 AU upwind from the 0 AU line. The magenta arrow indicates the streaming direction of the termination shock particles from the shock along the field line to V1. Bottom panel shows similar plot for V2, showing field lines 3.0 and 5.0 AU upwind of the 0 AU line. Note that in both views the solar magnetic field spirals clockwise with increasing distance outward.

angle agrees with the observed flows ($-28.6°$ and $-37.4°$ respectively).

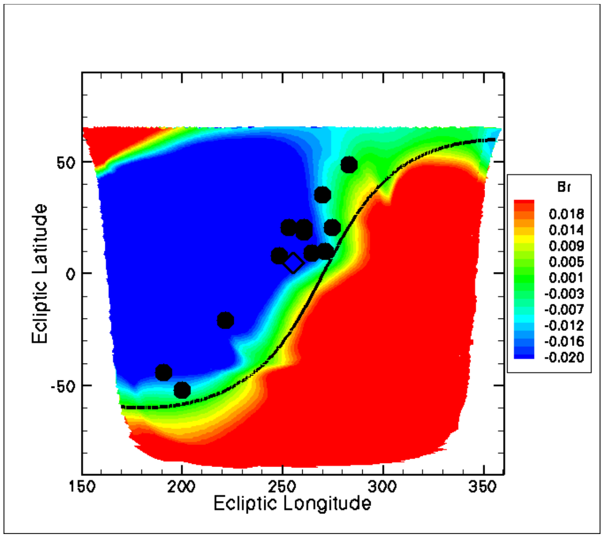

Fig. 4. The radio source location as a function of the interstellar magnetic field (BISM) direction for BISM, in the HDP plane (with $\alpha = 45°$). It shows the surface of the heliopause converted to ecliptic coordinates. The direction of the nose of the heliosphere (diamond) and the galactic plane (black lines) are indicated for reference. The green band is the location of the radio sources (at Br=0)

4. DISCUSSION AND CONCLUSIONS

We showed in our recent works summarized here, that an interestellar magnetic field can distort the heliosphere explaining the different observational asymmetries detected. We were able to constrain the direction as being in a direction different from the orientation in large scale that is in the plane of the disk of the galaxy; but rather in a plane inclined $60° - 90°$ from that plane with a small angle ($30° - 45°$) between the interstellar magnetic field and velocity. However, future work needs to be done to include and access the effect of additional factors not included in the model. Some of these factors are the *Neutral H atoms*: The model does not include the neutral hydrogen atoms that interact with the ionized component by charge exchange. This can affect the quantitative amount of asymmetry (Pogorelov et al. 2007). An important aspect is that the neutrals H have a long mean free path and need to be treated kinetically. The inclusion of the neutral H atoms will tend to symmetrize the solution and quantitatively affect the degree of asymmetry as seen recently by Pogorelov et al. 2008 (see also Izmodenov et al. 2005) where the neutrals tend to rotate the plane of the distorted heliopause away from the plane of the local interstellar magnetic field by $\approx 15°$. From our previous work, the plane of the local interstellar magnetic field 60° to 90° from the galactic plane (rotated clockwise from a view from the Sun) agrees with the particle streaming and radio observations; with the plane 90° from the galactic plane having the best agreement. With the inclusion of the neutrals, we predict that the plane of the local interstellar magnetic field will be between 60° to 90° from the large scale plane of the interstellar magnetic field. Another factor is the *Solar Cycle*: As noted above, the solar cycle affects the solar wind and the magnetic field imbedded in it. The heliospheric current sheet (HCS) is known to change its inclination with respect to the solar rotation axis as the solar cycle progresses. The flows produced by the HCS and the solar cycle in the heliosheath have not yet been studied in detail. Opher et al. (2003, 2004, 2005) had investigated the effect of the current sheet in the heliosheath. This requires a very high numerical resolution, a challenge for future studies. With the solar cycle there will be also more global merger interaction regions (that result in coronal mass ejections) that will disturb this interaction as well. However, we expect that although details of the heliosheath structure will be affected, a global asymmetry still will remain produced by an external agent, the interstellar magnetic field.

An interesting new factor that came from the observations by Voyager 1 and 2 is that the termination shock is a *Energetic-Particle Mediated Shock* (Richardson et al. 2008). The temperature at the sheath was significantly lower than the value expected. The heliosheath plasma has only about 20% of the pre-shock solar wind energy. The remaining energy must be transmitted to some other components of the heliosheath, possible the pick up protons or other particles and waves. These aspects should be included in future modeling of the interaction of the solar system with the interstellar medium.

Finally, our results show that the fact that the orientation of the local magnetic field differs from the large scale magnetic field could be a result in a turbulence in the interstellar medium (Jokipii et al. 2007) or a consequence of a local distortion in the Local Bubble. In any case these works show the importance of magnetic field effects in the interaction of magnetized winds and shocks and should be extended to other astrophysical objects.

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