Approximate Mirror Symmetry in Heliospheric Plasma Flow Explains \textit{VOYAGER 2} Observations

J. Grygorczuk,$^\ast$ A. Czechowski$^\ast$ and S. Grzedzielski$^\ast$

$^\ast$Space Research Centre PAS, ul.Bartycka 18A, 00-716 Warszawa, Poland

Accepted Year Month Day. Received 2015 February Day; in original form 2015 February 11

ABSTRACT

The Sun and the undisturbed interstellar magnetic field and plasma velocity vectors ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$) define a mirror symmetry plane of the flow at large heliospheric distances. We show that for the $\mathbf{B}_{\text{IS}}$ direction defined by \textit{IBEX} Ribbon center, the radial direction of \textit{Voyager 2} over the last decade, and the (thermal proton) plasma velocity measured by the spacecraft since 2010.5, are almost parallel to the ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$)-plane, which coincides in practice with the Hydrogen Deflection Plane. These facts can be simply explained if approximate mirror symmetry is also maintained on the inner side of the heliopause. Such approximate symmetry is possible since the solar wind ram pressure is almost spherically symmetric and the plasma beta value in the inner heliosheath is high. In the proposed symmetry, the plasma flow speed measured by \textit{Voyager 2} in the inner heliosheath is expected to rotate more in the transverse than in the polar direction (explanation alternative to McComas & Schwadron (2014)), in evident agreement with available spacecraft data (our Fig.1).

Key words: Sun: heliosphere – solar wind – ISM: magnetic fields.

1 INTRODUCTION

Both \textit{Voyager} spacecraft continue their journey away from the Sun through the heliospheric interface region. \textit{Voyager 1} ($\text{V1}$) has already crossed the heliopause (HP) (Burlaga et al. 2008; Heerikhuisen & Pogorelov 2011; Katushkina et al. 2011). In current heliospheric modeling, the HDP is generally identified with the ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$) plane (Izmodenov et al. 2005; Stone et al. 2013; Gurnett et al. 2013), the boundary that separates the heliospheric plasma from the interstellar one, and is now operating in the interstellar medium at a distance of 130 AU (early 2015) from the Sun. \textit{Voyager 2} ($\text{V2}$), at 106.8 AU from the Sun, still penetrates the inner heliosheath region.

At the time when \textit{Voyagers} commenced their outward journey neither the strength nor direction of the interstellar magnetic field (ISMF, $\mathbf{B}_{\text{IS}}$) was known. In 2009, the \textit{Interstellar Boundary Explorer} (\textit{IBEX}) discovery of the ribbon (McComas et al. 2009) indicated the probable direction of the ISMF as the ribbon center (RC) (Funsten et al. 2009).

2 GEOMETRICAL COINCIDENCES

It is noteworthy that each of the \textit{Voyagers} trajectories happens to have a special orientation (instances of geometrical coincidence) with respect to the direction defined by the RC. The first such case was discussed in Grygorczuk, Czechowski & Grzedzielski (2014). In that paper we pointed out that $\text{V1}$ trajectory shares the same heliographic latitude ($\sim 34.5^\circ$) with the RC. This led us to a simple explanation why the magnetic field directions measured by $\text{V1}$ on both sides of the HP were so similar.

In the second case, to be discussed now, the $\text{V2}$ spacecraft trajectory direction is close (within $\sim 2^\circ$) to the plane (the ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$) plane) which contains the position of the Sun and the directions of undisturbed interstellar plasma flow ($\mathbf{V}_{\text{IS}}$) and the \textit{IBEX} RC ($\mathbf{B}_{\text{IS}}$). This plane was pointed out (Grygorczuk et al. 2011) to be close to the hydrogen deflection plane (HDP, the plane defined by the interstellar H and He inflow velocity vectors, Lallement et al. (2007, 2010)). In current heliospheric modeling, the HDP is generally identified with the ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$) plane (Izmodenov et al. 2005; Pogorelov & Zank 2006; Opher et al. 2006; Pogorelov et al. 2008; Heerikhuisen & Pogorelov 2011; Katushkina et al. 2013).

If the supersonic solar wind were fully spherically symmetric with no interplanetary magnetic field, the ($\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}}$) plane would obviously had been the mirror symmetry plane of the problem. The symmetry is broken for a number of causes: fast/slow wind, angle and time dependent solar activity, solar rotation, Parker magnetic field, etc. However, if these effects are relatively weak, an approximate mirror symmetry should be discernible also in the inner heliosheath.

In this letter we show that $\text{V2}$ measurements agree...
3 PLASMA VELOCITY OBSERVATIONS

The V2 trajectory inclination relative to the \((B_{IS},V_{IS})\) plane has been small from \(\sim 2005\) (Fig. 1, Fig. 2). At the end of 2014 it is still less than 2° (Fig. 2). Fig. 3 shows that, over the last 10 years, excepting about two years after the termination shock crossing by V2, the plasma flow vectors measured by V2 have been approximately parallel to \((B_{IS},V_{IS})\) plane, a clear confirmation that this plane is indeed an approximate symmetry plane of the flow.

In Figure 1 the V2 positions and measurements are shown projected on the all-sky map. We assume that the \(B_{IS}\) direction is the same as the position of the RC according to Funsten et al. (2009) (filled square), which is close to the energy-averaged RC position (Funsten et al. 2013) (empty square). The great circles representing the \((B_{IS},V_{IS})\) plane (red line) and the HDP (black line) are then quite close to each other. For measurements between 2010 and 2014, the V2 positions (empty circles) and the yearly averaged plasma velocity vectors (black crosses) are with this interpretation. Since V2 position is close to the \((B_{IS},V_{IS})\) plane, the plasma velocity field measured by V2 should be approximately parallel to this plane. We find that this is indeed the case for the plasma flow vectors which come from V2 measurements since 2010.5.
shown. The red crosses show the six-month averages of plasma velocity direction which was instrumentally corrected (Richardson & Decker 2014).

It can be seen how well the measured velocity directions follow the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane being also close to the HDP. For comparison, we also show (by the dotted line) the position of the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane for another choice of the \(\mathbf{B}_{1S}\) direction corresponding to the position of RC obtained from the highest energy IBEX data (Funsten et al. 2013) (triangle). It is clear that the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane defined in this way is not a symmetry plane of the flow.

4 DISCUSSION

The restriction of the plasma flow vector at \(V_2\) to the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane explains also the observation by McComas & Schwadron (2014) that, as \(V_2\) moves deeper into the heliosheath, the flow speed rotates more in the transverse than in the polar direction. In Figure 4 this would be represented by the flow direction moving along the great circle (representing the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane) away from the heliospheric nose and from the \(V_2\) trajectory direction and consequently towards the region where the circle is approximately tangent to the local heliographic parallel. The flow direction would therefore have a substantially larger transverse component than the direction of \(V_2\) trajectory, while staying (approximately) in the same plane as the \(V_2\) trajectory and \(\mathbf{V}_{1S}\) direction.

The symmetry relative to the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane (determined solely by the parameters of the local interstellar medium) must be to some degree broken by the structure of the inner heliosphere. In particular, the solar wind is known to consist of two components (slow and fast) with the distribution dependent on the heliographic latitude. However, the solar wind energy flux (ram pressure) is more symmetric (Le Chat et al. 2012), which may reduce the effect on the global heliospheric structure.

The solar magnetic field (in particular, the Parker spiral) is not symmetric relative to the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane. However, its effect on the bulk plasma flow in the heliosheath is likely to be small. It was shown by McComas & Schwadron (2014) based on separation of the IBEX ENA intensities into a part coming from the energetic ions outside the HP (IBEX Ribbon) and another part due to ions in the inner heliosheath (Global Distributed Flux) (Schwadron et al. 2014), that the energy density of the heliosheath plasma, determined mainly by the non-thermal ions, exceeds by far the magnetic energy density estimated from the \(V_1\) and \(V_2\) data (plasma-beta \(\sim 20\)). This means that the magnetic field in the heliosheath can not induce a significant departure from the symmetry impressed by the external situation.

McComas & Schwadron (2014) relate the \(V_2\) measurements of the heliospheric plasma flow to distribution of the integrated plasma pressure inferred from IBEX ENA observations (Schwadron et al. 2014). They identify the region of high heliosheath plasma pressure (approximately represented by a blue contour in our Figure 1) and argue that the plasma flow is directed away from the point of maximum pressure (blue circle in our Figure 1), which differs from the position of the heliospheric nose (He inflow direction). However, we note that, in this scenario, the flow

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**Figure 3.** The inclination angle of the proton velocity vectors to the \((\mathbf{B}_{1S}, \mathbf{V}_{1S})\) plane versus time. Shown are daily and 25-day averages (dots and line, respectively). Crosses correspond to the angles obtained using the corrected plasma velocity vectors (Richardson & Decker 2014). The \(\mathbf{B}_{1S}\) and \(\mathbf{V}_{1S}\) are defined as in Figure 1.

**Figure 4.** The angle between the proton velocity (measured by \(V_2\) between 1990 and 2015) and the \(V_2\) direction. Shown are daily and 25-day averages (dots and line, respectively). Crosses correspond to the angles obtained using the corrected plasma velocity vectors (Richardson & Decker 2014).

**Figure 5.** Blow-up of part of Figure 4 showing the evolution of observed plasma velocity direction during \(V_2\) journey outwards. The crosses show the \(V_2\) data corrected for the instrument response (Richardson & Decker 2014) (six-month averages, red) and obtained from the raw data (yearly averages, black). The data points are numbered (corrected data) or marked by letters consecutively in time. The numbers indicate half year periods (1: 2010.25, 2: 2010.75, 3: 2011.25, 4: 2011.75, 5: 2012.25, 6: 2012.75, 7: 2013.25, 8: 2013.75, 9: 2014.10). The 9th period is shorter. The letters correspond to years (a: 2010, b: 2011, c: 2012, d: 2013, e: 2014).
velocity direction would lie in the plane defined by the V2 position and the point of maximum pressure (dashed blue line in our Figure 1).

As shown in Figure 4, V2 measurements follow the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane. Combination of this (approximate) symmetry with the geometrical coincidence of V2 position (in years 2013-2015) with the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane explains therefore in a natural way the averaged observed plasma velocity vectors (crosses in Figure 1) without recurring to the idea of heliosheath plasma being pushed away from the excess pressure region near the nose as speculated in McComas & Schwadron (2014).

Nevertheless, McComas & Schwadron (2014) idea that the flow should be linked with the pressure distribution is important. If a strict mirror symmetry relative to the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane were valid, one would expect that the high plasma pressure region should have the same symmetry. Figure 1 shows that the high pressure region is bisected by the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane, but not into equal parts. However, the edge of the high pressure region near the V2 position is approximately perpendicular to the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane. This implies that the local pressure gradient is likely to cause the plasma flow along the plane, as observed by V2.

The asymmetry of the pressure distribution obtained by Schwadron et al. (2014) and used by McComas & Schwadron (2014) is not necessarily in conflict with our results. This is because the pressure they consider is integrated over the line-of-sight (LOS). It is therefore affected also by the region close to the termination shock, where V2 velocity measurements deviate significantly from the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane (see Figures 3 & 4). The velocity measured during first half of the year 2010 is in fact close to the dashed blue line in Figures 1 and 3, which, as we have pointed out above, corresponds to the pressure distribution used by McComas & Schwadron (2014). The symmetry with respect to the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ may then hold for the local (not integrated) pressure distribution at larger distances from the termination shock, where V2 velocity measurements follow the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane.

5 CONCLUSIONS

V2 position near the HDP plane permits a check of mirror symmetry of the heliosheath (inner and outer) plasma flow with respect to this plane. Our main result is that V2 observations are consistent with this symmetry.

Assuming that the $\mathbf{B}_{\text{IS}}$ direction is given by the IBEX RC and the $\mathbf{V}_{\text{IS}}$ direction by the neutral interstellar He flow, the plasma velocity measured by V2 lies in the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane (almost identical with the HDP). As V2 approaches the heliopause, the direction of plasma velocity rotates, still within the $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane. This explains why the transverse component of the plasma velocity at V2 becomes larger than the polar one.

The V2 data suggest that the mirror symmetry with respect to $(\mathbf{B}_{\text{IS}}, \mathbf{V}_{\text{IS}})$ plane is restricted to the outer part of the inner heliosheath. The plasma pressure distribution obtained from IBEX data is integrated over the full LOS length (Schwadron et al. 2014). This may explain why it departs from this symmetry.

Because V2 location is approximately in the symmetry plane, we expect that the heliospheric plasma flow at the heliopause will be approximately parallel to the interstellar plasma flow just outside the heliopause, and anti-parallel to the interstellar magnetic field. Figures 1 and 5 show that the plasma velocity at V2 location in fact evolves towards the anti-field direction.

At the heliopause, the draped ISMF would, in general, differ from the undisturbed ISMF. However, V2 trajectory direction is close to perpendicular (97°) relative to the $\mathbf{B}_{\text{IS}}$. In Grygorczuk, Czechowski & Grzedzielski (2014) we showed that the magnetic field immediately outside the heliopause observed by V2 should then be similar in direction to the undisturbed ISMF (RC).

ACKNOWLEDGMENTS

This work was supported by the Polish National Science Center grant 2012-06-M-ST9-00455.

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Heliospheric Symmetry Explains VOYAGER 2 Observations

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