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The Heliosphere: What Did We Learn in Recent Years and the Current Challenges

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As the Sun moves through the interstellar medium it carves a bubble called the heliosphere. A fortunate confluence of missions has provided a treasury of data that will likely not be repeated for decades The measurements in-situ by the Voyager spacecrafts, combined with the all-sky images of the heliospheric boundaries by the Interstellar Boundary Explorer and CASSINI missions have transformed our understanding of heliosphere. In particular one of the first surprises was that both Voyager spacecrafts found no evidence for the acceleration of the anomalous cosmic rays (ACRs) at the termination shock as expected for approximately 25 years. Another challenge are the energetically particles intensities and the plasma flows that are dramatically different at Voyager 1 and 2. There are several other observations that are key challenges to the heliospheric models that indicate that the nature of the heliosheath (the region where the solar wind is subsonic) is much more complex than thought, such as (a) Why the azimuthal magnetic flux is not conserved along the Voyager 1 trajectory? (b) What causes the flow stagnation region seen at Voyager 1? (c) What causes the unexpected observation of a depletion-region beginning in 2012 at Voyager 1? These observations point to the need to move past the standard description of the heliosphere. In this paper, I will review the state-of-the art of our understanding of this "new heliosphere". In late 2012 Voyager 1 observed several events that indicated a magnetic connectivity between the heliosheath magnetic field and the interstellar medium magnetic field; where the energetic particles of the heliosheath leaked out while the galactic cosmic rays penetrated the heliosheath. With the radio observations confirming densities of the interstellar medium, there is a consensus that Voyager 1 left the heliosphere in September 2012 and entered the

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interstellar medium. We will review as well our current understanding of the nature of the heliopause. The knowledge gain from the edge of the heliosphere will have consequences for other astrospheres and astrosheaths where the magnetic nature of the winds could be much more complex that previously thought.

1 Introduction

"O Mar sem fim sera grego ou troiano, o mar sem fim sera português; The Ocean that has an end will be greek or trojan; the Ocean without an end will be portugues", Fernando Pessoa.

As the Sun moves through the interstellar medium its solar wind carves a bubble called the *heliosphere*. The solar wind is supersonic with wind speeds around 400–800 km/s and as it approaches the edge of the *heliosphere* it goes through a shock, called the termination shock (TS). Beyond the termination shock the solar wind is subsonic as it approaches the very edge that separates the solar wind domain from the interstellar medium (ISM), called the *heliopause* (HP). The HP is thought a tangential discontinuity where the pressure of the solar wind equalizes the pressure from the ISM. The structure of the heliosphere with its different components is seen in Fig. 1.

The *termination shock* (*TS*) marks the boundary where the supersonic solar wind decelerates to slower subsonic speeds. The *heliopause* (*HP*) is the boundary separating the hot solar wind and the colder, denser interstellar plasma and is often considered as the boundary of the heliosphere. The region between the TS and HP with decelerated compressed hot solar wind is called the *heliosheath*. The interstellar medium is disturbed by the interaction with the heliosphere. Depending on the properties of the local interstellar medium a *bow shock* or *bow wave* forms in the interstellar plasma in front of the heliosphere.

There are several basic features of the very nature of heliosphere that are still not well understood. These aspects stem from the very "shape" of the heliosphere; the extent of its tail; the nature of the heliosheath; the structure of the interstellar medium just ahead of it. Both the in-situ measurements by Voyager spacecrafts and the remote energetic neutral atoms (ENA) maps from IBEX and CASSINI help us solve some of the problems but brought many more puzzles. These missions will continue to unravel more surprises and help us constrain some of the models. However only with a revisit of this region with a modern instrumentation; we will be able to shade light on the very fundamental aspects of our home within the galaxy, the heliosphere.

The shape of the heliosphere and the structure of the interface are determined by various physical processes. Interstellar hydrogen atoms penetrating into the heliosphere interact with the solar wind protons in a charge exchange process creating an energetic population of ions called *pick up ions*. Early theoretical studies (Baranov and Malama 1993) predicted that the charge exchange process decelerates the solar wind and pushes the heliosphere boundary toward the Sun.

Both solar wind and interstellar medium are magnetized and the magnetic field is one of the key elements determining the structure of the outer heliosphere. A tilted interstellar magnetic field distorts the shape of the heliosphere producing the asymmetry of the TS and HP (Fig. 2). The B_{ISM} distort the heliosphere pushing the southern side closer to the Sun. The heliospheric asymmetry was confirmed by the crossing of the TS by Voyager 2, 10 AU closer to the Sun than V1 (Stone et al. 2008), although part of the asymmetry could be due to time-dependent effects (as argued by works such as Pogorelov et al. 2009).

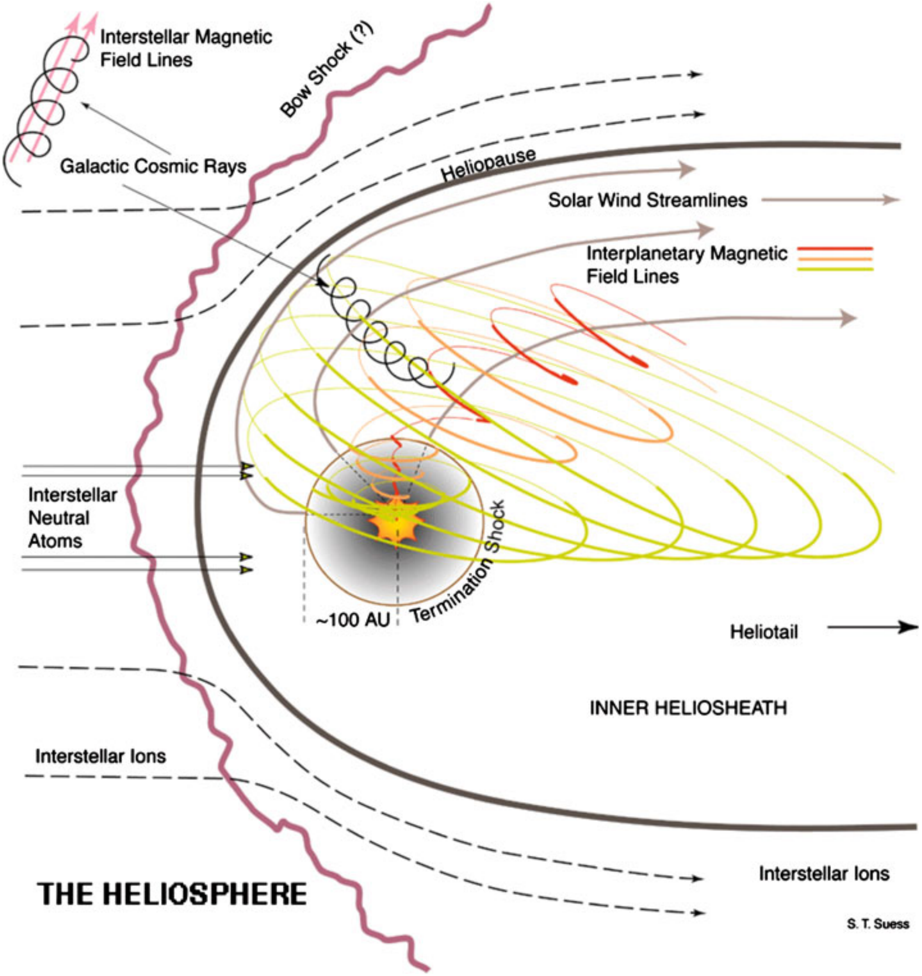


Fig. 1 Structure of the region where solar wind interacts with the ISM. SOURCE: Jet Propulsion Laboratory (1999a), courtesy of Steven T. Suess

The very nature and direction of the magnetic field ahead of the heliosphere is being debated. In order to explain the observed heliospheric asymmetries seen by Voyager (Opher et al. 2009; Izmodenov et al. 2009) suggest a strong interstellar magnetic field with the strength of ~ 4 μG and north-south component producing a tilt angle ~10–20° relative to the interstellar flow direction v_{ISM} (in respect to the Sun). Anther constrain on the B_{ISM} is the deflection of the H atoms with respect to the He atoms (Lallement et al. 2005, 2010) that constrain the plane B–V of the $B_{ISM} - v_{ISM}$ to be in what is referred as the "Hydrogen Deflection Plane" (60° from the ecliptic plane). In 2009, the Interstellar Boundary Explorer (IBEX) revealed that the energetic neutral atoms maps produced a ribbon of higher intensity around energies ~1 keV (McComas et al. 2009). There is an ongoing debate where the ribbon is produced and by which mechanism; although generally it seem to be organized by the direction where the radial component of B_{ISM} goes to zero ($B_{ISM} * r = 0$). Works that try to fit the IBEX ribbon by mechanisms that produce them outside the Heliopause (e.g.,

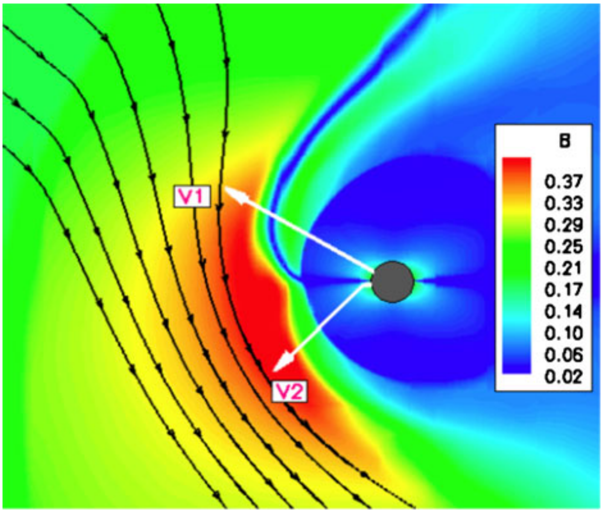


Fig. 2 Tilted interstellar magnetic field (*black curves*) creates asymmetric heliosphere. Trajectories by the *white arrows* of Voyager 1 and 2 are shown by *white arrows* (Opher et al. 2006)

Heerikhuisen et al. 2010); use a direction where the title angle is larger ∼30–40° relative to the interstellar flow direction and intensity not exceeding 3.5 μG with a B–V plane that differ from the HDP plane by 20°. These mechanisms assume secondary charge exchange in which the energetic neutral atoms (ENAs) charge exchange in the plasma outside the heliopause creating pick-up ions (PUIs). It is assumed that these PUIs will retain a ring-beam distribution with the velocity component along the interstellar magnetic field for sufficient time until they are charge exchanged again. These "secondary" ENAs will be enhanced in the locations where $B_{ISM} * r = 0$. This debate can only be solved as the Voyager mission or a future one will adventure farther into the interstellar medium ahead of the Heliosphere.

Another debate is the extent with which the influence of the heliosphere in the local interstellar medium and how B_{ISM} drape around the heliosphere; if as an ideal draping (i.e., draping on a surface without interacting with the surface itself) or mediated by another process (such as temporal instabilities; or reconnection). The expected direction of B_{ISM} implies that the interstellar magnetic field is not parallel to the solar Parker spiral magnetic field, which has an east-west direction. The models predicted the dramatic rotation of the magnetic field direction after the heliopause crossing. However when Voyager 1 crossed the HP at the distance of ∼120 AU in August 2012 observations revealed completely unexpected behavior of the magnetic field. The magnetic field magnitude increased from 1 μG in the heliosheath to ∼4 μG outside the HP but there was almost no change in the direction of the magnetic field. These data sparked a search for physical processes responsible for such behavior of the magnetic field at the heliosphere boundary. Recent work (Opher and Drake 2013) suggested that the draping of the interstellar magnetic field B_{ISM} around the HP is strongly affected by the solar wind magnetic field. As it approaches the heliopause B_{ISM} twists and acquires the east-west component. The physical reasons of such interaction of the heliospheric and interstellar magnetic fields remain to be understood. Some recent works argue that the observed direction of B_{ISM} outside the HP can be explained by draping around an ideal surface (Isenberg et al. 2015). Others explain the change in direction by temporal instabilities (Krimigis et al. 2013; Florinski et al. 2015; Pogorelov et al. 2014).

Another recent debate is the very shape of the heliosphere and the extent of its tail. The long accepted view of the shape of the heliosphere is that it is a comet-like object (Parker 1961; Baranov and Malama 1993) with a long tail opposite to the direction in which the

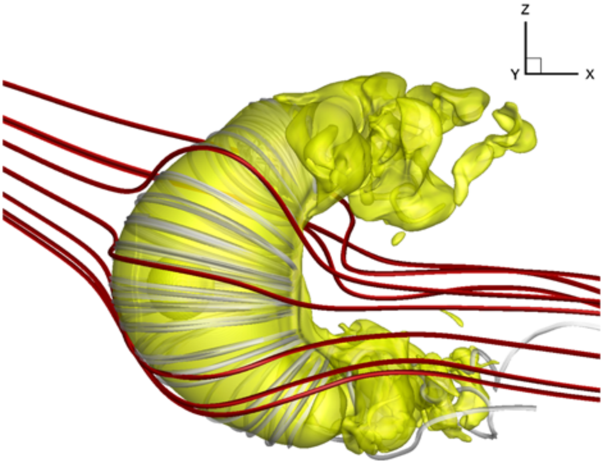


Fig. 3 Two-lobe structure of the heliosphere. *Yellow surface* shows the heliopause surface. *Grey curves* show the solar magnetic field lines, *red curves*—interstellar magnetic field lines (Opher et al. 2015)

solar system moves through the local interstellar medium (ISM). The solar magnetic field at a large distance from the Sun is azimuthal, forming a spiral (the so called "Parker spiral") as a result of the rotation of the Sun. The traditional picture of the heliosphere as a cometary-like structure comes from the assumption that even though the solar wind becomes subsonic at the termination shock as it flows down the tail, it is able to stretch the solar magnetic field. Opher et al. (2015) argued based on MHD simulations, that the twisted magnetic field of the Sun confines the solar wind plasma and drives jets to the north and south very much like some astrophysical jets (Fig. 3).

The two lobes are formed by the magnetic tension of the solar azimuthal magnetic field that in the heliosheath resist being stretched by the subsonic flows. The ratio between the force stretching the magnetic field due to the flows and the magnetic tension (hoop stress) resisting the stretch is given by $\mathrm{F_{streatch}/F_{tension}} \sim \mathrm{P_{ram}/2P_B}$ where $\mathrm{P_{ram}}$ is the ram pressure and $\mathrm{P_B}$ is the magnetic pressure. In the heliosheath this ratio is <1 so the magnetic tension (hoop stress) is sufficient to resist the stretching by the flows and can collimate jets. The result is a tail divided in two separate plasmas confined by the solar magnetic field.

For our local interstellar medium (ISM), the pressure is not strong enough to force the two lobes in a single tail. For astrospheres where the ISM ram pressure is strong enough the two lobes might join in a unique tail.

In the heliosheath the plasma pressure is generally much higher than the magnetic pressure, so it might seem surprising that the magnetic field controls the formation and structure of the jets. As shown in Drake et al. (2015) the overall structure of the heliosheath is controlled by the solar magnetic field even in the limit in which the ratio of the plasma to magnetic field pressure, $\beta = 8\pi \mathrm{P/B^2}$, is large. The tension of the solar magnetic field produces a drop in the total pressure between the termination shock (TS) and the heliopause. This same pressure drop accelerates the plasma flow downstream of the TS into the North and South directions to form two collimated jets.

Other magnetospheres (such as Earth, Siscoe et al. 2004, and Saturn, Zieger et al. 2010; Jia et al. 2012) exhibit a two-lobe structure. These structures are not related to the phenomena discussed in this paper, but to reconnection of the down-tail component of the draped solar magnetic field that produces a dominant midtail x-line. The key ingredient here is the solar magnetic field that confines and collimates the solar wind and the ISM pressure that maintains the separation of the two lobes in the tail.

Astrophysical jets around massive black holes are thought to originate from Keplerian accretion disks and are driven by centrifugal forces (Blandford and Payne 1982). However, the jets in the case of the heliosphere are driven downstream of the termination shock similar to what was proposed for the Crab Nebula (Chevalier and Luo 1994; Lyubarsky 2002). In this region of subsonic flows, the magnetic tension (hoop) force is strong enough to collimate the wind. The tension force is also the primary driver of the outflow. (Fig. 3, Opher et al. 2015).

The overall two-lobe structure is consistent with the ENA images from IBEX that for the first time mapped the heliotail. Such images show two lobes (McComas et al. 2013) with an excess of low energy ENA (<1 keV) and a deficit at higher energy (>2 keV) around the solar equator. The ENA images from Cassini (Krimigis et al. 2009; Dialynas et al. 2013; at much higher energies, 5–55 keV) revealed intensities that were comparable in the direction of the nose and tail. The observers therefore concluded that the heliosphere might be "tailless" because the emission from these high-energy ENAs is believed to come from the heliosheath. The two-lobe heliosphere is in fact almost "tailless" with the distance down the tail to the ISM between the lobes being nearly equal to the distance toward the nose. McComas et al. (2013) interpreted the ENA tail measurements as a result of a slower wind to the fact that the Sun has been sending out fast solar wind near its poles and slower wind near its equator. With additional ENA measurements through an extended solar cycle it will be possible to distinguish between the two scenarios.

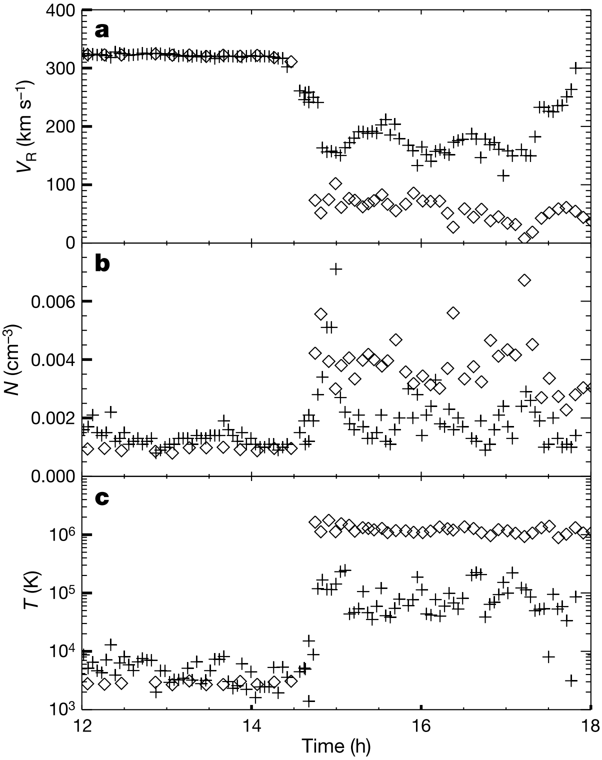
2 Termination Shock

Both Voyager 1 and 2 (V1 and V2) are now beyond the TS, V1 most likely beyond the HP, although there are works that disagree that V1 is beyond the HP (Fisk and Gloeckler 2013; 2014; McComas and Schwadron 2012; Schwadron and McComas 2013a).

The main disagreement stems from the magnetic field measurements that indicate that the magnetic field as measured by V1 didn't change direction across that boundary. We will come back to that later on when we discuss the HP. V2 is the only spacecraft (among the Voyagers) that carry a working plasma instrument (although the plasma flows in the RT plane can be inferred from the particle anisotropies from V1—Richardson and Decker 2014).

With the crossing of TS by V2 that carried the working plasma instrument, it become clear that the TS was not a just a one-fluid MHD perpendicular shock as previously expected. One of the surprises was that the heliosheath plasma temperature was much colder, by an order of magnitude than expected if all the energy upstream was transferred to the plasma thermal population (Richardson et al. 2008) (Fig. 4). The measurements downstream the TS are consistent with 80 % of the energy transferred to the suprathermal population, the pick up ions (Gloeckler et al. 2005; Zank et al. 1996). Pick-up ions, are not measured by Voyager spacecrafts. *In fact there is a gap in energy between the thermal plasma* (*at energies* <1 keV) *to 40 keV*, the lowest energy measured by the LECP instrument. It is also possible that electrons played an important role in the energy budget stilling part of the energy downstream (Zieger et al. 2015). Again there is a gap between what the plasma instrument measure ($\sim$ eV) to the lowest energies at LECP (30 keV). It is possible that hot electrons play an important role in the TS crossing and downstream in the heliosheath thermodynamics (Chalov and Fahr 2013; Chashei and Fahr 2013; 2014). This can only be resolved with a new visit to that region with proper instrumentation that bridge the gap in those energies; i.e., able to measure the suprathermal PUI population from 1 keV–40 keV and energetic

Fig. 4 From Richardson et al. (2008). The V2 data measured at TS (crosses), "in comparison with V2 data measured at Neptune's inbound bow shock crossing (*diamonds*). The solar wind parameters upstream of Neptune are normalized to those upstream of the TS; the timescales are identical. The solar wind speed (**a**; Neptune data divided by 1.3) at the bow shock fell by a factor of four but at the termination shock the speed decreased by a factor of only two. The density (**b**; Neptune data divided by five) at the bow shock increased by a factor of four, but at the termination shock by a factor of two. The major difference is in the temperature (**c**; Neptune data divided by two): at the bow shock it increased by a factor of 100, but at the termination shock by a factor of only ten. The differences between these two shocks are probably caused by the greater abundance of pickup ions at the TS



electrons in the same energy. Only then we will be able to definitively probe the structure of the TS and the thermodynamics of the HS.

3 Heliosheath

As Voyager 1 and 2 adventured into the region where the solar wind is subsonic, the helisheath (HS) it became clear that there are several observations that challenge our understanding of that region. While global models advanced rapidly in sophistication in the last decade, these models are still not able to predict self-consistently the flows, fields and particles behavior in the HS. Furthermore, none of the current standard global models predict the very thin HS (∼30–40 AU) implying that Voyager 1 (V1) did indeed cross the HP.

There are several observations that are key challenges to the heliospheric models:

(a) The flows at V1 and Voyager 2 (V2) are very different; (b) the presence of a flow stagnation region seen at Voyager 1; (c) the V1 observations suggest that the magnetic flux in the HS is not conserved; (d) the fact that the Anomalous Cosmic Ray (ACR) spectrum roll out well into the heliosheath; (e) the thin heliosheath; and (f) different behavior of energetic particles at V1 and 2; including dropouts of ∼1 MeV electrons and the most energetic ACRs at V2.

One of the biggest puzzles is why the flows in the heliosheath are so different at V1 and 2 (Fig. 5). After six years in the sheath, V2 flow magnitudes remain high, near 150 km/s, while V1 flows dropped to zero after 2010 and are sometimes negative. In fact, all the components of the speed at V1 became small in 2010 (Krimigis et al. 2011). Current global models

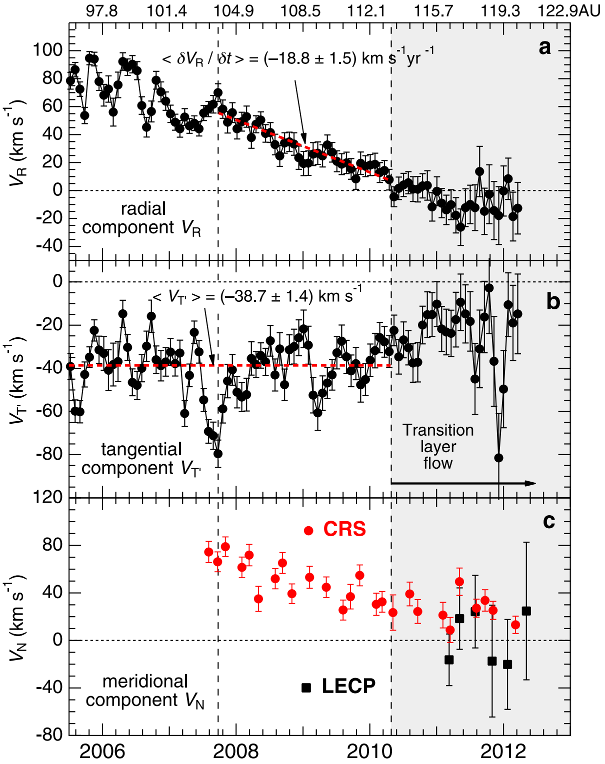


Fig. 5 Very different flows on board of V1 (*left panel*) and 2 (*right panel*). V1 doesn't measure directly the flows. They are inferred. The velocity components in V1 are calculated from measurements of 53–85 keV ion intensities. The components that V1 is able to extract are in the RT plane in the R–T–N heliographic polar coordinates in which the transverse (+T) direction is that of planetary motion around the Sun and +R is the radial direction relative to the Sun. Panel (**b**) shows the VR components as well as density N; temperature T and the RT = tan −1(VR/VT) and RN = tan −1(VR/VT) angles on V2

don't correctly predict the observed flows at V1 and V2 either in magnitude or direction. All current models (Opher et al. 2009; Ratkiewicz and Grygorczuk 2008; Izmodenov et al. 2009; Pogorelov et al. 2007) predict the HS flows will slowly turn to the flanks and to the poles as the Voyagers move deeper into the sheath. Instead, the V2 flows turn much more rapidly in the transverse direction than in the normal direction. Is the HP flatter than we thought or are we missing something else?

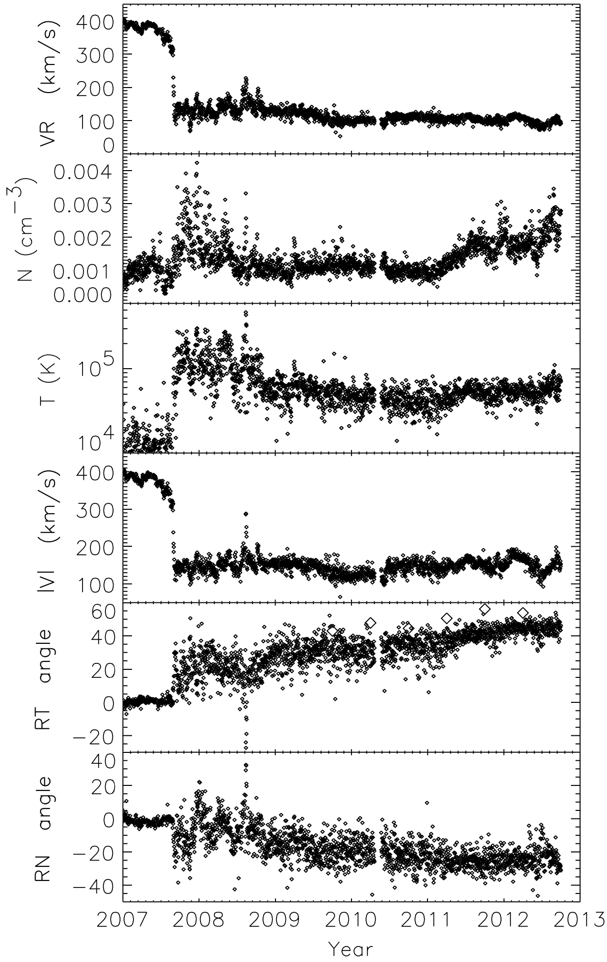
In particular, the zero values of radial flow at V1 pose a challenge to the models, since in current models the flow rotates parallel to the HP and the radial component gradually decreases asymptotically (not abruptly) to zero, and it should become zero only at the HP itself.

There have been recent suggestions that the flows can be explained by the gradients in pressure as shown by the integrated pressure flux of PUIs (McComas and Schwadron 2014)

Another puzzle comes from the magnetic field. We expect that from flux conservation $\mathrm{B_T V_R R} \sim$ const. However, when $\mathrm{V_R}$ decreased at V1 the magnitude of $\mathrm{B_T}$ didn't increase as expected (Richardson et al. 2013) (Fig. 6). Even as $\mathrm{V_R}$ went to zero $\mathrm{B_T}$ stayed around 0.1–0.2 nT (Burlaga and Ness 2012). (The exact conservation is $B_T V_\perp L \sim const.$, where $V_\perp = \sqrt{V_R^2 + V_N^2}$, and L is the separation between streamlines.) The non-conservation of magnetic flux cannot be explained by solar cycle variations of the solar wind and magnetic field intensity (Michael et al. 2015).

After the crossing of the TS by V1 and then by V2, one of the first surprises was that both Voyager spacecrafts found no evidence for the acceleration of the anomalous cosmic rays (ACRs) at the TS, as expected for approximately 25 years (Fisk et al. 1974). The expectation

Fig. 5 (*Continued*)



was that the ACRs were accelerated at the largest shock in the heliosphere, the TS. The ACR intensities not only didn't peak at the shock, but their intensity kept increasing as the spacecraft moved deeper into the sheath (Decker et al. 2010; Cummings et al. 2008). This finding generated several hypotheses for the ACRs acceleration mechanisms and locations: in the flanks of the shock (McComas and Schwadron 2006); in "hot spots" in a turbulent TS (Kota 2010; Guo et al. 2010); deep in the sheath; by reconnection (Lazarian and Opher 2009; Drake et al. 2010); or by turbulence processes also deep in the hot HS (Fisk and Gloeckler 2009).

Another mystery comes from the different behavior of energetic particles at V1 and V2 (Fig. 7). The particles at V2 show variations of intensity of more than three orders of magnitude correlated with periods when the spacecraft was in and out of the sector region (as indicated by Wilcox data) (Hill et al. 2014), while the intensities at V1 remained steady. When V2 is in the sector region the intensities are substantially higher then when it is in the unipolar region. There is more than a three order of magnitude energy range (highest energies not shown) over which ions and electrons vary coherently with the passage of the temporally varying spatial structure, the edges of the sector region.

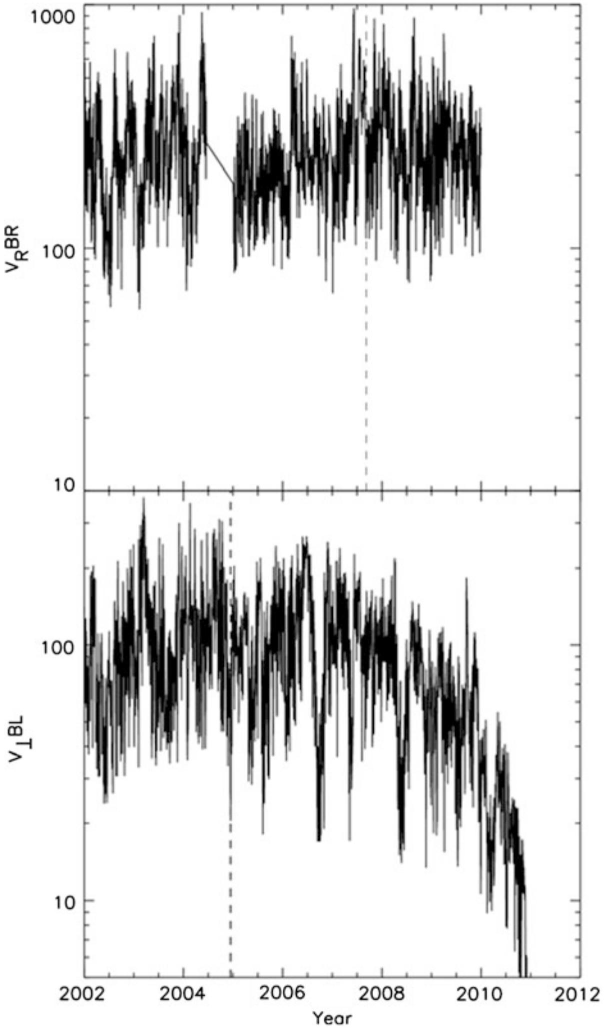


Fig. 6 What happened to the missing azimuthal magnetic flux at Voyager 1? The magnetic flux observed at V2 (*top*) and V1 (*bottom*). B is normalized by the values at 1 AU, V is in km/s and L is in AU. The *vertical dashed lines* show the TS locations (from Richardson et al. 2013)

There is also the problem of the HS thickness. Most models predict a thickness of ∼50 AU even after accounting for time dependence (Richardson and Wang 2010; Provornikova et al. 2014). Models that include both the thermal and suprathermal components, such as pick-up ions (e.g., Malama et al. 2006) predict some reduction in the thickness. But these models still don't match the observed heliosheath thickness of 27 AU.

Which other aspects of the nature of the HS are we missing in our models that could thin the HS?

To solve these puzzles, in the last couple of year have been several suggestions for additional effects such as reconnection in the sector region (the region where the solar magnetic field reverses polarity) and near the HP, turbulence, and time dependent effects.

Reconnection within the sector region (as suggested by Opher et al. 2011; Drake et al. 2010) explains the ACR spectrum rolling over well into the HS by acceleration from reconnection. It can also explain the dropout of particles on V2; while particle were steady at V1 by different transport properties within a reconnected sector region – given that V2 was

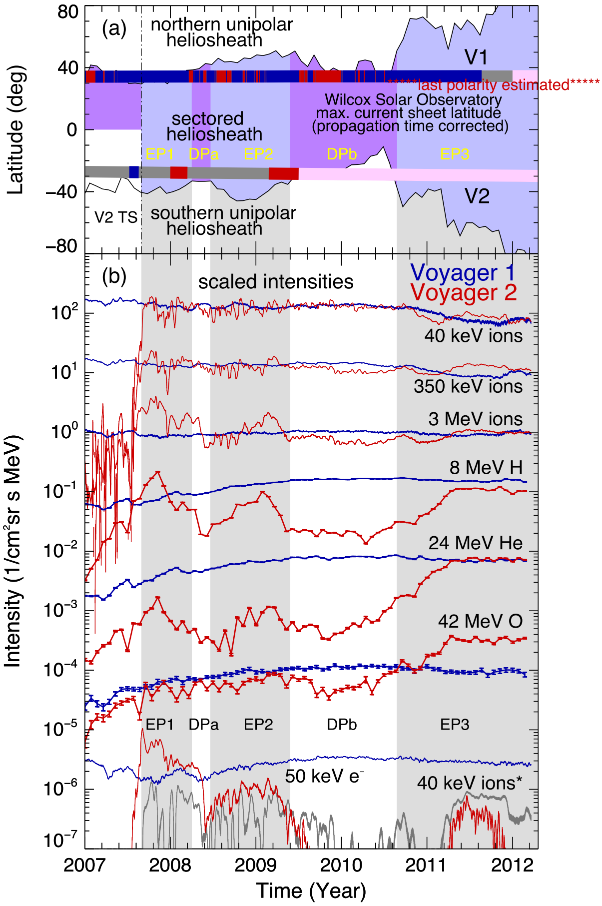


Fig. 7 Temporal variations of the latitudinal boundaries of the sectored HS and V1 and 2 energetic ion and electron intensities, where V2 shows a clear correspondence to the sector configuration (Hill et al. 2014)

in an out of the sector while V1 was immersed within it throughout its trajectory (Opher et al. 2011). Reconnection can also explain the missing azimuthal magnetic flux at V1 and potentially the flow stagnation region seen at V1 (Opher et al. 2012).

Reconnection within the sector region is a new regime of reconnection different than any other location in the heliosphere; is where plasma β (ratio of thermal to magnetic pressure) is high (while usually reconnection occurs in regions of low plasma β) and the guide field is zero (anti-symmetric reconnection). In that regime (Opher et al. 2011; Schoeffler et al. 2013) the magnetic islands are very elongated and the magnetic profile is similar to the sector (Fig. 8). This poses a challenge to the magnetometer on Voyager 1 and 2 that is tuned to strong field for the strong fields of the outer planets and not for the week fields of the heliosheath. The uncertainty on the magnetometer on V1 is 0.03 nT in each component and on V2 0.05 nT while the average field intensity in the HS is 0.1 nT.

We need a way to extract energy from the HS. Is reconnection within the sector region (as suggested by Opher et al. 2011; Drake et al. 2010) sufficient (Fig. 8)? Perhaps the HS has a strong turbulent component (as suggested by Fisk and Gloeckler 2013)? Are temporal effects such as instabilities (Pogorelov et al. 2012; Florinski et al. 2015) or other non-ideal MHD effects important? Most likely instabilities such as Rayleigh–Taylor instability won't be present because of the stabilization effect of the interstellar magnetic field. Izmodenov et al.

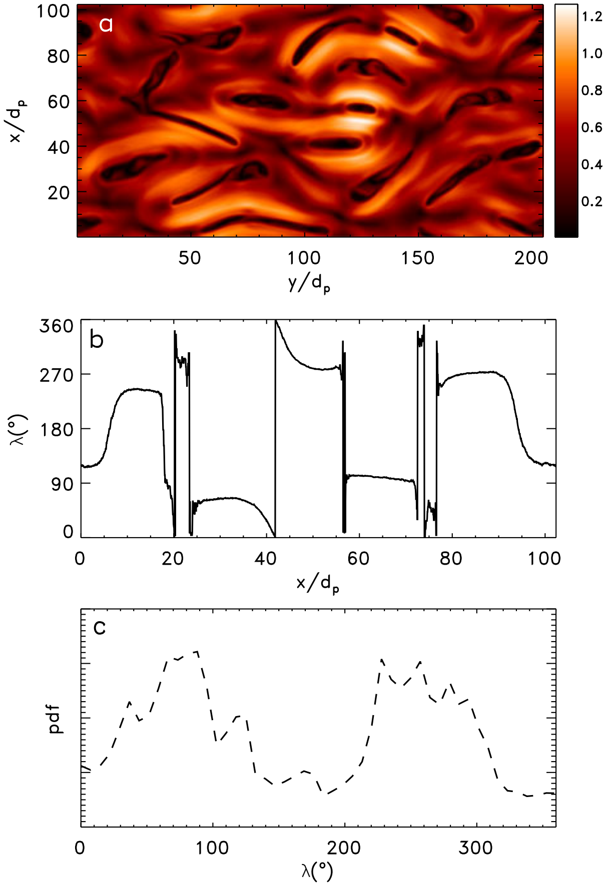


Fig. 8 Multi-current system in its final stage after reconnection ceased. Elongated magnetic islands are formed with intense magnetic field at the walls. The *bottom panels* show the magnetic field magnitude, direction, and distribution function for a cut through the model results (Opher et al. 2011)

(2009) suggests that electron thermal conduction can thin significantly the heliosheath; in the limiting case where the thermal conduction is very effective the heliosheath was thinned to 32 AU.

4 Heliopause

Between May and August 2012 there was a series of puzzling events. The cosmic ray flux increased rapidly in May. Then in August the intensity of particles that were accelerated in the heliosphere (from ∼30 keV to MeV) decreased to background levels (intensity decreases of a factor of ∼1000). At the same time the galactic cosmic rays intensity again increased, this time to the highest level ever observed. The magnetic field magnitude simultaneously increased (Fig. 9). This transition had been dubbed the “heliocliff”. One of the expected signatures of the crossing of the HP, was that the magnetic field direction would significantly change. This is expected because the solar magnetic field just inside the HP is azimuthal, or east-west, on average (called the “Parker field”), while the magnetic field in the interstellar medium (derived from several indirect indicators) is widely believed to be inclined significantly to the east-west direction (Izmodenov et al. 2009; Opher et al. 2009;

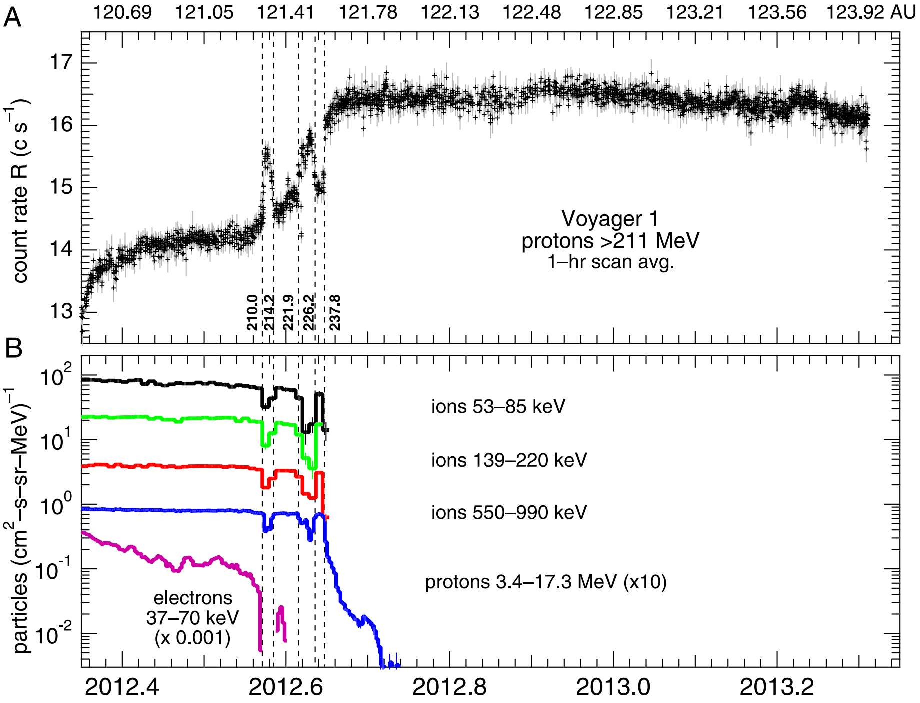


Fig. 9 Overview of the energetic particle observations at V1, 2012.35 to 2013.40 showing the contrary behavior of GCRs and lower-energy particles (from Krimigis et al. 2013)

Pogorelov et al. 2009; Ratkiewicz and Grygorczuk 2008). The absence of a significant rotation in the direction of the magnetic field at the times of dropouts of energetic particles were initially interpreted as indicating that V1 was still in the HS (Burlaga et al. 2013; Krimigis et al. 2013; Stone et al. 2013; Fisk and Gloeckler 2013; McComas and Schwadron 2012) although some models suggested the contrary (Swisdak et al. 2013).

However, in September of 2013 the plasma wave team announced the detection of 2–3 kHz plasma waves, so the plasma densities indicated V1 was in the interstellar medium (ISM) (Gurnett et al. 2013), although not all agree (Fisk and Gloeckler 2013; McComas and Schwadron 2012, 2013a).

If V1 were beyond the HP, then why is the magnetic field outside the HP still within $\sim 20^\circ$ of the Parker spiral direction (Burlaga and Ness 2014) and thus very different from the B direction expected deeper in the ISM? Could this difference be due to the shape of the HP and magnetic draping geometry, magnetohydrodynamic (MHD) instabilities, temporal aspects, or not having really crossed HP? Opher and Drake (2013) propose that, regardless of the direction in the ISM, near the HP the field twists to the Parker direction (Fig. 11). Not all modelers agree and this question is being hotly debated. Some argue that *ideal* draping, i.e., draping on a surface without communication between the solar and interstellar magnetic field can account for that (e.g., Grygorczuk et al. 2014). Do other aspects such as reconnection or turbulence play a role in this local rotation? The implications of understanding the behavior of the magnetic field ahead of the HP has consequences not only for what V2 will encounter as it approaches and crosses the HP, but for what V1 will see as it adventures farther away from the HP into the ISM.

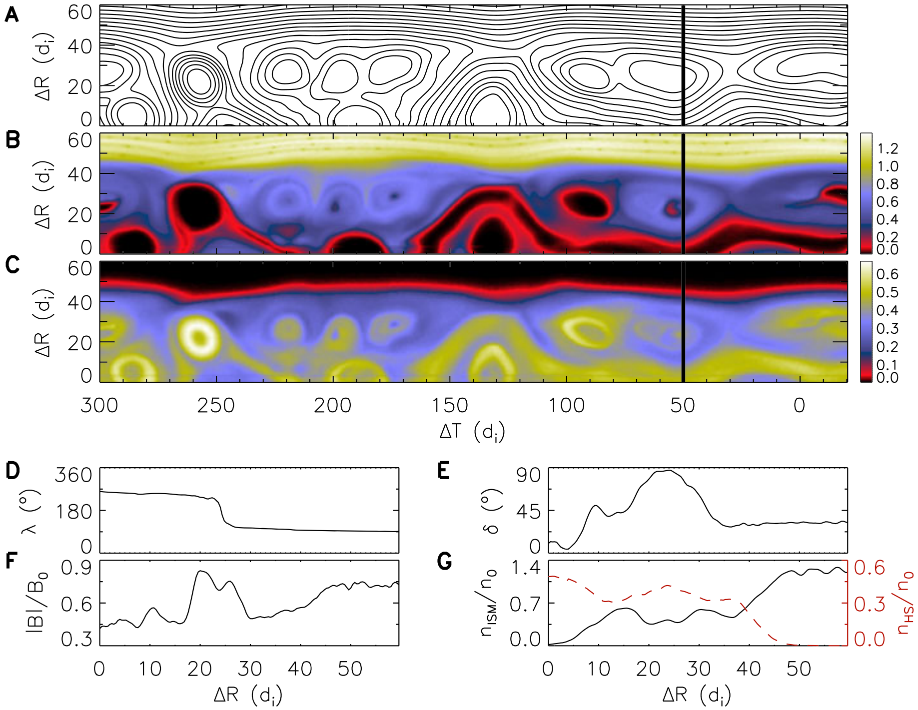
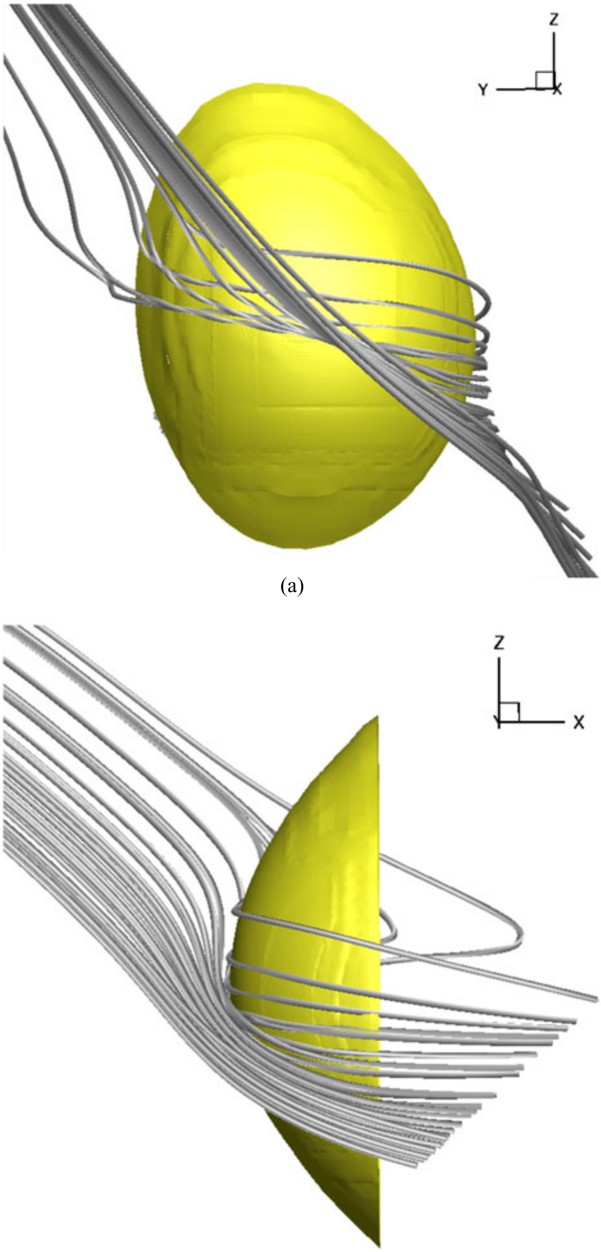


Fig. 10 Structure of the HP and adjacent LISM and HS at late time from the PIC simulation. In the R/T plane in (**A**) the magnetic field lines and in (**B**) and (**C**) the number density n_{LISM} (n_{HS}) of particles originally in the LISM (HS). Panels (**D**)–(**G**) are cuts along the vertical line in panels (**A**)–(**C**). In (**D**) λ is the angle of B in the R–T plane with respect to the R direction. In (**E**) δ is the angle between B and the R–T plane. In (**F**), the magnitude of B and, in (**G**), the number density n_{LISM} (*solid*) and the number density n_{HS} (*dashed red*) (from Swisdak et al. 2013)

Swisdak et al. (2013) based on particle-in-cell simulations, based on cuts through the MHD model at V1's location, suggest that the sectored region of the HS produces large-scale magnetic islands that reconnect with the interstellar magnetic field while mixing the local interstellar medium (LISM) and HS plasma. Cuts across the simulation reveal multiple, anti-correlated jumps in the number densities of LISM and HS particles at magnetic separatrices where there is essentially no magnetic field rotation (Fig. 10). The absence of rotation at these dropouts is consistent with the V1 observations. In this model (Swisdak et al. 2013) the authors argue that V1 had crossed the HP at the end of July 2012. Soon after this paper was published, the Voyager team reached the conclusion that V1 was in the interstellar space based on the detection of radio emissions (Gurnett et al. 2013).

Other works proposed that the HP dropouts can be explained by MHD reconnection predicting islands structures before the crossing of the HP (Strumik et al. 2013).

It is debated within the community if similar structure should be expected or will be seen when V2 will cross the HP. In any case the plasma instrument on board of V2 will only be sensitive to the thermal component. In order to sort out the different scenarios this region should be revisited with sensitive magnetometer and a particle instrument covering the suprathermal populations especially in the gap between 1 keV–40 keV.



(a)

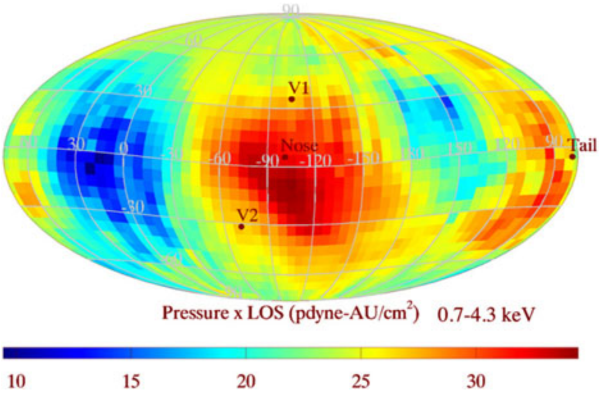
(b)

Fig. 11 View at the nose of the heliosphere from the interstellar medium towards the Sun. The nose of the HP is shown in the *yellow* iso-surface (defined by $\ln T = 11.9\text{–}12$). The *gray field lines* are the B_{ISM} wrapping and twisting around the HP (Opher et al. 2013)

5 ENA Observations of the Global Structure of the Heliosphere

Another way to probe the global structure of the heliosphere is through energetic neutral atoms (ENAs). Both Interstellar Boundary Explorer (IBEX) and CASSINI/INCA instruments mapped that region in different energy ranges. IBEX is a small explorer mission

Fig. 12 From Schwadron et al. (2014). Pressure of plasma protons that form observed ENAs integrated over line-of-sight (LOS) as observed by *IBEX* and referenced to the inertial frame *IBEX*-Hi measurements from *IBEX*-Hi (from 0.7 to 4.3 keV) from 0.7 to 4.3 keV



that revolves around the Earth returning ENAs images in the range 0.2 keV–4.3 keV range (McComas et al. 2009). CASSINI/INCA measures ENAs in much higher energy range (∼5.4–55 keV) (Krimigis et al. 2009). Both spacecrafts measured unexpected features, IBEX, a so called- “ribbon” around 1 keV energies and CASSINI/INCA a so- called “belt” around 4–13 keV. The IBEX “ribbon” seem to be organized by the interstellar magnetic field $B_{\mathrm{ISM}} \cdot R = 0$ (or the location where the radial component of $\mathrm{B}_{\mathrm{ISM}}$ is zero) and prompted a series of papers trying to explain its origin. In any case these data demonstrated as well as the Voyager heliospheric asymmetries that the heliosphere is strongly affected by the interstellar magnetic field.

All the different theories have pros and cons when compared to the data as summarized by McComas et al. (2011). Because of the ordering with $B_{\mathrm{ISM}} \cdot R = 0$ most proposed mechanisms are outside the heliosphere in the outer heliosheath; Some proposed mechanisms make use of secondary charge exchange (e.g., Heerikhuisen et al. 2010); magnetic mirror (Chalov et al. 2010); etc. However there is an issue of scattering and stability of the pick-up ions (PUIs) in the local ISM (Florinski et al. 2010) so more recent mechanisms use some kind of a trapping mechanism (Schwadron and MComas 2013b). Chalov et al. (2010), similarly to Heerikhuisen et al. (2010) consider the pick-up ion (PUI) population that is produced by charge exchange between interstellar protons and heliospheric ENAs in the case of negligible scattering. They consider the motion of these PUIs around $\mathrm{B}_{\mathrm{ISM}}$ that gets compressed outside the heliopause. The regions of the strong magnetic field can be considered as magnetic mirrors. The location of the magnetic mirrors is where the PUIs spend a considerable longer time (since their parallel speeds are small) so are the ideal places for a production of ENAs. Therefore the positions of the magnetic mirrors (where the radial component of $\mathrm{B}_{\mathrm{ISM}}$ is zero) are the location of the IBEX ribbon.

Very few works tackled the origin of the CASSINI belt that seem to organize itself in a “belt” in a location similar but not equal to the IBEX ribbon.

Recently, the IBEX team separated the distributed flux emission from the ribbon (McComas et al. 2013; Schwadron et al. 2014) (Fig. 12). The distributed flux emission gives a global view of the structure of the heliosphere since it’s believed to be produced in the inner heliosheath. In particular the tail emission seem to be organized by a two-lobe structure. The ENA tail observations (McComas et al. 2013) reveal two lobes at high latitudes and depletion in low latitudes of high energy ENAs (∼4 keV) while in low energies (∼0.7 keV) the tail appears as two separate enhancements in low latitudes. McComas et al. suggested that these observations resulted from the spatial separation of slow and fast winds. The ENA images from Cassini (Krimigis et al. 2009;

Dialynas et al. 2013; at 5–55 keV) revealed intensities that were comparable in the direction of the nose and tail. The observers therefore concluded that the heliosphere might be “tailless” because the emission from these high-energy ENAs is believed to come from the heliosheath. The two-lobe heliosphere is almost “tailless” with the distance down the tail to the ISM between the lobes being comparable to the distance to the ISM at the nose.

Moreover the ENA emissions show strong time variations (McComas and Schwadron 2014; Dialynas et al. 2013) that need to be explained.

Finally an interesting complement is the low energy ENAs that are order of magnitude higher than models predict. The low energy ENAs (measured by IBEX-Lo) struggle with signal-to-noise ratio so the statistics is poor. The low energy ENAs could indicate that additional heating has to be occurring within the heliosheath (Opher et al. 2013) or that there are additional pick-up ion population that is important outside the HP (Desai et al. 2014).

6 Conclusions

As described above there are several challenges to our understanding of the nature of the heliosheath, the heliopause and even the very global structure of the heliosphere. To really understand the nature of the heliosheath and help resolve between the different scenarios, a new visit to that region is necessary with proper instrumentation, with high sensitivity magnetometer and energetic particle instrument that bridge the gap in those energies; i.e., able to measure the suprathermal PUI population from 1 keV–40 keV and energetic electrons in the same energy.

The problem that the IBEX team faced (similar problem with CASSINI/INCA) is the sensitivity of the instruments requiring 3 years to be able, for example, to separate the tail emission from the rest, or the distributed flux. In the meantime, with new proposed missions such as IMAP that propose a much high sensitivity ENAs we will be able to constrain further the global structure of the heliosphere.

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