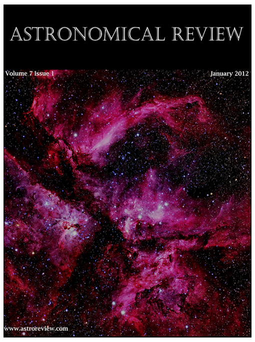

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The Heliosheath: The Ultimate Solar System Frontier

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Abstract

The recent measurements *in-situ* by the Voyager spacecrafts, combined with the all-sky images of the heliospheric boundaries by the Interstellar Boundary Explorer (IBEX) mission have transformed radically our knowledge of the boundaries of the heliosphere. Concepts that lasted decades are being revisited due to their puzzling measurements. In this review, I will cover some of these puzzles and what we are learning regarding the dynamic nature of the heliosheath.

Introduction

The study of the interaction of the solar system with the interstellar medium saw a flurry of activity in the last couple of years. Similar to opening a "Pandora's box," as we deepen into the heliosheath, new surprises emerge. The Voyager spacecraft in the heliosheath [1-5] combined with all-sky images of the heliospheric boundaries by the Interstellar Boundary Explorer (IBEX) [6] and Cassini mission [7], changed and re-wrote what we know about how the solar system interacts with the interstellar medium. Their puzzling measurements have provoked a revision of concepts that lasted decades. This review will focus mainly on the heliosheath and on the Voyager spacecraft measurements.

The sun's solar wind carves a bubble into the interstellar medium, called the heliosphere. The heliosphere is separated from the interstellar medium by three interfaces: the first of them is the termination shock (TS), where the supersonic solar wind becomes subsonic. The transition happens in a sharp discontinuity in space, where the solar wind is subsonic beyond that point. The region beyond the TS is called the heliosheath, where the solar wind is subsonic. The last boundary beyond the heliosheath is called the heliopause (HP), which is thought to be a tangential discontinuity. The HP is where the internal pressure from the solar wind equilibrates the external pressure from the interstellar medium (ISM). We know the distance of the TS through the crossing of Voyager 1 (V1) in December 2004 [3] at 94 AU in the northern hemisphere, while Voyager 2 (V2) crossed it in the southern hemisphere in August 2007 at 84 AU [4]. Both spacecrafts are now beyond the TS. V1 is thought to be 30 AU deep in the sheath, while V2 is thought to be 20AU in the sheath [7]. This estimate takes into account the fact that the heliosphere "breathes" with the solar cycle, i.e., the boundaries move in and out. The thickness of the heliosheath is not known, although models predict that its thickness is between 50-70 AU at V1 and V2 [9,10].

It is now, when the Voyager spacecrafts are close to leaving the solar system, that we are faced with so many unexpected observations. Since 1958, when Eugene Parker suggested the possibility that the Sun had a wind [11], there have been a number of observations of the solar wind via missions (e.g. ACE, Ulysses) Most of them were done near Earth at 1AU, some (e.g., Cassini,) ventured to Saturn. All the measurements confirmed the basic model that Parker predicted. V1 and V2 are the only spacecraft that have ventured deep into the heliosphere, returning data on how the solar wind behaves at large distances from the Sun (see for example review by [12]), and showing how much more complex the solar wind behaves at these far distances. In the next section of this article, I review some of the unexpected observations. In the sections following that, I describe what we know about the asymmetric heliosphere, proposing the possibility that the heliosheath is a giant reconnection laboratory. Finally, I draw some conclusions, and comment on what are likely expected to be the next observations.

Surprises in the Heliosheath

After the crossing of the TS by V1 and then by V2, one of the first surprises was that both Voyagers found no evidence for the acceleration of the anomalous cosmic rays (ACRs) at the TS, as expected for approximately 25 years [13]. The ACRs are particles that are originally neutrals from the interstellar medium, which get ionized near the Sun and picked up by the solar wind. The expectation was that the ACRs were accelerated at the largest shock in the heliosphere, the TS. The ACRs not only didn't peak at the shock, but their intensity kept increasing as the spacecraft deepened into the sheath [14, 15]. This finding generated several suggestions, such as different locations where ACRs are accelerated: in the flanks of the shock [16]; in "hot spots" in a turbulent TS [17,18]; deep in the sheath; by reconnection [19 20]; or by turbulence processes [21-23]. In the next couple of years, Voyager observations will provide the measurements to distinguish between these different proposed scenarios.

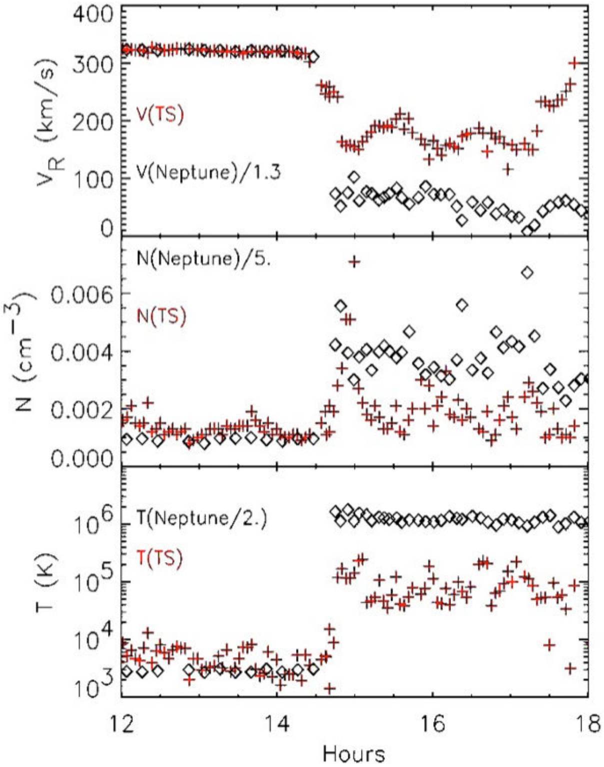

Figure 1: Colder heliosheath. The radial speed, density and temperature in the heliosheath (red) are compared to that expected (black) from the crossing of Neptune. Note that the velocity drop and density increase were much less than expected, and the temperature increase was <10% of what was expected (from Richardso et al. 2009). This is the temperature for the electrons and ions – the electrons are below the 10 eV threshold (occasionally we see a bit of the tail of the distribution) giving an upper limit of about 3 eV, factor of 10 below based on Neptune's magentosheath (Richardson, private communication)

Another surprise was that the heliosheath was much colder than expected [5] (Figure 1). 80% of the energy in the supersonic solar wind went into the suprathermal particles. Voyager only measures the thermal plasma.

The heliosheath is a new region of Space, and its nature is not currently well understood. Measurements of magnetic field and flows indicate that they are much more turbulent than in the supersonic solar wind [24-26]. The magnetic field measurements show the existence of magnetic holes, humps and compressible turbulence.

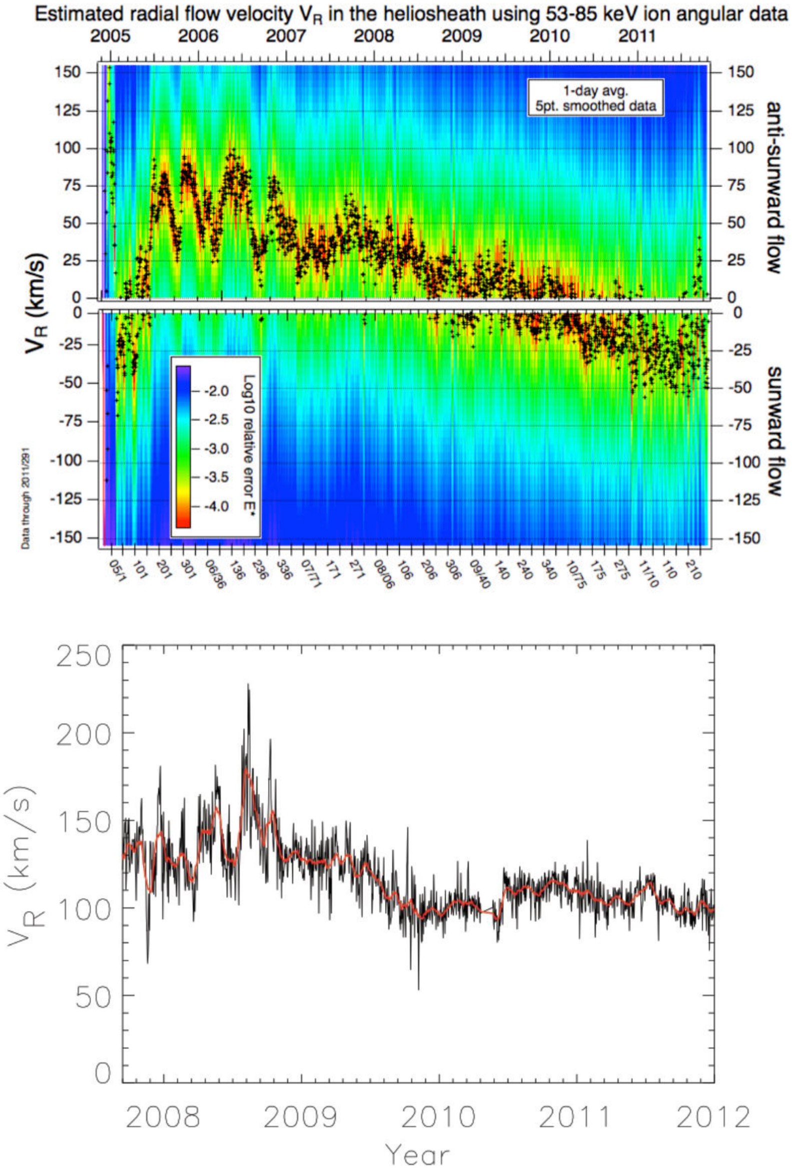

Figure 2: Flows on board of Voyager 1 (a- courtesy of Rob Decker) and 2 (b – courtesy of John Richardson). V1 doesn't measure directly the flows. They are infereed. The velocity components in V1 are calculated from measurements of 53-85 keV ion intensities. The components that V1 is able to extract are 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.

V1 and V2 continue to offer a series of challenging observations such as the Figure 1: Colder heliosheath. The radial speed, density and temperature in the heliosheath (red) are compared to that expected (black) from the crossing of Neptune. Note that the velocity drop and density increase were much less than expected, and the temperature increase was <10% of what was expected (from Richardson et al. 2009). This is the temperature for the electrons and ions – the electrons are below the 10 eV instrument threshold (occasionally we see a bit of the tail of the distribution), giving an upper limit of about 3 eV, a factor of 10 below expectations based on Neptune's magentosheath (Richardson, private communication) energetic electrons, which are dramatically different at each of the spacecraft. V1 electron intensities are very smoothly varying, showing a steady increase throughout most of the cruise through the heliosheath, whereas at V2 the electron variations vary by orders of magnitude on the scale of a year. There have been arguments that these measurements, are due to V2 being immersed in the sector region vs. being outside of it [27]. Other suggestions include temporal variations such as the rise of solar maximum conditions [28]. The ACRs are similarly different at between V1 and V2, but many of the ACRs have also been showing exponential intensity increases over the last year or so, driving levels above V1 and in fact, in some cases, to the highest ever measured.

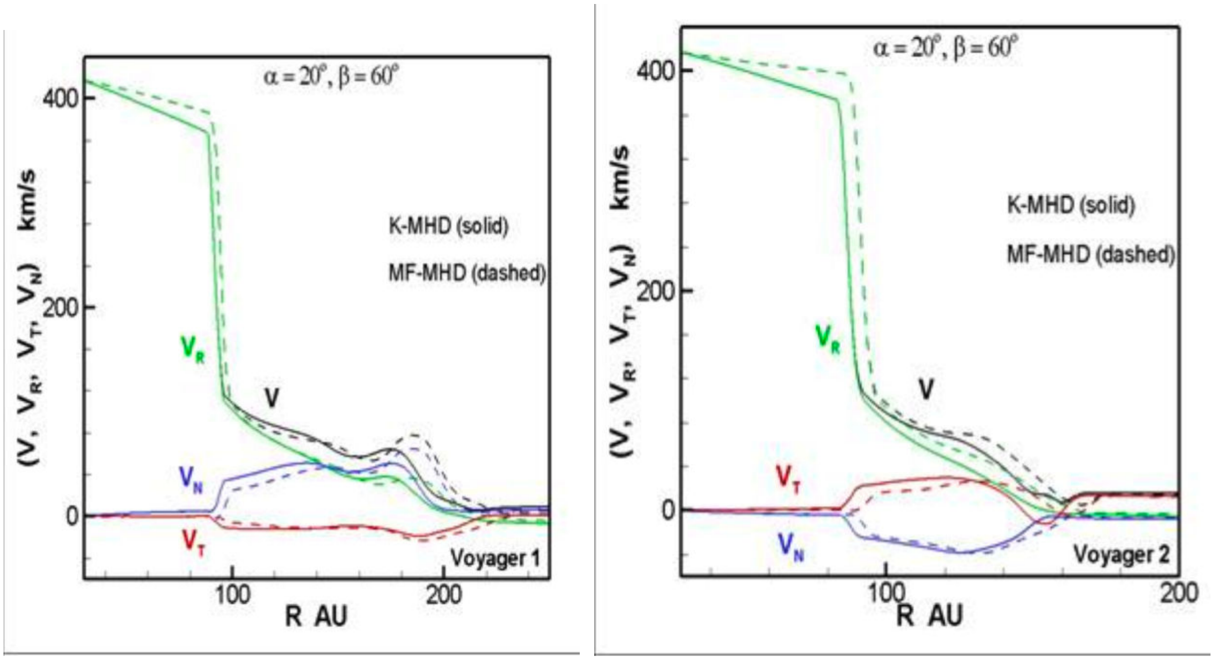

Figure 3: Flows at V1 (a) and 2 (b) from our K-MHD Model (from [34])

Another mystery comes from the solar wind flows: why are the V2 flows behaving so differently than at V1? After three years in the sheath, V2 flow value remained high, around 150-120km/s (Figure 2), while V1 flows dropped to zero, and more recently to negative values [29]. All current models [30-33] predicted the flows to slowly turn to the flanks and to the poles, as we deepen into the sheath. Instead, on board V2, the flows are turning almost all in the transverse direction and very little in the normal direction. Is the heliopause flatter than we thought, or is another effect playing a role?

The zero values of radial flow at V1 pose a challenge to the models, since in current models due to the rotation of the flow to parallel the HP, the radial component is gradually reduced asymptotically (not abruptly) to zero, and only at the HP itself. In particular, current global models (such as shown in Figure 3) don't correctly predict the flows at V1 and V2 as compared to the observations , either in magnitude or direction. Figure 2: Flows on board of Voyager 1 (a- courtesy of Rob Decker) and 2 (b – courtesy of John Richardson). 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. Figure 3: Flows at V1 (a) and 2 (b) from our K-MHD Model (from [34])

One reason for discrepancy could be the non-inclusion of the tilt between the solar rotation and magnetic field, that creates a sector region. Recently, we showed [27] with an unprecedented, highly refined simulation (cells < 0.01AU) that a wide sector-field affects dramatically the flows in the heliosheath (Figure 4). This simulation was the first to capture in details the dynamics of the sector in the heliosheath (see also [35]). In the 3D MHD simulation, different from the case that did not include the sector region, there is a region in the heliosheath where the radial solar speed is close to zero or negative.

Heliosheath as a Giant Reconnection Laboratory:
Much computational work has been done in exploring the global properties of the heliosphere. Until recently, despite their sophistication, none of these models included the tilt between the solar magnetic and rotation axes. The tilt between the rotation and magnetic axis creates the sector region, where the polarity of the heliospheric field periodically reverses sign. The sector region propagates from the Sun, across the TS, and is compressed in the heliosheath as the radial speed drops.

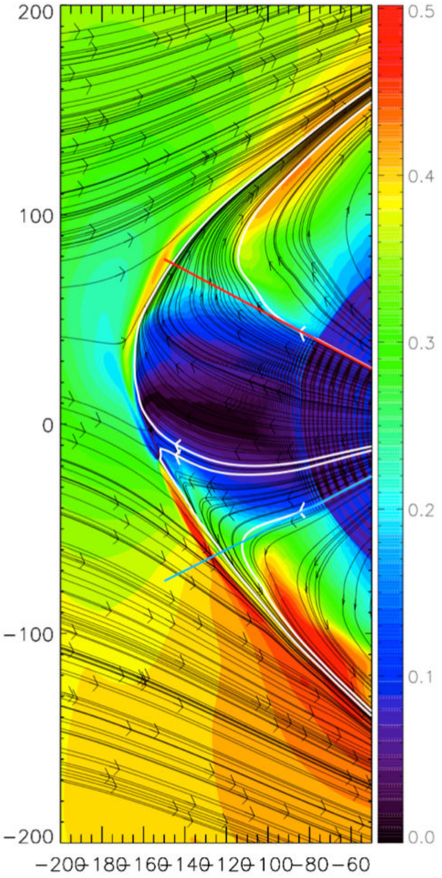

Fig 4: Meridional cut from a 3D MHD simulation showing the magnitude of the magnetic field (nT). The sector region of width of 60◦ is the blue-black region. The flow streamlines are shown in black. The boundary of the sector region is shown in the white streamlines. V1 trajectory and V2 are shown, respectively, in the red and blue lines (from[27]).

In recent works [20,27] we argued that the heliospheric magnetic field in the heliosheath, within the sector region, reconnected. The argument for reconnection in the sector lays in both the compression of the sector downstream of the TS and the thickness of the heliospheric current sheet. Based on 1AU data, the heliospheric current sheet thickness is upstream of the TS ~ 10,000 km. However, if this is the case, there is a significant uncertainty. We need 48s magnetic data upstream of the TS from the MAG instrument on Voyager to be sure that this is the case. This data still need to be analyzed. Using the density upstream the TS (n ~ 0.001/cm^3), the ion inertial scale ~ 8400 km. Considering the parameters downstream of the TS, the heliospheric current sheet thickness is ~ 3,300 km, based on compression from upstream, while the ion inertial scale ~ 4800 km (n ~ 0.003/cm^3). The thickness of the heliospheric current sheet is on the same order of the ion inertial scale, and collision-less reconnection should onset in the heliosheath. We see similar compression and onset in Earth's magnetosphere [36].

Based on the above arguments, we argued then that the magnetic field in the heliosheath within the sector is not laminar, but instead filled with nested magnetic islands. The magnetic islands/bubbles formed during reconnection of the sector region upstream of the HP, are convected with the flows as the sector boundary is carried to higher latitudes, filling the heliosheath upstream of the HP. Fig 4: Meridional cut from a 3D MHD simulation showing the magnitude of the magnetic field (nT). The sector region with width of 60◦ is the blue-black region. The flow streamlines are shown in black. The boundary of the sector region is shown in the white streamlines. V1 trajectory and V2 are shown, respectively, in the red and blue lines (from [27]).

We argue that due to the increased pressure of the interstellar magnetic field, [9,37] the sector region and embedded islands are carried mostly to the northern hemisphere. We predict an asymmetry of the magnetic structure between the northern and southern hemispheres, and between the heliosheath sectored region and the field outside of it. Therefore, we predict that the northern hemisphere will be predominantly a disordered field filled with magnetic islands, and not a laminar field (Figure 5).

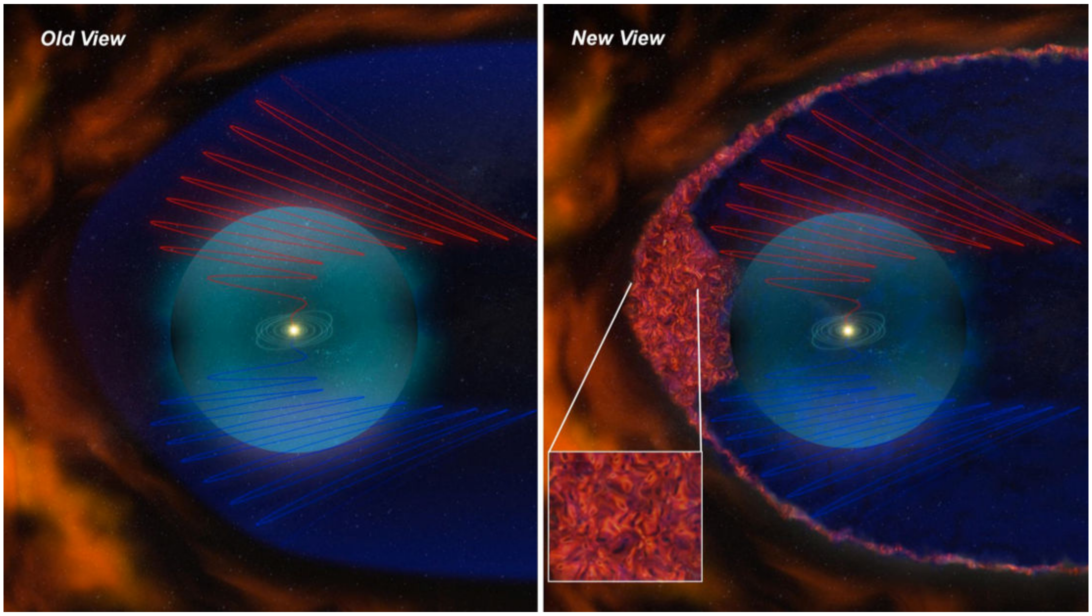

Figure 5: Old and new views of the heliosheath. Red and blue spirals are the gracefully curving magnetic field lines of orthodox models. Reconnection will create a sea of bubbles that will fill out the heliosheath (credit NASA).

In addition, we performed reconnection simulations of a sectored magnetic field, using a PIC code that, surprisingly, exhibits characteristics similar to the *Voyager* data. The magnetic field exhibits reversals, but with a more erratic spacing than the initial state. Reconnection of the nested islands is suppressed, due to the approach to the firehose marginal stability condition, so plasma flows are irregular, and only occasionally exhibit traditional reconnection signatures. We refer to the late-time non-reconnecting magnetic islands as "bubbles," because in cross section they more closely resemble a nested volume of soap bubbles than a system of reconnecting islands.

The disordered heliospheric magnetic field near the HP will effect the entrance and modulation of galactic cosmic rays electrons, making the northern hemisphere more "transparent." The galactic cosmic rays electrons, traveling along the interstellar magnetic fields, can enter and percolate through the heliosphere. The ones entering the northern hemisphere will travel through the disordered field of the sector region, while those in the southern hemisphere will access a laminar field more quickly, and escape. We therefore expect a north–south asymmetry in the intensity and modulation of the galactic cosmic rays electrons. The sector region vary with solar cycle, but this could indicate that a large portion of the heliosheath has magnetic field that reconnected.

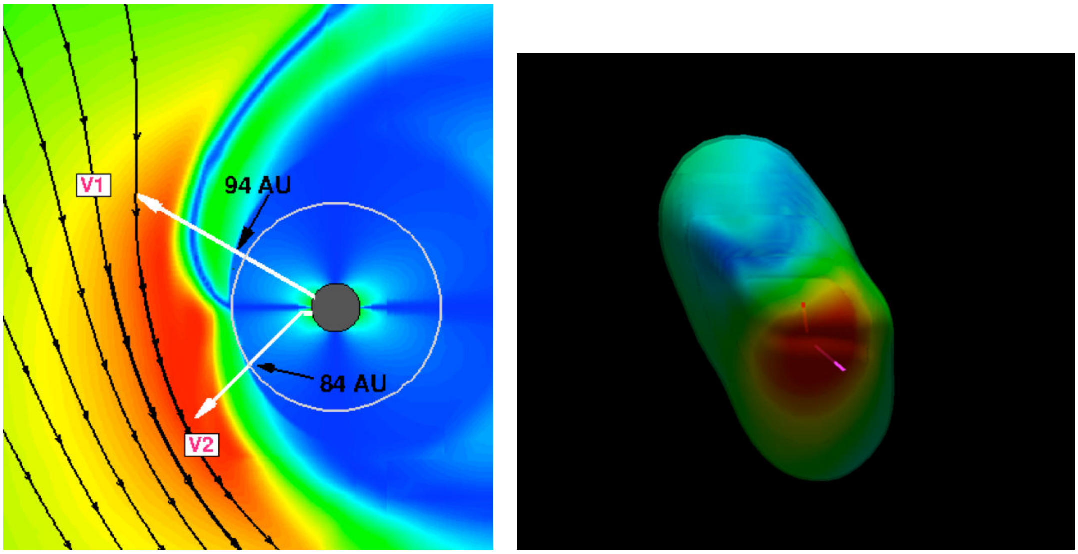

Figure 6: Image [left] showing the squashed heliosphere due to the interstellar magnetic field [9] and the locations of the termination shock as measured by the V1 and 2 spacecrafts.

It is very important to understand this region of space because of the critical role it plays in modulating the intensity of galactic cosmic rays that penetrate into the inner solar system, and reach Earth. The next challenge is to detect directly these “bubbles” in the Voyager magnetic field data. Figure 6: Image [left] showing the squashed heliosphere due to the interstellar magnetic field [9] and the locations of the termination shock as measured by the V1 and 2 spacecrafts. Figure 5: Old and new views of the heliosheath. Red and blue spirals are the gracefully curving magnetic field lines of orthodox models. Reconnection will create a sea of bubbles that will fill out the heliosheath (credit NASA). The magnetic field data on board Voyager has large uncertainties and this task will prove challenging.

Asymmetric Heliosphere:

The crossing of the TS by V1 and V2 with 10AU difference in distance (95AU vs. 85AU) confirmed that the solar system is asymmetric, and that the interstellar magnetic field just outside our home is strong enough to influence the shape and direction of our bubble, the heliosphere. It was not expected that the interstellar magnetic field would play a major role in shaping the outer heliosphere. Models predict that the heliosphere looks very similar to a *football* ball punched in one hemisphere (Figure 6). Earlier, the differing deflection of the H atoms relative to the He atoms measured by SOHO/SWAN, had also indicated an influence of the interstellar magnetic field [38]. The IBEX and Cassini measurements seem to be organized by the interstellar magnetic field as well.

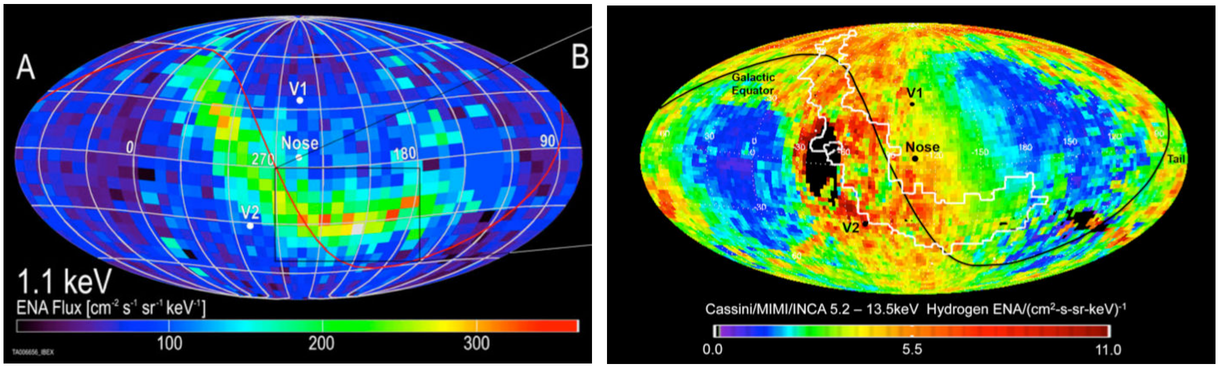

Figure 7: (a) The unexpected ribbon seen in 0.9-1.5keV in IBEX (adapted from [6]) and (b) the INCA Belt in 5 – 13 keV [45]

The asymmetry of the TS and the heliosphere was already seen a couple of years before the spacecrafts crossed the TS. Beams of particles accelerated at the shock, and arrived in opposite directions to V1 and

V2, indicating that the spacecraft was connected to the shock in opposite directions once the magnetic field connection occurred -- like cars in a freeway, the particles streamed to the spacecrafts. The connectivity indicated an asymmetric TS [37,39].

To explain asymmetries in the TS location as well as the magnetic connectivity and flows in the heliosheath [40], the interstellar magnetic field has to lie in a plane 30- 40° away from the plane of the disk of the galaxy [30,40] and be strong, between 3.7-5.5 μG, providing most of the pressure in the local cloud [30]. This intensity can be contrasted with estimates of the strength of the uniform magnetic field, Bu, and random magnetic field, Br, components of the magnetic field in the interstellar medium. Galactic synchrotron emission shows magnetic spiral arms with a total strength Bt ≈ 6 μG and Bu ≈ 4 μG. Pulsar data show evidence for reversals of the field direction with Galactic radius and yield Br ≈ 5 μG and Bu ≈ 1.5 μG [41]. In large distances (~pc) measurements indicate that the field is along the disk of the galaxy [42]. Turbulence in the ISM [43] or draping in the ISM clouds [44] can explain this change in direction.

Figure 8: The heliosphere as a test bed for other astrospheres (image from WISE bow shock image, Zeta Ophi [54]).

Even though this review focused on the heliosheath from Figure 7: (a) The unexpected ribbon seen in 0.9-1.5keV in IBEX (adapted from [6]) and (b) the INCA Belt in 5 – 13 keV [45] Figure 8: The heliosphere as a test bed for other astrospheres (image from WISE bow shock image, Zeta Ophi [54]). the point of view of the *in-situ* observations by Voyager, there are complementary observations that reveal our lack of understanding of the heliosheath. IBEX provided us global maps of the interaction between the solar system and the interstellar medium through the energetic neutral maps. The IBEX energy range is from 0.9-1.5keV (Figure 7a). The INCA instrument on board of CASSINI provided similar maps, but in the energy range of 5-13keV (Figure 7b). Both maps indicated that the emission was in a shape of a ribbon (IBEX) or belt (CASSINI) and not a uniform emission, as models previously predicted[46,47]. These global maps integrate the emission along the line of sight, so it is important while interpreting these results to know where the energetic neutral atoms are produced. For the IBEX ribbon there are several mechanisms suggested [48], neither of them satisfactory in terms of reproducing all the features of the IBEX ribbon. Some of these mechanisms place it beyond the HP [49,50], while others place it near the TS [51]. The IBEX ribbon appears to be evolving on timescales as short as six months [52], placing a strong constraint that the emission should be coming from within the heliosheath. This corroborates studies such as [53] that show that there is no much change between the power spectra of the ribbon from the extended spectra. A challenge for future studies is to unravel the location and mechanism with which the ribbon (and band) are produced. Most likely it will reveal a new aspect of the heliosheath that has been ignored so far.

Conclusions: What is next?

In the next couple of months to years, we expect for the first time to have a man-made object leave the heliosphere. Probably V1 will be the first to cross, followed by V2. This expectation is based on the current models, although this is still a matter of debate. Definitively more surprises are expected to unfold. A large effort in the community is being made now to predict which signatures we will detect with the crossing of the HP. The fact that the magnetic field might be non-laminar means that global MHD simulations might not be sufficient to compare in-situ data of the approach and crossing of the HP.

In the past few years, we were lucky to have an extended solar minima. The quiet solar wind minimized the effect of temporal variations in the heliosheath and allowed us to explore the global spatial structure of the heliosphere. With the increased solar activity, it is very important to tackle not only how the sector region varies with the solar cycle, but also the effect of temporal transients, as well. This review doesn't address the previous work done in exploring the effect of temporal phenomena, but certainly this will play a role in the next couple of years, as we unravel the structure of the heliosheath.

The heliosphere is our only example of an astrosphere (see for example - Figure 8) where we have *in-situ* data. Through the study of the heliosphere, we are learning that astrospheres are far more complex than previously thought. The future measurements by Voyager will reveal the detailed structure of the HP. We will unlock questions such as: How are cosmic rays filtered (modulated) in their entry into the heliosphere? What is the role of instabilities near the HP? How thick is the heliopause?
Hopefully, we will then have a better understanding of this last frontier of the solar system -- the heliosheath.

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