THE DYNAMIC HELIOSPHERE & ITS INTERACTION WITH THE LISM: Open questions & future perspectives.

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Introduction: The Voyager 1 and Voyager 2 (V1 & V2) crossings of the termination shock (TS) in 2004 and 2007, respectively, at distances of ~94[1,2] and ~84 AU[3,4] led to the discovery of the previously unknown reservoir of ions and electrons that constitute the heliosheath (HS), between the TS and the heliopause (HP), whereas their crossings of the HP, in 2012[5-8] and 2018[9-13] at ~122 AU and ~119 AU, respectively, pinpointed the extent of the upwind heliosphere's expansion into the Local Interstellar medium (LISM) and its rough symmetry. Both crossings were associated with a virtual depletion of particles of solar origin at all levels, an abrupt increase of GCR, magnetic field and plasma density upstream of the HP, whereas the temperature was found higher than expected. All parameters were previously significantly underestimated in most models of the heliosphere.

Apart from the similarities between the V1 and V2 crossings, some substantial differences were also idendified[9] (Figure 1). For example, the V1 crossing of the heliopause was associated with the discovery of a flow stagnation region that was observed before the boundary, possibly due to flux tube interchange instability at the HP[5]. Unlike V1, which found two interstellar flux tubes that had invaded the HS with strong anticorrelations in GCRs, V2 found no similar precursors to the HP[10].

The Voyager *in situ* measurements were complemented by global images using remotely sensed ENAs from IBEX[14] at ~1AU (<6 keV) and Cassini/INCA[15,16] at ~10 AU (5.2-55 keV), revealing a number of previously unanticipated heliospheric structures such as the "Ribbon", a bright and narrow stripe of ENA emissions between the V1 and V2 directions, that is thought to lie beyond the HP[17] with its center coinciding with the direction of the local interstellar magnetic field (ISMF) and "sits" on top of the Globally Distributed Flux, and the "Belt", a broad band of emission in the sky, identified as a high intensity, relatively wide and nearly energy independent ENA region (>5.2keV range), that wraps around the sky sphere in ecliptic coordinates, passing through the "nose", the "anti-nose" and the ecliptic poles, and corresponds to a "reservoir" of particles that exist within the HS, constantly replenished by new particles from the solar wind[18] (SW).

In anticipation of the IMAP mission at ~1AU (expected launch in 2024[19]), and the ongoing discussions for an Interstellar Probe mission (beyond 2030) traveling well beyond the HP (http://interstellarprobe.jhuapl.edu/), this White Paper lists three open science questions (among many others that are not discussed here) that can only be answered by exploiting a combination of *in-situ* ion measurements and remotely sensed ENAs.

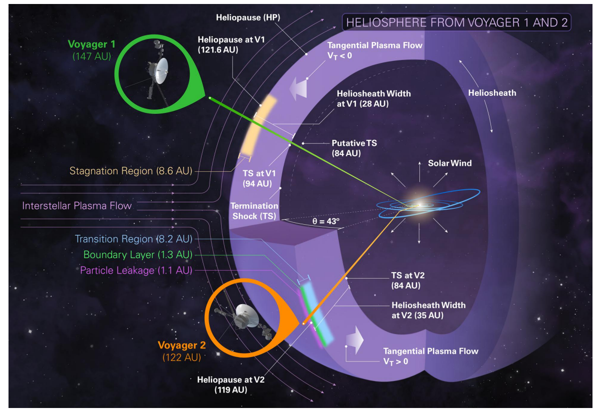

Figure 1. Concept of the global heliosphere summarizing the findings of V1 and V2. (*From Krimigis et al.*[9])

Where are the heliosphere boundaries and how thick is the HS? *In situ* measurements of >28 keV ions in the HS from V1&2/LECP provided "ground truth" to the global ENA images through overlapping energy ranges of both ions and neutrals, proving that the >5.2 keV INCA/ENAs originate in the HS[15,16,18], allowing the deduction of the magnetic field upstream of the HP[20,21], and the HS thickness[21,22] toward both the V1&2 directions with good accuracy (Figure 2).

However, there is currently a **disconnect between the observations and heliosphere models** towards explaining the fundamental force balance, responsible for the formation of the entire bubble and the locations of the TS and HP through the Solar Cycle (SC), and **lack of simultaneous *in-situ* particle and fields and ENA measurements** at the same energies, the combination of which can provide invaluable input toward exploring the structure of the HS and serve as long-term precursors to the HP and TS locations.

The examination of the SW pressure at 1 AU when propagated to the position of V1 and V2[9], showed that it has a large effect on the position of the TS, by as much as 10 AU (recent modelling argues for a TS fluctuation of ±9.0 AU over the last SC[23]), but minimal effect at the position of the HP, showing an offset of ~3-4 AU as predicted in heliosphere models[23-25]. However, most of the current models of the global heliosphere, yield thicknesses of the HS that are substantially larger (>50 AU) than measured by the Voyagers and inferred by the combination of Cassini/INCA ENAs and Voyager/LECP ions (~27-35 AU for the upwind hemisphere)[21,22]. A recent multi-ion MHD model[26] predicts a significantly reduced HS width, whereas a Monte Carlo model[27,28] that explains the transport of GCRs through the heliosphere was able to accurately obtain the V1&2 TS and

HP crossings, together with the putative near-TS crossing reported by LECP in 2002[29], which may well point toward a more symmetric upwind hemisphere.

A "missing" pressure component towards exploring the dynamics of the global HS and its interaction with the LISM? After the V1 and V2 respective crossings of the TS, it was found that the HS pressure is dominated by suprathermal particles (Figure 2), a fact that was verified by several studies using V1&2/LECP and plasma measurements[30], a combination of Voyager and Cassini/INCA ENAs[20,21] together with MHD models[26]. Recent calculations[31] on the total effective pressure in the heliosphere and comparison with IBEX observations[32] provided additional evidence that the HS dynamics are driven by suprathermal energetic processes. The shocked thermal plasma upstream of the TS remained supersonic, as only 20% of the upstream energy density went into heating the downstream thermal plasma, whereas the rest of the SW energy was transferred into heating pickup ions[33] and >15% transferred to the >28-keV protons[34]. This may well be translated to the prominent hardening break in the >28-keV H^+ energy spectra (Figure 2) that was attributed to an accelerated "core" interstellar pickup ion distribution at the TS, through shock drift acceleration and particle scattering in the vicinity of the shock[35], as one of the possible mechanisms.

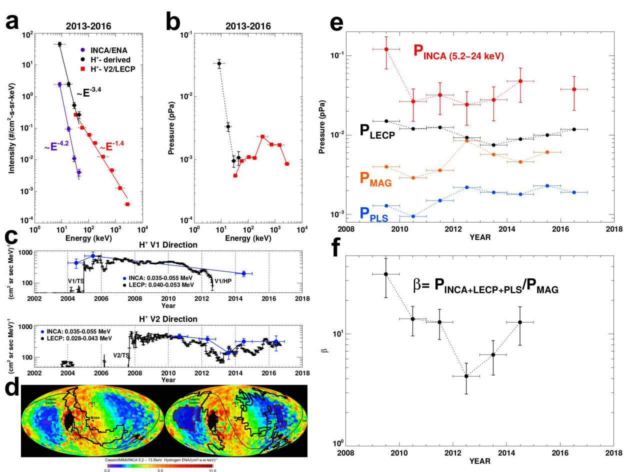

Figure 2. (a) Average 5.2-55 keV ENA energy spectra (INCA) around the V2 pixel, together with the deduced H^+ spectra (L_{V2} = 35.2 AU & n_H=0.12 cm^{-3}) and the *in-situ* ~28-3,500 keV ion energy spectra (V2/LECP). (b) The corresponding 5.2-3,500 keV H^+ pressure. (c) INCA/ENA measurements compared directly with the *in situ* LECP ion histories (*Dialynas et al.*[16,21]). (d) 2003-2009 images of 5.2-13.5 keV ENAs (ecliptic coordinates) comparing the location of the INCA defined Belt with the IBEX identified ribbon (black lines) at 1.7 keV and 4.29 keV (*from Dialynas et al.*[18]) (e) Yearly averaged pressure profiles of ~5.2-24 keV ENA-derived H^+ enclosing the V2 pixel from INCA, 28-3,500 keV H^+ from V2/LECP, >10 eV H^+ from V2/PLS, and magnetic field, as a function of time from 2009 to 2016. (f) Yearly H^+ partial pressure (PLS, INCA, and LECP) divided by the magnetic field pressure (MAG) inside the heliosheath for the 2009-2014 time period. (*From Dialynas et al.*[21])

The *in-situ* measurements from Voyager 1&2 and remotely sensed Cassini/INCA ENAs showed that the HS consists of a reservoir of superthermal particles and weak magnetic fields, characterized by plasma with β values that are always >>1 and mostly >10, exhibiting a local minimum that corresponds to the minimum of SC23 with a time delay of 2-3 years[16,21] (Figure 2). The 5.2-24 keV H^+ pressures from INCA dominate the 5.2-3,500-keV pressure distribution being about a factor of ~4 higher than the >28 keV LECP pressures over the 2009-2016 time period and a factor of ~30 higher than the measured PLS thermal pressure over the same time period[21]. Underestimating the energetic ion pressure, and/or miss-representing the energetic ion spectral shape may lead to a false understanding for the pressure balance inside the HS.

Clearly, **the shape of the ion energy spectra** play a **critical role** toward determining **the acceleration mechanisms inside the HS**, while the **combined use of *in-situ* ions, magnetic fields and ENAs** can provide accurate estimates of the HS thickness, the interstellar neutral H density and magnetic field upstream of the HP, and **delineate the components of the ion pressure in the HS**. **Imaging the heliosphere in ENAs, essentially translates to imaging the pressure of the global HS**, whereas the combination of such measurements with *in-situ* particle spectra, providing differential pressure profiles, can reveal the force balance that forms our solar bubble.

The dynamic properties of >5.2 keV INCA/ENA from the heliosheath have been shown to adequately correlate with the V1&2/LECP in-situ measurements as a function of time, presenting a compelling case that the >30 keV ions must distribute themselves throughout the HS by a mechanism faster than pure advection with the thermal SW ions and that the variations in these measured ENA-ion intensities are related to the decline and rise of the SC, as manifested in the variation of the SW itself, suggesting also that the modulation of superthermal ions over the SC is global throughout the HS[16,36]. At the same time, the <6 keV IBEX/ENA measurements have been shown to relate to the dynamic properties of the SW over the pressure changes during the SC[37,38]. Moreover, the ~4.29 keV IBEX channel measurements, that have been shown to match the >5.2 keV INCA measurements[18] (Figure 2), provided the most adequate representation of the above process, presenting the shortest time delay and largest change as a function of time[38].

Consequently, **ENA imaging over a broad energy range** and from a changing vantage point (inside and ultimately outside the Heliosphere) **over at least a SC is required**. ***In-situ*** ion measurements from **inside the HS over a significant fraction of the SC are also required** to investigate the dynamical force balance. At the same time, **the total charge density** (via the electron density, e.g. PWS instrument[8,13,39]) is important in order to know that all the ions are accounted for.

Why is the shape and size of the global heliosphere different when looking in different ENA energies? All measurements described above show clear evidence of a "deflating" and "inflating" heliosphere following the pressure changes of the SC. However, the detailed physics that explains the interaction of the heliosphere with the LISM is yet to be revealed. **The interpretations based on different ENA measurements (e.g. different energies) point to conflicting views for the global configuration of the heliosphere.**

Since the V1&2 became IS missions, it was identified that the IS flow is not the primary driver of the interaction of the heliosphere with the LISM, but rather it is the pressure of the IS magnetic field that configures the HS, as was initially suggested by Cassini/INCA-Voyager studies[15,18]. A recent interpretation of the Cassini/INCA and Voyager data[16,36] argued for **a roughly symmetric, diamagnetic bubble-like heliosphere, with few substantial tail-like features.** This interpretation was based on the high pressure and beta inside the HS, the strong IS magnetic field compared to the IS flow properties, and the similarities between INCA/ENAs towards the nose and tail and the V1&2/LECP (nose) ions, as a function of time, showing that **the heliotail may be distorted and extend to a few 100s of AU, but not to 10,000s of AU as in the comet-type configuration**. This concept is also consistent with ENA measurements from IBEX-Lo[40,41], based on the inferred pressure towards the V1 direction. Furthermore, the calculated distances of the TS and HP in IBEX-Hi ENAs[42] showed a "comet-type" configuration at ~1.1 keV ENAs and a round configuration in ~4.29 keV with the HP toward the tail extending to ~300 AU. Recent analyses[43] of Ulysses observations toward accessing the SW properties, determined that the distance from the Sun to the source of IBEX-Hi ENAs in the heliotail is ≥289-489AU (assuming a TS at ~160 AU).

In contrast, other studies[44] show that IBEX-Hi ENAs toward the tail form due to the presence of fast/slow wind, where **both the external dynamic and magnetic pressures strongly affect the heliosphere**, producing an "intermediate configuration", consistent with models that support the interpretation of **a comet-type heliosphere**[45]. Recent interpretations[38], based on (unsuccessful) modeling[46] of IBEX, INCA and HSTOF measurements, also support the notion of the classical paradigm of a comet-type configuration.

Advanced MHD models for the global heliosphere[25,47] argue that the magnetic tension of the solar magnetic field plays a crucial role in organizing the SW into **two jet-like structures, producing a croissant-like shape** for the heliosphere, where the distance to the HP towards the tail and nose is on the same order, whereas the inclusion of the thermal ions and the PUIs as separate plasmas[26] show that the energy loss of PUIs in the HS due to charge exchange with neutral H deflates the heliosphere, **producing an even more bubble-like configuration**. Other models also demonstrate confinement by the solar magnetic field but remain consistent with a tail that is elongated[24,48]. Recently, the HelMod model[27,28] toward explaining the evolution of GCRs in the heliosphere acknowledges that the dominant contribution to the stagnation pressure comes from the IS magnetic field and was able to accurately fit the Voyager measurements and obtain their crossings from the TS and HP using a dimensionless stagnation pressure that corresponds to a diamagnetic bubble-like heliosphere.

Missing measurements: After the Cassini mission end (15-Sep.-2017), a >6 keV ENA detector is not currently active. Moreover, a >6 keV He and O ENA measurement has not been made possible to date. IMAP-Ultra will extend to energies of ~300 keV and (depending on its efficiency) is expected to measure the H, He and O ENA distributions. To address the questions listed above, the combination with *in-situ* ions (e.g from an ISP mission) at the same energies is of paramount importance. We note that, to date, there have been no *in-situ* ion measurements at ~6 to <28 keV, i.e. between the V2/PLS energy range (PLS failed on V1 during the 1980s) and the V1&2/LECP (V1/LECP spans the energy range beyond ~40 keV).

References: **[1]** Decker et al. [2005]-doi:10.1126/science.1117569, **[2]** Stone et al. [2005]-doi:10.1126/science.1117684, **[3]** Decker et al. [2008]-doi:10.1038/nature07030, **[4]** Stone et al. [2008]-doi:10.1038/nature07022, **[5]** Krimigis et al. [2013]-doi:10.1126/science.1235721, **[6]** Stone et al. [2013]-doi:10.1126/science.1236408, **[7]** Burlaga et al. [2013]-doi:10.1126/science.1235451, **[8]** Gurnett et al. [2013]-doi:10.1126/science.1241681, **[9]** Krimigis et al. [2019]-doi:10.1038/s41550-019-0927-4, **[10]** Stone et al. [2019]-doi:10.1038/s41550-019-0928-3, **[11]** Burlaga et al. [2019]-doi:10.1038/s41550-019-0920-y, **[12]** Richardson et al. [2019]-doi:10.1038/s41550-019-0929-2, **[13]** Gurnett & Kurth [2019]-doi:10.1038/s41550-019-0918-5, **[14]** McComas et al. [2009]-doi:10.1126/science.1180906, **[15]** Krimigis et al [2009]-doi:10.1126/science.1181079, **[16]** Dialynas et al. [2017]-doi:10.1038/s41550-017-0115, **[17]** McComas et al. [2017]-doi:10.3847/1538-4365/aa66d8, **[18]** Dialynas et al. [2013]-doi:10.1088/0004-637X/778/1/40, **[19]** McComas et al. [2018]-doi:10.1007/s11214-018-0550-1, **[20]** Krimigis et al. [2010]-doi:10.1063/1.3529994, **[21]** Dialynas et al. [2019]-doi:10.1029/2019GL083924, **[22]** Krimigis et al. [2011]-doi:10.1038/nature10115, **[23]** Izmodenov et al. [2008]-doi:doi:10.1016/j.asr.2007.06.033, **[24]** Izmodenov & Alexashov, [2015]-doi:10.1088/0067-0049/220/2/32, **[25]** Opher et al. [2015]-doi:10.1088/2041-8205/800/2/L28, **[26]** Opher et al. [2020]-doi:10.1038/s41550-020-1036-0, **[27]** Boschini et al. [2019]-doi:10.1016/j.asr.2019.04.007, **[28]** Boschini et al. [2020]-arXiv:2006.01337(to appear in *ApJ-S*), **[29]** Krimigis et al. [2003]-doi:10.1038/nature02068, **[30]** Decker et al. [2015]-doi:10.1088/1742-6596/577/1/012006, **[31]** Rankin et al. [2019]-https://doi.org/10.3847/1538-4357/ab3d9d, **[32]** Schwadron et al. [2014]-doi:10.1088/0067-0049/215/1/13, **[33]** Mostafavi et al. [2020]-WP in HELIO2050, **[34]** Richardson et al. [2008]-doi:10.1038/nature07024, **[35]** Giacalone & Decker, [2010]-doi:10.1088/0004-637X/710/1/91, **[36]** Dialynas et al. [2017]-doi:10.1088/1742-6596/900/1/012005, **[37]** Reisenfeld et al. [2016]-doi:10.3847/1538-4357/833/2/277, **[38]** McComas et al. [2020]-doi:10.3847/1538-4365/ab8dc2, **[39]** Kurth & Gurnett, [2020]-https://doi.org/10.3847/2041-8213/abae58, **[40]** Galli et al. [2016]-doi:10.3847/0004-637X/821/2/107, **[41]** Galli et al. [2017]-doi:10.3847/1538-4357/aa988f, **[42]** Zirnstein et al. [2018]-https://doi.org/10.3847/1538-4357/aac016, **[43]** Zirnstein et al. [2020]-https://doi.org/10.3847/1538-4357/ab9605, **[44]** McComas et al. [2013]-doi:10.1088/0004-637X/771/2/77, **[45]** Zirnstein et al. [2016]-doi:10.3847/0004-637X/826/1/58, **[46]** Czeckowski et al. [2020]-https://doi.org/10.3847/1538-4357/ab5b14, **[47]** Kornbleuth et al. [2018]-https://doi.org/10.3847/1538-4357/aadbac, **[48]** Pogorelov et al. [2015]-doi:10.1088/2041-8205/812/1/L6