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A future interstellar probe on the dynamic heliosphere and its interaction with the very local interstellar medium: *In-situ* particle and fields measurements and remotely sensed ENAs

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The recently published Interstellar Probe (ISP) study report describes a pragmatic mission concept with a launch window that starts in 2036 and is expected to reach several hundreds of astronomical units past the heliopause within a time frame of ≥50 years (https://interstellarprobe.jhuapl.edu/Interstellar-Probe-MCR.pdf). Following the ISP report, this paper, that will also be accessible from the Bulletin of the AAS (BAAS) in the framework of the Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033 (Dialynas et al., A future Interstellar Probe on the dynamic heliosphere and its interaction with the very local interstellar medium: *In-situ* particle and fields measurements and remotely sensed ENAs, 2022a), aims to highlight the importance of studying the physics of the interactions pertaining to the expanding solar wind that meets the plasma, gas and dust flows of the very local interstellar medium, forming the complex and vast region of our astrosphere. We focus on three fundamental open science questions that reveal the dynamical nature of the heliosphere A) Where are the heliosphere boundaries and how thick is the heliosheath B) Is there a "missing" pressure component towards exploring the dynamics of the global heliosheath and its interaction with the very local interstellar medium C) Why does the shape and size of the global heliosphere appear different in different

Energetic Neutral Atom energies? We argue that these questions can only be addressed by exploiting a combination of *in-situ* charged particle, plasma waves and fields measurements with remotely sensed Energetic Neutral Atoms that can be measured simultaneously from the instruments of a future Interstellar Probe mission, along its trajectory from interplanetary space through the heliosheath and out to the very local interstellar medium.

KEYWORDS

interstellar probe, heliosphere, heliosheath, Voyager, Cassini, energetic neutral atoms, very local interstellar medium, solar wind

1 Introduction

Launched in 1977, the Voyager 1 and Voyager 2 (V1 and V2) missions surveyed the interplanetary space for 27–30 years (**Figure 1A**). Their measurements (**Figure 1B**; see also review article from Dialynas et al. (2022b)) showed a general decrease in ~0.14–0.22 MeV ion intensities as the inverse square of the radial distance from the Sun with a minimum at about the year 2000, followed by a gradual increase thereafter. These measurements revealed also for the first time the evolution of the outward propagating solar wind through the interplanetary space, together with the effects of Solar Particle Events (SEPs) and Corotating Interaction Regions (CIRs), from one AU (1 Astronomical Unit = 150×10^6 km) up to the termination shock. Higher energy ions (**Figure 1C**) showed a general increase in interplanetary space, presenting intensity dropouts in anti-correlation with the solar activity over the solar cycle (**Figure 1D**).

The heliosheath, the domain of Pickup Ions (PUIs) and Anomalous Cosmic Rays (ACRs) between the termination shock and the heliopause, is characterized as a “reservoir” of charged particles; ions and electrons mainly from the solar wind that are quasi-trapped in a large-scale magnetic field. Similar reservoirs are also found throughout the inner Solar System (< 5 AU) when filled with SEPs or CIRs, and the ring currents of Earth and the gas giants (e.g., Jupiter and Saturn) when energized by magnetic storms (Roelof, 2015).

Several key open science questions drive the need for more detailed *in-situ* particle and fields measurements and remotely sensed Energetic Neutral Atom (ENA) observations from a future Interstellar Probe (ISP; McNutt et al., 2022; Brandt et al., 2022b) mission to:

- Understand the physics of the large scale reservoir that constitutes the heliosheath.
- Unveil the processes that govern the transport and acceleration of particles inside the heliosheath.
- Understand the locations and/or the physical processes that occur in the “walls” of our solar bubble, such as the termination shock and heliopause.
- Characterize the interaction of the heliosheath with the Very Local Interstellar Medium (VLISM) and the structure and physics of the VLISM itself.
- Finally, understand the force balance that controls our Sun’s astrosphere, together with its shape and size.

2 *In-situ* ions and remotely sensed ENAs

The crossings of V1 and V2 from the termination shock in 2004 and 2007, respectively, at distances of ~94 (Decker et al., 2005; Stone et al., 2005) and ~84 AU (Decker et al., 2008; Stone et al., 2008) led to the discovery of the previously unknown reservoir of ions and electrons that constitute the heliosheath. The V1 and V2 crossings of the heliopause (although other interpretations exist, e.g., Fisk and Gloeckler (2014); Fisk and Gloeckler (2022)), in 2012 (Burlaga et al., 2013; Gurnett et al., 2013; Krimigis et al., 2013; Stone et al., 2013) and 2018 (Burlaga et al., 2019; Gurnett and Kurth, 2019; Krimigis et al., 2019; Richardson et al., 2019; Stone et al., 2019) at ~122 AU and ~119 AU, respectively, pinpointed the extent of the upwind heliosphere’s expansion into the VLISM and its rough symmetry. The Voyagers also showed for the first time that the heliosheath alone filters ~65% of the very high energy Galactic Cosmic Rays (GCR), providing an immense shield that protects our Solar System from the harsh galactic radiation (overall ~25% of GCRs reach 1 AU; **Figure 1C**). Both crossings of the heliopause 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 at the heliopause, 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 and puzzling differences were also identified (Krimigis et al., 2019) (**Figure 1E**). 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 boundary (Krimigis et al., 2013). The use of Low Energy Charged Particle (LECP; Krimigis et al., 1977) measurements in V1, revealed the existence of a radial inflow of ~40–139 keV ions within the heliosheath, for ~9–10 AU before the heliopause crossing and a radial outflow over a spatial scale of ~28 AU past the heliopause (Dialynas et al., 2021), that corresponds to an ion population leaking from the heliosheath into interstellar space; although a different interpretation for these measurements may indicate that V1 is still surveying the heliosheath (Fisk and Gloeckler, 2022). Unlike V1, which found two interstellar flux tubes that had invaded the heliosheath with strong anticorrelations in GCRs, V2 found no similar precursors to the heliopause (Stone et al., 2019). Clearly, the interstellar space upstream at the heliopause is not a “calm sea” of rarefied plasma and fields (e.g., Gurnett et al., 2021, and references therein).

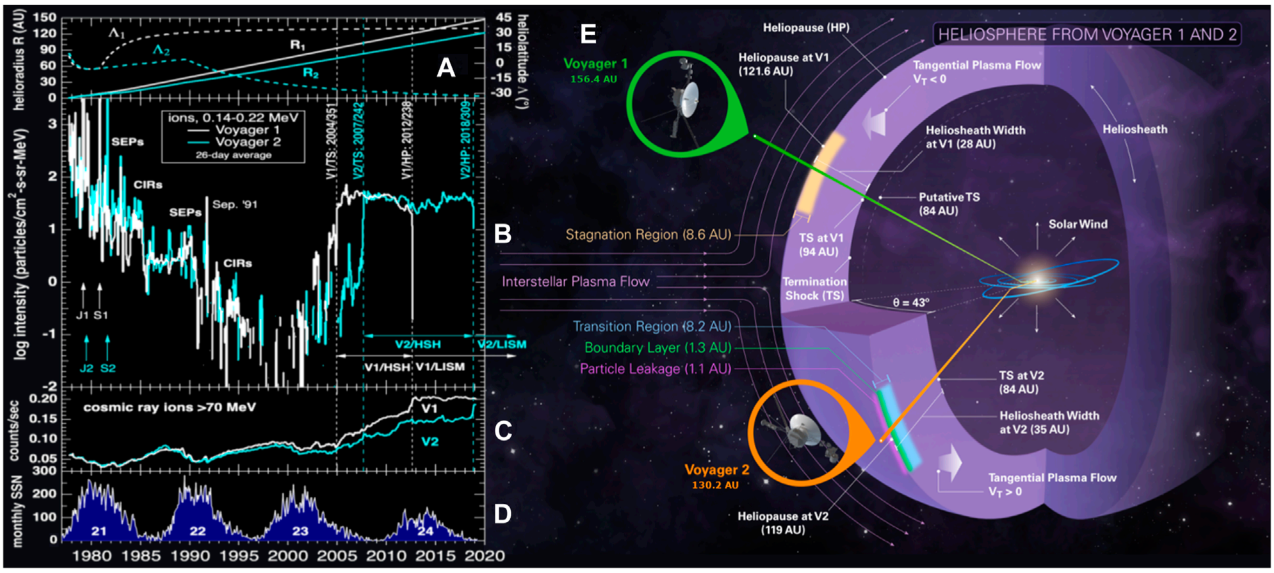

FIGURE 1
(A) The trajectories of V1 and V2 since their launch in 1977, through interplanetary space, the termination shock and heliopause until 2020, together with the LECP measurements of **(B)** 0.14–0.22 MeV ions and **(C)** >70 MeV Galactic Cosmic Rays (GCR), that correspond to **(D)** four full solar cycles (from Dialynas et al. (2022b)). **(E)** A Concept of the global heliosphere summarizing the findings of V1 and V2 (From Krimigis et al. (2019)).

The Voyager *in-situ* observations/findings, which guide the requirements (baseline) for the particle and fields measurements from a future ISP mission, were complemented by global images using remotely sensed Energetic Neutral Atoms (ENAs), revealing a number of previously unanticipated heliospheric structures (**Figure 4**). The Interstellar Boundary Explorer (IBEX; McComas et al., 2009) measurements at ~1 AU (<6 keV) showed the existence of the "Ribbon", a narrow stripe (FWHM of ~15°) of ENAs between the V1 and V2 directions, that is thought to form beyond the heliopause (McComas et al., 2017) and "sits" on top of a Globally Distributed Flux (GDF) that is largely of heliosheath origin (Dialynas et al., 2013; McComas et al., 2017). Images from Cassini/Ion and Neutral Camera (INCA; Krimigis et al., 2009; Dialynas et al., 2017b) at ~10 AU (5.2–55 keV) showed the "Belt", a broad band of emission in the sky, identified as a high intensity, relatively wide (FWHM ~50°–80°) and nearly energy independent ENA region, that wraps around the sky sphere and has been unarguably proven to correspond to a "reservoir" of particles that exists within the heliosheath, constantly replenished by new particles from the solar wind (Dialynas et al., 2013), and two prominent "Basins" where the ENA minima occur, also of heliosheath origin. Previous research has shown that the GDF evolves with increasing energy to form the Belt beyond ~5.2 keV (e.g., Dialynas et al., 2013, see also **Figure 4**), both originating from the heliosheath, whereas the Ribbon is formed through a secondary ENA process beyond the heliopause and has evolved differently than the GDF (and the Belt) as a function of time (McComas et al., 2017). These structures drive the angular and energy resolution requirements of an ENA detector in a future ISP mission, and the need of ENA imaging from a changing vantage point along its trajectory, that would reveal the changes of the Belt/Ribbon in width and intensity/pressure within the Solar Cycle (SC).

3 Where are the heliosphere boundaries and how thick is the heliosheath?

In-situ measurements of >28 keV ions in the heliosheath from V1and2/LECP provided "ground truth" to the global ENA images through overlapping energy ranges of both ions and ENAs (**Figure 2**), proving that the >5.2 keV INCA/ENAs are the manifestation of the hot plasma ions sampled by the Voyagers locally, and illuminate the region of enhanced particle pressure that lies between the termination shock and the heliopause (Krimigis et al., 2009; Dialynas et al., 2017b). This allowed the deduction of the magnetic field upstream of the heliopause (Krimigis et al., 2010; Dialynas et al., 2019; Dialynas et al., 2020), and the heliosheath thickness (Krimigis et al., 2011; Dialynas et al., 2019) toward both the V1and2 directions. The propagated solar wind pressure to the position of V1 and V2 (Krimigis et al., 2019), showed that it has a large effect on the position of the termination shock, by as much as 9–10 AU (e.g., Krimigis et al., 2003; Izmodenov et al., 2008), but minimal effect at the position of the heliopause (offset of ~3 to 4 AU; e.g., Izmodenov et al. (2008); Izmodenov and Alexashov (2015); Opher et al. (2015)) (see also **Figure 1E**). By contrast, most models of the global heliosphere yield thicknesses of the heliosheath that are substantially larger (>50 AU) than measured by the Voyagers (**Figure 1E**) and inferred by the combination of Cassini/INCA ENAs and Voyager/LECP ions (Krimigis et al., 2011; Dialynas et al., 2019; Kleimann et al., 2022).

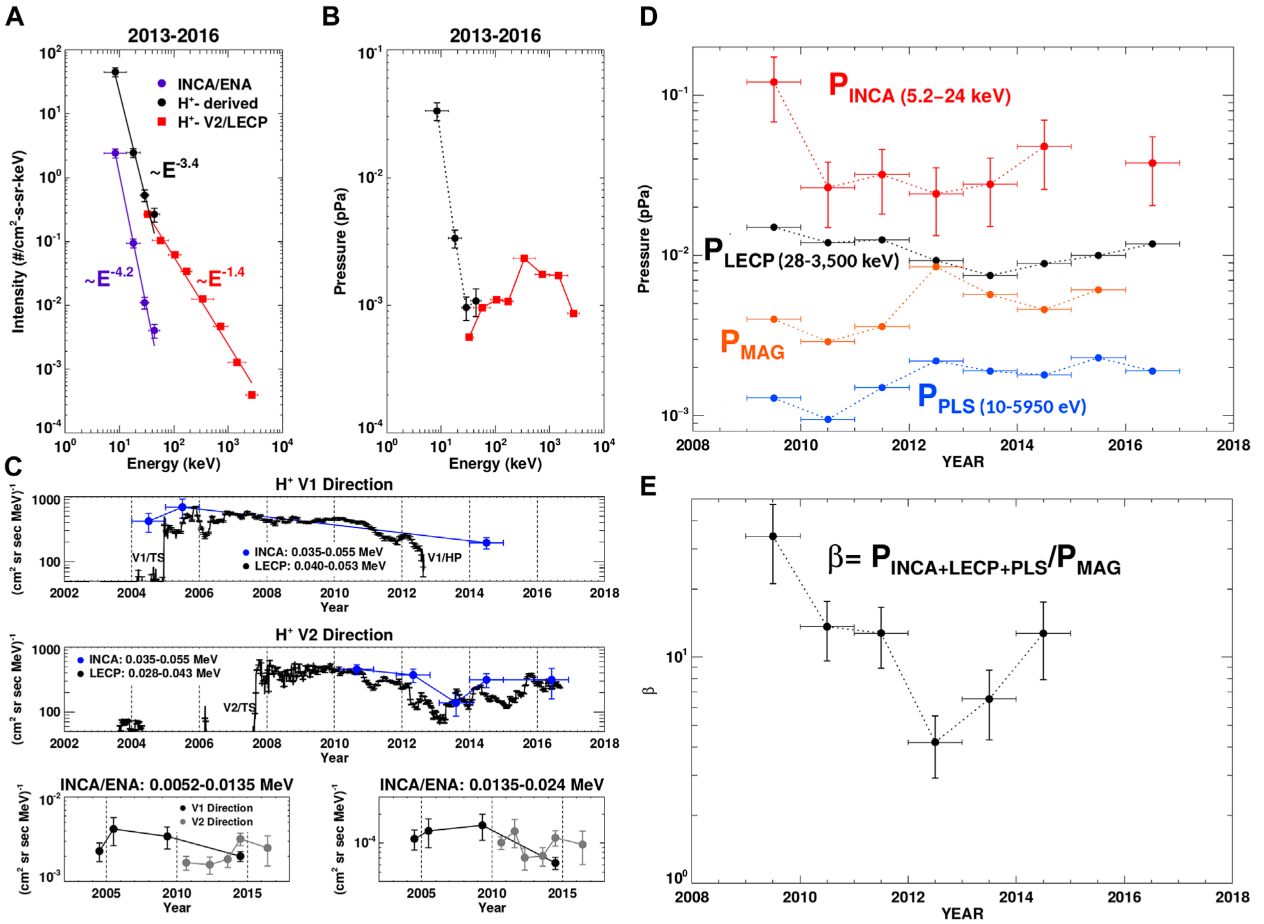

FIGURE 2
(A) Average 5.2–55 keV ENA energy spectra around the V2 pixel, as measured by Cassini/INCA and the deduced H^+ spectra (L_{V2} = 35.2 AU and n_H = 0.12 cm^{-3}) compared with *in-situ* ~28–3,500 keV ion energy spectra as measured by V2/LECP. **(B)** The corresponding 5.2–3,500 keV H^+ partial pressure in pPa per each energy bin (in keV). **(C)** INCA/ENAs compared directly with *in-situ* LECP ion histories (Dialynas et al., 2017b; Dialynas et al., 2019). **(D)** Partial pressure of ~5.2–24 keV ENA-derived H^+ enclosing the V2 pixel (INCA), 28–3,500 keV H^+ (V2/LECP), >10 eV H^+ (V2/PLS; measuring ions that comprise the bulk of the plasma), and magnetic field, as a function of time; **(E)** beta inside the heliosheath (Dialynas et al., 2019).

Although both steady-state (Izmodenov and Alexashov, 2015) and time-dependent (Izmodenov and Alexashov, 2020) kinetic magnetohydrodynamic (MHD) simulations show that it is not possible to obtain the heliosheath thickness as measured by Voyager with the same set of data-driven boundary conditions, adding electron thermal conductivity and under the assumption that the plasma flow is isothermal (Izmodenov et al., 2014), the observed distances to the termination shock and heliopause are obtained, when thermal pressure is decreased in the heliosheath. The use of a κ-distribution (Heerikhuisen et al., 2008) also results in reduced pressure, but as shown by the combination of LECP and INCA measurements (Dialynas et al., 2019), a single κ-distribution underestimates the partial pressure that lies in the ~5.2–24 keV energy range. A thin heliosheath may also be obtained due to charge-exchange losses of PUIs in the heliosheath (Opher et al., 2020) or loss of a fraction of ACRs whose energy comes from the solar wind (Guo et al., 2018) or due to time-dependent instabilities (Borovikov and Pogorelov, 2014).

4 A "missing" pressure component toward exploring the dynamics of the global heliosheath and its interaction with the VLISM?

The V1 and V2 respective crossings of the termination shock, showed that the non-thermal plasma dominates the dynamics of the heliosheath (Roelof et al., 2010) (**Figures 2D,E**), a fact that was verified by the V1and2/LECP and plasma measurements (Decker et al., 2015), the combination of Voyager and INCA/ENAs (Krimigis et al., 2010; Dialynas et al., 2019) together with MHD models (Opher et al., 2020). Recent calculations (Rankin et al., 2019; Dialynas et al., 2020) on the total effective pressure in the heliosphere and comparison with IBEX observations (Schwadron et al., 2014) provided additional evidence. The shocked thermal plasma downstream of the termination shock remained supersonic, as only 20% of the solar wind energy density went into heating the thermal ions, whereas ~65% was transferred

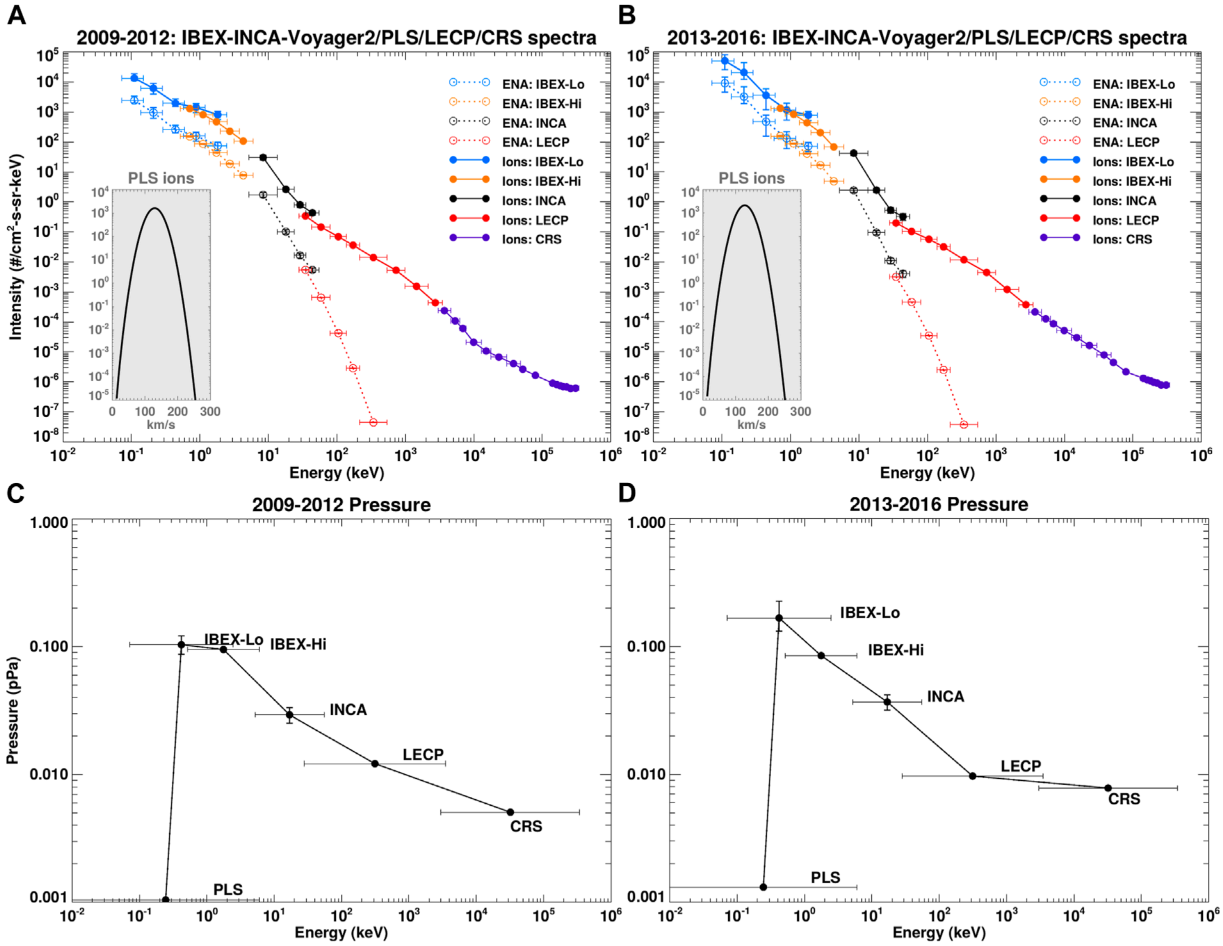

FIGURE 3
Average 0.11–55 keV ENA energy spectra (IBEX, INCA) in the pixels enclosing the position of V2, together with the deduced H^+ spectra (L_{HS} = 35 AU and n_H = 0.12 cm^{-3}), and the 0.028–344 MeV ion energy spectra measured *in-situ* (LECP, CRS) for **(A)** 2009–2012 and **(B)** 2013–2016. The inlays indicate the 10 to 5,950 eV ion intensities derived from fits to the PLS data with an isotropic Maxwellian. The ~28–540 keV LECP measurements are converted to ENAs, providing a prediction for the upcoming IMAP. If IMAP observed similar energy, this would indicate that these ENAs are the result of charge-exchange interactions inside the heliosheath. Possible differences would enable the search for different source and/or acceleration mechanisms **(C, D)** The average 10 eV to 344 MeV H^+ partial pressures inside the heliosheath, within the energy ranges covered by each different instrument (PLS, IBEX-Hi, IBEX-Lo, INCA, LECP and CRS) using the measurements in panels **(A)** and **(B)** (details in (Dialynas et al., 2020).

into heating PUIs and ~15% transferred to the >28-keV protons (Richardson et al., 2008). This may well be translated to the prominent hardening break in the >28-keV H^+ energy spectra (**Figure 2A**). Ion speeds kept decreasing inside the heliosheath until Voyager entered a finite transition layer of almost zero radial and meridional plasma flow velocity for several AU (Krimigis et al., 2011; Decker et al., 2012).

The *in-situ* measurements from the Voyagers and remotely sensed Cassini/INCA ENAs showed that the heliosheath consists of a reservoir of superthermal particles and weak magnetic fields, characterized by plasma with β values that are always ≫1 and mostly >10 (β = ratio of particle pressure over magnetic field pressure), exhibiting a local minimum that corresponds to the minimum of SC23 with a time delay of 2–3 years (Dialynas et al., 2017b; Dialynas et al., 2019) (**Figure 2E**). A recent (Dialynas et al., 2020) combination of ~10 eV to 344 MeV measurements of ions and ENAs (**Figures 3A,B**), representative of the heliosheath conditions about the minimum of SC23 and onset of SC24, showed that the spectra exhibit a series of softening and hardening breaks, indicative of possible ion acceleration processes inside the heliosheath. These measurements showed that the overall shape of the ion spectrum inside the heliosheath deviates substantially from a single κ-distribution (Scherer et al., 2022) (or a single Maxwellian). PUIs dominate the particle pressure (**Figures 3C,D**), but suprathermal particles provide a significant contribution that cannot be neglected. Underestimating the energetic ion pressure (>5.2 keV), and/or miss-representing the energetic ion spectral shape may lead to a false understanding for the pressure balance inside the heliosheath.

A recent analysis (Gkioulidou et al., 2022) showed the existence of an energy-dependent discrepancy between models and the 0.52–55 keV measured spectra, indicating that the termination shock may not accelerate the PUIs to sufficient energies. Thus, further acceleration inside the heliosheath *via* additional physical processes is required to account for the observed ENA fluxes by

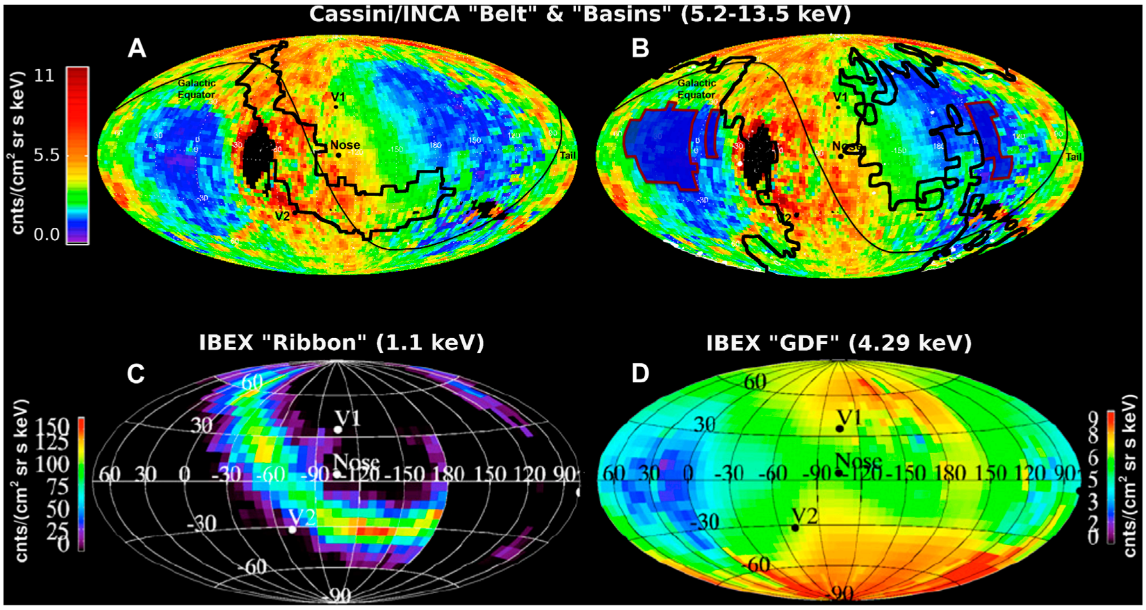

FIGURE 4
(Top) Image of heliospheric ENAs in the range of ~5.2 to 13.5 keV, in ecliptic coordinates showing the "Belt" and the "Basins", as detailed in the text. The black outlines at each image enclose the regions of maximum ENA intensities of **(A)** IBEX-Hi at ~1.1 keV and **(B)** IBEX-Hi at ~4.29 keV (Dialynas et al., 2013) (Bottom) Image of heliospheric ENAs from IBEX at **(C)** ~1.1 keV showing the "Ribbon" and **(D)** ~4.29 keV showing the ENA fluxes from the GDF (Schwadron et al., 2011).

IBEX and INCA. The dynamic properties of >5.2 keV INCA/ENA from the heliosheath have been shown to adequately correlate with the V1and2/LECP *in-situ* measurements as a function of time, presenting a compelling case that the >30 keV ions must distribute themselves throughout the heliosheath by a mechanism faster than pure advection with the thermal solar wind ions. Furthermore, the variations in these measured ENA-ion intensities are related to the decline and rise of the solar cycle, as manifested in the variation of the solar wind itself, suggesting also that the modulation of superthermal ions over the solar cycle is global throughout the heliosheath (Dialynas et al., 2017b; Dialynas et al., 2017a). At the same time, the <6 keV IBEX/ENA measurements have been shown to relate to the dynamic properties of the solar wind over the pressure changes during the solar cycle (Reisenfeld et al., 2016; McComas et al., 2020). Moreover, the ~4.29 keV IBEX measurements have been shown to match the >5.2 keV INCA measurements (Dialynas et al., 2013) (**Figure 4B**) and provide the most adequate representation of the above process, presenting the shortest time delay and largest change as a function of time (McComas et al., 2020).

5 Why does the shape and size of the global heliosphere appear different in different ENA energies?

All measurements described above show clear evidence of a "deflating" and "inflating" heliosphere following the pressure changes of the solar cycle (Dialynas et al., 2017b). However, the detailed physics that explains the interaction of the heliosphere with the VLISM is still an open question and debated in the literature (e.g., Dialynas et al., 2022b; Kleimann et al., 2022).

Since the V1and2 became interstellar missions, it was identified that the interstellar flow is not the primary driver of the interaction of the heliosphere with the VLISM, but rather it is the pressure of the interstellar magnetic field that mainly configures the heliosheath, as was initially suggested by Cassini/INCA-Voyager studies (Krimigis et al., 2009; Dialynas et al., 2013). The use of 5.2–55 keV ENA data from Cassini/INCA combined with V1 (>40 keV) and V2 (>28 keV) *in-situ* ions from LECP (Dialynas et al., 2017b; Dialynas et al., 2017a) 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 heliosheath, the strong interstellar magnetic field compared to the interstellar flow properties, and the similarities between INCA/ENAs towards the nose and tail and the V1and2/LECP (nose) ions, as a function of time. It was also stressed, however, that the heliotail may be distorted/stretched and extend to a few 100s of AU, but not to ~20,000 AU as in the traditional (long tail) comet-type configuration. This concept is also consistent with ENA measurements from IBEX-Lo (~10 eV to ~2 keV; Galli et al., 2016; Galli et al., 2017), based on the inferred pressure towards the V1 direction, showing also that *via* the trace-back times of ENAs, the region of ENA production has a similar distance toward the poles and toward the flanks of the heliotail. The calculated distances of the termination shock and heliopause based on IBEX-Hi ENAs (~0.52 to ~6 keV; Zirnstein et al., 2018) showed a "comet-type" configuration at ~1.1 keV ENAs and a bubble-like configuration at ~4.29 keV with the heliopause toward the tail extending to ~300 AU. The use of 11 years of IBEX-Hi observations showed that the heliosphere extends at least ~350 AU tailwards (Reisenfeld et al., 2021), in agreement with recent analyses (Zirnstein et al., 2020) of Ulysses observations of the solar wind, where the distance from the Sun to the source of ENAs in the heliotail was shown to be ≥ 289-489AU (assuming a termination shock at ~160 AU in the downwind direction).

Other studies (McComas et al., 2013) using IBEX-Hi ENAs show a tail that forms due to the presence of fast/slow wind, where both the external dynamic and magnetic pressures strongly affect the heliosphere, producing an "intermediate configuration", that remains consistent with a long tail configuration that may extend out to several 1000s of AU. Recent interpretations (McComas et al., 2020), based on modeling of the 0.52–6 keV IBEX-Hi and 58–88 keV SOHO/HSTOF measurements (Czechowski et al., 2020) support the notion of the traditional (long tail) comet-type configuration (heliotail extending to ~20,000 AU).

Advanced MHD models for the global heliosphere (Opher et al., 2015; Kornbleuth et al., 2018) argue that the magnetic tension of the solar magnetic field plays a crucial role in organizing the solar wind into two jet-like structures, producing a "croissant-like" shape for the heliosphere, where the distance to the heliopause towards the tail and nose is on the same order. Including the thermal ions and PUIs as separate plasmas (Opher et al., 2020) results in a more deflated heliosphere, as a result of energy loss of PUIs in the heliosheath due to charge-exchange. Other models also demonstrate confinement by the solar magnetic field but remain consistent with a tail that is elongated (Izmodenov and Alexashov, 2015; Pogorelov et al., 2015). The comparison (Kornbleuth et al., 2021) of the Boston University-croissant (Michael et al., 2021) and Moscow long-tail (Izmodenov and Alexashov, 2020) models showed collimation of the heliosheath plasma by the solar magnetic field and identical solutions up to at least ~300 AU downwind. The HelMod model (Boschini et al., 2019, 2020) toward explaining the evolution of GCRs in the heliosphere acknowledged the dominant role of the interstellar magnetic field and obtained the V1/V2 crossings of the termination shock and heliopause using a dimensionless stagnation pressure that corresponds to a diamagnetic bubble-like heliosphere.

6 Key points and recommendations

Following the ISP study report (https://interstellarprobe.jhuapl.edu/Interstellar-Probe-MCR.pdf; McNutt et al., 2022; Brandt et al., 2022b), a pragmatic mission concept (launch window starts in 2036), traveling well beyond the heliopause, and in anticipation of the IMAP mission (McComas et al., 2018) at ~1 AU (launch in 2025) acting as a high-res "guide" to ISP, this paper highlighted the importance of studying the physics of the interactions pertaining to the expanding solar wind that meets the plasma, gas and dust flows of the VLISM, forming the complex and vast region of our astrosphere (see also Brandt et al., 2022a; Dialynas et al., 2022a; DeMajistre et al., 2022; Hill et al., 2022; Lavraud et al., 2022; Mostafavi et al., 2022; Opher et al., 2022; Provornikova et al., 2022; Sokół et al., 2022; Sterken et al., 2022). We focused on three fundamental open science questions that can only be addressed by exploiting a combination of *in-situ* charged particle, plasma waves and fields measurements with remotely sensed ENAs, that are measured simultaneously on the future ISP mission.

In **Section 3** we showed that 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 -especially- the locations of the termination shock and heliopause through the solar cycle, and lack of simultaneous *in-situ* particle, fields and ENA measurements at the same energies, the combination of which can provide invaluable input toward exploring the structure of the heliosheath and serve as long-term precursors to the heliopause and termination shock locations (e.g., review articles Dialynas et al., 2022b; Kleimann et al., 2022). We argue that the combination of *in-situ* particle and fields measurements with remotely sensed ENAs over the evolving solar cycle is required, in order to identify a) the way(s) that multi-scale solar wind structures propagate and evolve in the outer heliosphere, b) the resulting plasma flows inside the heliosheath, c) the role of charge exchange, d) the changes in the termination shock and heliopause locations in response to pressure pulses, shocks, and waves in the solar wind.

In **Section 4** we showed that the shape of the ion energy spectra plays a critical role toward determining the acceleration mechanisms inside the heliosheath, while the combined use of *in-situ* ion distributions, magnetic fields and remotely sensed ENAs can constrain/provide accurate estimates of the heliosheath thickness, the interstellar neutral H density and magnetic field upstream of the heliopause, and delineate the components of the ion pressure in the heliosheath. Imaging the heliosphere in ENAs, essentially translates to imaging the pressure of the global heliosheath, whereas the combination of ENAs with *in-situ* particle spectra, providing differential pressure profiles, can reveal the force balance that forms our solar bubble (e.g., review article Dialynas et al., 2022b). We argue that ENA imaging over a broad energy range and from a changing vantage point (inside and ultimately outside the Heliosphere) over at least a solar cycle is required. Synergistic use of *in-situ* ion measurements from inside the heliosheath over a significant fraction of the solar cycle are also required to investigate the dynamical force balance. At the same time, the total charge density (*via* the electron density, e.g., from a plasma wave -PWS- instrument; Gurnett et al., 2013; Gurnett and Kurth, 2019; Kurth and Gurnett, 2020) is important in order to know that all the ions are accounted for.

In **Section 5** we showed that interpretations based on different ENA energies reveal non-conclusive views for the global configuration of the heliosphere: it is consistent with a stretched bubble when looking at ~10 eV to ~2 keV ENAs (IBEX-Lo), but it becomes consistent with the traditional long tail (comet-type) configuration when looking at ~0.5 to 6 keV ENAs (IBEX-Hi). The heliosphere is consistent with a stretched bubble of a few 100s of AU at 5.2–55 keV ENAs (INCA; combined with >28 keV *in-situ* measurements from V1and2 LECP) and "returns back" to a long-tail configuration at 58–88 keV ENAs (HSTOF). Surprisingly, the ENAs at the energies of a few keV, where IBEX-Hi and INCA channels partially overlap, point to a global heliosphere that is consistent with a stretched bubble with a tail of a few 100s of AU. While the > 6 keV ion charge-exchange lifetimes ($\tau \sim (n_H \sigma v)^{-1}$, where n_H is the neutral hydroden density, σ is the charge-exchange cross sections and v is the ion velocity) increase with increasing energy, we argue that ENA images of the heliosphere over a broad energy range (>50 keV) and from a vantage point beyond the heliopause, will provide a unique way of discerning its global structure (e.g., Galli et al., 2019; DeMajistre et al., 2022).

7 Short discussion on missing measurements

The science goals that became the focus of the present study are only a small part of the fundamental questions posed by numerous works (referenced throughout the manuscript), detailing on the measurements of V1, V2, Cassini, IBEX and New Horizons missions concerning the physics of the heliosphere, that drive the requirements of a future ISP mission.

Undoubtedly, V1 and V2 made substantial discoveries and posed new and exciting questions about the interactions of the heliosphere with the VLISM, being the only missions to date that have transcended through the boundaries of our solar bubble (now surveying through interstellar space). However, because the Voyagers were initially designed to perform planetary flybys, due to instrument limitations (e.g., partial charged particle observations and/or insufficient magnetic field resolution, etc.), they have also left several science questions unresolved. On the other hand, relying on measurements from the New Horizons mission (currently located at ~55 AU from the Sun) would not suffice, as it includes a rather limited scientific payload (e.g., it does not carry a magnetometer or a plasma wave instrument), whereas depending on its power budget the spacecraft may not provide measurements well beyond the termination shock and/or (especially) close (or beyond) the heliopause. An ISP would become the only spacecraft to carry the necessary instrumentation to provide *in-situ* charged particle and fields measurements, alongside remotely sensed ENAs throughout the heliosphere, with no energy gaps and with sufficient resolution.

Here we will only briefly discuss the required measurements from a future ISP mission, but we highlight that the details of the baseline ISP mission architecture, trajectory options, required measurements, example payload instruments and comparison with active and past missions can be thoroughly reviewed in the published ISP report (https://interstellarprobe.jhuapl.edu/Interstellar-Probe-MCR.pdf) and the recently published works of McNutt et al. (2022) and Brandt et al. (2022b), Brandt et al. (2023), and references therein.

The determination of plasma flow velocities, densities, temperatures and magnetic fields is critically important for understanding the acceleration of particles in the solar wind and the helioseath, the physics at the termination shock and the heliopause, plasma wave generation and propagation, wave-particle interactions, plasma turbulence, magnetic reconnection, etc., but also to determine the important charge fraction of the VLISM, the shocks of solar origin (e.g., Gurnett et al., 2021) and/or the very weak emissions that are barely detectable from Voyager/PWS (e.g., Ocker et al., 2021), together with its overall thermal properties (e.g., see review articles by Dialynas et al. (2022b); Kleimann et al. (2022); Richardson et al. (2022)). Such studies would require a combination of high time and energy resolution plasma measurements from ~3 eV/q (with high signal-to-noise ratio; SNR) up to PUI energies, with a plasma wave detector that would measure the emissions around the electron plasma frequency, and high sensitivity that would allow for independent measurements of the plasma density and temperature in the VLISM (<3 eV), alongside magnetic field observations in the nT range with pT resolution.

Distinguishing between different acceleration processes of ACRs and determining their source, together with their relation to singly charged PUIs (e.g., see review article by Giacalone et al. (2022)), requires measuring the intensities and anisotropies of protons, He, Li-Be-B, C, N, O, Ne as well as other heavy ions within the energy range of 100s of keV to ~100 MeV/nuc. At the same time, the Voyager missions demonstrated that further measurements of the intensities and anisotropies of GCRs are needed, to study their sources, modulation by the heliospheric shielding, solar dynamics over the solar cycle, together with the properties of the unshielded GCR spectra in the ISM, including rare species and isotopes that were not measured in V1 and V2.

In direct response to the science questions posed in this paper, it should be highlighted that, to date, there have been no *in-situ* ion measurements at a very crucial part of the ion distribution that contributes substantially to the ion processes in the heliosheath and the heliopause, i. e., PUI energies up to about 28 keV, corresponding to energies between the V2/PLS energy range (V1/PLS failed during the 1980s) and the V2/LECP (V1/LECP takes measurements at the energy range beyond ~40 keV). As explained in his paper, because PUIs carry a substantial part of the particle pressure inside the heliosheath, their role in the dynamics of the outer heliosphere and the VLISM is dominant. Noteably, even if New Horizons reaches well beyond the termination shock, its instrumentation is not designed to measure multiple and heavier species of PUIs. Thus, determining the role of the thermal plasma, PUIs and energetic particles in the interaction between the heliosheath plasma and the VLISM (the relation of ACRs to singly charged PUIs, etc.), highly relies on the existence of a future ISP mission. Furthermore, measuring the intensities and distributions of energetic charged particles (of keV energies) beyond the heliopause (that drop to a level of ~1% of that in the heliosheath) requires significantly improved SNR measurements (compared to the Voyagers), a factor that depends on the design of the corresponding detector on the future ISP. Such higher sensitivity instrumentation is imperative to explore the state of the VLISM.

From the perspective of remotely sensed ENA measurements, it should be noted that after the end of the Cassini mission (15-Sep.-2017), a >6 keV ENA detector that takes images of the heliosphere is not currently in operation. Moreover, >6 keV He and O ENA images have not been made possible to date. IBEX will remain operational until at least 2025, the year when its successor (IMAP) will be launched and cover the energy range of ~10 eV to 300 keV with three ENA imagers. IMAP-Lo and IMAP-Hi will produce better global ENA maps with improved angular and temporal resolution with respect to IBEX. 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. These upcoming IMAP observations may help substantially to resolve some of the open questions surrounding the Ribbon, the GDF and the Belt, but to address the questions and conundrums listed in this paper, the combination of ENA images with *in-situ* ions (from a future ISP mission) at the same (broad) energy range, and from a changing vantage point inside the heliosphere and eventually well beyond the heliopause is of paramount importance. Imaging the heliosphere in ENAs from a vantage point far beyond the heliopause is particularly important when considering the question about discerning its global shape and structure.

Data availability statement

The present work does not involve a new analysis of any Cassini/MIMI observations, Voyager 1 and 2 measurements or other spacecraft data. The measurements included in **Figures 1–4** can be acquired from the repositories that are indicated by the corresponding manuscripts, as referenced in each Figure caption, i.e., doi:10.1088/0004-637X/778/1/40, doi:10.1038/s41550-017-0115, doi:10.1029/2019GL083924, doi:10.3847/2041-8213/abcaaa, doi:10.1007/s11214-022-00889-0, doi:10.1038/s41550-019-0927-4, doi:10.1088/0004-637X/731/1/56.

Author contributions

All authors have equally contributed to all aspects of the manuscript. The manuscript represents their contribution to the Decadal Survey for Solar and Space Physics (Heliophysics) 2024–2033, that will also be accessible from the Bulletin of the AAS (BAAS): Dialynas et al., A future Interstellar Probe on the dynamic heliosphere and its interaction with the very local interstellar medium: *In-situ* particle and fields measurements and remotely sensed ENAs, 2022a. All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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