The Structure of the Global Heliosphere as Seen by In-Situ Ions from the Voyagers and Remotely Sensed ENAs from Cassini

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Abstract
The exploration of interplanetary space and our solar bubble, the heliosphere, has made a big leap over the past two decades, due to the path-breaking observations of the two Voyager spacecraft, launched more than 44 years ago. Their in-situ particle and fields measurements were complemented by remote observations of 5.2 to 55 keV Energetic Neutral Atoms (ENA) from the Cassini mission (Ion and Neutral Camera-INCA), revealing a number of previously unanticipated heliospheric structures such as the “Belt”, a region of enhanced particle pressure inside the heliosheath. The Suprathermal Time Of Flight (HSTOF) instrument on the Solar and Heliospheric Observatory (SOHO) also provided information of 58–88 keV ENAs from the heliosphere. In this chapter we provide a brief discussion for the contribution of the Voyager 1 and 2 Low Energy Charged Particle (LECP) observations that provided “ground truth” to the ENA images from Cassini/INCA towards addressing fundamental questions for the heliosphere’s interaction with the Very Local Interstellar Medium.

Keywords Voyager 1 · Voyager 2 · LECP · In-situ ions · Cassini · INCA · SOHO · HSTOF · Heliosphere · ENA
1 Introduction

Voyager 1 and Voyager 2 (V1 & V2) reached the termination shock (TS) (e.g. Decker et al. 2005, 2008), the dynamical surface where the free expansion of the supersonic solar wind (SW) terminates and becomes the heated non-thermal plasma region called the heliosheath (HS). These crossings led to the discovery of the reservoir of ions and electrons that constitute the HS (e.g. Krimigis et al. 2011; Decker et al. 2012, 2015), the region between the TS and the outer boundary of our heliosphere, called heliopause (HP), the interface between our solar bubble and the galaxy (e.g. Krimigis et al. 2013, 2019).

The 5.2–55 keV Energetic Neutral Atom (ENA) images from the Ion and Neutral Camera (INCA) instrument on Cassini (Krimigis et al. 2009) placed the local Voyager measurements in a global context and revolutionized our notions about the formation and interactions of the global heliosphere (e.g. Dialynas et al. 2017b), providing important insights on the plasma processes that occur at the utmost, distant boundaries of our solar bubble. Lower energy ENAs (see Galli et al. 2022; this journal) from the Interstellar Boundary Explorer (McComas et al. 2009) showed the existence of an unexpected, bright, narrow stripe of ENA emissions (called “Ribbon”) between the directions of the Voyagers, that is thought to form beyond the heliopause and sits on top of a Globally Distributed Flux (GDF) of ENAs (Schwadron et al. 2011), that are most likely of heliosheath origin (McComas et al. 2017b). First information on 58–88 keV ENAs from a ±17° band above and below the ecliptic were also presented about a decade earlier from the High energy Suprathermal Time Of Flight (HSTOF) instrument on the Solar and Heliospheric Observatory (SOHO) (e.g. Hilchenbach et al. 1998), whereas the oldest all-sky images of the global heliosphere date back to the beginning of the year 2000 from Cassini/INCA (Westlake et al. 2020).

Protons (H+) are the most abundant species in space and since a proton plasma does not emit photons, the ENAs, created by the proton-neutral gas interactions through the charge-exchange (CE) process (e.g. Lindsay and Stebbings 2005), provide the only way to remotely visualize their population. The solar wind fills the heliosphere with ions and the surrounding LISM that penetrates our solar system is the source of a neutral gas component, mostly in the form of slow moving atomic Hydrogen (H) particles, with densities of ∼0.09–0.12/cm³ in the heliosheath (e.g. Dialynas et al. 2019; Swaczyna et al. 2020). This neutral gas distribution flowing through the heliosphere is an important indicator of the source, loss, and transport processes in our solar bubble, providing a marker for the solar wind interactions with the Very Local Interstellar Medium (VLISM), manifested in the local plasma-neutral processes inside the heliosphere. Over the past decade, we have identified that the >5.2 keV ENAs are the manifestation of the hot plasma ions sampled by the Voyager spacecraft locally, and illuminate the region of enhanced particle pressure that lies between the TS and the HP (e.g. Dialynas et al. 2019, 2020).

In the subject paper we focus on the significant contribution of the >28 keV in-situ ions from the Low Energy Charged Particle (LECP) instruments on V1 & V2 when combined with the >5.2 keV remotely sensed ENAs from Cassini/INCA, toward studying the physics of the heliosphere. We also refer to the contribution of the >58 keV ENA observations from SOHO/HSTOF. Section 2 provides a brief description of the LECP, INCA and HSTOF instruments. Sections 3 and 4 provide an overview of the recent, key discoveries from the Voyager and Cassini missions, respectively, whereas Sect. 5 discusses the science we have been able to achieve through the combination of in-situ ions with remotely sensed ENAs. Solar cycle effects are described in Sect. 6 and the results concerning the shape of the global heliosphere are presented in Sect. 7. We conclude with a short summary in Sect. 8.
The LECP experiment (Krimigis et al. 1977) on both V1 & V2 utilize two distinct solid-state detector configurations, namely the Low Energy Magnetospheric Particle Analyzer (LEMPA) that performs basic ion-electron measurements and the Low Energy Particle Telescope (LEPT), mainly a composition instrument, that were designed to measure the charged particle distributions in the planetary magnetospheres and interplanetary space. After a long period of a 100% duty cycle in interplanetary space, the LECP detectors proved their ability to measure the differential intensities of charged particles in and beyond the termination shock, at the heliopause and in the Very Local Interstellar Medium (VLISM). The LECP on V1 detects ions and electrons with energies of $\sim 40$ keV to 60 MeV/Nuc and $\sim 26$ keV to $> 10$ MeV, respectively, together with an integral ion measurement of $> 211$ MeV, whereas the LECP on V2 provides measurements of the ion and electron distributions over the $\sim 28$ keV to $\sim 60$ MeV/Nuc and $\sim 22$ keV to $> 10$ MeV energy ranges, respectively, along with an integral ion measurement of $> 213$ MeV. The detectors are capable of providing angular information via a mechanically stepped platform (e.g., Decker et al. 2005), which allows extracting information of the energetic ion flow anisotropies.

The INCA instrument was part of the Magnetospheric Imaging Instrument (MIMI; Krimigis et al. 2004) on board the Cassini spacecraft (orbiting Saturn, at $\sim 10$ AU, from 1 July 2004 to 15 September 2017), with the principal objective to image the energetic particle distributions within Saturn’s magnetosphere. However, owing to its large geometry factor of $\sim 2.4$ cm$^2$ sr and a broad field of view (FOV) of $90 \times 120^\circ$, INCA possessed a high sensitivity to detect very low ENA intensity events in the heliosphere and image large parts of the sky sphere. INCA was capable of measuring the distributions of ENAs over the energy range of $\sim 5.2$ to $\sim 55$ keV and could analyze the composition (H and O groups), velocity, and direction of the incident ENAs via several discrete energy passbands that were defined through the time-of-flight (TOF) technique (TOF7-4: 5.2–13.5 keV, 13.5–24 keV, 24–35 keV, 35–55 keV). Specific information about the measurement techniques, pixel exclusion criteria and viewing geometries can be found in Krimigis et al. (2009), Dialynas et al. (2013, 2017b), Westlake et al. (2020).

The HSTOF instrument (Hovestadt et al. 1995) on the Solar and Heliospheric Observatory (SOHO) orbiting about the Sun-Earth L1 point, has a geometric factor $\sim 0.22$ cm$^2$ sr to resolve incident $\sim 58$ to 88 keV H from $\sim 28$ to 58 keV/n He ENAs and from higher energy H and He ions. HSTOF has a FOV of $4 \times 34^\circ$, with its aperture looking at an angle of $37^\circ$ of the Sun-Earth line resulting in a useful field of view within $\pm 17^\circ$ from the ecliptic. Specific information about the measurement techniques and viewing geometries can be found in Czechowski et al. (2008).

### 3 In-Situ Measurements in the Heliosphere with V1 & 2/LECP

V1 and V2 surveyed the interplanetary space for $\sim 27$–30 years. After flying-by Saturn (1980), Voyager 1 shifted course to follow a heliocentric trajectory toward the general direction of the solar apex, whereas almost a decade later, after flying-by Neptune (1989), Voyager 2 was directed south of the ecliptic (Fig. 1a). The LECP instruments on both V1 and V2 showed a general decrease in low energy ion intensities (e.g. 0.14–0.22 MeV; Fig. 1b) 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, before reaching the TS, pinpointing for the first time the previously unanticipated size of the heliosphere and the scale of the possible heliospheric asymmetry.
Fig. 1  (Top) A schematic representation of the global heliosphere according to the findings of LECP through the crossings of boundaries of the TS and HP by V1 north and by V2 south of the ecliptic plane, as detailed in the text (Krimigis et al. 2019). (Bottom) The trajectories (a) of V1 and V2 since their launch in 1977, through interplanetary space, the TS and HP, until 2020, together with the LECP measurements of (b) 0.14–0.22 MeV ions and (c) $> 70$ MeV Galactic Cosmic Rays, that correspond to (d) four full solar cycles.
Meanwhile, the Voyagers were able to identify the effects of distinct Solar Energetic Particle (SEP) events in interplanetary space. Albeit the fine structure of individual SEP injections can be easily identified by near-Earth missions (e.g. measured in ~ 1 MeV protons from ACE at ~ 1 AU and Ulysses at ~ 5 AU), they appear as Merged Interaction Regions (MIRs) or Global MIRs at the outer heliosphere, where their properties are highly compressed (Decker et al. 2000). Both Voyagers recorded distinct time periods of corotating interaction regions (CIRs) where charged particles are accelerated at interplanetary shocks resulting from the interaction of the high-speed solar wind originating in the “coronal holes” at the Sun, with the preceding slower solar wind (Fig. 1b).

Despite the fact that the features of individual SEPs in the V2 and V1/LECP observations were effectively reduced after traveling for several AU in interplanetary space, and their intensities were dropped by a few orders of magnitude, the > 1 MeV up to ~ 30 MeV Anomalous Cosmic Ray (ACR) protons showed clear evidence for the passage of large-scale heliospheric disturbances that were associated with solar active periods. Over the same time period, the Galactic Cosmic Ray ions (e.g. > 70 MeV; Fig. 1c) showed a general increase in interplanetary space, presenting distinct dropouts in anti-correlation with the solar activity over the solar cycle (Fig. 1d).

The schematic representation of the global heliosphere (Krimigis et al. 2019), shown in Fig. 1 (top) provides a brief summary of the findings from V1 & V2/LECP since the year 2003 up to the end of 2018. The following paragraphs expand on some of the details (see also Richardson et al. 2022; this journal).

3.1 The Termination Shock

The time period beyond late 2000, when V1 was located at a distance of ~ 80 AU, is of particular interest, pertaining a sustained increase of < 2 MeV protons in V1/LECP (Decker and Krimigis 2003) with a less intense but more structured activity evident in the V2/LECP measurements. What stands out in the time period from mid-2002 to early 2003 is a large increase in the V1 ACR and GCR measurements, that did not seem to have a counterpart at V2. This observation implied that the spacecraft exited the supersonic solar wind, possibly beyond the TS, at a distance of ~ 84–85 AU (Krimigis et al. 2003). This large increase in the ion and electron measurements, was not associated with an ACR and/or GCR Forbush decrease, whereas the plasma flow became subsonic (an upper limit of ~ 50 km/s) during the crossing. These features lasted for ~ 6 months before the spacecraft re-entered the supersonic solar wind at a distance of ~ 87 AU.

In August 2007, V2 also entered the HS (Decker et al. 2008), after crossing the TS ~ 10 AU closer in than V1, at a distance of ~ 84 AU, −26° ecliptic latitude. Unlike the case of V1, the intensities of energetic ions and electrons started increasing only ~ 32 days prior to the crossing, whereas the LECP measurements from 2005 and beyond were anisotropic,
Table 1  Voyager 1 & Voyager 2 at the Termination Shock (Decker et al. 2005, 2008; Krimigis et al. 2019 and references therein)

|                  | Voyager 1                                                                 | Voyager 2                                |
|------------------|---------------------------------------------------------------------------|------------------------------------------|
| Putative Near-TS crossing | 1 August 2002 at ~ 84–85 AU from the Sun; Lat. 34.0°; Anti-sunward streaming ions (beyond 2003). | No counterpart at V2                      |
| Crossings        | 16 December 2004 at ~ 94 AU from the Sun; Lat. 34.1°                      | 31 August 2007 at ~ 83.65 AU; Lat. −27.5° |
| GCRs             | The energy spectrum of ~ 0.5 to 3.5 MeV is a power law form in energy of $E^{-1.41 \pm 0.15}$, consistent with a weak TS. Both the ACR and GCR intensities did not peak at the TS. | The > 70 MeV protons indicate modulation of intensities (probably due to SC variations and to passage of transient disturbances, such as the Forbush decrease in March 2006) |
| Low Energy Ions and Electrons | Factor of ~ 10–50 increase of 0.04–17.6 MeV ions from 2002.58 to 2003.10 (85.3–87.3 AU) followed by an abrupt decrease during 2003.10 to 2004.07 (87.3–90.8 AU) with small fluctuations, followed by high intensities between 2004.07 to 2004.96 (90.8–94.0 AU) with superposed ~ 13-day and ~ 26-day variations. Short-lived intensity spikes of ions since 2004.96 (~ 94 AU), followed by a sustained factor of 10 increase at the lowest energies and lesser increases at higher energies. Same signatures for 0.35–1.5 MeV electrons. Ion spectrum from 40 keV to ~ 20 MeV not consistent with acceleration at the TS. | Unlike V1 (except for some increases due to the passage of a MIR in March of 2006) the < 0.2–0.3 MeV ions remained near background until 210/2007, 32 days before the TS crossing followed by higher intensities than V1 downstream of the TS (also in > 0.3 MeV ions). Similar signatures are shown for 22 keV to 1.5 MeV electrons. Spectra measured in the SW show large energy-dependent variations but diminish within 7–8 days of TS crossing where they become flatter in V2 ($\gamma = 1.24 \pm 0.05$) downstream of the TS than in V1 ($\gamma = 1.67 \pm 0.03$) |
| Plasma Velocities | Outward SW radial flow at ~ 100 km/s from 2004/352 to 2005/018, when the radial flow becomes predominantly negative (sunward) between ~ −50–0 km/s up to 2005/110; Flow becomes ~ 50 km/s beyond 179/2005. | TS ions in the upstream SW between 2005 and 242/2007 were anisotropic, but unlike V1 beamed mainly sunwards along the spiral interplanetary magnetic field (+T direction) |
| Pressure and $\beta$ about the HP | The 0.04–4 MeV particle pressure dominates the magnetic field pressure and $\beta > 1$ from 2002.5 to 2003.1 and also from 2004.0 to 2005.5 (based on 2002 extrapolated magnetic field data) | The 0.028–3.5 MeV energetic ion (non-thermal) pressure in the heliosheath is comparable to (or exceeds) both the thermal plasma pressure and the scalar pressure of the magnetic field. |
| SW dynamic pressure | ~ 1.8–2.4 nPa ~ 1 yr before the putative near-TS crossing in Aug. 2002 and ~ 2.2–3.2 nPa ~ 1 yr before the TS crossing in Dec. 2004 | ~ 1.81–2.2 nPa ~ 1 yr before the TS crossing in Aug. 2007 |

but directed mainly sunwards along the spiral interplanetary magnetic field. The intensities of energetic particles beyond the TS were somewhat higher than those observed by V1, but they were also sustained beyond the TS (see Table 1).
3.2 The Heliosheath

A few months after V1 had crossed the inward-moving TS, and all associated effects with this movement had subsided, the spacecraft explored the shocked solar wind in the heliosheath. The intensities of 0.04–4.0 MeV ions showed only small variations with time (of a few percent) whereas the radial component of the plasma velocity, as inferred by the 58–85 keV ion measurements in LECP (Decker et al. 2005), varied from ~30 to 90 km/s. At the same time, the energy spectrum retained a power law form in energy, with a spectral index of ~−1.54 ± 0.10 (see also Fisk and Gloeckler 2006; Gloeckler et al. 2008 and references therein).

Voyager 1 surveyed the HS for ~8 years, traveling for ~28 AU past the TS, during which period it measured a gradual decay of low energy ions and ACRs beyond about the year 2009, up to the year 2012 where it crossed the outer boundary of the heliosphere (Fig. 1b, Fig. 3C). Since the year 2005, LECP on V1 measured a gradual decrease of the radial velocities of low energy ions, from ~70 km/s to ~0 km/s with a rate of ~−18.8 ± 1.5 km/(s yr) at ~116 AU from the sun, that subsequently remained stable for about eight months, indicating that the spacecraft had entered a finite transition layer of zero radial and meridional plasma flow velocity for several AU within the heliosheath (Krimigis et al. 2011; Decker et al. 2012; see also Fig. 3D, E, F).

By contrast, the measured 0.03–3.5 MeV ion spectra by LECP, as soon as V2 entered the HS, were somewhat harder than those in V1 and the spectral index exhibited substantial variability (Decker et al. 2008). Although the ion intensities in V2 and associated particle pressure varied over a comparable range with those in V1, the time scale was quasi-periodic (~12–35 days), continuously since crossing the TS, changing its character every ~6 months (Decker et al. 2009). Those suprathermal ions measured by LECP in the heliosheath are pickup ions (PUI) that account for a substantial part of the plasma pressure, and the overall intensity variations are associated with the solar wind stream interaction regions. Thus, the temporal pattern observed at V2 was attributed to variations that are being driven by quasi-recurrent pressure variations in the solar wind at ~−30° heliolatitude, after its interaction with the termination shock (Roelof et al. 2010).

Overall, despite the significant separation between the two Voyagers above and below the ecliptic equator, the ion intensity time profiles at both spacecraft throughout the heliosheath were very similar in both shape and number (Decker et al. 2015; see also Fig. 5B). Ion and electron intensities in V2 showed a decline to minima early 2013, beyond which period suprathermal particles increase rapidly, as a result of the decline of SC23 and the rise of SC24, as manifested in the variation of the solar wind.

3.3 The Heliopause

After the discovery of the reservoir of ions and electrons that constitute the heliosheath (HS), V1 passed through an unexpected “depletion region”, where a decrease in ions of solar origin (by a factor of ~10³) and a simultaneous increase of high energy cosmic rays (~9.3%) occurred (Fig. 1b, c), showing for the first time that our solar bubble shields Earth from the harmful GCR radiation by ~75%.

This region, the heliopause, forms part of the interface between the solar plasma and the galaxy, that was crossed by V1 in August 2012 (Krimigis et al. 2013; Stone et al. 2013 and references therein) at a distance of ~122 AU from the Sun. Some six years later, V2 also crossed the heliopause in November 2018 (Krimigis et al. 2019 and references therein) at ~119 AU, pinpointing the extent of the upwind heliosphere’s expansion into the Very
Table 2  Voyager 1 & Voyager 2 at the Heliopause (Krimigis et al. 2019 and references therein)

|                         | Voyager 1                                                                 | Voyager 2                                                                 |
|-------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------|
| Crossings               | 25 August 2012 at ~ 121.6 AU from the Sun; Lat. 34.5°, Lon. 174°           | 5 November 2018 at ~ 119 AU from the Sun; Lat. ~32.2°, Lon. 218.3° (~ 43° east of V1) |
| GCRs                    | Onset of increase in > 211 MeV on 129/2012 for ~ 108 days (~ 1.08 au), followed by multiple episodes of magnetic flux tubes from 210/2012–238/2012 (~ 0.3 AU). Overall increase in GCR rate of 30% | Onset of increase in > 213 MeV on 215/2018 (~ 118.2 AU) for ~ 95 days (~ 0.82 AU), followed by a step-like increase on 309/2018 (~ 119 AU) up to 10/2019 (~ 65 days; ~ 0.57 AU). Overall increase in GCR rate of ~ 20%. |
| Low Energy Ions and Electrons | Onset of increase of 53 keV–17.6 MeV ions on 310/2011 (~ 119 au) followed by gradual decrease up to 210/2012 with multiple episodes (in anti-correlation with GCR) up to 238/2012 (~ 121.6 AU). A decrease of 37–70 keV electrons up to 210/2012; similar signature as the corresponding V2. | Onset of increase of 28 keV–17.3 MeV ions on 150–153/2018 (~ 117 AU), followed by a gradual decrease and punctuated by an abrupt decrease on 309/2018 (~ 119 AU). Onset of decrease of 35–61 keV electrons on 150–153/2018, with precipitous drop on 226/2018 (~ 118.3 AU) with pronounced intensity fluctuations, reaching background levels a few days before 309/2018. |
| Velocities              | Relatively small fluctuations in the Tangential Component (~ 40 km/s on average in -T direction). Stagnation region shown in the Radial component from ~ 113 AU (with a width of ~ 8.6 au), with ~ 0 km/s up to the HP; showing periods of $\mathcal{V}_g < 0$ km/s; flux tube interchange instability | Fluctuations between ~ 60 km/s to ~ 160 km/s in Tangential component (+T direction), with occasional excursions of > 50 km/s. A Radial component of < 100 km/s; occasionally close to ~ 0 km/s. Possible transition region (onset ~ 2016.25; width ~ 8.2 AU) with variable flow patterns in both radial and azimuthal components. |
| Pressure and $\beta$ about the HP | The 0.04–4 MeV particle pressure dominates the magnetic field pressure, similar to V2, and $\beta > 1$. However, $\beta < 1$ within 1 AU of the HP. | The 0.03–3.5 MeV particle pressure dominates the magnetic field pressure and $\beta > 1$ until 2018.6, within 1 AU from the HP crossing. |
| SW dynamic pressure     | ~ 1.2–1.6 nPa (January to March 2010) ~ 2.5 yr before the HP crossing; minimum of SC23. | ~ 2.1–2.3 nPa (April to June 2016) ~ 2.5 yr before the HP crossing; maximum of SC24. |

Local Interstellar medium (VLISM) 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 in Voyager 2 was found substantially higher than expected (Richardson et al. 2019).

Despite the similarities between the V1 and V2 crossings, some substantial differences were also identified (Table 2; see also Krimigis et al. 2019). Although the HP is not significantly affected by the pressure changes of the outward propagating solar wind over the solar cycle, presenting a displacement of ~ 3–4 AU between solar min and solar max, the dynamic nature of the boundary was revealed in the form of a flow stagnation region at V1 that was observed by LECP before the HP. The LECP measurements showed that the boundary may...
Fig. 2 (A) Image of heliospheric ENAs in the range of $\sim 5.2$ to 13.5 keV, in ecliptic coordinates showing the “Belt” and the “Basins”, as detailed in the text. The location of local interstellar flow (nose), its opposite (tail), solar apex (SA), and anti-apex (SAA), as well as the positions of Voyager 1 and 2 in the heliosheath are marked; the local ISMF direction as was inferred in studies before the V1 crossing of the heliopause in 2012 is indicated. (B) The same data plotted in galactic coordinates. All-sky spectral index maps organized in (C) ecliptic and (D) Galactic coordinates that resulted from the power-law fits of the 5.2–55 keV ENA data (adapted from Krimigis et al. 2009; Dialynas et al. 2013)

be susceptible to a flux tube interchange instability, where the cold, high-magnetic field flux tubes enter the heliosheath, and vice versa (Krimigis et al. 2013). 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 (Stone et al. 2019).

Recently, Dialynas et al. (2021) using the sectored LECP measurements in V1, identified a radial inflow of $\sim 40–139$ keV ions within the heliosheath, for $\sim 10$ AU before the heliopause crossing and a radial outflow over a spatial scale of $\sim 28$ AU past the heliopause. These particles correspond to an ion population leaking from the HS into interstellar space, most likely due to the flux tube interchange instability at the boundary and propagate to Voyager 1. 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).

4 Remote Observations of $> 5.2$ keV ENAs from MIMI/INCA

The first images of the global heliosphere, using $> 5.2$ keV ENA measurements obtained with MIMI/INCA over the 2003–2009 time period were published in Krimigis et al. (2009), showing two striking and unexpected signatures (Fig. 2A, B): (a) the “Belt”, a broad band of emission in the sky, identified as a high intensity, relatively wide ENA region that encircles the celestial sphere and (b) the “Basins”, identified as two extended heliosphere lobes where the ENA minima occur. The ENA measurements are moderately well organized in galactic coordinates, with the Belt presenting a prominent tilt of $\sim 30^\circ$ with respect to the galactic equator, whereas the Basins are shown to roughly coincide with the galactic north and south poles, although their boundaries were also tilted $\sim 30^\circ$ to the galactic equator. These observations were verified in Westlake et al. (2020) that showed $> 5.2$ keV INCA images over the year 2000 during the trajectory of Cassini cruise to Jupiter and out to Saturn.
4.1 General Characteristics of the Belt

A detailed analysis (Dialynas et al. 2013) in three different coordinate systems (Ecliptic, Galactic and ISMF), showed that the Belt is a broad structure that extends to a latitudinal width of $\sim 50^\circ$ to $\sim 100^\circ$ (FWHM) in galactic coordinates, whereas comparing the strongest 5.2–55 keV ENA fluxes from the Belt to the weakest ones in the Basins, the maps showed an intensity ratio of $\sim 4–5$. The longitudinal profiles of ENAs showed that although their peak positions may vary for different energies throughout the Belt, its width does not seem to be energy dependent. However, a lack of uniformity concerning the morphology of the Belt was identified, as the ENA profiles presented statistically significant variations in all INCA TOF channels, with relative peaks across the Belt. The different shape in latitude within such a broad structure suggested that the latitude dependent solar wind influences the heliosheath, exhibiting a durable signature, which is consistent with both the V1 and V2 LECP measurements, where the intensity showed small variations with time before the year 2009 (e.g. Decker et al. 2010).

The 5.2–55 keV ENA spectra are consistent with a power-law form in energy ($J_{\text{ENA}} \sim E^{-\gamma}$), being softer ($4.0 < \gamma < 4.4$) within the Belt region and harder ($3.4 < \gamma < 4.0$) in the surrounding regions, following the ENA intensity changes (Fig. 2C, D). The nose region is associated with the strongest shock structure where the interstellar dynamic pressure related to the relative motion of the local interstellar cloud is highest. However, both the ENA intensities and the spectral slopes in Dialynas et al. (2013) are almost indistinguishable between the nose and the tail regions, a fact that provided preliminary indications that the observed ENA tail fluxes are not likely the result of a longer integration path (longer LOS), as was initially suggested in Krimigis et al. (2009). We will further expand on this point in Sect. 7.

In comparing the $\sim 5.2–55$ keV INCA/ENA spectra sampled from the Belt, with the $< 6$ keV ENA features shown from IBEX (see Galli et al. this journal), Dialynas et al. (2013) posed the question concerning the source region of these ENAs, and considered the possibility that so-called Globally Distributed Flux (GDF) ENAs evolve with increasing energy to form the Belt ENAs at high energies. Based on a spectral comparison between the IBEX and INCA ENA measurements, the authors concluded that there is substantial evidence that the GDF and the Ribbon are distinct features that originate from different source plasma populations, i.e. heliosheath and outside the heliopause, respectively. McComas et al. (2017a) showed that the Ribbon evolved differently than the GDF over the 2009–2017 time period and that the combination of $< 5$ keV observations strongly support a secondary ENA source for the Ribbon that lies outside the heliopause, whereas the GDF is considered to form within the heliosheath.

4.2 Characteristics of the Basins

Although not extensively studied in the literature, the heliosphere “Basins” deserve special attention. The role of possible known background sources that could potentially trigger the instrument’s microchannel plates, and ultimately contribute to the observed ENA counts (especially in those low ENA intensity regions), namely X-ray, ultraviolet and extreme ultraviolet radiation, have been evaluated by Krimigis et al. (2009) and found to be insignificant when compared with the measured foreground INCA ENAs. Later analyses (Dialynas et al. 2013) considered the potential contribution of galactic cosmic rays in the INCA/ENA measurements and revealed no statistically significant correlations. Consequently, despite the low ENA intensities, the Basins are consistent with foreground ENAs that are products of
charge exchange interactions that occur between the TS and the HP, as is the case with the Belt ENAs. The detailed physics related to their formation remains somewhat enigmatic, although Dialynas et al. (2017b) speculated on the possibility that they may be related to emptying of plasma due to reconnection processes in the heliosphere (e.g. Opher et al. 2015; Kivelson and Jia 2013).

The INCA Basins compare well with the dimmest < 6 keV IBEX-ENA features (McComas et al. 2013), as both of the IBEX “lobes” fall rather well into the INCA Basins” that extend further in both longitude and latitude. However, the so-called IBEX starboard lobe (125°–150° longitude, S30°–N30° latitude) seems to be dwarfed by the corresponding Basin.

4.3 “Between” the Belt and the Basins

ENA images from Cassini, obtained soon after the spacecraft left Jupiter’s system (2003; Dialynas et al. (2015); Fig. 5) showed that the transition from the high ENA intensities between the Belt ENAs from the tail to the low ENA intensities in the Basin occurs via a “transition region” that serves as a relatively smooth boundary, with a spatial width of ∼ 30° (∼ 60° to ∼ 30° in ecliptic longitude), identified throughout the 5.2–55 keV ENA emissions in the heliosheath, that no theory had predicted before. The peak-to-basin ENA intensity gradient in the heliosheath was found to be almost invariant as a function of both ecl. latitude and energy, with an average value of 2.4% per degree.

In comparing with the IBEX measurements, the authors argued that the ratio of the peak Ribbon flux to the underlying Globally Distributed Flux (GDF), as a function of the IBEX energies (e.g. Schwadron et al. 2011) yields a number of < 7% per degree at ∼ 1 keV and < 3% per degree at ∼ 4 keV. The transition of the peak ENA fluxes to the dimmest features in the ENA maps, from eV to keV, is sharper at low energies and becomes progressively smoother with increasing energy, and seems to be consistent with the fact that the Ribbon is most distinctly apparent between 1 keV and 2 keV, but broadens and changes its shape with increasing energy, to match the Belt at > 5.2 keV (Dialynas et al. 2013).

5 Combined > 5.2 keV ENA and > 28 keV Ion Spectra

Due to overlapping energies between the Voyager/LECP lowest energy channels and the > 24 keV INCA channels, the Voyagers provided “ground truth” to the remotely sensed ENAs from Cassini. In result, the ENA (Cassini) and the ion spectra (Voyager 1 and Voyager 2) were successfully combined in the directions of both spacecraft (e.g. Krimigis et al. 2009; Dialynas et al. 2019, 2020; Fig. 3A, B) to discuss longstanding questions concerning the ion energetics inside the heliosheath. The consistency between the remotely sensed > 5.2 keV ENAs from INCA at ∼ 10 AU and the < 6 keV ENAs from IBEX at ∼ 1 AU has also been shown via successful combinations of their energy spectra (e.g. Dialynas et al. 2020). SOHO/HSTOF would provide an extension of the H ENA spectrum to 88 keV. However, beyond about the year 2005, as soon as V1 entered the heliosheath, only the flank regions were accessible to the SOHO/HSTOF observations, whereas both the V2 and V1 trajectories inside the heliosheath were outside the ecliptic latitude limits of the HSTOF observation region.

5.1 The Shape of ENA and Ion Spectra in the Heliosheath

The shape of the ion energy spectra play a critical role toward determining the pressure balance and acceleration mechanisms inside the heliosheath. The ∼ 5.2–55 keV ENA spectra
Fig. 3  (A) Average 110 eV to 55 keV ENA energy spectra from IBEX and INCA in the pixels enclosing the position of Voyager 2, together with the corresponding deduced H$^+$ spectra (details in the text), and the 28 keV to 344 MeV ion energy spectra measured \textit{in-situ} by LECP and CRS on V2 from the beginning of 2009 to the end of 2012. The inlay indicates the 10 to 5950 eV ion intensities derived from fits to the PLS data with an isotropic Maxwellian. The \(~ 28–540 \text{ keV} \) LECP measurements are converted to ENAs (red dotted line) using $L_{HS} = 35 \text{ AU}$ and $n_H \sim 0.12 \text{ cm}^{-3}$. (B) The same for the time period from the beginning of 2013 to the end of 2016 (details in Dialynas et al. 2020). The 58–88 keV ENA measurements from HSTOF (gray points) correspond to the time period from 1996 to 2003, and are not sampled from the direction of Voyager 2, but cover the forward part and flanks of the heliosheath within \(~ 155^\circ \) of the apex direction (Hsieh et al. 2010). (C) Differential intensity of 53–85 keV H$^+$ as detected in V1/LECP’s Sectors 1 and 5. (D) The plasma flow velocity in the radial and tangential direction as derived from LECP (Decker et al. 2012). (E) Schematic illustration of the solar wind radial flow inside the termination shock and the expected deflection of the heliosheath flow between the termination shock and the heliopause, together with the (F) the unexpected transition layer discovered by V1 inside the heliosheath. ENA measurements from Cassini/INCA together with \textit{in-situ} ions from LECP in V1 have also revealed the location for the heliopause (Krimigis et al. 2011)

from Cassini around the Voyager 1 and Voyager 2 pixel in Krimigis et al. (2009) showed that they are consistent with a Power Law form in energy of \(~ E^{-4} \) that become substantially less steep when converted to ions (see Sect. 5.2) and fit smoothly to the V1 and V2 LECP spectra \(~ E^{-1.5} \) with a possible hardening break at the energy range covered by LECP. A detailed analysis in Dialynas et al. (2019) using INCA/ENA and V2/LECP measurements verified the findings of Krimigis et al. (2009), showing also that the hardening break in the ion spectrum occurs within the \(~ 24 \) to \(~ 80 \text{ keV} \) energy range, i.e. detectable at the

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INCA ENA spectra when converted to ions. They also showed that the overall shape of the > 5.2 keV spectra deviate substantially from a single $\kappa$-distribution or a single Maxwellian distribution that has been used to describe the particle spectra from eV to MeV energies inside the heliosheath, as such an approach would underestimate both the intensities and partial pressure in the HS.

Observations from the New Horizons spacecraft at $\sim$ 38 AU (McComas et al. 2017b) showed that the pickup ion distribution is heated in the frame of the solar wind, before reaching the termination shock (see also Zirnstein et al. 2022; this journal). Prior to the V1 and V2 encounters with the termination shock, it was anticipated that the shock would accelerate the Anomalous Cosmic Rays. However, the $\sim$ 10 to 100 MeV intensities in both V1 and V2 did not peak at the termination shock (Stone et al. 2005, 2008) and the shocked thermal plasma remained supersonic, with a substantial part of the upstream solar wind energy density being transferred into heating pickup ions and $>15\%$ to $>28$ keV protons. Only $\sim 20\%$ went into heating the downstream thermal plasma (Richardson et al. 2008). This may be translated to the prominent hardening break in the $>28$ keV part of the H$^+$ distribution in Fig. 3A, B.

A new analysis (Dialynas et al. 2020) reporting on a unique combination of $\sim$ 10 eV to $\sim$ 344 MeV in situ ion measurements from PLS, LECP, and CRS experiments on V2, together with remotely sensed $\sim$ 110 eV to $\sim$ 55 keV ENA measurements from IBEX and INCA, revealed several important characteristics concerning the properties of the ion energy spectra inside the heliosheath. The ENA and ion spectra in Fig. 3A, B can be considered to be representative of the heliosheath conditions between the years 2009–2016, about the minimum of SC23 and onset of SC24, taken $\sim$ 1.5 yr after the V2 TS crossing to $\sim$ 1.5 yr before the HP crossing of Voyager 2.

In principle, the ENA spectra at $\sim$ 0.11 to 6 keV (IBEX) exhibit an “ankle” break beyond about 1.1 keV (Schwadron et al. 2011), but become significantly softer at the INCA energies ($>5.2$ keV), with a possible hardening break at $>35$ keV, which, when converted to ions (Krimigis et al. 2009; Dialynas et al. 2019, 2020), becomes consistent with the in situ ion measurements from LECP on V2. The conversions of the in situ $\sim$ 28 to 540 keV ions from LECP result in ENA spectra that fit smoothly to the measured 5.2–55 keV INCA spectra, with comparable power-law slopes, while their intensities are also consistent with the measured 58–88 keV ENAs from HSTOF (Hsieh et al. 2010), despite the fact that the HSTOF data do not correspond to the direction of Voyager 2 and are sampled from a different time period. The totality of these observations suggest that despite the very low ENA fluxes at $>88$ keV, if IMAP-Ultra (McComas et al. 2018b) observed a similar energy, this result would indicate that these ENAs are the result of charge exchange interactions inside the HS, whereas possible differences would point toward a different source region and/or acceleration mechanism(s).

The in situ ion energy spectra from LECP at $\sim$ 28 keV to 4 MeV, on both V1 and V2 are consistent with a power law of $\gamma \sim -1.4$ or a $\kappa$-distribution index of $\sim -1.63$ (e.g., Decker et al. 2005; Dialynas et al. 2019) and fit smoothly with the $>3$ MeV spectra from CRS, whereas the observed hardening break beyond about 100 MeV is most likely due to GCRs. Although the hardening break beyond about 10 MeV within the time period from 2009 to 2012 may be related to a local disturbance at V2 that was caused by a global merged interaction region (Richardson et al. 2017), the most plausible interpretation is that the ACR spectrum evolved substantially from 2007 through at least the end of year of 2010 and the beginning of 2011, meaning that the ACR spectrum was not the expected power law at the termination shock in 2007, but unfolded as V2 traveled through the HS.
5.2 Determining the Heliosheath Thickness

One of the most intriguing observations since the Voyager missions crossed the TS and the HP, is the unexpectedly thin heliosheath of \( \sim 28 \text{ AU} \) (in V1 direction) and \( \sim 35 \text{ AU} \) (in V2 direction), that most models for the global heliosphere are not able to obtain (see Kleimann et al. 2022; this journal). In the pre-INCA imaging era, and before the Voyagers surveyed the heliosheath, heliosphere models and measurements provided broad estimates for the size of the heliosphere and the distances to the termination shock and the heliopause (e.g. review articles in von Steiger et al. 1996). The pioneering work of Davis (1955) concluded that the pressure balance between the solar emission and a local interstellar magnetic field of \( \sim 10^{-5} \) gauss would occur at \( \sim 200 \text{ AU} \), whereas later modeling efforts placed the termination shock at a distance of \( \sim 90 \text{ AU} \) and the heliopause at \( \sim 145 \text{ AU} \) (Washimi and Tanaka 1996), with the general consensus about that time being that the heliopause would be more than \( \sim 30\% \) (Axford 1996) to 50\% (Baranov and Malama 1993; Washimi 1993) further out from the termination shock. The 2–3 kHz radio emissions from Voyager 1 and Voyager 2 (Gurnett et al. 1993) placed the distance to the heliopause between 116 and 177 AU and the termination shock at \( \sim 70–120 \text{ AU} \) (Lee 1996). Due to the powerful synergy between \( > 28 \text{ keV} \) in-situ ions and \( > 5.2 \text{ keV} \) ENAs (in overlapping energy bands), the contribution of remote sensing on this front was unequal.

Assuming that the \( \sim 5.2–55 \text{ keV} \) ENAs from INCA originate in the heliosheath, between the termination shock and the heliopause, Krimigis et al. (2009) normalized the intensity of the highest ENA energy channel (\( \sim 45 \text{ keV} \)) about the Voyager 1 pixel, to the overlapping Voyager 1 H\(^+\) channel (\( \sim 46 \text{ keV} \); taking measurements within the heliosheath) to obtain a \( L_{V1} \sim 3.6 \text{ AU cm}^{-3} \) for any choice of the neutral hydrogen density \( J_{\text{ion}} = J_{\text{ENA}}/(\sigma_{10} n_H L) \) and \( J_{\text{ion}} \sim 80 J_{\text{ENA}} \), where \( \sigma_{10} \) are the energy depended charge exchange cross sections for the corresponding H\(^+\)–H interaction; Lindsay and Stebbings 2005). The authors noted that the heliosheath thickness may well be different at other locations across the Belt and given all assumptions pertained to the calculation, the \( L \) can change up to \( \sim 40\% \). Adopting a \( n_H \sim 0.1 \text{ cm}^{-3} \), the authors estimated the thickness of the heliosheath in the V1 direction to be \( \sim 36 \text{ AU} \).

As Voyager 1 progressed into the heliosheath, traveling \( \sim 22 \text{ AU} \) past the termination shock, Krimigis et al. (2011) presented observations that contradicted the notion of the heliopause being a sharp discontinuity that separates solar material from the interstellar plasma (see Sect. 3.2 and Krimigis et al. 2013). Using the same normalization technique (described above) the authors refined their calculations and predicted that Voyager 1 would cross the heliopause at a distance of \( \sim 121 \text{ AU} \) from the sun, i.e. calculating the HS thickness in the V1 direction as \( \sim 27(–11, +26) \text{ AU} \) (Fig. 3E, F). The V1 crossing of the heliopause occurred \( \sim 1 \text{ month} \) later than anticipated by Krimigis et al. (2011), in August 2012 (Krimigis et al. 2013) at a distance of \( \sim 121.6 \text{ AU} \), showing that the heliosheath towards the nose (at V1 direction) is much more compressed than previously anticipated.

The SOHO/HSTOF ENA observations before the year 2003 were also used to provide a calculation for the thickness of the heliosheath. By combining the \( > 40 \text{ keV} \) ions from LECP on Voyager 1 inside the heliosheath, the 58–88 keV H and 28–58 keV He ENAs from HSTOF (covering the forward part and flanks of the heliosheath within \( \sim 155^\circ \) of the apex direction), and assuming a neutral hydrogen distribution of \( n_H \sim 0.1 \text{ cm}^{-3} \), Czechowski et al. (2006) provided a first estimation for the heliosheath thickness in the direction of Voyager 1 as \( L \sim 75 \text{ AU} \). Refining their calculations, Czechowski et al. (2008) estimated the thickness of the forward sector of the heliosheath as \( L = 42 \pm 12 \text{ AU} \) by restricting the region over which the HSTOF data were averaged to \( \pm 45^\circ \) in longitude from the heliospheric nose, assuming a \( n_H \sim 0.1 \text{ cm}^{-3} \).
The SOHO/HSTOF measurements, averaged over quiet times within the years 1996–2006 were combined in Hsieh et al. (2010) to provide an estimate for the thickness of the heliosheath in both the V1 and V2 directions, ranging between $\sim 21 \pm 6$ AU (for V1) and $\sim 28 \pm 8$ AU (for V2), with an average value of $\sim 25 \pm 8$ AU. Their results were compared with the 0.1–4.0 keV ENA measurements from IBEX and numerical simulations of ions below the LECP energy threshold provided by Giacalone and Decker (2010), reaching to the conclusion that 5.2–55 keV INCA/ENA flux (Krimigis et al. 2009) cannot be consistent with the measurements by IBEX and SOHO/HSTOF, because it would require larger values of $L$. However, the authors noted that they were unaware of the cause of the disagreement. Notably, the ENAs in Krimigis et al. (2009) are sampled from a time period that corresponds roughly to the maximum of SC23 toward its declining phase (2003–2009) and as shown in several INCA-Voyager studies (e.g. Dialynas et al. 2017b), there is a known time dependence of both $>5.2$ keV ENAs and $>28$ keV ions, in response to the SC phases, with a time delay of $\sim 2–3$ yrs (see also Sect. 6).

Despite the initial disturbances in 0.03–3.5 MeV ion spectra in LECP, after the Voyager 2 spacecraft crossed the termination shock (Fig. 3C; Decker et al. 2009; described also in Sect. 3.2), the ion intensity time profiles at both V1 and V2 inside the HS became very similar in both shape and number (e.g. Dialynas et al. 2017b). The normalization of the intensity of the highest INCA/ENA energy channel about the V2 pixel, to the lowest V2 H$^+$ channel over the 2013–2016 time period (Dialynas et al. 2019), resulted in a HS thickness along the V2 trajectory of $L \sim (35.2 \pm 8.6)$ AU, assuming a neutral Hydrogen density of $n_H \sim 0.12$ cm$^{-3}$, suggesting a HP crossing from V2 at $\sim 119.2$ AU. Almost a year before, in November of 2018, V2 had crossed the HP at a distance of $\sim 119$ AU (Krimigis et al. 2019).

Unlike the case of Krimigis et al. (2011) that predicted accurately the location of the heliopause in the V1 direction, the crossing of V2 from the heliopause occurred prior to the Dialynas et al. (2019) estimations, whereas their calculations became relevant to the correct location of the HP, only under the assumption of a neutral hydrogen density of $\sim 0.12$ cm$^{-3}$. This number contradicted the indirectly measured densities from the Plasma Wave (PWS) instrument in V1 of $\sim 0.1$ cm$^{-3}$ immediately upstream of the HP, ranging between 0.09–0.11 cm$^{-3}$ (Gurnett et al. 2015), up to 0.14 cm$^{-3}$ at distances of $\sim 20$ AU past the HP, causing the authors to note that they could not determine whether their inferred density is due to a possible density gradient between the V1 and V2 LISM locations or if it is simply a manifestation of the wide range of densities that were found to be increasing radially outward along the V1 trajectory, upstream of the HP.

The inferred neutral hydrogen density in Dialynas et al. (2019) was confirmed a year later from the PWS observations in V2, reporting a large density gradient in the VLISM, where the plasma oscillations implied a density of about 0.12 cm$^{-3} \pm 15\%$ (Kurth and Gurnett 2020). In concert with these observations, a new analysis of measurements from the Solar Wind Around Pluto instrument on New Horizons resulted in an interstellar neutral hydrogen density at the termination shock of $\sim 0.127 \pm 0.015$ cm$^{-3}$ (Swaczyna et al. 2020).

A different analysis from Dialynas et al. (2020) used the derived density of 0.12 cm$^{-3}$ and $L \sim 35$ AU to accurately combine the in-situ measurements from V2/PLS/LECP/CRS together with remotely sensed IBEX-Hi/Lo and INCA ENAs about the V2 pixel over the 2009–2016 time period, showing the consistency between the IBEX and INCA ENA fluxes. These observations, together with other results that are discussed in this paper, proved that the ground truth measurements from the $>5.2$ keV ENAs from Cassini/INCA and in-situ LECP ions from Voyager 1 & 2, provide the necessary means towards discussing the physics of the heliosphere and its interactions with the local interstellar medium.
5.3 Determining the Pressure Balance and Beta in the Heliosheath

One of the many exciting findings, after the V1 and V2 respective crossings from the termination shock, concerns the properties of the heliosheath plasma in comparison with the measured magnetic field along the V1 and V2 trajectories (e.g. Fig. 4). The first estimation for the proton pressure inferred by the > 5.2 keV ENAs was presented in Krimigis et al. (2009), assuming an average heliosheath thickness throughout the heliosphere of \( \sim 50 \) AU, whereas images of the tail pressure from the INCA data were presented in Dialynas et al. (2015), that also discussed the possible configuration of the tail magnetic field.

Decker et al. (2015) provided a thorough presentation of the in-situ V1 and V2 measured parameters inside the heliosheath and showed that the partial pressures of suprathermal ions (> 28 keV from LECP) in both the V1 and V2 directions are persistently higher than the plasma pressure (derived from the 0.1–6 keV measurements from PLS at V2 as \( P_{\text{PLS}} = (1 + 0.35)NkBT_p \), where \( N \) is the plasma density, \( T_p \sim 10^5 \) K is the \( \text{H}^+ \) temperature and \( k_B \) is the Boltzmann constant), and the pressure derived from the magnetic field, throughout the heliosheath. The calculated plasma beta, i.e. the ratio of the particle pressure to the magnetic field pressure, using these measurements showed substantial fluctuations (with an average value of \( \beta = P_{\text{PLS}+\text{LECP}} / P_{\text{MAG}} \sim 5 \)) but remained well above unity, since the termination shock, where \( \beta \) was about 1. Here we should -again- consider the fact that the evolution of
the suprathermal ion intensities in the V1 and V2 LECP were remarkably similar, in both shape and number, until V1 crossed the heliopause.

A combination of measurements from \(\sim 5.2–55\) keV ENAs from INCA, together with the \(>28\) keV in-situ ions from LECP in V2 over the 2009–2016 time period (Dialynas et al. 2019), showed that the \(\text{H}^+\) partial pressure from the \(5.2–24\) keV INCA channel alone, is a factor of \(\sim 4\) higher than the \(>28\) keV pressure from LECP, and a factor of \(\sim 30\) higher than the measured PLS thermal pressure over the same time period (Fig. 4A). Thus, the plasma beta with these measured parameters in V2 inside the heliosheath seems to be persistently \(\gg 4\) on average (Fig. 4B), presenting a local minimum that corresponds to the minimum of SC23 (Solar Cycle effects are discussed in Sect. 6).

Clearly, the \(5.2–24\) keV \(\text{H}^+\) pressure dominate the suprathermal (\(>5.2\) keV) pressure distribution, indicating that the energetic proton distribution covered by the Cassini/INCA is critically important for determining the pressure balance inside the HS that cannot be neglected. As the \(0.7–4.3\) keV \(\text{H}^+\) inferred partial pressure from IBEX in the V2 direction was found to be \(\sim 27\) pdyn AU/cm\(^2\), which translates to a partial pressure of \(\sim 0.077\) pPa (with \(L \sim 35\) AU), \(\sim 40\%\) of the \(0.7–24\) keV partial pressure is accounted for by the \(5.2–24\) keV part of the ion distribution.

Including an extended set of measurements both in-situ ions and remotely sensed ENAs from \(\sim 0.1\) keV to \(\sim 344\) MeV over the 2009–2016 time period in the V2 direction (Fig. 4C, D), and given all assumptions concerning the origin of \(<6\) keV ENAs, Dialynas et al. (2020) showed that a rough limit of \(\beta\) is \(\sim 49\), whereas the PUIs and suprathermal particles dominate the pressure inside the HS. Both the thermal component (e.g. \(\sim 0.1–6\) keV from PLS) and the magnetic field pressures have a substantially small contribution to the total pressure inside the HS. These observations indicate that the upwind HS is a high-pressure region that exhibits diamagnetic behavior (Krimigis et al. 2009; Dialynas et al. 2017b).

### 5.4 Estimating the Magnitude of the B-Field Upstream at the Heliopause

Imaging the heliosphere in at least the \(>5.2\) keV ENAs essentially translates to imaging the ion pressure distribution inside the heliosheath and the combined use of ENAs together with plasma and suprathermal ions from V2 and V1, can be used to infer critical quantities in the upstream medium.

Soon after the presentation of the first INCA images, Krimigis et al. (2010) made a first order calculation concerning the pressure balance in the heliosphere, including the novel \(>5.2\) keV ENA measurements obtained from INCA over the 2003–2009 time period. They concluded that the required magnetic pressure outside the heliopause in order to balance the pressure from the heliosheath should be \(\sim 0.164\) pPa, which translates to an upper limit for the B-field magnitude upstream the HP of \(\sim 0.64\) nT. Although this value was significantly greater from what was expected from theoretical models, as soon as V1 crossed the heliopause, the B-field magnitude “jumped” to a high value of \(<0.6\) nT, that then dropped to \((0.48 \pm 0.04)\) nT (Burlaga and Ness 2016), fluctuating about this value to date. A subsequent analysis (Dialynas et al. 2019) that considered the \(>5.2\) keV ENA observations from INCA and \(>28\) keV ion measurements from Voyager 2, estimated that the required magnetic pressure outside the heliopause should be at the order of \(\sim 0.086\) pPa, which translates to a B-field of \(\sim 0.47\) nT which was again consistent with the magnetic field measurements shown in Burlaga and Ness (2016).

By taking ENA and ion measurements over an extended energy range of \(\sim 0.1\) keV to \(\sim 344\) MeV along the V2 trajectory, Dialynas et al. (2020) calculated that the total pressure inside the heliosheath is at the order of \(\sim 0.251\) pPa, which is consistent with the results.
Fig. 5  (A) An update on the yearly intensity images of 5.2–13.5 keV ENAs (2003–2014; Dialynas et al. 2017b) including the ENA images from the year 2000 (Westlake et al. 2020) and ENA images from the year 2016 (Dialynas et al. 2019). Blackened pixels are due to the principal corrections to the images that involve removal of potential contamination from Saturn’s magnetosphere and from the general direction of the Sun. (B) The 35 to 55 keV INCA/ENA measurements (top) enclosing the V1 pixel and converted to ion intensities using $L_{V1} \sim 28$ AU and $n_H \sim 0.1$ cm$^{-3}$, compared directly with the in situ 40 to 53 keV LECP ion histories and (bottom) the $> 35$ keV INCA/ENA measurements around the V2 pixel, using $L_{V2} \sim 35.2$ AU and $n_H \sim 0.12$ cm$^{-3}$, as detailed in the text, compared directly to the 28 to 43 keV LECP ion histories at V2. (C) Yearly ENA time profiles in the anti-nose direction, within the Belt, for different latitudes from Rankin et al. (2019) using data-driven models and IBEX observations. This pressure is expected to be carried out to the HP and with a simplified method that -nevertheless- considers also the pressure from GCRs in the upstream medium, concluded that the required IS magnetic field strength in order to balance the calculated pressure from the heliosheath should be $\sim 0.67$ nT. This estimation is consistent with the measured magnetic field in the direction of V2 after the HP crossing, which was measured to be $\sim 0.68 \pm 0.03$ nT (Burlaga et al. 2019). The magnetic field strength upstream at the HP (at the “compressed” VLISM region, where the interaction takes place) however, remained $> 0.4$ nT out to $\sim 25$ AU past the HP (e.g. V1; Burlaga et al. 2020), and may be smaller in the pristine ISM (e.g. Zank et al. 2013).

6 Dependence of Ions and ENAs over the Solar Cycle

The evolution of the global ENA heliosphere over a 16-year observation period (Fig. 5A) shows that the Belt reduces in both intensities and width until at least 2011–2012, followed by a recovery thereafter (Dialynas et al. 2017b,a). This characteristic does not seem to be limited to a particular part of the celestial sphere, but it is global, throughout the heliosphere and correlates well with the min to max sunspot numbers toward the declining phase of SC23 and the onset of SC24, presenting a minimum between 2008–2010, and with the corresponding min to max approximately $\times 2$ changes of the measured solar wind flux and
pressure over SC23 and SC24, that showed a minimum at about the year 2010, followed by a recovery. The ENA spectra sampled from the Belt become harder over the same time period, following the ENA intensity decrease and, furthermore, as we approach solar minimum, the Belt and Basin spectra become almost indistinguishable. The rise of the new solar cycle is associated with the increase of the $\sim 5.2$–$55$ keV ENA intensities (and in-situ ions from V1 & V2) and softening of the ENA spectra within the Belt.

At the same time, the dynamic properties of $> 5.2$ keV ENAs from Cassini/INCA within the heliosheath (converted to ions using standard parameters; see Sect. 5) correlate adequately with the V1 & 2/LECP in-situ measurements in overlapping energy bands as a function of time, following their respective termination shock crossings into the heliosheath (Dialynas et al. 2017b; Fig. 5B). As the solar wind is thought to be the source population of heliosheath plasma, the dynamic properties of ENA and ions from the heliosheath are apparently strongly related to the dynamic properties of the solar wind over the solar cycle (during the 2000–2016 observation period), with a 2–3 year time delay, which is an effect of the time difference between the actual minimum on the Sun and its manifestation in the heliosheath due to solar wind propagation (Dialynas et al. 2017a).

These observations verify that the heliosheath is the source region of $\sim 5.2$–$55$ keV ENAs and present 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. The variations in the 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.

The ENA spectral slope variations over time are indicative of the bimodal nature of the solar wind and its evolution over the solar cycle, that is, due to the large-scale variations of the solar wind that are governed by the 11-year solar cycle, i.e. toward solar minimum, the solar magnetic field weakens and the polar coronal holes, where the fast and rarefied solar wind originates, expand to low latitudes, resulting in changes in the dynamic pressure of the solar wind that -apparently- have measurable consequences (in both ENA and ions) in the dynamics of the heliosheath. Interestingly, the slopes of the ENA spectra during the observed solar minimum in the nearly equatorial region (e.g. in the anti-nose region) show very little change over time (Dialynas et al. 2017b), possibly as a result of the fact that the slow and dense solar wind during solar minimum does not vanish, but remains confined to $\pm 20^\circ$ latitude, within the streamer belts.

Reisenfeld et al. (2016) employed seven years of $< 6$ keV IBEX observations showing that the heliosheath pressure derived from the ENA fluxes together with the ENA energy spectra at both the north and south poles correlate well with the solar cycle, especially when considering the $\sim 4.29$ keV IBEX channel. Further, the IBEX ENA intensities showed enhancements with a time delay of $\sim 3$ yrs after a solar wind dynamic pressure increase (by $\sim 50\%$) that occurred during 2014 (McComas et al. 2018b). Again, the $\sim 4.29$ keV IBEX channel measurements, that have been shown to match the $> 5.2$ keV INCA measurements (Dialynas et al. 2013), provides the most adequate representation of the above process, presenting (as expected) the shortest time delay and largest change as a function of time.

At higher energies, the $\sim 58$–$88$ keV H ENA and $\sim 28$–$58$ keV He ENA observations from HSTOF between 1996 and 2005 towards the apex direction (Hilchenbach et al. 2006) remained inconclusive about a possible variation of ENAs at these energies over the solar cycle and the authors concluded that their potential sources are CIRs, solar energetic particle events, pre-accelerated pickup ions as well as low-energy (up to few hundred keV) anomalous cosmic ray ions in the outer heliosphere, close to and beyond the solar wind termination shock. The CIRs as a potential source of the HSTOF ENAs have been previously
shown also in the simulations of Kóta et al. (2001), along with the possibility that in addition to PUIs, the gravitationally focused He cone may also be a source of ENA inside the heliosphere. A re-examination of the 1996–2005 HSTOF measurements (Czechowski et al. 2018) showed that the flux in the years 1996–1997 is higher than in the 1998–2005 period for the cases of the so-called “forward sector” (210°–300°), the “forward and flanks sector” (255° ± 155°), and the “heliotail sector” (30°–120° or 50°–100°).

The effects of a “deflating” and “inflating” heliosphere following the pressure changes of the solar cycle were partially examined in Krimigis et al. (2019), showing that the pressure near 84 AU at V1 during the putative TS crossing in mid-2002 (Krimigis et al. 2003) was similar to that during the V2 TS crossing (at, again, 84 AU), whereas at the actual V1 TS crossing at 94 AU, the pressure was substantially higher. The analysis also revealed that the V2 crossing of the HP at ~119 AU occurred over much higher solar wind pressure conditions than V1 (twice as high), yet the HP crossing distance was nearly the same in both cases (~122 AU for V1). Apparently, the solar wind pressure has a large effect on the position of the TS, by as much as 10 AU, but minimal effect at the position of the HP, showing an offset of ~3–4 AU (see also Scherer and Fahr 2003; Izmodenov et al. 2008; Izmodenov and Alexashov 2015).

7 The Shape of the Global Heliosphere with Cassini/INCA & V1 & 2/LECP

Since the Parker (1961) publication, the shape and interactions of the heliosphere with the very local interstellar medium had been discussed in the context of a magnetosphere/comet-like heliotail, but it wasn’t until the Krimigis et al. (2009) publication where the combination of Voyager 1 and Voyager 2 measurements from the termination shock and the heliosheath, together with remotely sensed ENAs from the global heliosphere from Cassini/INCA, that the “bubble-like” heliosphere model in Parker (1961) was considered as a possible heliospheric configuration.

Krimigis et al. (2009) suggested an important modification to the historic Parker (1961) model, by replacing the shock-heated thermal plasma pressure at the termination shock with the ENA-inferred nonthermal proton pressure that fills the heliosheath, thus moving the interaction with the ISMF from the termination shock to the heliopause. This publication provided first evidence for the possibility of a “diamagnetic” bubble heliosphere that forms under the influence of a strong ISMF. After ~11 years of continuous imaging the heliosphere with Cassini/INCA, Dialynas et al. (2017b) provided hard evidence that the > 5.2 keV ENAs are the manifestation of the hot plasma ions sampled by the Voyager spacecraft locally, and illuminate the region of enhanced particle pressure between the TS and the HP.

As explained in the previous paragraphs (see also Fig. 5), following the V1 and V2 respective crossings from the termination shock, it was found that:

– the > 28 keV in-situ ion spectra were found to be in remarkable agreement in both shape and number, throughout their trajectories within the heliosheath, despite the > 138 AU separation between the two spacecraft (+35° and −34° latitude);
– the ~24–55 keV ENA time profiles about the Voyager pixels accurately correlate with the in-situ ion measurements from both Voyager 1 and Voyager 2 in overlapping energy bands, throughout their trajectories in the heliosheath, presenting the same decrease and minima, suggesting also that the source of these ENAs is -in-fact- the region between the termination shock and the heliopause;
Fig. 6 A composite, conceptual representation of the global heliosphere summarizing its basic properties, based on remotely sensed ENAs from Cassini/INCA and in-situ ions from Voyager 1 and 2/LECP (Dialynas et al. 2017b), showing the rough direction of the IS magnetic field (gray solid lines) and IS flow (red arrows), together with the TS and the HP locations, marked at the distances observed by the Voyagers. The near-TS crossing from V1 in mid-2002 (Krimigis et al. 2003, 2019) is also shown (white dashed line). The heliosheath includes a Belt of varying ENA intensities and is the source region of the $>5.2$ keV ENAs from Cassini/INCA. The interstellar flow impinges the nose and is deflected around a roughly symmetric heliosheath that interacts directly with the strong interstellar magnetic field.

- the overall appearance of the images and time profiles throughout the INCA energy range ($\sim 5.2–55$ keV) suggests that the source region of ENAs at $<24$ keV, below the V1/V2 ion threshold, is also the heliosheath;
- the ENA and in-situ ion time profiles show that the dynamic properties of ENAs and ions from the heliosheath are strongly related to the dynamic properties of the solar wind over the solar cycle, with a 2–3 year time delay that is consistent with the time difference between the actual SC minimum on the Sun, its manifestation in the heliosheath due to solar wind propagation and transport of suprathermal particles beyond the termination shock, and the subsequent ENA detection by INCA at $\sim 10$ AU;
- the comparison between $>5.2–55$ keV ENAs from the anti-nose region and the $>24$ keV ENAs from the nose, presents a compelling case that the modulation of superthermal ions over the solar cycle is global throughout the heliosheath. Suprathermal ions distribute themselves throughout the heliosheath by a mechanism faster than pure advection with the thermal solar wind ions, whereas the variations in the ENA-ion intensities are strongly related to the decline of SC23 and the rise of SC24, as manifested in the variation of the solar wind itself.

These observations were interpreted in the context of a high plasma beta heliosheath, that was measured in-situ by the Voyager missions and remotely by Cassini/INCA, together with the knowledge that the magnetic field upstream at the heliopause was measured to be
strong in both the V1 (∼ 0.48 nT) and V2 (∼ 0.68 nT) directions and still fluctuates about an average value of ∼ 0.48 nT to date (in the direction of V1) for at least ∼ 28 AU past the heliopause.

Based on these points, and other details that are not thoroughly explained here, Dialynas et al. (2017b) argued for a roughly symmetric, diamagnetic bubble-like heliosphere, with few substantial tail-like features (Fig. 6). The authors stressed, however, that a perfectly symmetric and stable heliosphere would not be physically possible and, in addition, a tail-nose asymmetry has been shown to exist in models including Hubble Space Telescope observations of H-Lyα absorption. Thus, the heliosphere bubble can inflate with time in either the anti-nose direction or along the direction of the interstellar magnetic field, whereas an “inflating” and “deflating” heliosphere has been shown in various INCA-Voyager studies. Dialynas et al. (2017b) concluded that these observations altogether are indicative of the “breathing mode” of the heliosphere, that provides a roughly symmetric time-dependent obstacle to the inward interstellar flow.

Although the Voyager missions showed unarguably 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 mainly configures the heliosheath, the anisotropic ram pressure of the interstellar medium is not entirely negligible and is expected to impose some distortion in the anti-nose direction, showing that the heliotail may extend to a few 100’s of AU (based on the “trace back” times of INCA ENAs; Dialynas et al. 2017a), but not to 10,000–20,000 of AU as in the traditional (long tail) comet-type configuration (e.g. Pogorelov et al. 2017), and/or in the “intermediate configuration” inferred from IBEX-Hi measurements (McComas et al. 2013), where both the external dynamic and magnetic pressures are thought to be comparable and strongly affect the heliosphere. The traditional (long tail) structure of the heliosphere is also argued for in Pogorelov et al. (2015) and Czechowski et al. (2020).

By contrast, a heliosphere with a short heliotail is consistent with analyses from the combination of Voyager and IBEX-Lo measurements (Galli et al. 2016), where the thickness of the heliosheath in the tail is estimated to be at the order of a few 100’s of AU (∼ 220 ± 110). A subsequent analysis from Galli et al. (2017) concluded that the averaged ENA intensities support a rather spherical shape of the termination shock and a heliosheath thickness between 150 and 210 AU for most regions of the downwind hemisphere (∼ 280 in central tail), showing also that via the trace-back times of IBEX ENAs, the region of ENA production has a similar distance toward the poles and toward the flanks of the heliotail. Although our ability to visualize the HS thickness via the ENA observations is limited by the distance over which the ENAs are replaced by lower energy neutrals through charge exchange with the IS flow (“cooling length”; Schwadron et al. 2011), it should be noted that the cooling length increases with energy and for high energy ENAs, e.g. ≥ 45 keV, is ≥ 370 AU (Dialynas et al. 2017b). Recently, Reisenfeld et al. (2021) used IBEX-Hi observations over 11 years to show that the heliosphere extends at least ∼ 350 AU tailwards, which is consistent with the estimated distance to ENA source (derived from IBEX-Hi measurements) in the heliotail of ∼ 290–490 AU (Zirnstein et al. 2020), implying that the heliosphere resembles more like a distorted bubble with a heliotail of a few 100’s of AU (Dialynas et al. 2017b) than the traditional (long-tail) configuration of 10,000–20,000 AU.

The “trace-back” times of ENAs have also been employed to calculate the distances of the termination shock and heliopause, and thus the heliosheath thickness, in various directions in the sky from the IBEX-Hi measurements. Zirnstein et al. (2018) showed a “comet-type” configuration at ∼ 1.1 keV ENAs and a round configuration in ∼ 4.29 keV with the heliopause toward the tail extending to ∼ 300 AU. Despite the unexpectedly thin heliosheath towards the nose direction, as measured by both Voyager 1 (∼ 28 AU) and Voyager 2 (∼ 35 AU),
which are accurately obtained by the combination of INCA and LECP measurements, the “trace back” times of ENAs in Reisenfeld et al. (2016) showed a ∼ 160 and 210 AU thickness for the heliosheath towards the N and S poles, respectively. These spatial scales are in agreement with the Dialynas et al. (2017b,a) and Galli et al. (2016, 2017) calculations.

The roughly symmetric “bubble-like” heliosphere is also apparent in recent advanced MHD models for the global heliosphere arguing 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 heliotail that extends to ∼ 300 AU (Opher et al. 2015, 2020). Furthermore, the evolution of GCRs, as measured by the Voyager 1 and Voyager 2 in the heliosphere was accurately obtained in the HelMod model (Boschini et al. 2019, 2020), together with their respective crossings from the termination shock, the heliopause and the putative near-TS crossing shown in Krimigis et al. (2003), using a dimensionless stagnation pressure that corresponds to a “diamagnetic bubble-like” heliosphere.

One important aspect of the parameters pertained to the concept of the rough bubble-like heliosphere is that it precludes the formation of a bow shock, that was initially suggested by McComas et al. (2012), albeit under a different notion. The understanding in Dialynas et al. (2017b) is that due to the strong interstellar magnetic field, the Mach number of the local interstellar medium can be significantly decreased and the flow can become submagnetosonic, leading to the inability of forming a bow shock, a situation that was previously shown in magnetohydrodynamic simulations (e.g. Kivelson and Jia 2013). The model used the mini magnetosphere of Ganymede, embedded in the sub-Alfvenic flow of Jupiter’s magnetospheric plasma as a proxy to explain the features in the IBEX ENA measurements, such as the Ribbon, and provided a coherent physical picture demonstrating the formation of an effectively tailless heliosphere, with extended lobes and no bow shock, in a sub-Alfvenic local interstellar medium flow.

8 Concluding Remarks

In the subject paper we provided a brief overview of the findings of ENAs and ions from the Voyager and Cassini missions since the Voyagers crossed the termination shock, following their survey through the heliosheath and their respective crossings from the heliopause, out to the VLISM. We have also argued for the significance of the combined use of in-situ ions and remotely sensed ENA measurements, showing that the > 28 keV ions from V1 & 2/LECP provide “ground truth” to the > 5.2 keV ENAs, addressing longstanding questions concerning the physics of the heliosphere, such as the shape and properties of the ion spectra inside the heliosheath, the pressure balance and plasma beta in the heliosheath that points to the implications for the magnetic field upstream at the heliopause, the thickness of the heliosheath, the effects of the solar cycle through the outward propagating solar wind that result in an “inflating and deflating” heliosphere, together with the implications of these measurements towards addressing the global shape of the heliosphere.

Future missions, such as the upcoming IMAP mission (McComas et al. 2018a) and the Interstellar Probe mission (McNutt et al. 2019) would benefit from all science products resulted from Cassini and the Voyagers.

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