Response times of Cassini/INCA > 5.2 keV ENAs and Voyager ions in the heliosheath over the solar cycle

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Abstract. Both a magnetosphere-like tail and a bubble model of the heliosphere were posited by E. N. Parker in 1961. Recently, we showed that heliosheath ions are the source of > 5.2 keV Energetic Neutral Atoms (ENA), whose images of the heliosphere exhibit a rough nose to anti-nose (tail) global symmetry that resembles a diamagnetic bubble. The comparison between energetic neutral atom (ENA) global images of the heliosphere obtained with the Ion and Neutral Camera (INCA) on board Cassini and ions measured in-situ by the Low Energy Charged Particle experiment (LECP) on board Voyager 1 and 2 (V1/V2) in overlapping energy bands over an 11-year period shows that the heliosphere responds promptly, within ~2-3 years, to outward propagating solar wind changes in both the nose and tail directions. Here we focus on the recovery of solar cycle 24 and the response times of > 5.2 keV ENAs to show that this ~2-3-year time delay is consistent with a “tail” of ~80-120 AU. This preliminary rough calculation is generally consistent with lower energy ENA data (E < 6 keV, from the IBEX-Lo and IBEX-Hi) and is supported by recent modelling of the heliosphere.

1. Introduction

The Sun’s atmosphere is not static, but expands in the form of a magnetized fluid called solar wind, reaching to distances of potentially hundreds of Astronomical Units (1 AU = 1.5×10⁸ km), shaping our local bubble, called “heliosphere”, through its interaction with the Local Interstellar Medium. This process occurs with a 22-year periodicity (two full Solar Cycle), during which the general properties of the solar wind change drastically [1]. The question of how the heliosheath responds to the variability of solar wind conditions and in what manner this response is connected to the solar activity through the solar cycle is of paramount importance for understanding the physics of the Heliosphere and has been the subject of many theoretical models (e.g. [2],[3],[4],[5],[6]). Voyagers 1 and 2 (V1, V2) discovered the reservoir of ions and electrons that constitute the heliosheath after crossing the termination shock [7],[8] north and south of the ecliptic plane at 94 [9],[10],[11] and 84 AU [12], respectively. Owing to the coexistence of ions and neutrals in the heliosphere that allows the charge-exchange reaction to take place, the local measurements by each Voyager were placed in a global context by remote sensing images using ENAs obtained with the Ion and Neutral Camera (INCA) on-board Cassini [8],[13] orbiting Saturn (~10 AU away from the Sun).

ENA imaging of the heliosphere was long anticipated [14] and the recent ENA observations from eV (e.g. Interstellar Boundary Explorer-IBEX) to keV (e.g. Ion and Neutral Camera-INCA) energy range have already revolutionized our understanding about the formation and interactions of
the global heliosphere, providing insights on the plasma processes at ~100 AU that were substantially at variance with previous theories and models. For example, the narrow bright ENA stripe known as IBEX-ribbon (E < 5.6 keV) [15] that is most likely formed outside the heliopause [16] is surrounded by the Globally Distributed Flux (GDF), probably of heliosheath origin [17],[18],[19].

In fact, a rough comparison of IBEX ENAs with INCA [20] led us to propose that the globally distributed flux and the ribbon are distinct features that originate from different source plasma populations and that [...] different energies in IBEX correspond to different layers of the heliospheric structure starting from outside the heliopause and moving inward to the heliosheath at the high energy channel (E < 5 keV) [...] A very interesting recent analysis of the proton velocity distributions in the inner heliosheath [21] provides a coherent picture: [...] Consequently, the energy spectrum of at least the background ENAs [22] observed from a given direction is fed differently from different regions across the inner heliosheath. This offers the opportunity to indirectly probe the spatial structure of the latter. Depending on the source region of the ribbon ENAs [for a review see [23]] this applies also to these particles. [...].

At higher energies (E > 5.2 keV), first images of the heliosphere with Cassini/INCA [24], revealed the existence of a prodigious (yet unexpected) broad band of emission in the sky, called
“Belt” (Figure 1a) that wraps around the celestial sphere in ecliptic coordinates, passing though the heliospheric nose, tail (henceforth called “anti-nose”) and the ecliptic poles [8],[20]. Recently, we have shown that the heliosheath ions are the source of INCA/ENA, whereas the combined use of > 5.2 keV ENAs and in-situ LECP ions, have demonstrated that the heliosphere responds promptly, within ~2-3 years, to outward propagating solar wind changes in both the nose and anti-nose directions [25]. Taking into account the V1 measurement of a ~0.5 nT [26] interstellar magnetic field (ISMF) and the high plasma beta in the heliosheath [13], we have concluded that the heliosphere behaves as a diamagnetic bubble with little substantial tail-like features, consistent with recent modelling [27],[28],[29],[30]. Although different interpretations and models of the V1 measurements exist, showing that the spacecraft may not have exited to interstellar space [31],[32], a fact that can possibly point to a heliosheath with different magnetic properties [33] other than a “diamagnetic bubble”, such a view does not preclude the rough nose-“anti-nose” symmetry shown in our recent analysis [25].

Given the line-of-sight integral that determines the ENA intensity, assessing any proposed interpretation of the shape and properties of the heliosheath requires the evaluation of the physical properties of the underlying source proton population in the heliosphere in the broad context of the solar wind. A significant advantage of the INCA/ENAs is that they correspond to a time period that partly overlaps with solar cycle 23 and the ongoing solar cycle 24 and at the same time they can be directly contrasted with in-situ ion measurements from the heliosheath sampled by V1 and V2 in overlapping energy bands. The aforementioned recent developments in this direction [25] verified our previous interpretations [8],[13],[20],[34],[35],[36], and partly addressed key questions; the Belt was previously identified as a relatively stable feature as a function of energy, corresponding to a reservoir of particles that exist within the heliosheath, constantly replenished by new particles from the solar wind [20]. Consequently, the Belt ENAs are expected to be associated with a region of enhanced particle pressure that is formed between the termination shock and the heliopause and contributes to balancing the pressure of the ISMF [8],[13],[34], forming a roughly symmetric time-dependent obstacle to the inward interstellar flow; an 11-year “breathing mode” of the global heliosphere, manifested by the outward propagating changes of the solar wind through the solar cycle.

The present paper is organized as follows: Section 2 provides the necessary “background” information concerning the INCA experiment and the ENA measurements presented in this study. Section 3 presents the > 5.2 keV ENA measurements over the 2003-2014 time period and compares the “nose” and “anti-nose” ENA intensities as a function of time together with in-situ ion measurements from the heliosheath and solar wind energy input. Section 4 extends the interpretations shown in our recent analysis by focusing on the recovery of ENA intensities after the onset of solar cycle 24. In Section 5 we present a summary of our results and discuss the features that need to be explored in our future analyses.

2. Data and experiment details

The INCA imager is part of the Magnetospheric Imaging Instrument (MIMI) [24] on board the Cassini spacecraft in orbit around Saturn’s (~10 AU from the Sun) since 1st July of 2004. INCA utilizes a large geometry factor of ~2.4 (cm$^2$ sr) and a broad field of view (FOV) of 90$^\circ$ in the azimuthal direction and 120$^\circ$ in the perpendicular direction; nominal angular resolution is ~5$^\circ$ for Hydrogen. The detection of ENAs is then based on the time-of-flight (TOF) technique, and several discrete energy passbands are defined within the energy range of ~5.2 to ~200 keV.

The ENA data used in this study correspond to four TOF channels within the energy range of 5.2-55 keV (defined by each energy channel passbands as $E = \sqrt{E_i:E_{i+1}}$, ~8.4, 18.0, 29.0, 43.9 keV) and to both “spin” and “stare” imaging periods, i.e. a rotation around the spacecraft Z-axis (spin axis) that results in a scan over 360$^\circ$ across the sky, and also periods of staring in a fixed direction in the sky sphere, respectively. Previous analyses (e.g. [8],[20]) have shown that possible “background” sources are insignificant when compared with the measured foreground INCA ENAs, whereas all time periods where INCA was surveying Saturn’s plasma sheet or pointing in the general direction of the Sun were excluded from our analysis (e.g.[20]).
The resulting INCA images (Figure 1a) represent a set of 320x160 pixel maps and, to the extent that our pixel exclusion criteria (as described above and in [8],[20],[25]) are successfully applied, we assert that the ENA data are consistent with Poisson counting statistics: all measured counts (C) that are accumulated in the INCA detector per each pixel are bounded to an uncertainty that is equal to \( \sqrt{C} \). The ENA emissions in the keV energy range are relatively low differential intensity events (\( j = C/(\text{cm}^2\cdot\text{sr} \cdot \text{sec} \cdot \text{keV}) \)), resulting in relatively high uncertainties (\( \delta j = \delta C/(\text{cm}^2\cdot\text{sr} \cdot \text{sec} \cdot \text{keV}) \)). Thus, to ensure credible statistics we average the measured intensities over several pixels in both the longitude and latitude direction, as explained in the captions of each of the Figures 1, 2, 3.

Figure 1b illustrates the longitudinal dependence of the combined 2003-2009 ENA intensities for various latitudes, verifying that the peak intensities - on average - between the nose and anti-nose directions are nearly similar throughout the INCA energy range (although only the lower, 5.2-13.5 keV and higher, 35-55 keV energy channels are included in this Figure). As shown before [20] and also in Figure 1d, the 5.2-55 keV ENA spectra are fairly consistent with a single power law form in energy \( (j \sim E^{-\gamma}) \). The INCA spectra (Figure 1c,d) are softer \((4.0 < \gamma < 4.4)\) roughly within the belt region and harder \((3.5 < \gamma < 4.0)\) in the surrounding regions (basins, where the ENA minima occur), following the ENA intensity changes shown in Figure 1a,b. The ENA spectral index shows no noticeable asymmetry between the nose and anti-nose directions, while its spatial dependence with latitude is nearly similar (within error bars). The consistency of the ENA intensities, taken together with the convergence of the ENA energy spectra between the nose and anti-nose directions, provide indisputable evidence that the global heliosphere must be roughly symmetric. However, we must keep in mind that, as explained in [25], a perfect symmetry not only would require a negligible ram pressure of the interstellar flow [8], but also, models including Hubble Space Telescope observations of H-Ly\( \alpha \) absorption have been interpreted as showing a nose–tail asymmetry [37]. Thus, although this nose-tail asymmetry can be in fact attributed to the non-negligible anisotropic ram pressure of the interstellar medium, we stress that such distortion would differ substantially from any heliosheath structure that includes a very prolonged tail [16].

3. Global ENA emissions over Solar Cycles 23 & 24

A quantitative examination of ENA histories in both the anti-nose as well as the V1 and V2 directions (towards the nose) during the 11-year period (Figure 2) reveals a substantial decay of the belt intensities (by a factor of \( \sim 3 \) among all TOF channels) that is not “symptomatic”, but closely correlated with the declining phase of solar cycle 23. The gray-scaled lines in Figure 2 illustrate the time profiles of ENAs at \( \sim 80\text{-}100 \) deg in ecl. longitude (where the approximate center of the anti-nose belt lies) and for various latitudes above and below the ecliptic equator (20°x20° averaging).

The first Cassini/INCA image during 2003 was taken three years after the onset of the declining phase of SC23 (where solar activity was high enough, SSN~70), that exhibited a late solar minimum (“deep” solar minimum) during late 2009 to early-2010, where the solar activity was effectively minimized (SSN < 20) and onset of SC24 occurred. As shown in Figure 2, the year 2003 is associated with high ENA intensities emanating from the anti-nose region, that decrease in following years to levels found in the basins by 2011-2012. However, the rapid recovery of ENA intensities beyond 2012 is associated with the onset of solar cycle 24 where solar activity is gradually restored towards the new solar maximum. Note that solar cycle 24 is expected to be among the smallest cycles in this century [38].

These observations have important implications for our understanding of the global heliosphere, especially if we take into account the following factors:

a) The decay of ENAs in the nose and anti-nose directions present similar time dependence: The blue and red lines in Figure 2 illustrate the time profiles of ENAs in the V1 and V2 directions respectively, taking into account the displacement of both spacecraft over the observation period: V1 and V2 travel through the HS with velocities of \( \sim 3.6 \) AU/yr and \( \sim 3.2 \) AU/yr respectively. From 2003 up to 2015, V1 slowly ascends in ecliptic latitude with a speed of \( \sim 0.03°/\text{yr} \) (and \( \sim 0.25°/\text{yr} \) in ecliptic longitude), i.e. over an 11-year time period the displacement of V1 in the ecliptic plane is \( \sim 0.33° \) in
latitude and ~2.75° in longitude, which is well below the 5°x5° pixel averaging that we perform in our INCA/ENA measurements (and roughly comparable, in the longitude direction, with the INCA pixel width). By contrast, V2 descends in ecliptic latitude with a speed of ~0.6°/yr and ~0.17°/yr in ecliptic longitude. This results in an apparent (and more important, compared with V1) movement of V2 in the ecliptic sphere of ~6.6° in latitude and ~1.9° in longitude over an 11-year time period. The 5°x5° pixel averaging that we perform in our ENA intensities ensures enough counts to produce statistically significant results (reflected in the error bars of Figure 2) and at the same time defines a relatively narrow region around both V1 and V2 for a meaningful comparison between the LECP ions and INCA ENAs (which will be explained in point b). To avoid possible “spatial effects” (especially in the V2 direction) over the 11-year period that we analyze here, our averaged 5°x5° ENA intensities take into account the displacement of both spacecraft in ecliptic coordinates, by always keeping the V1 and V2 positions at the center of the averaging bins (henceforth “V1” and/or “V2 pixels”). With the above in mind, Figure 2 shows that although the decrease of ENA intensities in V1 and V2 pixels persists up to the year 2012/2013, the overall profiles between the nose and anti-nose ENAs are very similar within error bars (a 1-year uncertainty should be taken into account here due to the time averaging that we perform in the ENA intensities). Therefore, the ENA intensities between the nose and anti-nose regions are not only consistent in an average sense (Figure 1), but exhibit a consistent time variability.

Figure 2. Yearly ENA time profiles in the anti-nose direction (gray scale lines), averaged over 20x20° in the approximate center of the belt compared with the ENA measurements averaged over 5x5° enclosing the V1 and V2 positions (blue and red lines, respectively).

b) In-situ ions and remote-sensed keV ENAs in the heliosphere are directly comparable and the source of >5.2 keV ENAs is the heliosheath: V1 crossed the TS at ~94 AU [9],[10],[11] while it recently crossed the HP at a distance of ~122 AU (where the complete evacuation of keV ions and simultaneous increase of galactic cosmic rays occurred) [35]. Below the ecliptic equator, V2 crossed the TS at a distance of ~84 AU [12] and still surveys the heliosheath. As shown in [25], the >5.2 keV
ENA intensities in the directions of both V1 and V2 have undergone a significant decrease during the time period 2009 to 2013 (by a factor of ~2.3), very similar to the > 30 keV in-situ ion decrease (by a factor of ~2.7) at V2 (V1 crossed the HP on 2012.65). Furthermore, the period after 2013 is characterized by a turn-up in both ENA (tail and in V2 direction towards the nose, by a factor of ~2) and ion intensities (~1.5). Also, as explained in our recent publication [25], despite the ~138 AU separation between the two Voyagers (~35° above and ~34° below the ecliptic equator, respectively), the ion intensity histories and spectra at both spacecraft are very similar in both shape and numbers. Furthermore, they are closely correlated with the ENA intensities at the two different latitudes of both V1 and V2, a fact which indicates that the modulation of superthermal ions during the solar cycle is global throughout the heliosheath. Most importantly, however, the coherence in the overlapping energy ranges of ions and ENA at E > 28 keV in the variability measured in-situ by V1,2 and remotely by Cassini, shows that the source of ENA is definitely the heliosheath. Given the similarity in the overall appearance of the images throughout the INCA energy range (~5-55 keV), we infer that the source of ENAs at <30 keV (i.e. below the V1,2 ion threshold) to also be the heliosheath. In contrast, the source of the IBEX-ribbon at lower energies (<6 keV) is not clear [16] and could lie beyond the HS due to processes yet to be revealed. It is likely, however, that the IBEX-defined Globally Distributed Flux-(GDF)[17] is also the HS [19]. For example, despite a 10-70% ENA reduction in the 1.1-4.29 keV pole measurements [39] over the 2008-2011 time period, the 0.71 keV IBEX channel showed no decrease in ENAs during that same period. This is yet another indication that the GDF and the Ribbon are possibly two distinct features that originate from different source plasma populations (heliosheath and outside the heliopause, respectively) as proposed earlier [20]. We should note, however, that a solar cycle connection to the N–S pole IBEX ENA variations (north and south pole respectively) showed no decrease in ENAs during that same period. This is yet another indication that the GDF and the Ribbon are possibly two distinct features that originate from different source plasma populations (heliosheath and outside the heliopause, respectively) as proposed earlier [20]. We should note, however, that a solar cycle connection to the N–S pole IBEX ENA variations (north and south pole respectively) has recently been reported [40].

The intensity profile of ENA and ion measurements at ~100 AU and beyond are directly comparable to the solar wind energy input at 1 AU: As explained above, the SSN can be used as proxy for the solar cycle phases and we have used these measurements to connect solar activity with the ENAs and ions in the heliosheath. Recent studies [41] have undertaken a significant effort to calculate the solar wind parameters as a function of time for the in-ecliptic solar wind data at 1 AU from the OMNI database. The solar wind energy flux and density at 1 AU show a coherent decay with time (peak to basin ratio of ~2) up to early 2010 and a recovery in both quantities thereafter (e.g. Figure 9 in [41]). This, as expected (e.g. see [1]), is consistent with the measured SSN and overall solar activity explained in the previous paragraphs over the declining phase of solar cycle 23 and onset of solar cycle 24. Consequently, the plasma output from the sun at 1 AU is directly contrasted and connected with the intensity changes in both ENA and ions at ~100 AU and beyond, i.e. inside the heliosheath. The ~2-3 years time difference between all aforementioned quantities will be discussed in detail in paragraph 4 where we elaborate on the travel times of ENAs and ions in the heliosphere and provide a quantitative calculation of the width of the heliosheath based on those travel times.

As explained elsewhere [34], the transition of the high ENA intensities in the tail to the low ENA intensities in the Basin, that occurs at ~60° to 30° in ecl. longitude (previously defined as “transition region”), is identified in all energy ranges and serves as a relatively smooth boundary, with a spatial width of ~30° deg in ecl. longitude, between the very low and high ENA emissions in the heliosheath. The ENA intensities in this region diminish with an average spatial rate of ~2.4% /degree, that is nearly constant as a function of energy. Here we note that by contrast to the belt, the ENA intensities in the basins remain essentially stable with time throughout the INCA energy range.

Figure 3 illustrates the evolution of the global ENA heliosphere over the time frame of an 11-year observation period (2003-2014), that involves a general reduction of the Belt in both intensities and width, up to at least the year 2011/2012 and a recovery thereafter, that is clearly shown in both the 5.2-13.5 and 35-55 keV channels, above and below the ecliptic equator. Thus, the rate through which the transition region is diminished is also variable with time (as expected), presenting its minimum value over the years 2011-2012 where the Belt ENA intensities are effectively minimized. This observation may act as an indirect assessment (which will be examined in our future work) of the
fact that the heliosphere, independently of its shape (even if it is “bubble-shaped” as we conclude) cannot be a closed and unaltered system through time, since the solar wind energy input has to be evacuated somehow.

First, the solar wind is the source population of heliosheath plasma but, due to the measured high plasma beta in the heliosheath contrasted with the relatively low stagnation pressure exerted from the interstellar flow, the heliosphere is expected to exhibit a diamagnetic behavior [25]. Therefore, the dynamic properties of ENA from the heliosheath are apparently strongly related to the dynamic properties of the solar wind over the solar cycle and can quantitatively relate to the properties of the heliosphere interactions with the local interstellar medium. Secondly, the ENA intensity gradient in the transition region translates to a partial pressure gradient in the same region, which in turn produces a variable “shielding current” as a function of time. Therefore, in combining the above two points, we infer that the heliosphere bubble may remain diamagnetic throughout the solar cycle phases, but it is not expected to remain a perfectly symmetric and unaltered sphere, as the pressures, pressure gradients and -in turn- the “shielding currents” in the heliosheath are in fact time-depended.

Figure 3. a) Longitudinal distributions of the 5.2-13.5 keV, averaged over 11x9 (Latitude, longitude) in ecliptic coordinates for both above (top) and below (bottom) the ecliptic equator for the time period of 2003-2014 following the declining phase of solar cycle 23 and the onset of Solar cycle 24. b) the same as in (a) for the 35-55 keV ENAs.

Consequently, the heliosphere bubble can inflate with time in either the anti-nose direction (as “tail” models suggest) or along the direction of the interstellar magnetic field (as in the Parker-Bubble model). The recent model that shows a view of the heliosphere with two prominent polar jets [27],[28],
provides one of the possible ways through which the solar wind input can be evacuated from the heliosphere.

4. Recovery times of ENAs over the onset of solar cycle 24 and the width of the heliosheath.

We now draw our attention to the recovery times of ENAs in the heliosphere. Figures 2 and 3 show a clear, but explainable, mismatch of ~2-3 years between the observed ENA minimum and the minimum of cycle 23 as measured by the SSN and the solar wind energy input at 1 AU (described in paragraph 3 of the present paper). In fact, given our results, this time delay enables us to re-think the following question, which goes to the heart of our analysis: *If the time profile of V1 and V2 LECP >28 keV ions are indicative of the solar wind changes through the SC inside the HS, when should V2 be expected to “measure” the solar minimum of solar cycle 23 (occurred in early 2010) and detect the recovery at the onset of solar cycle 24?*

![Figure 4. Recovery times of ENAs of different energies (5.2-55 keV), as a function of the heliosheath width using Eq.1 and the parameters explained in the text. The inset focuses on the ~2-3 year recovery times of >5.2 keV ENAs, for which a heliosheath of ~80-120 AU width is obtained.](image)

V2 crossed the termination shock at \( L_{TS} \sim 84 \) AU, whereas its position in early 2013 was at \( L \sim 102 \) AU (-34° ecliptic latitude). Both V1 and V2 measured that the field aligned streaming velocities of ions cannot be more than \( \sim 100 \) km/s, typically around \( V_{\text{plasma}} \sim 60-80 \) km/s or even lower. The solar wind at the nearly ecliptic equator travels with a speed of \( V_{\text{SW}} \sim 400-500 \) km/s. Therefore, it takes the solar wind \( t_{\text{SW}} = L_{TS}/V_{\text{SW}} \sim 0.7 \) to 1 year to reach the termination shock in the V2 direction. From this point on it would require an additional time of \( t_{\text{plasma}} = (L-L_{TS})/V_{\text{plasma}} \sim 1 \) to 1.4 yrs for the plasma to reach the V2 position. Consequently, as the minimum intensity in keV ions towards the nose (V2 direction) occurred during the first days of 2013, a time delay of > 2.4 years between the solar cycle parameters and the measured ions at V2 (and V1) can be in fact regarded as indicative of the time difference between the actual minimum on the Sun and its manifestation in the heliosheath; this is simply due to the solar wind propagation up to the termination shock and the subsequent plasma
propagation with relatively low speeds in the heliosheath. This simple calculation together with the observed consistency between ENAs and ions in the heliosheath implies that no source regions, other than the heliosheath itself, and no sources other than the solar wind itself are needed to explain the time variation of the measured > 5.2 keV ENAs. The above picture is also consistent with the rapid recoveries in both ENA intensities from the V2 pixel and V2/LECP (in-situ) ion measurements after 2013. So, the question here is: can we estimate the thickness of the heliosheath given the recovery times of ENAs? Before getting into the details of this question, we need to be reminded that ENAs and ions are consistent in both the V1 and V2 pixels, whereas the ENA spectra are found to be in excellent agreement between the nose and antinose regions. Therefore, we can -at this point- estimate the width of the global heliosheath by providing simple calculations, although the details of this will be examined in future analyses.

Here we can make the reasonable assumption that the termination shock is roughly symmetric around the sun, located at \( L_{TS} \sim 90 \) AU, which is also consistent with recent modelling that depicts a view of the heliosphere which includes a symmetric termination shock \([30]\). Again, we can adopt an average solar wind speed \( V_{SW} \sim 450 \) km/s. Although the plasma speed inside the heliosheath (in the V1 and V2 pixels) was found to be typically \( V_{plasma} < 100 \) km/sec (e.g. \([42, 43]\)), recent models show that the average magnetosonic speed towards the tail can be as low as \( \sim 50 \) km/sec (e.g. \([27]\)) and as high as \( \sim 140 \) km/sec (e.g. \([22]\)).

Figure 4 shows the recovery times of ENAs as a function of heliosheath width after incorporating the numbers explained in the aforementioned paragraph in the following simple equation:

\[
T_{Recovery} = L_{TS}/V_{SW} + L/V_{plasma} + (L_{TS} + L)/V_{ENA}(E)
\] (1)

where \( V_{ENA}(E) \) is the energy-dependent speed of ENAs (e.g. a 10 keV H ENA travels with a speed of \( \sim 1400 \) km/sec whereas a 45 keV is twice as fast, i.e. \( \sim 2800 \) km/sec), and \( L \) is the spatial range in which the charge exchange reaction takes place. Since we have concluded that our ENA measurements are produced by the interaction between the ions and neutrals from inside the heliosheath, we can in fact match this parameter \( (L) \) to the actual width of the heliosheath. Here we also need to be reminded that the ENA emission is optically thin (that is, ENA intensity cannot be significantly reduced between the termination shock and INCA, located at \( \sim 10 \) AU from the Sun). Further, although, ENAs will be generated throughout the whole distance from \( L_{TS} \) to \( L_{TS} + L \), which means that Eq. 1 would yield a wide range of recovery times for ENAs of a given energy, we have selected to adopt a method shown elsewhere \([40]\), making the simplifying assumption that charge exchange will take place near \( L/2 \) (so, replace \( L \) with \( L/2 \) in Eq. 1).

With the above assumptions, Figure 4 shows that the >5.2 keV ENAs would be consistent with a heliosheath width of 80 - 120 AU towards the tail (due to the ~2-3 yrs recovery after solar minimum). It is noted that the differences in the travel times of ~10 keV ENAs compared to 45 keV ENAs from a heliosheath that is as thick as ~100 AU is only a few months (~3 months), whereas the differences between higher energy ENAs (>20 keV) are practically insignificant (see inset of Figure 4). ENAs of lower energies (e.g. at ~1 keV, not shown here) would require ~3.5 to 4.3 years to travel back from a HS with a width of ~80 to 120 AU (and the differences in travel times of low energy ENAs are much more important). This view and the above calculations are consistent with the fits of the IBEX-Hi/ENA measurements from the North (N) and South (S) poles \([40]\), where the inner heliosheath thickness is found to be \( \sim 210 \) AU in the north and \( \sim 160 \) AU in the south. This is also consistent with the heliosheath tail thickness of \( \sim (220\pm 110) \) AU, inferred by IBEX-Lo measurements \([44]\).

5. Summary and Conclusions

After our most recent work \([25]\), we have used an extended set of >5.2 keV INCA/ENA measurements over the time period of 2003-2014 to re-evaluate our previous assessments and further provide preliminary calculations to show that the ~2-3 yrs time delay between the SSN and solar wind...
energy input at ~1 AU with the measured ENAs at ~10 AU from Cassini is consistent with a heliosheath with a thickness of ~80-120 AU in all directions.

As it becomes transparent in recent publications, using a variety of different ENA measurements from eV (IBEX-Lo, IBEX-Hi) to 10s of keV (INCA), but most importantly due to the comparison of INCA/ENAs with in-situ LECP ions, together with the recent V1 crossing of the heliopause, we seem to obtain the same (or similar) result, depicted in Figure 5: A roughly symmetric heliosheath that can be ~29 AU in the V1 direction [35], up to 70 AU in the V2 direction [36], ~160 and 210 AU towards the N and S poles respectively [40] and ~100 to 220 AU towards the tail [25],[44].

Figure 5. A composite, conceptual representation of the global heliosphere summarizing its basic properties in three dimensions, based on both remote ENA and in-situ ion measurements from Cassini/INCA and LECP/V1 and V2, respectively (published in [25]). The heliosheath includes a belt of varying ENA intensities (colour-coded with relative scale ranging from 1 (blue) to 12 (red)) surrounding the termination shock and extending to the heliopause. The asymmetric termination shock crossings from V1 and V2, above and below the ecliptic equator respectively, together with the heliopause crossing of V1 are shown. The heliosheath is possibly ~30–50% thicker towards the V2 direction (compared to the V1 direction), inconsistent with a compressed heliosheath in the Southern hemisphere. The interstellar flow (red arrows) impinges the nose and is deflected around a roughly symmetric nose to anti-nose heliosheath that interacts directly with the strong interstellar magnetic field (gray lines).

At this point we should also be reminded of two very important observations: The first is that the plasma beta inside the heliosheath, as measured along the trajectories of both Voyager 1 and Voyager 2, showed that the particle pressure was persistently much higher than the magnetic pressure at all times [13]. Second, after Voyager 1 exited the heliopause it measured a strong interstellar
magnetic field of ~0.5 nT [45] (much stronger than was anticipated in the past), as was predicted by the joint use of INCA and Voyager measurements [13]. In combining all the aforementioned points, we regard our measurements to be consistent with a roughly symmetric, bubble-like heliosphere that exhibits diamagnetic behavior. This notion, as far as the broad context of the heliosphere interaction with the local interstellar medium is concerned, is consistent with the Parker-bubble model [46] (compared with the “magnetosphere-type” Parker model). A modified version of the Parker-bubble was suggested as a plausible interpretation of the “early” INCA measurements [8], and was proved in our recent analysis [25].

Together with the above recent developments, modern heliosphere modelling seems to provide a similar view: Magnetohydrodynamic modelling using the mini magnetosphere of Ganymede embedded in the sub-Alfvénic flow of Jupiter’s magnetospheric plasma [29], was used as a proxy for the heliosphere and resulted in a “tailless” structure with no bow shock. The sensitivity of MHD models to seemingly “small” changes in the interstellar magnetic field was clearly demonstrated [47], from a heliosphere that includes a strong bow shock when B~0.2 nT, to no bow shock when B~0.4 nT. In other recent studies [30] the “Parker-bubble” was tested and a heliosphere with a symmetric termination shock was concluded when using an interstellar magnetic field close enough (0.44 nT), comparable to the measured one (~0.5 nT). Finally, a very recent and challenging model [27],[28] depicts a view of the heliosphere with turbulent jets deflected into the tail region by the interstellar wind (a “croissant-type” heliosphere), but not strong enough to drive a “comet-type” tail.

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