# Plasma pressures in the heliosheath from Cassini ENA and Voyager 2 measurements: Validation by the Voyager 2 heliopause crossing

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## **Key Points:**

- "Ground truth" Energetic Neutral Atom and ion data in the heliosphere estimate the reported Heliopause crossing by V2 at  $\sim 119$  AU
- The normalization of Energetic Neutral Atom and ion intensities yields an interstellar neutral hydrogen density of  $n_H \sim 0.12 \text{ cm}^{-3}$ .
- The 5.2-24 keV H<sup>+</sup> pressures dominate the 5.2-3500 keV distribution whereas pressure balance implies that  $B_{ISMF} \sim 0.5$  nT.

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### Abstract

We report "ground truth", 28-3500 keV in-situ ion and 5.2-55 keV remotely sensed ENA measurements from Voyager 2/Low Energy Charged Particle (LECP) detector and Cassini/Ion and Neutral Camera (INCA), respectively, that assess the components of the ion pressure in the heliosheath. In this process, we predict an interstellar neutral hydrogen density of ~0.12 cm<sup>-3</sup> and an interstellar magnetic field strength of ~0.5 nT upstream of the heliopause in the direction of V2, *i.e.* consistent with the measured magnetic field and neutral density measurements at Voyager 1 from August 2012, when the spacecraft entered interstellar space, to date. Further, this analysis results in an estimated heliopause crossing by V2 of ~119 AU, as observed, suggesting that the parameters deduced from the pressure analysis are valid. The shape of the >5.2 keV ion energy spectra play a critical role towards determining the pressure balance and acceleration mechanisms inside the heliosheath.

# Plain Language Summary

The Voyager missions, together with Cassini, provide the only combination of spacecraft to date that can establish "ground truth" at ~100 AU and beyond, and has recently settled the long standing issue on the dual heliosphere models, showing that the heliosphere behaves as rough diamagnetic-bubble. Leveraging from the synergy between remote sensed ENAs and in-situ measured ions we estimate (accurately) the recently reported V2 heliopause crossing at ~119 AU, showing that the shape of the ion energy spectra play a critical role towards determining the pressure balance and acceleration mechanisms inside the heliosheath. In anticipation of measurements from V2 after it crossed the heliopause, the normalization of ENA and ion intensities provides an important insight on the properties of the Local Interstellar Medium, showing an interstellar neutral hydrogen density of  $n_H \sim 0.12 \text{ cm}^{-3}$  and a magnetic field upstream of the heliopause of  $B_{ISMF} \sim 0.5 \text{ nT}$ .

## 1 Introduction

For more than half a century, the shape and interactions of the Sun's astrosphere (the heliosphere) with the Local Interstellar Medium (LISM) over the solar cycle, have been modeled with increasingly sophisticated techniques [Davis, 1955; Dessler, 1967; Baranov et al., 1971; Fahr et al., 2000; Zank and Muller, 2003; Opher et al., 2004; Washimi

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et al., 2007; Izmodenov et al., 2008, 2009; Pogorelov et al., 2013]. However, none of the past theories and models were corroborated by measurements, an inherent limitation that was removed only after the first space probes, Voyager-1 and Voyager-2 (V1 & V2) reached the inner boundary of the heliosphere (termination shock, TS) in 2004 and 2007, where the supersonic solar wind (SW) terminates at the shock front, at distances of  $\sim 94$  [Decker et al., 2005; Stone et al., 2005] and  $\sim 84$  Astronomical Units (1 AU equals the distance between Earth and Sun,  $\sim 150$  million km) [Decker et al., 2008], respectively, discovering the reservoir of ions and electrons that constitute the heliosheath (HS), between the TS and the heliopause (HP).

The two Voyagers are traversing the heliosphere in the upstream (nose) hemisphere, where the interstellar flow impinges, and have made two of the key discoveries in heliospheric physics during this decade: The heliopause crossings by V1 in August of 2012 [*Krimigis et al.*, 2013; *Stone et al.*, 2013; *Burlaga et al.*, 2013] at a distance of ~122 AU, +35° ecliptic latitude and the crossing by V2 in November of 2018 (https://www.jpl.nasa.gov/news /news.php?feature=7301) at a distance of ~119 AU, -34° from the ecliptic equator.

Remote observations from Cassini (in orbit around around Saturn at ~10 AU until 15 Sep. 2017) were used to image for the first time the so-called "heliotail" in 2003 [Dialynas et al., 2015] through its dedicated Energetic Neutral Atom (ENA) detector (Ion and Neutral Camera-INCA; Krimigis et al. [2004]), providing the first full-sky image of the heliosphere in 5.2-55 keV ENAs [Krimigis et al., 2009] and at <6 keV ENAs from the Interstellar Boundary Explorer (IBEX) mission, at ~1 AU [McComas et al., 2009]. In situ measurements of >28 keV ions in the heliosheath using the Low Energy Charged Particle (LECP) instrument [Krimigis et al., 1977] on board both Voyagers provided "ground truth" to the global ENA images through overlapping energy ranges of both ions and neutrals.

As the ENAs measured by INCA have been shown to originate in the HS [*Dialy-nas et al.*, 2013, 2017a], the resulting Cassini/INCA images (e.g. Figure 1a) provide a marker for the local plasma-neutral processes inside the heliosheath. Figure 1a shows a "Belt" of varying ENA intensities, identified as wide ENA region that wraps around the celestial sphere in ecliptic coordinates, passing through the "nose" the "anti-nose" (tail) and the north and south heliosphere poles, together with two prominent "Basins", identified as two extended heliosphere lobes, where the ENA minima occur [Krimigis et

al., 2009; Dialynas et al., 2013], placing the V1&2 ion data in a global context. The source of the IBEX-defined "Ribbon", identified as a bright and narrow stripe of ENA emissions between the V1 and V2 directions, is thought to lie beyond the heliopause [*McComas et al.*, 2017a], with its center coinciding with the direction of the local interstellar magnetic field (ISMF), but the origin of the IBEX-defined globally distributed flux [*Livadiotis et al.*, 2011] may well be the heliosheath [*Dayeh et al.*, 2011], as also inferred in [*Dialynas et al.*, 2013].

The combination of remotely imaged 5.2-55 keV INCA/ENAs, together with >40keV in-situ ion measurements from the Low Energy Charged Particle (LECP) experiment on V1 [Decker et al., 2005] in the heliosheath (HS) have been used in the past to predict the V1 heliopause crossing [Krimigis et al., 2011] and the magnitude of the interstellar magnetic field [Krimigis et al., 2010] with good accuracy. Key discoveries through the LECP experiment's measurements of >28 keV (V2) ions, taken together with the 5.2-55 keV INCA/ENAs, showed that the heliosphere responds promptly, within  $\sim$ 2-3 years, to outward propagating solar wind changes in both the nose and tail directions over the solar cycle and suggested a diamagnetic "bubble-like" heliosphere with few substantial tail-like features [Dialynas et al., 2017a,b]. This bubble heliosphere concept is consistent with recent advanced modeling [Opher et al., 2015; Drake et al., 2015; Kivelson and Jia, 2013; Golikov et al., 2017; Opher et al., 2019] as well as ENA observations from the IBEX mission [Galli et al., 2016, 2017], and has settled the issue on the dual heliosphere models first posited by Parker [1961] over five decades ago, concerning the properties and time evolution of the heliosphere and its interaction with the Local Interstellar Medium (LISM).

#### 2 5.2-3500 keV Energy Spectra in the Heliosheath

ENAs are products of charge exchange (CE) [Lindsay and Stebbings, 2005] between fast protons and the "background" neutral hydrogen (H) gas flowing through the heliosheath [Krimigis et al., 2009; McComas et al., 2009]. Due to overlapping energy bands between INCA and LECP we are able to deduce with certainty the nonthermal energetic ion contribution in the overall HS dynamics (Figure 1b,c). Thus, the normalization (see Krimigis et al. [2009]) of the intensity of the highest ENA energy channel (~35-55 keV) measured remotely at ~10 AU to the lowest V2 H<sup>+</sup> channel (~28-40 keV) making in-situ ion measurements inside the HS, yields a HS thickness along the V2 trajectory of  $L_{V2} \sim (35.2$   $\pm$  8.6) AU (the uncertainty in L<sub>V2</sub> is calculated from the error propagation function due to the measured uncertainties in the ENA and ion intensities), assuming a neutral Hydrogen density of n<sub>H</sub> ~0.12 cm<sup>-3</sup>, and suggests a HP crossing at ~119.2 AU (Figure 1b). In November of 2018 V2 crossed the HP at a distance of ~119 AU, indicating that our calculation is not only relevant, but it once again highlights that the source of the 5.2-55 keV ENAs detected with Cassini/INCA is the HS.

Roelof et al. [2012] showed that consideration of the Compton-Getting factor [Compton and Getting, 1935] in ENA and ion measurements in V2 (and V1) over the time period before 2012, may increase the estimate of the HS radial thickness by some percentage. The radial plasma velocities in V2, however, are decreasing, from  $\sim$ 80-90 km/s in 2013 to gradually approaching zero values towards 2016. Taking an average radial plasma speed of  $V_r \sim 40$  km/s and a spectral index for the lower LECP channels of  $\gamma \sim 1.7$  (see Figure 3a), then the estimated heliosheath width in the V2 direction  $(L_{V2})$  is related to the Compton-Getting corrected value  $(L'_{V2})$  as  $L'_{V2}/L_{V2} = (1 + V_r/V)^{2(\gamma+1)} = (1 + 40/2520)^{5.4}$ = 1.088 [e.g Roelof et al., 2012]. This number indicates that our estimate of the heliosheath width (L<sub>V2</sub>  $\sim$ 35.2 AU) can be increased by  $\sim$ 8.8%, which translates to  $\sim$ 3.1 AU, i.e. much smaller than the calculated error bar ( $\pm$  8.6 AU). Therefore, although the Compton-Getting correction has been initially considered, it was found to be small because of the low velocities in the HS during the time period in question. Overall, these ENAs serve as important indicators of the acceleration processes that the parent  $H^+$  population undergoes inside the HS, thus imposing a key constraint on any future interpretation concerning the HS dynamics.

Although the Plasma (PLS) instrument on V1 [Bridge et al., 1977] failed in 1980, the Plasma Wave (PWS) instrument [Scarf and Gurnett, 1977] is in full operational condition, thus detecting electric field emissions, which can be related to the electron density from the frequency of electron plasma oscillations. Assuming that the equilibrium ionization fraction,  $n_e/(n_e+n_H)$ , is ~ 50% for the LISM, then the neutral hydrogen  $(n_H)$ density is directly comparable to the measured electron density  $n_e$ . Consequently, with V1 traversing the LISM since 2012, the neutral hydrogen density upstream of the HP has been indirectly measured [Gurnett et al., 2013, 2015] to be ~0.09-0.11 cm<sup>-3</sup> (although densities up to ~0.14 cm<sup>-3</sup> were also found at distances ~20 AU past the HP as reported in Gurnett and Kurth [2017]), i.e. consistent with the 0.12 cm<sup>-3</sup> that was used here. For clarity, we repeated the calculation after assigning a neutral density of ~0.1 cm<sup>-3</sup>, show-



Figure 1. (a) A combination of 320x160 pixel INCA/ENA images (5.2-13.5 keV) organized in ecliptic coordinates, over the 2013-2016 time period, after the ENA and ion minimum, that corresponds to the onset of SC24. (b) Average 5.2-55 keV ENA energy spectra of the INCA/ENA data in the pixels enclosing the position of Voyager 2 ( $5^{\circ}x5^{\circ}$ ), together with the deduced H<sup>+</sup> spectra and the 28-3500 keV ion energy spectra measured in-situ by Voyager 2/LECP measurements over the time period 2013-2016. Horizontal bars indicate the INCA and LECP energy passbands for H ENAs and ions, respectively. The spectra are fitted with a power law form in energy in a least square sense; relative percentage errors in the spectral slope, do not exceed 8%. (c) The 5.2-3500 keV H<sup>+</sup> pressure energy spectra inside the heliosheath, derived from the measurements shown in panel (b), using L<sub>HS</sub>=35.2 AU and n<sub>H</sub> ~0.12 cm<sup>-3</sup>.

ing a HS thickness of  $L_{V2} \sim (42.2 \pm 10.3)$  AU, which is roughly consistent with the V2 HP crossing within the calculated uncertainties. Past observations from Ulysses/SWICS [*Gloeckler et al.*, 2001] and other measurements [see *Bzowski et al.* [2008]] were also consistent with values about 0.1 cm<sup>-3</sup>.

At this point we cannot determine if there is a possible density gradient between the V1 and V2 LISM locations along the HP boundary, or if the inferred  $n_H \sim 0.12 \text{ cm}^{-3}$ in the V2 direction is only a manifestation of the wide range of densities, that were found to be increasing from ~0.09 to 0.14 cm<sup>-3</sup> radially outward along the V1 trajectory, upstream of the HP. In principle, an electron density gradient does not necessarily imply a corresponding neutral Hydrogen density gradient, which is affected by the addition of neutrals via upstream charge exchange between the deflected plasma protons flowing around the HP and the incoming interstellar neutral H-atoms, thus forming a rather weak "hydrogen wall", which then depends on the presence and strength of a bow shock upstream of the HP (see *Dialynas et al.* [2017a] and references therein).

The shape of the ion energy spectra play a critical role towards determining the pressure balance and acceleration mechanisms inside the heliosheath. The average ENA energy spectra in Figure 1b are consistent with a power-law form in energy  $(J_{ENA} \sim E^{-(4.2 \pm 0.2)})$ , whereas the resulting ENA-derived H<sup>+</sup> spectrum is less steep  $(J_{ENA-derivedH+} \sim E^{-(3.4 \pm 0.2)})$ because of the energy dependence of the CE cross sections, as explained in [Krimigis et al., 2009]. Recent observations from the New Horizon spacecraft at  $\sim 38$  AU [McComas et al., 2017b] showed that the pick-up ion distribution is heated in the frame of the solar wind with increasing distance, before reaching the TS region at  $\sim 90$  AU. Although the TS was considered to be a site at which Anomalous Cosmic Rays (ACRs) are accelerated, the  $\sim 10-100$  MeV intensities in both V1 & V2 did not peak at the TS as expected [Stone et al., 2005, 2008]. Contrary to expectations, the shocked thermal plasma upstream of the TS remained supersonic, as only 20% of the upstream energy density went into heating the downstream thermal plasma [*Richardson et al.*, 2008]. The rest of the SW energy was transferred into heating pickup ions (PUI) and >15% transferred to the >28keV protons. This is translated to a prominent hardening break (less steep spectrum) in the >28 keV part of the H<sup>+</sup> distribution (e.g. Figure 1b) that was attributed to an accelerated "core" interstellar pickup ion distribution at the TS, through shock drift acceleration and particle scattering in the vicinity of the shock [Giacallone and Decker, 2010], as one of the possible mechanisms.

This characteristic seems to persist throughout the heliosheath as shown in Figure 1b, where the >28 keV spectra fit smoothly to the ENA-derived H<sup>+</sup> spectra at the energy range of ~24-80 keV, but the overall 28-3500 keV ion spectra exhibit a rough power law form in energy with  $J_{LECP} \sim E^{-(1.4\pm0.1)}$ . As explained in *Dialynas et al.* [2013], the INCA spectra exhibit hardening breaks at >35 keV (e.g. Figure 1b), which, due to the uncertainties related to the INCA/ENA measurements, are accounted as not statistically significant (therefore, the spectra can be described by a single power-law function that applies to the whole INCA energy range, as was also shown in Figure 1b). However, a simple power law fit in the 24-55 keV ENA-derived H<sup>+</sup> intensities, shows that the spectra are consistent with a ~ $E^{-(1.7\pm0.8)}$  law in this energy range. At the same time, the V2/LECP ion spectra exhibit a turn-up in the intensities at the energy range of 28-80

keV, thus informing that the change in the power law slope over the whole 5.2-3500 keV distribution (hardening break) occurs within the 24-80 keV energy range. Interestingly, the 28-80 keV LECP distribution follow a  $\sim E^{-(1.7\pm0.1)}$  law, i.e. both the 24-55 keV ENA-derived H<sup>+</sup> measurements and the 28-80 keV V2/LECP ones have the same rough slope (Figure 3a).

Despite the >140 AU separation between the two Voyagers (+35° and 34° latitude, respectively) since they both entered the heliosheath to date (they are ~165 AU apart today), the ion spectra at V1 and V2 inside the heliosheath are very similar in both shape and number as a function of time (e.g. *Decker et al.* [2009] and also Figure 2c,d, this study). In addition, they are in good agreement with the INCA/ENA data when converted to  $H^+$  using standard parameters explained earlier, in overlapping energy bands (e.g.*Dialynas et al.* [2017a] and Figure 2c,d this study).

#### **3** Pressure Balance in the Heliosheath

After the V1 and V2 respective crossings of the TS, it was found that the heliosheath pressure is dominated by suprathermal particles. While the >28 keV partial pressure distribution is measured in-situ by LECP, we use the ENA measurements converted to ions in the HS to compute the partial plasma pressure at >5.2 keV  $(P(dynes/cm^2) = (8\pi/3)(m/2)^{1/2}J_{ion}E^{1/2}\Delta E)$ , where  $E = \sqrt{E_1 \cdot E_2}$  is the midpoint of the measured energy in each energy channel,  $E_1, E_2$  are each channel passbands,  $\Delta E = E2 - E1$ , m is the proton mass and  $J_{ion}$ is the proton intensity; note that by substituting p = mv in this equation, we obtain  $\Delta P = (4p/3)J_{ion}\Delta E$ , as used in *Dialynas et al.* [2015]), a range where many of the PUIs associated with the TS and heliosheath reside. The 5.2-24 keV H<sup>+</sup> pressures shown in Figure 1c dominate the 5.2-3500 keV pressure distribution, which indicates that the 5.2-55 keV part of the energetic H<sup>+</sup> distribution covered by the Cassini/INCA is critically important for determining the pressure balance inside the heliosheath and cannot be neglected.

The H<sup>+</sup> partial pressure from the 5.2-24 keV INCA channel is a factor of ~4 higher than the >28 keV LECP pressure (on average) throughout the 2009-2016 time period and a factor of ~30 higher than the measured PLS thermal pressure over the same time period (Figure 2a). The partial plasma beta shown in Figure 2b ( $\beta = P_{particle}/P_{MAG}$ ) inside the HS is persistently >>4 on average (a local minimum that corresponds to the



Figure 2. (a) Yearly averaged pressure profiles of (red line) remotely sensed 5.2-24 keV ENAderived H<sup>+</sup> over 5°x5° enclosing the V2 pixel, (black line) 28-3500 keV H<sup>+</sup>, (blue line) >10 eV H<sup>+</sup> and (orange line) magnetic field from Cassini/INCA, V2/LECP, V2/PLS and V2/MAG experiments, respectively, as a function of time from 2009 to 2016. (b) Yearly H<sup>+</sup> partial pressure (PLS, INCA, LECP) divided by the magnetic field pressure (MAG) inside the heliosheath for the 2009-2014 time period. (c) 35-55 keV INCA/ENA measurements averaged over 5°x5° enclosing the V1 pixel and converted to ion intensities using L<sub>V1</sub> ~28 AU and n<sub>H</sub> ~0.1 cm<sup>-3</sup>, compared directly with the in-situ 40-53 keV LECP ion histories (see *Dialynas et al.* [2017a] for details). (d) The same as (c) for the >24 keV INCA/ENA measurements around the V2 pixel, using L<sub>V2</sub> ~35.2 AU and n<sub>H</sub> ~0.12 cm<sup>-3</sup>, as derived in Figure 1b, compared directly with the 28-43 keV LECP ion histories at V2. (e) 5.2-24 keV pressure contributed by H<sup>+</sup> inside the heliosheath (between the TS and the HP) computed from spectra deduced from the ENA observations using a varying heliosheath thickness and hydrogen density towards the upstream (nose) hemisphere, as detailed in the text. The mean relative percentage error is ~15%

minimum of SC23 with a time delay of ~2-3 years as explained in *Dialynas et al.* [2017a,b]) pointing towards a heliosphere that exhibits diamagnetic behavior. Although magnetic field measurements for the year 2016 are not yet available, if we assign a magnetic field strength at V2 in 2016 of the order of B~0.14 nT (roughly comparable to 2015), we obtain  $\beta_{2016}$  ~6.6 over 2016. Here we should note that the calculations in Figure 2b do not take into account the partial pressure that corresponds to the IBEX energy range,

that would result in even higher numbers for the plasma- $\beta$ , and would further support the arguments provided in this study.

The belt is a relatively stable feature as a function of energy, and corresponds to the reservoir of particles inside the HS, constantly replenished by new particles from the SW. As also argued in *Krimigis et al.* [2010] and *Dialynas et al.* [2015], Figure 2e demonstrates that the belt ENAs are associated with a region of enhanced particle pressure that is formed between the TS and the HP and contribute significantly to balancing the pressure of the ISMF. Although only part of the anti-nose (downstream hemisphere) is covered in the 2013-2016 INCA/ENA measurements, the partial 5.2-24 keV H<sup>+</sup> pressure is roughly comparable between the upstream and downstream hemispheres, at least in the regions where the belt is identified, whereas the partial pressure at the basins are a factor of ~6-7 lower.

The overall pressure distribution in Figure 2e, taken together with the time variant pressure distributions shown in Figure 2a, the ENA and ion intensities shown in Figure 2c and the  $\beta$ -parameter shown in Figure 2b are consistent with the concept of a roughly symmetric HS that behaves as a diamagnetic bubble, as shown in the conceptual model of *Dialynas et al.* [2017a]. Although, as noted earlier, we cannot determine with certainty the possibility of a neutral hydrogen density gradient between the V1 and V2 LISM locations along the HP boundary, the pressures shown in Figure 2e are computed from spectra deduced from the ENA observations using a varying heliosheath thickness and hydrogen density towards the upstream (nose) hemisphere: ~35 AU and 0.12 cm<sup>-3</sup> over the -90° to -30° in latitude (consistent with the V2 HP crossing), ~28 AU and 0.1 cm<sup>-3</sup> over +30° to +90° in latitude (consistent with the V1 measured parameters) and ~31 AU and 0.11 cm<sup>-3</sup> over -30° to +30° in latitude (to compensate for a possible density gradient). Despite these uncertainties, the overall 5.2-24 keV partial pressure around the V1 and V2 pixels (Figure 2e) is ~0.033 pPa, whereas the peak to basin partial pressure (belt to basins, respectively) in Figure 2e is within the range of ~0.092-0.014 pPa.

The measurements shown here can be used to address the pressure balance at the interaction region between the HS and the LISM, i.e. the heliopause. On average, the partial 0.7-4.3 keV H<sup>+</sup> pressure in the V2 (and V1) direction from IBEX is found to be  $\sim 27$  pdyn AU cm<sup>-2</sup> [*McComas and Schwadron*, 2014] and assuming a HS thickness of  $\sim 35$  AU this yields P<sub>0.7-4.3keV</sub>  $\sim 0.077$  pPa. At higher energies, the 5.2-24 keV partial

pressure fluctuates about ~0.025 to 0.105 pPa over the 2009-2016 time period, with an average value of  $P_{5.2-24keV} \sim 0.05$  pPa, whereas the V2/LECP partial pressure is  $P_{>28keV} \sim 0.013$ pPa (ranging from 0.008 to 0.016 pPa over 2009-2016). The magnetic field pressure is much smaller, i.e.  $P_{MAG} \sim 0.005$  pPa whereas the thermal pressure is also ~0.005 pPa [Krimigis et al., 2010]. Thus, the overall (isotropic) pressure in the heliosheath is calculated by adding the aforementioned partial pressures, i.e.  $P_{HS} \sim 0.1522$  pPa. Krimigis et al. [2010], using measurements from V1 and V2 immediately downstream of the TS, presented the reasonable assumption that despite possible adiabatic cooling throughout the HS, this pressure would be carried out to the HP and that the thermal ram pressure will not affect the force balance at the HP (as there should be no flow across an ideal heliopause). Here we use average pressure measurements from inside the HS (from 2009) towards the HP (up to 2016) around the V2 pixel.

Neglecting the magnetic tension stress, and assigning  $P_{IS}$  (thermal) =0.01 pPa and  $P_{IS}(dynamic) = 0.0565 \text{ pPa} \text{ (adopted from Krimigis et al. [2010]), then } V^2/2 + P + B^2/2\mu_0$ should be constant along the flow streamline ( $\mu_0 = 4\pi x 10^7$  H/m, magnetic permeability), which means that the IS magnetic field pressure is  $P_{ISMF} \sim P_{HS}$  - [P<sub>IS</sub>(thermal)  $+ P_{IS}(dynamic) = 0.0857 \text{ pPa}$ , thus, providing an estimate of the IS magnetic field strength to be  $B_{ISMF} \sim 0.47$  nT. This number is the result of a rough estimate of the pressures inside the heliosheath and subject to parameters that are not accurately known in the upstream medium, but is consistent with the predicted magnetic field upstream of the HP that is derived from recent sophisticated modeling [Opher et al., 2019]. Further, previous estimates of the IS magnetic field using the 2003-2009 INCA measurements predicted  $B_{ISMF} < 0.6$  nT along the V1 direction [Krimigis et al., 2010] that were confirmed [Burlaga and Ness, 2016] after the V1 crossing of the HP. Although the magnetic field measurements upstream of the HP from V2 have not yet become available, and might differ from our estimate, these numbers are very close to the V1 measurements where  $B_{ISMF}$  fluctuated about ~(0.48 ±0.04) nT from 2012 [Burlaga and Ness, 2016] to date, i.e. up to at least 25 AU past the HP.

## 4 Discussion

We have demonstrated that the 5.2-55 keV INCA/ENA measurements, originating in the heliosheath, can be used to estimate (accurately) the recently reported V2 heliopause crossing at  $\sim$ 119 AU and delineate the components of the ion pressure in the heliosheath. We have also argued that those measurements are critically important for determining the pressure balance in the heliosheath, providing realistic numbers for the interstellar neutral Hydrogen density and magnetic field. Following the arguments provided in this study, we can further explore the consequences of underestimating and/or neglecting the shape/intensities of the 5.2-55 keV spectra from Cassini/INCA.



Figure 3. (a) The same measurements shown in Figure 1b fitting (black and red lines) only the 24-55 keV INCA-derived H<sup>+</sup> and the 28-80 keV V2/LECP ion data (black and red points, respectively), to demonstrate that these populations retain the same spectral slopes ( $\sim E^{-1.7}$ ), as detailed in the text. (b) Same measurements as in (a), incorporating a single  $\kappa$ -distribution that spans over the eV to MeV energy range with T<sub>p</sub>=0.26 keV (=3 x 10<sup>6</sup> K), n<sub>p</sub>=0.002 cm<sup>-3</sup> and  $\kappa$ =1.63 [Zirnstein and McComas, 2015; Zirnstein et al., 2018] as detailed in the text. (c) The same as in Figure 1c, incorporating the pressure that results from the  $\kappa$ -distribution shown in panel (b), calculated in the positions of the INCA and LECP channels.

Although  $\kappa$ -distributions are very useful towards characterizing the ion spectra in space plasmas [*Dialynas et al.*, 2017c], the overall shape of the >5.2 keV spectra deviates substantially from any simplified notion that may include a single  $\kappa$ -distribution to describe the particle spectra from eV to MeV energies, even if selected as an initial condition at the TS site that will, subsequently, be subjected to charge-exchange and velocity diffusion inside the heliosheath and may eventually roughly resemble the spectra shown in Figure 1c. For example, the V2/LECP ion spectra may be consistent with a  $\kappa$ -distribution (e.g. Zirnstein and McComas [2015]; Zirnstein et al. [2018]) using T<sub>p</sub>=0.26 keV (=3 x 10<sup>6</sup> K) [Heerikhuisen et al., 2008], n<sub>p</sub>=0.002 cm<sup>-3</sup> [Richardson and Decker, 2014] and  $\kappa$ =1.63 [Decker et al., 2005] at the TS and inside the HS. Although such an approach would likely fit the multi-hundred keV high energy tails measured by LECP with good accuracy, thus providing an adequate representation of this partial pressure, it would, at the same time, undershoot the 5.2-24 keV part of the H<sup>+</sup> distribution (Figure 3b,c). Specifically, the modelled H<sup>+</sup> pressure over the 2013-2016 time period in the 5.2-13.5 keV INCA channel would become ~0.00322 pPa (whereas the measured 5.2-13.5 keV H<sup>+</sup> pressure is ~0.033 pPa, i.e. a factor of ~10.3 higher). In the same manner, the modelled H<sup>+</sup> pressure in the 13.5-24 keV INCA channel would become ~0.0017 pPa (whereas the measured 13.5-24 keV H<sup>+</sup> pressure is ~0.0033 pPa, i.e. a factor of ~1.9 higher).

Evidently, by assuming a  $\kappa$ -distribution, the overall 5.2-24 keV pressure will be underestimated by a factor of ~6, and the 2009-2016 partial INCA pressure would become  $P_{5.2-24keV} \sim 0.0083$  pPa. Then the  $P_{HS}$  is ~0.109 pPa and  $P_{IS} \sim 0.042$  pPa, which in turn would give  $B_{ISMF} \sim 0.33$  nT, i.e. at least a factor of 1.6 lower than the measured magnetic field from V1, ~0.48 nT (and a factor of 1.9 lower than the magnetic field measured by V1 immediately upstream of the HP, ~0.6 nT, inside the "pile-up" region). Further, if one completely neglects the contribution of the 5.2-24 keV partial pressure to the overall pressure distribution inside the HS, then  $B_{ISMF} \sim 0.29$  nT. In the same manner, the  $\beta$ -parameter results much lower than unity, if only the PLS measurements are included.

Clearly, ~40% of the 0.7-24 keV partial pressure (~0.127 pPa) in the V2 direction is accounted for by the 5.2-24 keV part of the ion distribution (~0.05 pPa). Underestimating the partial particle pressure inside the HS, either due to a simplified model for the spectral shape that underestimates the 5.2-24 keV ion intensities, or neglecting the pressure that comes from this part of the distribution for whatever reason, results in  $B_{ISMF}$ values of ~0.29-0.33 nT that are frequently used in heliosphere models as an upper limit (e.g. *Bzowski et al.* [2017]). The combination of these values for the magnetic field together with substantially lower neutral densities upstream of the HP (e.g. 0.067 cm<sup>-3</sup>) to characterize the region immediately outside the HP, point to comet-type tails concerning the shape of the global heliosphere. These comet-type tails are contrary to observations that stem from both INCA (a rough bubble; *Krimigis et al.* [2009]; *Dialynas et al.* [2017a]) and IBEX (either a rough bubble as in *Galli et al.* [2016, 2017] or an intermediate situation as in *McComas et al.* [2013]), and with recent magnetohydrodynamic models [Opher et al., 2015; Drake et al., 2015; Kivelson and Jia, 2013; Izmodenov and Alexashov, 2015; Opher et al., 2019] concerning the heliospheric configuration.

#### Acknowledgments

This work was supported at JHU/APL by NASA under contracts NAS5 97271, NNX07AJ69G and NNN06AA01C and by subcontract at the Office for Space Research and Technology. The authors are grateful to all Cassini/MIMI and Voyager/LECP team members for useful discussions that made this work possible, and to E. C. Roelof for incisive comments. The authors are particularly grateful to M. Kusterer for software development and assistance with the Cassini/INCA data processing. The Cassini/MIMI and Voyager 1 & 2 LECP measurements, including the INCA/ENA and in-situ LECP ion data used in this study can be accessed through NASA public Planetary Data System (PDS: https://pds.nasa.gov/) together with the corresponding user guides.

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