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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 ~119 AU
• The normalization of Energetic Neutral Atom and ion intensities yields an interstellar neutral hydrogen density of n_H ~ 0.12 cm⁻³
• The 5.2- to 24-keV H⁺ pressures dominate the 5.2- to 3,500-keV distribution, whereas pressure balance implies that B_{ISMF} ~ 0.5 nT

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Plasma Pressures in the Heliosheath From Cassini ENA and Voyager 2 Measurements: Validation by the Voyager 2 Heliopause Crossing

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Abstract We report “ground truth,” 28- to 3,500-keV in situ and 5.2- to 55-keV remotely sensed ENA measurements from Voyager 2/Low Energy Charged Particle detector and Cassini/Ion and Neutral Camera, 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⁻³ and an interstellar magnetic field strength of ~0.5-nT upstream of the heliopause in the direction of V2, that is, 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 toward 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 have 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, as observed, suggesting that the pressure analysis are valid. The shape of the ion energy spectra play a critical role toward 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 ~ 0.12 cm⁻³ and a magnetic field upstream of the heliopause of B_{ISMF} ~ 0.5 nT.

1. Introduction

For more than half a century, the shape and interactions of the Sun’s atmosphere (the heliosphere) with the Local Interstellar Medium (LISM) over the solar cycle have been modeled with increasingly sophisticated techniques (Baranov et al., 1971; Davis, 1955; Dessler, 1967; Fahr et al., 2000; Izmodenov et al., 2008, 2009; Opher et al., 2004; Pogorelov et al., 2013; Washimi et al., 2007; Zank & Muller, 2003). 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 and 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 ~94 (Decker et al., 2005; Stone et al., 2005) and ~84 Astronomical Units (1 AU equals the distance between Earth and Sun, ~150 x 10⁶ 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 HP crossings by V1 in August of 2012 (Burlaga et al., 2013; Krimigis et al., 2013; Stone 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.
Figure 1. (a) A combination of 320 × 160 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- to 55-keV ENA energy spectra of the INCA/ENA data in the pixels enclosing the position of Voyager 2 (5° × 5°), together with the deduced H+ spectra and the 28- to 3,500-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- to 3,500-keV H+ pressure energy spectra inside the heliosheath, derived from the measurements shown in (b), using \( l_{HS} = 35.2 \) AU and \( n_H \sim 0.12 \) cm\(^{-3}\). INCA = Ion and Neutral Camera; ENA = Energetic Neutral Atom; LECP = Low Energy Charged Particle.

Remote observations from Cassini (in orbit around Saturn at \( \sim 10 \) AU until 15 September 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- to 55-keV ENAs (Krimigis et al., 2009) and at >6-keV ENAs from the Interstellar Boundary Explorer (IBEX) mission, at \( \sim 1 \) AU (McComas et al., 2009). In situ measurements of \( >28 \) keV ions in the HS using the Low Energy Charged Particle (LECP) instrument (Krimigis et al., 1977) onboard 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 (Dialynas et al., 2013, 2017a), the resulting Cassini/INCA images (e.g., Figure 1a) provide a marker for the local plasma-neutral processes inside the HS. 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 (Dialynas et al., 2013; Krimigis et al., 2009), placing the V1 and V2 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 HP (McComas, Zirnstein, Bzowski, Dayeh, et al., 2017), 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 HS (Dayeh et al., 2011), as also inferred in Dialynas et al. (2013).

The combination of remotely imaged 5.2- to 55-keV INCA/ENAs, together with \( >40 \) keV in situ ion measurements from the LECP experiment on V1 (Decker et al., 2005) in the HS, has been used in the past to predict the V1 HP crossing (Krimigis et al., 2011) and the magnitude of the ISMF (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- to 55-keV INCA/ENAs, showed that the heliosphere responds promptly, within \( \sim 2-3 \) years, to outward propagating SW 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, 2017b). This bubble heliosphere concept is consistent with recent advanced modeling (Drake et al., 2015; Golikov et al., 2017; Kivelson & Jia, 2013; Opher et al., 2015, 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 LISM.

2. The 5.2- to 3,500-keV Energy Spectra in the HS

ENAs are products of charge exchange (Lindsay & Stebbings, 2005) between fast protons and the “background” neutral hydrogen (H) gas flowing through the HS (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 (Figures 1b and 1c). 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+ channel (∼28–40 keV), making in situ ion measurements inside the HS, yields a HS thickness along the V2 trajectory of LV2 ∼ (35.2 ± 8.6) AU (the uncertainty in LV2 is calculated from the error propagation function due to the measured uncertainties in the ENA and ion intensities), assuming a neutral Hydrogen density of nH ∼ 0.12 cm−3, 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- to 55-keV ENAs detected with Cassini/INCA is the HS.

Roelof et al. (2012) showed that consideration of the Compton-Getting factor (Compton & 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 ∼80 to 90 km/s in 2013 to gradually approaching zero values toward 2016. Taking an average radial plasma speed of Vr ∼40 km/s and a spectral index for the lower LECP channels of γ ∼1.7 (see Figure 3a), then the estimated HS width in the V2 direction (LV2′) is related to the Compton-Getting corrected value (LV2) as

\[ \frac{L'_{V2}}{L_{V2}} = \frac{1 + V_r/V}{(1 + V_r/V)^{2/\gamma} + 1} = 1.088 \] (e.g., Roelof et al., 2012). This number indicates that our estimate of the HS width (LV2 ∼35.2 AU) can be increased by ∼8.8%, which translates to ∼3.1 AU, that is, much smaller than the calculated error bar (±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 & 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+ + 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−3 (although densities up to ∼0.14 cm−3 were also found at distances ∼20 AU past the HP as reported in Gurnett & Kurth, 2017), that is, consistent with the 0.12 cm−3 that was used here. For clarity, we repeated the calculation after assigning a neutral density of ∼0.1 cm−3, showing a HS thickness of LV2 ∼ (42.2 ± 10.3) AU, which is roughly consistent with the V2 HP crossing within the calculated uncertainties. Past observations from Ulysses/SWICS (Gloeckler & Geiss, 2001) and other measurements (see Bzowski et al., 2008) were also consistent with values about 0.1 cm−3.

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 ∼ 0.12 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−3 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 toward determining the pressure balance and acceleration mechanisms inside the HS. The average ENA energy spectra in Figure 1b are consistent with a power law form in energy \( J_{ENA} \sim E^{-(4.2±0.2)} \), whereas the resulting ENA-derived H+ spectrum is less...
steep $I_{\text{ENA-derivedH}^+} \sim E^{-(3.4 \pm 0.2)}$ because of the energy dependence of the charge exchange cross sections, as explained in Krimigis et al. (2009). Recent observations from the New Horizon spacecraft at $\sim$38 AU (McComas, Zirnstein, Bzowski, Elliott, et al., 2017) showed that the pickup ion distribution is heated in the frame of the SW 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 are accelerated, the $\sim$10- to 100-MeV intensities in both V1 and 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., 2013). The rest of the SW energy was transferred into heating pickup ions and $>$15% transferred to the $>$28-keV protons. This is translated to a prominent hardening break (less steep spectrum) in the $>$28-keV part of the $H^+$ 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 (Giacalone & Decker, 2010), as one of the possible mechanisms.

This characteristic seems to persist throughout the HS as shown in Figure 1b, where the $>$28-keV spectra fit smoothly to the ENA-derived $H^+$ spectra at the energy range of $\sim$24–80 keV, but the overall 28- to 3,500-keV ion spectra exhibit a rough power law form in energy with $I_{\text{LECP}} \sim E^{-(1.4 \pm 0.1)}$. 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- to 55-keV ENA-derived $H^+$ intensities shows that the spectra are consistent with a $\sim E^{-(1.7 \pm 0.8)}$ law in this energy range. At the same time, the V2/LECP ion spectra exhibit a turnup 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- to 3,500-keV distribution (hardening break) occurs within the 24- to 80-keV energy range. Interestingly, the 28- to 80-keV LECP distribution follow a $\sim E^{-(1.7 \pm 0.1)}$ law, that is, both the 24- to 55-keV ENA-derived $H^+$ measurements and the 28- to 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 HS to date (they are $\sim$165 AU apart today), the ion spectra at V1 and V2 inside the HS are very similar in both shape and number as a function of time (e.g., Decker et al., 2009; also Figures 2c and 2d of 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; Figures 2c and 2d of this study).

3. Pressure Balance in the HS

After the V1 and V2 respective crossings of the TS, it was found that the HS 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\text{(dynes/cm}^2\text{)} = (8\pi/3)(m/2)^{1/2}I_{\text{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, $E_1$ and $E_2$ are each channel passbands, $\Delta E = E2 - E1$, $m$ is the proton mass, and $I_{\text{ion}}$ is the proton intensity; note that by substituting $p = mv$ in this equation, we obtain $\Delta P = (4p/3)I_{\text{ion}}\Delta E$, as used in Dialynas et al. (2015), a range where many of the pickup ions associated with the TS and HS reside. The 5.2- to 24-keV $H^+$ pressures shown in Figure 1c dominate the 5.2- to 3,500-keV pressure distribution, which indicates that the 5.2- to 55-keV part of the energetic $H^+$ distribution covered by the Cassini/INCA is critically important for determining the pressure balance inside the HS and cannot be neglected.

The $H^+$ partial pressure from the 5.2- to 24-keV INCA channel is a factor of $\sim$4 higher than the $>$28-keV LECP pressure (on average) throughout the 2009–2016 time period and a factor of $\sim$30 higher than the measured PLS thermal pressure over the same time period (Figure 2a). The partial plasma beta shown in Figure 2b ($\beta = P_{\text{pickup}}/P_{\text{MAG}}$) inside the HS is persistently $\geq$4 on average (a local minimum that corresponds to the minimum of SC23 with a time delay of $\sim$2–3 years as explained in Dialynas et al., 2017a, 2017b) pointing toward 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 $\sim$ 0.14 nT (roughly comparable to 2015), we obtain $\beta_{2016} \sim 6.6$ 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...
Figure 2. (a) Yearly averaged pressure profiles of (red line) remotely sensed 5.2- to 24-keV ENA-derived H⁺ over 5° × 5° enclosing the V2 pixel, (black line) 28-to 3,500-keV H⁺, 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⁺ partial pressure (PLS, INCA, and LECP) divided by the magnetic field pressure (MAG) inside the heliosheath for the 2009–2014 time period. (c) The 35- to 55-keV INCA/ENA measurements averaged over 5° × 5° enclosing the V1 pixel and converted to ion intensities using LV1 ∼ 28 AU and nH ∼ 0.1 cm⁻³, compared directly with the in situ 40- to 53-keV LECP ion histories (see Dialynas et al., 2017a, for details). (d) The same as (c) for the >35-keV INCA/ENA measurements around the V2 pixel, using LV2 ∼ 35.2 AU and nH ∼ 0.12 cm⁻³, as derived in Figure 1b, compared directly with the 28- to 43-keV LECP ion histories at V2. (e) The 5.2- to 24-keV pressure contributed by H⁺ inside the heliosheath (between the termination shock and the heliopause) computed from spectra deduced from the Energetic Neutral Atom observations using a varying heliosheath thickness and hydrogen density toward the upstream (nose) hemisphere, as detailed in the text. The mean relative percentage error is ∼15%. INCA = Ion and Neutral Camera; LECP = Low Energy Charged Particle.

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 β-parameter shown in Figure 2b, is 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 HS thickness and hydrogen density toward the upstream (nose) hemisphere: ∼35 AU and 0.12 cm⁻³ over the −90° to −30° in latitude (consistent with the V2 HP crossing), ∼28 AU and 0.1 cm⁻³ over +30° to +90° in latitude (consistent with the V1 measured parameters), and ∼31 AU and 0.11 cm⁻³ over −30° to +30° in latitude (to compensate for a possible density gradient). Despite these uncertainties, the overall 5.2- to 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.

range that would result in even higher numbers for the plasma-β and would further support the arguments provided in this study.
The measurements shown here can be used to address the pressure balance at the interaction region between the HS and the LISM, that is, the HP. On average, the partial 0.7- to 4.3-keV $H^+$ pressure in the V2 (and V1) direction from IBEX is found to be $\sim$27 pdyn/Å² (McComas & Schwadron, 2014), and assuming a HS thickness of $\sim$35 AU, this yields $P_{0.7-4.3\text{keV}} \sim 0.077$ pPa. At higher energies, the 5.2- to 24-keV partial pressure fluctuates about $\sim$0.025 to 0.105 pPa over the 2009–2016 time period, with an average value of $P_{5.2-24\text{keV}} \sim 0.05$ pPa, whereas the V2/LECP partial pressure is $P_{5.2-25\text{keV}} \sim 0.013$ pPa (ranging from 0.008 to 0.016 pPa over 2009–2016). The magnetic field pressure is much smaller, that is, $P_{\text{MAG}} \sim 0.005$ pPa, whereas the thermal pressure is also $\sim 0.005$ pPa (Krimigis et al., 2010). Thus, the overall (isotropic) pressure in the HS is calculated by adding the aforementioned partial pressures, that is, $P_{\text{HS}} \sim 0.1522$ 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 HP). Here we use average pressure measurements from inside the HS (from 2009 toward the HP (up to 2016) around the V2 pixel.

Neglecting the magnetic tension stress and assigning $P_{\text{IS}}(\text{thermal}) = 0.01$ pPa and $P_{\text{IS}}(\text{dynamic}) = 0.0565$ pPa (adopted from Krimigis et al., 2010), then $V^2/2 + P + B^2/2\mu_0$ should be constant along the flow streamline ($\mu_0 = 4\pi \times 10^7$ H/m, magnetic permeability), which means that the IS magnetic field pressure is $P_{\text{ISM}} \sim P_{\text{IS}} - [P_{\text{IS}}(\text{thermal}) + P_{\text{IS}}(\text{dynamic})] = 0.0857$ pPa, thus, providing an estimate of the IS magnetic field strength to be $B_{\text{ISM}} \sim 0.47$ nT. This number is the result of a rough estimate of the pressures inside the HS 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 $B_{\text{ISM}} < 0.6$ nT along the V1 direction (Krimigis et al., 2010) that were confirmed (Burlaga & 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 $B_{\text{ISM}}$ fluctuated about $\sim (0.48 \pm 0.04)$ nT from 2012 (Burlaga & Ness, 2016) to date, that is, up to at least 25 AU past the HP.

4. Discussion

We have demonstrated that the 5.2- to 55-keV INCA/ENA measurements, originating in the HS, can be used to estimate (accurately) the recently reported V2 HP crossing at $\sim$119 AU and delineate the components of the ion pressure in the HS. We have also argued that those measurements are critically important for determining the pressure balance in the HS, 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- to 55-keV spectra from Cassini/INCA.

Although $\kappa$-distributions are very useful toward 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 electron volt to mega-electron volt 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 HS 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 & McComas, 2015; Zirnstein et al., 2018) using $\kappa_p = 0.26$ keV ($= 3 \times 10^6$ K; Heerikhuisen et al., 2008), $n_p = 0.002$ cm$^{-3}$ (Richardson & 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 multihundred kiloelectron volt 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- to 24-keV part of the $H^+$ distribution (Figures 3b and 3c). Specifically, the modeled $H^+$ pressure over the 2013–2016 time period in the 5.2- to 13.5-keV INCA channel would become $\sim 0.00322$ pPa (whereas the measured 5.2- to 13.5-keV $H^+$ pressure is $\sim 0.033$ pPa, i.e., a factor of $\sim 10.3$ higher). In the same manner, the modeled $H^+$ pressure in the 13.5- to 24-keV INCA channel would become $\sim 0.0017$ pPa (whereas the measured 13.5- to 24-keV $H^+$ pressure is $\sim 0.0033$ pPa, i.e., a factor of $\sim 1.9$ higher).

Evidently, by assuming a $\kappa$-distribution, the overall 5.2- to 24-keV pressure will be underestimated by a factor of $\sim 6$, and the 2009–2016 partial INCA pressure would become $P_{5.2-24\text{keV}} \sim 0.0083$ pPa. Then the $P_{\text{HS}}$
is \sim 0.109 \text{ pPa and } P_{15} \sim 0.042 \text{ pPa, which in turn would give } B_{\text{ISMF}} \sim 0.33 \text{ nT}, that is, at least a factor of 1.6 lower than the measured magnetic field from V1, \sim 0.48 \text{ nT} (and a factor of 1.9 lower than the magnetic field measured by V1 immediately upstream of the HP, \sim 0.6 \text{ nT, inside the “pileup” region}). Further, if one completely neglects the contribution of the 5.2- to 24-keV partial pressure to the overall pressure distribution inside the HS, then \( B_{\text{ISMF}} \sim 0.29 \text{ 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- to 24-keV partial pressure (\sim 0.127 \text{ pPa}) in the V2 direction is accounted for by the 5.2- to 24-keV part of the ion distribution (\sim 0.05 \text{ pPa}). Underestimating the partial particle pressure inside the HS, either due to a simplified model for the spectral shape that underestimates the 5.2- to 24-keV ion intensities or neglecting the pressure that comes from this part of the distribution for whatever reason, results in \( B_{\text{ISMF}} \) values of \sim 0.29-0.33 \text{ 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 \text{ cm}^{-3}) to characterize the region immediately outside the HP points 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 (Drake et al., 2015; Izmodenov & Alexashov, 2015; Kivelson & Jia, 2013; Opher et al., 2015, 2019) concerning the heliospheric configuration.

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