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Higher-energy plasma ions found near the termination shock: Analyses of Voyager 2 data in the heliosheath and in the outer heliosphere

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[1] We have found in the Voyager 2 (V2) plasma science data in the heliosheath (HS) near the termination shock (TS) high-energy ions (HEIs) in addition to the bulk plasma convective flow ions. The HEI detections temporally coincide with increased V2 plasma wave subsystem (PWS) activity in "event A" of Gurnett and Kurth (2008). Maxwellian fits to HEI detections indicate the HEIs are moving radially anti-Sunward with a proton speed of 600 km/s, a density of 10^{-4} cm^{-3}, and a thermal speed of 10 km/s. The heliosheath bulk convective protons have a speed of 204 km/s, a density of 0.0029 cm^{-3}, and a thermal speed of 26.7 km/s. The HEI flux and ram pressure are approximately 10% and 30% of those of the bulk HS flow. Since the HEI speed is both close to twice the solar wind speed and independent of the heliosheath bulk plasma speed, the HEIs may be detections of pickup protons formed in the solar wind and convected through the TS. The HEIs also are reminiscent of the pickup protons upstream of the Mars bow shock where their energy also was independent of the bulk plasma speed and attributed to multiple reflections off the Mars bow shock. Gurnett and Kurth's (2008) event A enhanced PWS activity may be generated by a two-stream instability from the interaction of these HEIs with the heliosheath bulk plasma ions. We present our findings, discuss their implications, and also present alternative interpretations.

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1. Motivation

[2] Voyager 2 (V2) was the first spacecraft to record detailed in situ measurements of the solar wind termination shock (TS) and its vicinity. During these historic observations, the plasma wave subsystem (PWS) observed an interval of enhanced activity: "event A" [*Gurnett and Kurth*, 2008]. Figure 1, adapted from *Gurnett and Kurth* [2008], shows event A on day 243.7, 2007 in the PWS data following the first V2 TS crossing near 83.7 AU, −27.5 degrees HGI (Heliographic Inertial Coordinate System) latitude, and 216.3 degrees HGI longitude. The PWS investigators identified "event A" with its enhanced signals in the 31.1 and 56.2 Hz channels as "Shock?" [*Gurnett and Kurth*, 2008]. The V2 plasma science (PLS) instrument [*Bridge et al.*, 1977; *Richardson et al.*, 2008] and magnetometer [*Burlaga et al.*, 2008] did not indicate event A was coincident with a shock [*Gurnett and Kurth*, 2008]. We suggest that alternatively the enhanced waves seen in the PWS data in event A may be due to a two-stream ion instability caused by the interaction between the convective bulk heliosheath (HS) plasma ions and a population of high-energy ions (HEIs). This interpretation is consistent with the simulation of *Gurnett et al.* [2008] suggesting the enhanced PWS signals near TS-3 (event B) in Figure 1 were due to two interacting ion beams.

[3] The plan of this paper is that we will present the evidence for the HEIs, summarize their characteristics, describe their likely source, the possible theoretical context of this source, their possible relation to the LECP (Low Energy Charged Particle) observations and to the plasma wave enhancements. In the Appendix A of this paper we briefly summarize several alternative interpretations of these HEI observations and respond to each in turn.

2. Detections and Analyses of High-Energy Ions (HEIs)

[4] Figure 2 shows the PLS ion energy per unit charge (E/Q) spectra as a function of average proton speed (v_p)

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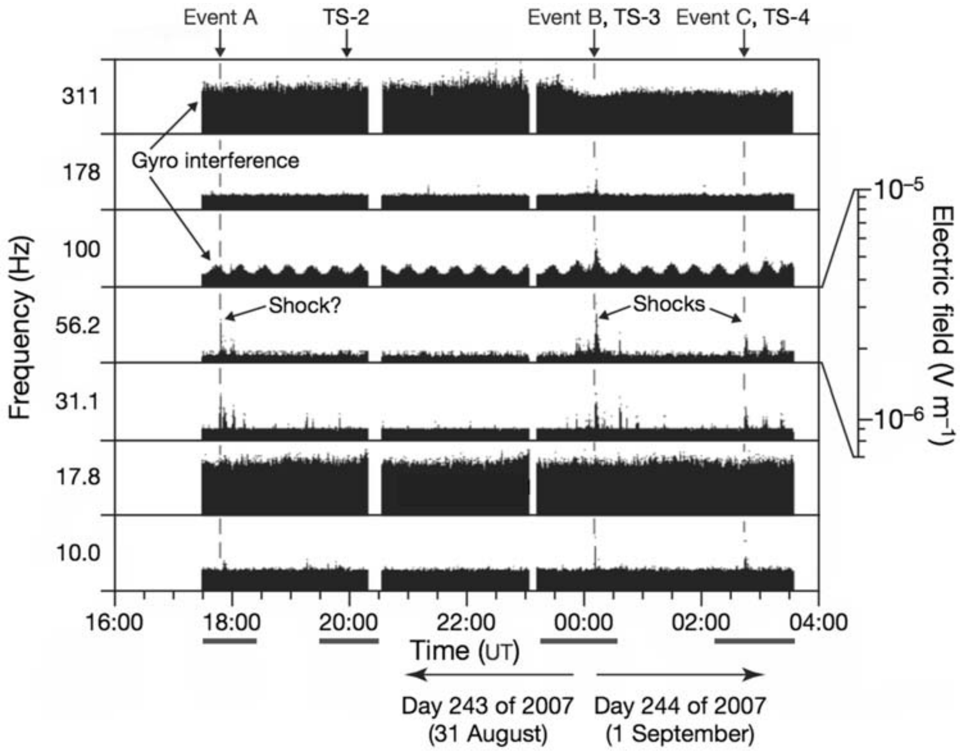

Figure 1. V2 PWS data [from *Gurnett and Kurth*, 2008] of the enhanced plasma wave signals associated with event A and the TS crossings in 2007. The four short horizontal bars below the lower axis indicate the approximate time periods covered in Figures 2–5.

during PWS event A, which occurred (Figure 1) between ~1730 and ~1820 UT on day 243, 2007. These B cup spectra of 16 (E/Q) steps in L mode [*Bridge et al.*, 1977] show that the bulk plasma flow appears below (E/Q) step 6 (v_p ~ 210 km/s). No significant plasma currents are measured on B cup for (E/Q) steps 7–11 (v_p ~ 277–477 km/s), or on (E/Q) steps 13–16 (v_p ~ 643–996 km/s), but occasional measurable currents are detected on (E/Q) step 12 (v_p ~ 554 km/s). We identify these elevated readings on (E/Q) step 12 as the "high-energy ions" or "HEIs" or the "HEI component" that are present during the period of enhanced plasma waves labeled as event A in the PWS data in Figure 1.

[5] In contrast to event A in Figure 1, near the event labeled TS-2 at ~2000 UT on day 243, there are no enhanced PWS signals. Figure 3 shows the B cup E/Q spectra near TS-2. While there are a few spectra where the HEIs are present at 554 km/s, these current readings are less than those in Figure 2 near event A. The vertical scales in Figure 3 are different from those in Figure 2. Generally the HEI currents near event A (Figure 2) are higher than those near TS-2 (Figure 3).

[6] In Figure 4 the B cup E/Q spectra initially show V2 in the outer heliosphere (OH) upstream of TS with a bulk convective plasma v_p of ~<300 km/s, and at 2316 UT, there is brief detection of the HEIs at 554 km/s corresponding to (E/Q) step 12. Later, V2 is in the HS after being overtaken by the TS, the detected plasma currents increase, and v_p decreases. At ~0000 UT to 0015 UT on day 244 the spectra are shown near the event labeled event B and TS-3 in Figure 1 on days 243/244. The V2 investigators [e.g., *Burlaga et al.*, 2008; *Gurnett and Kurth*, 2008; *Richardson et al.*, 2008] studied TS-3 in detail, describing its ramp, undershoot, overshoot, and other features. We note that the V2 experimenters focused on the shock properties near event B at the beginning of day 244, and the possible reforming of the termination shock there. The earlier PLS data shown in Figure 4 starting at 2316 UT on day 243 also show evidence in the first three E/Q spectra of the solar wind peak at 300 km/s and a lower energy peak near ~150 km/s that may be indicative of the convective heliosheath plasma. The solar wind peak at 300 km/s is absent in the next six E/Q spectra perhaps implying only the presence of convective heliosheath plasma possibly associated with a ripple in or the reforming of the termination shock. The solar wind peak reappears again in the two E/Q spectra before 2348 UT. These changes in the B cup E/Q spectra may characterize the intermixing of the heliosheath and solar wind plasma near the termination shock and/or ripples in the termination shock and/or the reforming of the termination shock. Figure 5 shows that near the event labeled event C and TS-4 in Figure 1 on day 244 v_p is ~<200 km/s, and the HEIs are present in only one B cup E/Q spectrum.

3. Characteristics of the High-Energy Ions (HEIs)

[7] Figure 6 shows Maxwellian fits to the bulk convective plasma distribution and to the HEIs for the L mode scan on day 243, 2007, during event A at 1753:17.600 UT for each of the sunward facing PLS detector cups A through C. The bulk plasma distribution is observed on the A, B, and C cups. These Maxwellian fits were performed with the usual PLS Maxwellian fit software used to provide PLS parameters.

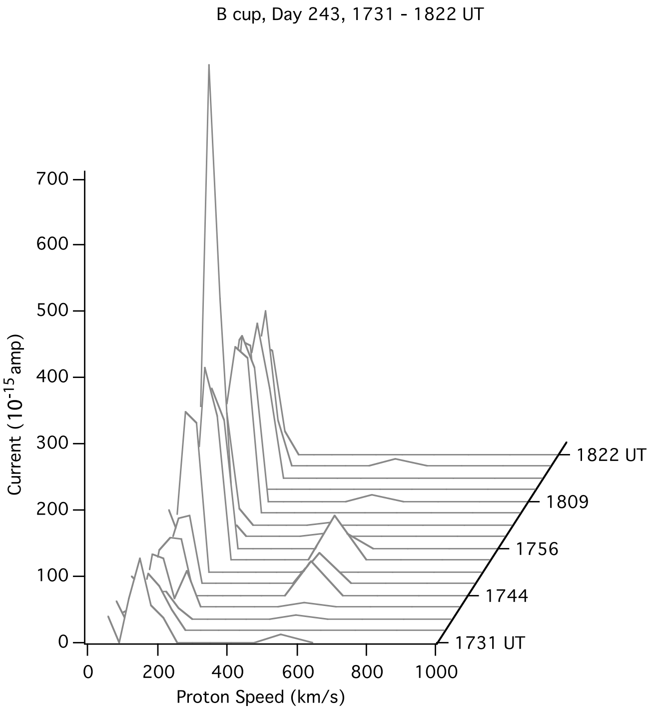

Figure 2. V2 PLS data showing E/Q spectra of ion detections on the B cup in L mode scans [*Bridge et al.*, 1977] as a function of v_p-average proton speed-near event A in the PWS data (Figure 1). Start times of some E/Q spectra are shown. The bulk plasma v_p is ~150–200 km/s. HEIs are not present in all spectra, but when they are, they are measured at E/Q step 12~1610 V, i.e., v_p of ~554 km/s. See Appendix for discussion of whether the elevated readings on E/Q step 12 should be taken at face value.

They were kindly provided to us by J. D. Richardson (private communication, 2009). Their results are summarized in Table 1. For completeness, Table 1 also includes the solar wind parameters upstream of the termination shock from the study by *Richardson et al.* [2008]. The Maxwellian fit gives for the bulk convective plasma distribution in the heliosheath the speed of ~204 km/s, the proton density of 0.0029 cm^{-3}, and the thermal speed of 26.7 km/s. For the HEIs the Maxwellian fit gives a speed of ~600 km/s, a density of 0.0001 cm^{-3}, and a thermal speed of 10 km/s. Since the Maxwellian fit assumes HEI detections on the ~sunward facing A, B, and C cups at E/Q step 12, the fit yields for the HEIs an approximately radial direction of propagation from the Sun. This fit is consistent with the E/Q step 12 detections on the B cup. While the Maxwellian fit assumes A cup detections on E/Q step 12, these elevated readings are usually detected on A cup on E/Q step 13. The predicted C cup detections on E/Q step 12 may be associated with the elevated readings often observed on E/Q step 12 and/or 13.

[8] Because of the radiation effects at Jupiter on the PLS, the detections on the A cup and C cup may be masked or contaminated by noise. Similarly, the Jovian radiation effects may have resulted in subtractions from the measured B cup current detections so that the B cup readings may be lower than they should be (Richardson, private communication, 2009).

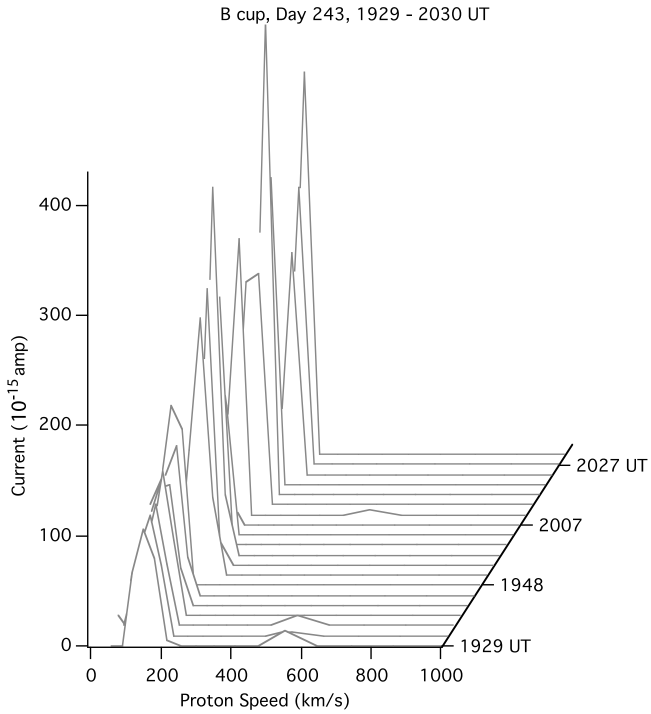

Figure 3. Same as Figure 2 near TS-2.

[9] The Maxwellian fits in Figure 6 imply that the HEI flux ($n_{HEI} \times v_{HEI}$) is ~10% of the heliosheath bulk convective plasma flux. Similarly, the HEI ram pressure ($n_{HEI} \times m_p \times (v_{HEI})^2$) is ~30% of that associated with the heliosheath bulk convective plasma flow; and the HEI thermal pressure ($n_{HEI} \times k \times T_{HEI}$) is ~1.3% of that associated with the heliosheath bulk convective plasma flow. If the B cup HEI

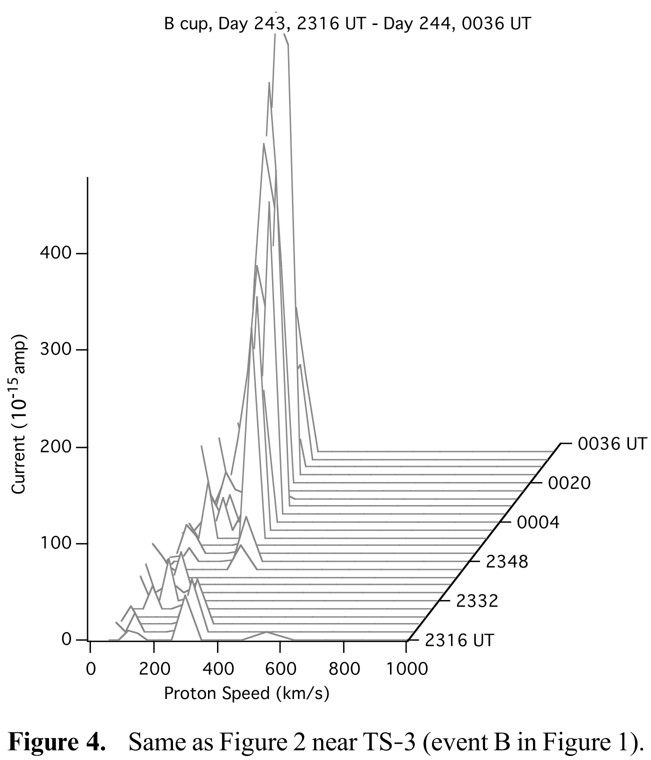

Figure 4. Same as Figure 2 near TS-3 (event B in Figure 1).

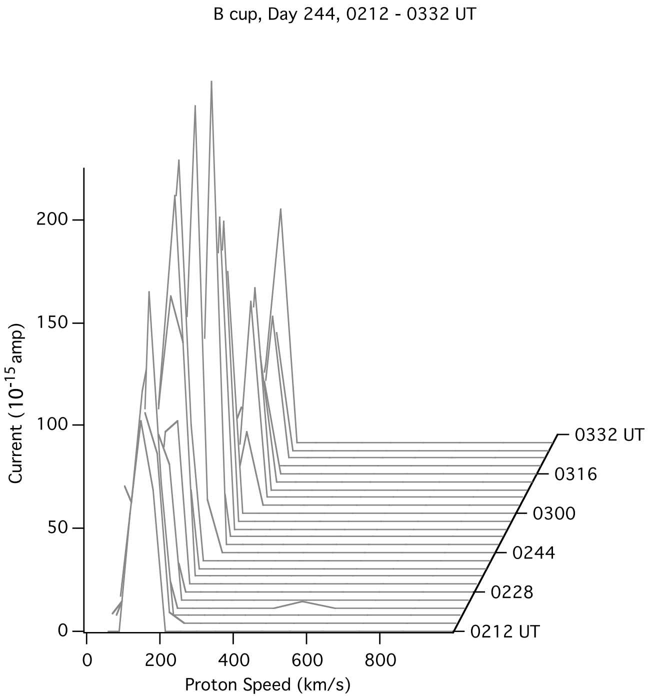

Figure 5. Same as Figure 2 near TS-4 (event C in Figure 1).

detections are underestimates of the actual HEI currents, a possibility mentioned previously, then the n_{HEI} term would also be an underestimate that would propagate through the flux, ram pressure, and thermal pressure estimates. Thus, these estimates are lower bounds implying that the HEI flux and ram pressure may be significant in the heliosheath and near the termination shock.

[10] To estimate the duration of the HEIs, we use the 192 s time interval of each PLS E/Q L mode scan. The longest consecutive series of elevated B cup readings on E/Q step 12 is shown in Figure 2 in association with PWS event A. There are minimal HEI elevated readings in the two E/Q spectra before 1744 UT. The 1744 UT E/Q spectrum and the E/Q spectrum immediately following it show substantial HEI elevated readings. If we include the elevated HEI readings in all four of these consecutive E/Q spectra and simply assume the HEIs were present during the entire 192 s interval during which each of these four E/Q spectra were obtained, then the longest duration of the HEIs is 4 × 192 s or 768 s or 12.8 min. Alternatively, if we include all four of these consecutive E/Q spectra but only consider the time interval between the first and last (fourth) HEI peaks, then the duration of the HEIs is 3 × 192 s or 576 s or 9.6 min.

[11] Similarly, to estimate the distance scale associated with the HEIs, we can include the entire duration of all four consecutive E/Q spectra with HEI currents in Figure 2 during event A starting with the two spectra before ~1744 UT or alternatively, only the time between the first and last HEI peaks in Figure 2. If we include the entire duration of all four E/Q spectra and assume the ambient HEI structure were moving at the heliosheath bulk convective speed of 204 km/s, then the thickness of the HEI structure would be ~156,672 km or ~24.6 R_E or ~3 r_g, where r_g is the proton gyroradius. *Zank et al.* [2009] estimate the proton gyroradius near the TS during the Voyager 2 TS crossings to be ~60,000 km (page 158, paragraph 2) to 63,000 km (page 160, below equation 9). Alternatively, if we include only the time between the first and last (fourth) peaks, then the thickness of the structure is 117,504 km or ~18.4 R_E or ~2 r_g. These distance scales may be an indication of the width or thickness of the blob, beam, or ripple associated with the HEIs. Following the two consecutive E/Q spectra starting at 1744 UT in Figure 2 where there are large HEI currents, there is an E/Q spectrum with no noticeable HEI currents. This E/Q spectrum is followed by another two E/Q spectra with large HEI currents. The distance scale associated with the lack of noticeable HEI currents also could be an indication of the distance between HEI beams or of the distance scale associated with ripples in the HEI beam. For this case, the distance between the HEI beams or the length of a ripple associated with the HEI beam is ~39,168 km or ~6 R_E or ~ <1 r_g.

4. Origin of the HEIs

[12] It is tempting to interpret the HEI readings as protons that were picked up in the solar wind and eventually reached the spacecraft in the heliosheath, but the apparent complexity of the TS environment leads to substantial uncertainty about the details. It appears impossible to know whether the TS was relatively stable when the protons were picked up, or whether it might have been rippling or reforming, and hence whether the protons followed a relatively direct path, or perhaps were reflected one ore more times off the termination shock. The latter case would be a significantly different mechanism from direct pickup, and the particles would be similar to the apparently shock-reflected ions reported near the Mars bow shock by *Dubinin et al.* [2006].

[13] When pickup protons are newly picked up from the neutral interstellar gas, their maximum speed should be approximately twice the local bulk convective plasma speed [*Gloeckler et al.*, 1994; *Intriligator et al.*, 1996]. The Maxwellian fit described previously gives the speed of the HEIs on 31 August and 1 September as ~600 km/s, which is very close to twice the 300–325 km/s of the bulk solar wind just upstream of the TS [*Richardson et al.*, 2008]. Each but one of the HEI detections in Figures 2–5 is from the HS where the bulk convective plasma v_p is 150–200 km/s [*Richardson et al.*, 2008]. The exception is the first E/Q spectrum in Figure 4 where there also is a solar wind peak at 300 km/s. Thus, the HEIs are moving significantly faster than the local heliosheath bulk plasma convective speed. One appealing interpretation of these HEI observations is that they are detections of pickup ions formed in the solar wind and convected through the TS into the heliosheath without significant pitch-angle scattering. Pickup ions would be expected to be formed in a narrow range of pitch angles because the inflowing neutral interstellar gas is nearly stationary relative to the motion of the solar wind plasma, and so each neutral atom or molecule would be moving in the same direction relative to the very nearly tangential interplanetary magnetic field lines before it is ionized. Preservation of the narrow distribution is needed both for consistency with the Maxwellian fit estimate of a beamlike distribution and for the particles to be detectable by the

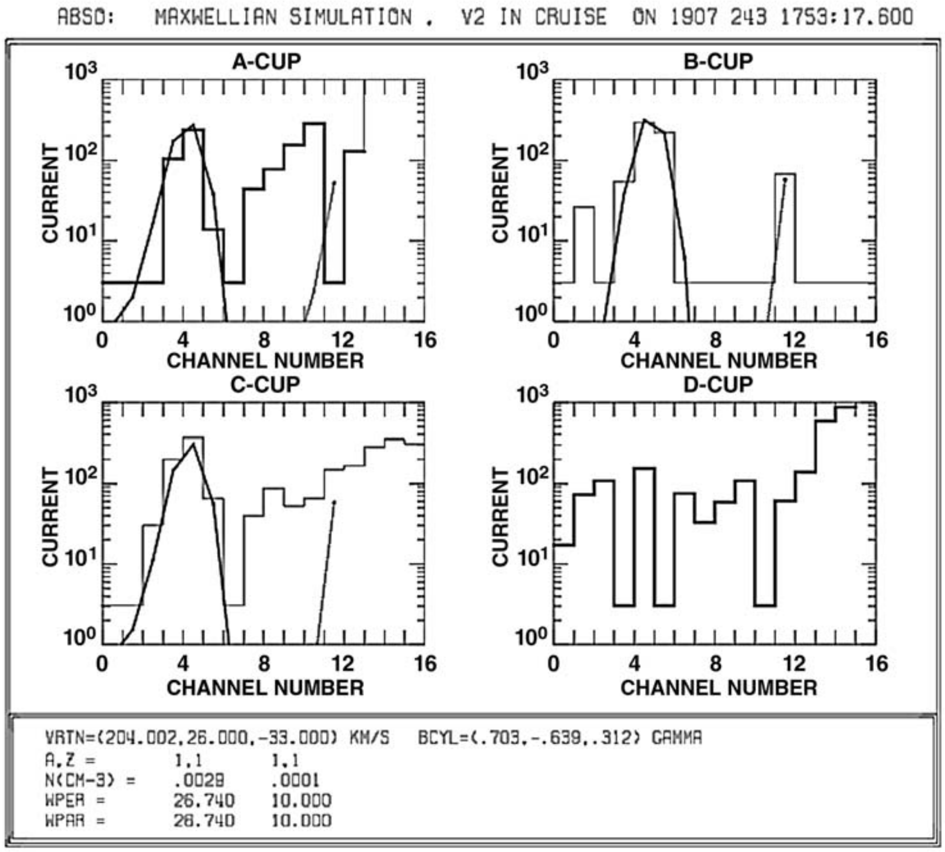

Figure 6. Maxwellian fit to the PLS L mode data obtained in the heliosheath starting at 1753:17.600 UT on day 243, 2007 (J. D. Richardson, private communication, 2009). The figure shows for the PLS A, B, and C cups the Maxwellian fit to the main heliosheath bulk flow convective plasma distribution peaking near E/Q step 5 with its v_p of ~204 km/s and the Maxwellian fit to the HEI distribution at E/Q step 12 with its v_p of ~600 km/s independent of the heliosheath bulk convective speed. The heliosheath bulk convective plasma distribution has a density of 0.0029 protons cm^{-3} and a thermal speed of 26.7 km/s. The HEI density is 10^{-4} cm^{-3} and its thermal speed is 10 km/s. While the fit predicts a detection of the HEIs on A cup in E/Q step 12 it is observed on A cup on E/Q step 13. The predicted detection on C cup may be observed on E/Q steps 12 and/or 13. There may be noise on A cup/C cup at these E/Q steps partially masking or contaminating these detections.

current collection system in the PLS instrument [*Bridge et al.*, 1977].

[14] Another plausible hypothesis for the origin of the HEIs is that they are part of a population of pickup protons that were multiply reflected off of the termination shock. As discussed above, the E/Q spectra in Figures 2–5 and the Maxwellian fit to the data in Figure 6 all indicate that the speed and temperature of the HEIs are not correlated with those of the local bulk convective plasma. These characteristics of the HEIs are particularly reminiscent of the pickup protons upstream of the Mars bow shock [*Dubinin et al.*, 2006], where the pickup proton energy was higher than expected and also independent of the bulk plasma speed. *Dubinin et al.* [2006] attributed these characteristics to multiple reflections off of the Mars bow shock. Thus, it is tempting to interpret the HEIs analogously as a beam of pickup protons, similar to those observed near foreshocks and/or in magnetosheaths of the Earth or other planets, that have undergone multiple reflections off the termination shock. This possibility also is consistent with the theoretical expectations of *Zank et al.* [1996], *Lee et al.* [1996], and others, who considered particle acceleration in the vicinity of the termination shock (see section 6).

5. Relation to LECP Measurements

[15] A related possibility is that these HEIs also could be the lower energy tail of a distribution of gyrating protons pumped up by one or more bounces off the front-side TS to energies that might be observed by the V2 LECP instrument

Table 1. Plasma Characteristics

Type of Plasma	Speed (km/s)	Density (cm^{-3})	Thermal Speed (km/s)
HEIs[a]	600	0.0001	10
Heliosheath[a] Bulk plasma	204	0.0029	26.7
Solar wind[b]	~300	0.0013	10

[a]From Figure 6.
[b]From *Richardson et al.* [2008].

[*Decker et al.*, 2008]. This possibility is suggested by reports of ions, often at much higher energies, including more than tens of MeV, observed in upstream foreshocks, near planetary bow shocks (e.g., Earth, Mars, Jupiter), and in planetary magnetosheaths [e.g., *Kucharek et al.*, 2004; *Bale and Mozer*, 2007; *Moses et al.*, 1985; *Bieber and Stone*, 1982]. The evidence indicates that these ions have been reflected off the respective shocks. For example, (*S. D. Bale et al.*, unpublished manuscript, 2008) compared Cluster data at four spacecrafts, reported the bursty nature of the ions near the foreshock of the Earth's bow shock, and found that the cross-shock potential varied from 23% to 236% of the ion energy change, so that the potential is frequently sufficient to reflect ions. Likewise, *Kucharek et al.* [2004] used Cluster data to identify gyrating and reflected ions at the quasi-perpendicular bow shock.

[16] In seeking confirming evidence for this interpretation, at first glance one might conclude that the 1 hour averaged LECP data in Figure 7 imply that if the HEIs of Figures 2–5 extend in energy up to at least 28 keV, then they are at an intensity level below the LECP background level. However, while these lowest energy LECP ions do not increase substantially until a few days after the TS crossings, comparisons at these lowest energies between the intensities before the first TS crossing (the dashed vertical line) with those after event A (the downward arrow) indicate almost a twofold increase. Since the HEI flux is ~10% of the bulk convective plasma flux, as discussed previously, perhaps this intensity increase can be attributed to the acceleration of HEIs or to the extension of their energy spectrum up to at least 28 keV. If the HEI spectrum extends to these energies, one would not expect them to be detectable by the PLS at the higher B cup E/Q steps given the PLS sensitivity. Returning again to Figure 7 and the LECP data, it is also possible to observe that after day 248, the intensity of >28 keV ions is going mainly toward +T (the positive tangential direction, measured in sector 7 of the instrument scans) and is higher than the ions going mainly toward −T (sector 3), an anisotropy resulting from plasma convection because of the Compton-Getting effect. This convective anisotropy (≈18%) also causes sector 7 to exceed sector 3 during days 242.5–246, on average, consistent with the PLS data; however, it is less obvious in Figure 7a due to the lower intensity during this period.

6. Theoretical Ideas

[17] *Zank et al.* [1996] and *Lee et al.* [1996] discuss the acceleration of pickup ions near interplanetary shocks and the termination shock. *Parker* [1963] predicted the formation of a termination shock. As initially implied by Parker and later stated more explicitly by *Zank et al.* [1996] and *Lee et al.* [1996], the termination shock is quasi-perpendicular, as confirmed by the Voyager 2 observations [*Burlaga et al.*, 2008; *Richardson et al.*, 2008]. As discussed in the study of *Zank et al.* [2009], *Zank et al.* [1996] investigated the interaction of solar wind ions and pickup ions with the termination shock and concluded "pickup ions …provide the primary dissipation mechanism for a perpendicular TS with solar wind ions playing a very much secondary role." *Lee et al.* [1996] investigated pickup ion energization by shock surfing at a quasi-perpendicular shock. They considered the incoming pickup ions with speeds "much less than that of the incoming plasma." *Lee et al.* [1996] showed "that substantial energy gains are possible for pickup ions at quasi-perpendicular shocks simply due to the laminar field at the shock." The HEIs we have identified in the Voyager 2 PLS data have a speed of 600 km/s approximately twice the bulk convective speed of the upstream solar wind protons in the outer heliosphere. This would be consistent with the HEIs being pickup protons that were picked up in the upstream solar wind within one proton gyroradius (r_g) of the site of PLS detection in the HS. *Zank et al.* [2009] estimate (page 158, paragraph 2) that upstream on the TS the pickup ion r_g is ~60,000 km. If these upstream pickup protons were being convected toward the TS at the bulk convective solar wind speed of ~300 km/s, then it would take them on the order of ~200 s to travel one proton gyroradius (r_g), which is approximately the duration of one PLS L mode E/Q scan (e.g., 192 s). Thus, it seems reasonable and, consistent with the study of *Zank et al.* [1996, 2009], that the HEIs observed on Voyager 2 in the HS in the vicinity of the TS appear to be pickup protons that are "beamlike" and moving antisunward in an approximately radial direction. This description of the HEIs also seems to be consistent with the results given by *Lee et al.* [1996] since they emphasize (page 4785, paragraph 2) that, in agreement with *Jokipii et al.* [1993], the motion of the ions are "confined to within one gyroradius of its original convected field line."

7. Relation of HEIs to Radio Wave (PWS) Enhancements

[18] Several lines of reasoning suggest that the interaction of the HEIs with the bulk convective plasma may have generated the plasma waves of event A by the two-stream ion instability. Figure 8b shows results from a 2.5-D hybrid simulation performed by *Gurnett et al.* [2008] in an effort to identify the origin of the waves associated with TS-3 (event B) in Figure 1. The high intensity of these broadband waves became clear when *Gurnett et al.* [2008] normalized the electric field energy densities, $E^2/8_\Pi$, by dividing by the plasma energy density, $8_\Pi nkT$; and normalized the frequencies, f, by dividing by the electron plasma frequency, f_p. This showed that the waves at TS-3 were "… more intense than most planetary bow shocks, and comparable to those observed at Neptune's bow shock," as seen by comparing the V2 PWS spectra with bow shock spectra at Jupiter, Saturn, Uranus, and Neptune [*Gurnett and Kurth*, 2008; *Gurnett et al.*, 2008]. The simulated spectra in Figure 8b depict two streams, the bulk plasma and a slower-moving population, predicted to explain the wave observations for the ramp region in TS-3. The measured E/Q spectra in Figure 4 show multiple peaks with v_p ~<300 km/s before the ramp. Hence, the simulation and the measured PLS data in Figure 4 agree reasonably well, suggesting a two-stream interaction could explain these waves.

[19] Returning now to the E/Q spectra in Figure 2, it is clear that the HEIs would be a population moving at a significantly different speed from the bulk convective plasma and that the HEI detections primarily occur between

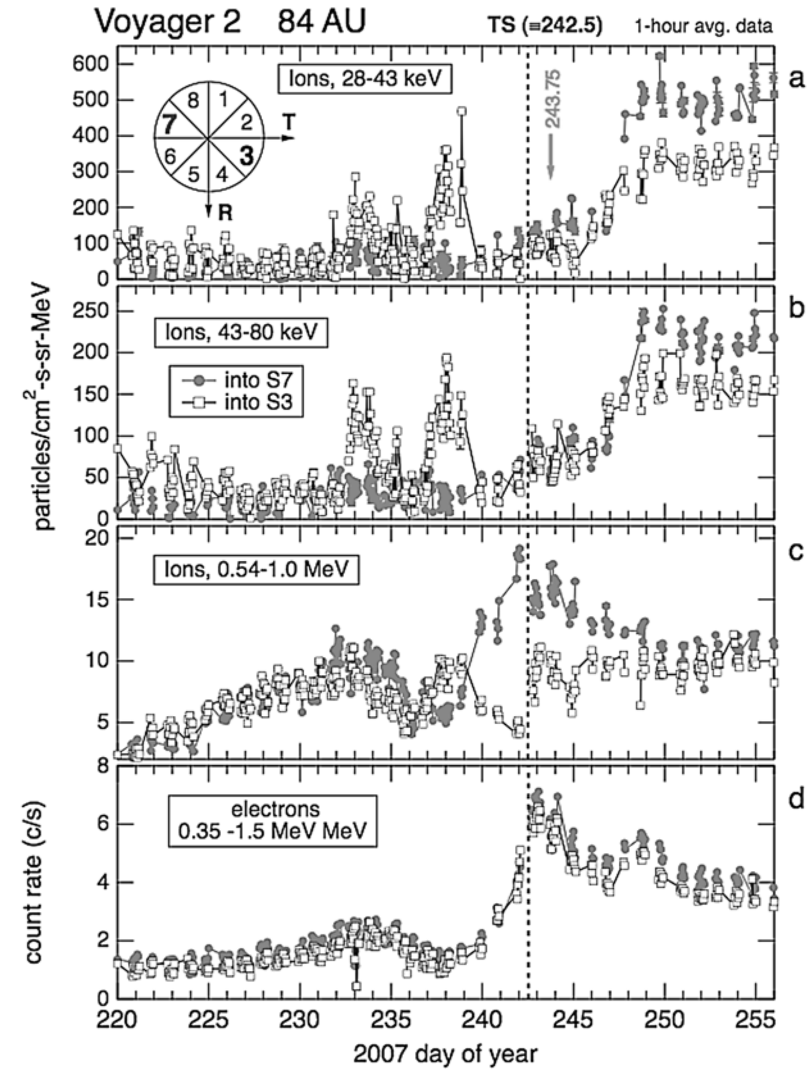

Figure 7. V2 LECP data near the TS. The dashed vertical line denotes the first V2 TS crossing. (a) The downward pointing arrow day 243.75 denotes event A and the PLS HEI detections. The data (corrected for background) are 1 hourly averaged to get one complete angular scan through 360°. Intensities from two sectors are plotted for each energy step. The sector labeled "7" shows ions going mainly toward +T, and sector "3" shows ions going mainly toward −T. While the lower energy ions do not increase substantially until a few days after the TS crossings, there is almost a twofold increase in the lowest energy particles (b) in the ions going toward +T (sector 7) when we compare their intensities before the first TS crossing (the dashed vertical line) with those just after event A (the downward pointing arrow). After approximately day 248, in Figures 7a and 7b, sector 7 is consistently higher than sector 3 due to plasma convection (Compton-Getting).

1731 and 1822 UT, around the time of event A. Thus, the observed E/Q spectra in Figure 2 qualitatively resemble the simulated spectra in Figure 8b. The differences are minor as follows: (1) the two E/Q peaks shown in Figure 2 and Figure 6 are more widely separated in speed, with one peak near 204 km/s and the other peak at 554–600 km/s, compared to the simulated v_b peaks in Figure 8 at ~153 and 255 km/s; and (2) assuming the ions are protons, the measured speed of the HEI peak in the observed detections is steady at ~554–600 km/s; and (3) the currents of the HEI detections vary and are often less than those of the bulk speed peaks, while in the Figure 8, Gurnett et al. simulation, the intensity of the higher-speed peak appears more constant and the intensity of the lower speed peak varies. Despite these minor differences, the overall correspondence strongly suggests that the two-stream ion instability may be responsible for the PWS enhancements associated with event A.

[20] In addition to this apparent agreement between the observed HEIs and the Gurnett et al. simulation, other observations show an association between plasma waves and ions that appear to have been reflected from shocks. For example, *Moses et al.* [1985] used 60 ms speed, magnetic, and PWS data of a strong (fast Mach number 16) (Mn = 16) quasi-perpendicular Jovian bow shock to reveal an abrupt

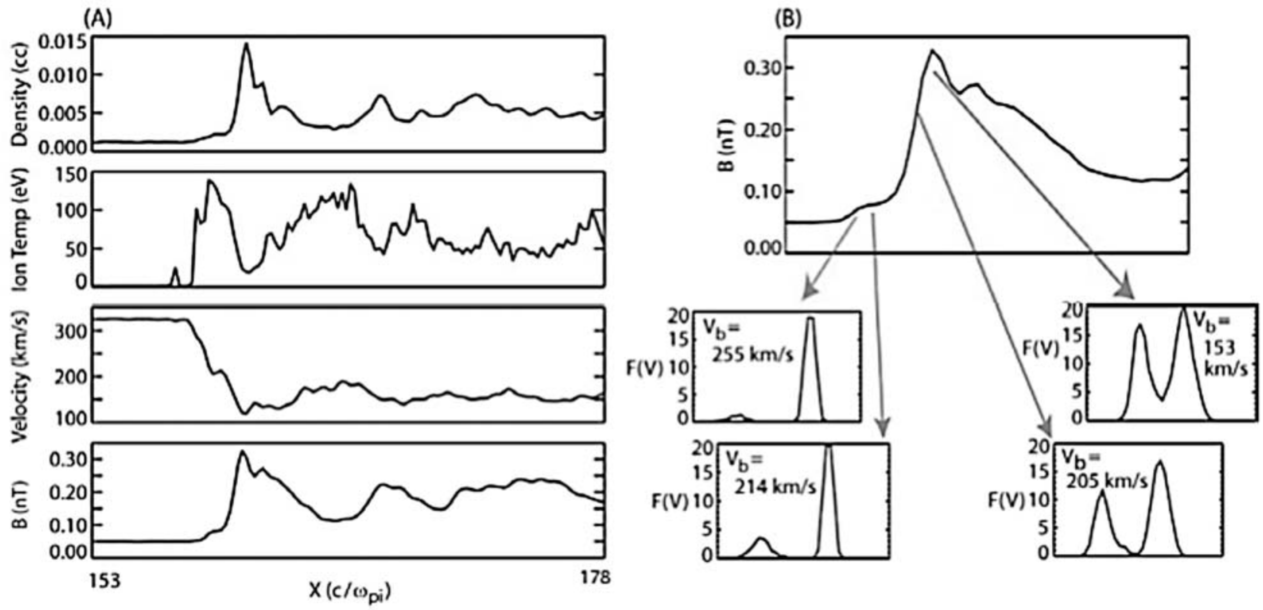

Figure 8. [From *Gurnett et al.*, 2008] (a) Results from a PIC plasma simulation and (b) the resulting ion velocity distributions. Note the similarities between the simulated ion distributions in Figure 8b and those we identified in Figure 2 associated with the V2 PWS event A data (Figure 1).

change in the spectrum at the leading edge of the shock foot. They concluded that the clear association with the foot region suggests that the bursty lower frequency waves were generated by reflected ions. They associated a burst of low frequency waves occurring slightly ahead of the foot with a lower density population of reflected ions preceding the bulk reflected ions.

8. Summary

[21] *Are the HEIs revealing a "real" physical phenomenon?* A natural question is whether these elevated readings or HEI detections on the B cup at E/Q step 12 ("the B12 channel") at the times described in the previous paragraphs are due to a physical phenomenon or are only spurious or random. One test of the validity of these HEI detections is that during a "control" interval of days 1–90, 2007, there were no HEI detections on the B cup. We have looked at the signals in the B12 channel from day 1, 2006 through 2008. During this 3 year period, we see only four time intervals with increases in the B12 currents: near day 335, 2006, centered on days 160, 245, and 345, 2007, and none in 2008. The event at day 245 coincides with the TS crossings we are presenting in this paper. The largest event is near day 345, 2007. During these four isolated intervals of HEI events, the signals in the B12 channel are observed at most in 20% of the spectra and usually far fewer. Thus, the HEI occurrences do not appear to have the characteristics of a constant background contamination.

[22] In short, while we do not know the specific origin of the HEIs (Figure 2) that we associate with the PWS event A (Figure 1), comparisons with several other studies make it tempting to speculate that these PWS enhancements are caused by a two-stream instability (Figure 8). Future analyses may help ascertain why the HEIs appear to have an approximately constant v_p of 554–600 km/s on the B-cup. Understanding the origin of these ions, whether as gyrating or pickup protons multiply reflected from the TS, and/or as newly born pickup ions, and/or from other acceleration processes, should help explain their observed energy and direction. Similarly, as summarized in the Appendix A, if the elevated PLS readings are not directly associated with HEIs, but rather with some changes in or effects of the plasma/spacecraft environment, or if the PLS elevated readings cannot be taken at face value, further study of them may reveal greater understanding of the physical environment and/or processes in the vicinity of the termination shock to help identify the physical cause of this situation.

Appendix A

[23] At this time we cannot completely eliminate the possibility that the elevated readings of E/Q step 12 on B cup (the B12 channel) and the perhaps associated A cup/C cup readings discussed above originate with something in the plasma/spacecraft environment that gives rise to an anomaly in the PLS so that the elevated readings should not be taken at face value. For example, it may be possible that a spacecraft mode change or arcing or spacecraft charging gave rise to an instrumental effect, etc. that produced these elevated readings. At this time, however, we cannot identify any specific plasma/spacecraft environmental origin that would cause an instrument anomaly producing these selective erroneous elevated readings. Since the Voyager 2 observations in the vicinity of the termination shock may be the only in situ data available for decades, for completeness, we are presenting the elevated readings in this paper with as much transparency as possible, so that they will be recorded in the scientific literature.

[24] In the material that follows, our format is generally an argument against the validity of the HEI detections is made and then a brief response to that argument is presented.

[25] One could say that a pickup ion distribution would have a peak in speed at 2 times the solar wind flow, so that (1) the speed (v_p) of the fast and thermal ions would be correlated and (2) the angle distribution would also give currents at lower speeds. With regard to (1) as discussed above, two possibilities for the origin of the HEIs are (a) pickup protons and (b) pickup protons reflected off the termination shock. In the case of (a) the speed of the HEIs is ~600 km/s which is consistent with its being a newly picked up proton at a speed (v_p) of ~2 times the upstream solar wind speed of 300 km/s and its being within approximately ~1 gyroradius of where it was picked up. In the case of (b), the measurements at Mars by *Dubinin et al.* [2006] show that the energy of the fast and thermal ions do not appear to be correlated since the fast ions are apparently accelerated by multiple reflections from the Mars bow shock. With regard to (2), perhaps the currents associated with the HEI angle distributions are not intense enough to be measured by the PLS or may be masked by the PLS performance which, as discussed previously, became less sensitive to plasma detections on B cup following the V2 Jupiter flyby.

[26] No increase in the next higher (B13) or lower (B11) E/Q channel is observed. However, given the relatively low currents observed in the B12 channel, one might not expect the intensities of the currents in the off peak E/Q steps (e.g., in the B11 and B13 channels) to be observable given the PLS sensitivity. Moreover, as discussed previously, the B cup became less sensitive to plasma detections following the V2 Jupiter flyby.

[27] The regions of increased B12 E/Q currents are regions of lower A12 E/Q currents throughout 2007, suggesting shifts in the noise levels of the cups. However, these regions with the elevated B12 E/Q channel readings also do have increased readings on the A13 E/Q channel. The C12 and C13 channels have high background noise levels, so a current increase could not be unambiguously detected. However, as discussed above, we believe it is more likely that the HEI detections are either evidence of multiple reflections of protons off of the termination shock, analogous to those reported by *Dubinin et al.* [2006] upstream of the flanks of the Mars bow shock, or detections of ions picked up in the solar wind and convected more or less directly to the spacecraft.

[28] To further investigate the width of the plasma distribution, we examined the PLS M mode data that has eight times the E/Q resolution of the L mode data so that in principle it could resolve a distribution that would be detected on only one L mode E/Q step (e.g., B12, A13). Unfortunately, since the M mode channels would see a factor of 8 less current in each cup, we found that the current readings were below the PLS noise level. We find, however, in the PLS M mode data a persistent noise spike in channel B93 and/or B94, which is in the E/Q range covered by B12 of the L mode. This suggests the PLS instrument may be responding strangely in this E/Q range. The M mode spike persists through most of 2007. In contrast, as discussed previously, the HEIs we report that we found in the B cup E/Q step 12 L mode data are only present on four occasions: one time interval in 2006; three time intervals in 2007, and not at all in 2008.

[29] Another possibility is that a higher mass ion caused the observed peak in the currents. However, a cold fast beam of heavier ions flowing along the field would be at too high an angle to the instrument aperture to be observed, and there is no evident source for a population of heavier ions. As discussed above, the V2 HEIs near the TS appear to be similar to the higher energy protons upstream of the Mars bow shock [*Dubinin et al.*, 2006] whose energy also did not track that of the comoving plasma. *Dubinin et al.* [2006] attributed the higher-energy upstream protons to multiple reflections off the Mars bow shock. Similarly, as discussed previously, the HEIs could be pickup protons from the outer heliosphere upstream of the TS where the bulk convective solar wind speed is ~300 km/s so that these pickup protons have a speed of ~2 × ~300 km/s so that the ~600 km/s HEI speed is approximately "tracking" the upstream solar wind speed.

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