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Implications of the Voyager 1 and 2 Particle and Field Observations around their respective Heliopause Crossings

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Abstract. The numerous contrasts between the Voyager 1 particle and field observations around its heliopause crossing in 2012 and the corresponding observations by Voyager 2 in late 2018 and the beginning of 2019 are consistent with understanding the heliopause itself as the separator between the solar system magnetic field and the interstellar medium magnetic field, at a location that varies in response both to short-term effects of plasma instabilities and longerterm bulk motions of the heliosheath. Plasma flows in the respective regions provide a framework for explaining the observed decreases with heliopause distance of the count rates of both solar system solar and anomalous cosmic rays diffusing outward from the heliopause and galactic cosmic rays diffusing inward. Formation of excited hydrogen atoms by chargeexchange collisions in interstellar plasma displaced and accelerated (as described in the discussion of solar system cosmic rays) by the motion of the heliosphere provides a mechanism for producing recently recognized anomalous Lyman alpha emissions around the front of the heliosphere. We discuss the consequent possibility of previously unobserved Lyman alpha emissions associated with shock propagation in the local interstellar medium.

1. Introduction

It is a pleasure to recognize and honor Randy Jokipii (Figure 1) and to acknowledge his many significant predictions and key analyses in space physics and astrophysics. Jokipii has been a friend and inspiration worldwide to many researchers on plasmas and energetic particles, including at Carmel Research Center, Inc.

Figure 1. We are indebted to Randy Jokipii for his many important contributions, including predictions of phenomena that might be found within the heliosphere, beyond the heliopause, and analyses of Voyager and other spacecraft observations throughout these regions.



The Voyager 2 (V2) data publicly available on the web show that evidence for the V2 approach to the heliopause (HP) started in the plasma system (PLS) in May and in the cosmic ray system (CRS) and magnetometer in August 2018. The count rate of particles with energies >70 MeV/nucleon (the most convenient aggregate measure of the local density of galactic cosmic rays (GCRs)) began to creep up similarly to the observations when Voyager 1 (V1) approached the HP. The GCR inflow may have enhanced V2's observed plasma slowing, like the GCR effect at the V2 TS crossing (Florinski, et al. [17]). Various plasma, energetic particle, and magnetic field data show that the V2 crossing of the HP occurred in early November, 2018, after a much more prolonged approach than was observed at V1.

The decline in the count rate at V2 of solar system particles with energies >0.5 MeV/nucleon (solar and anomalous cosmic rays (ACRs) well below 70 MeV/nucleon in energy) after the HP crossing reached the GCR rate, as after V1's HP crossing, so then only GCRs were present. The decline at V2 was slower and less regular than the decline at V1, but the energetic particle and magnetic field data show that V1 saw three forward HP crossings and two reverse ones, implying two brief emergences into the local interstellar medium (LISM) before the final permanent one, while the V2 emergence was unique. V1 and V2 both crossed near 120 AU but respectively near (174, 35N) and (218, 32S).

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Comparing the V1 and V2 data show that at V1 the magnetic field magnitude changed significantly at each forward and reverse HP crossing but unexpectedly the field direction changed very little, prompting doubts that these events were genuine HP crossings, versus crossings of a boundary between differing plasma regions within the heliosheath. However, the available preliminary V2 "Quick Look" (QL) magnetic field parameters indicate a brief period of large perturbations in field magnitude around the HP crossing, after which the field magnitude was little different from before. The QL data also show a sharp direction change at the HP crossing but are not adjusted by calibration, hence may not show a direction change when corrected. The V2 QL data agree with the V1 mag evidence that the HP itself is a current sheet. The LISM magnitudes at both spacecraft are similar.

The following sections describe how these observations are consistent with a conceptual framework derived from a combination of the V2 plasma observations, energetic neutral atom observations from other spacecraft, and recent theoretical computations. Furthermore, the inferred plasma dynamics of the interaction of the front of the heliosphere with the LISM serendipitously provides a possible explanation for anomalous Lyman alpha observations recently reported from the V1 ultraviolet spectrometer and the ALICE instrument on New Horizons, and combining this explanation with our previous analyses of shock propagation in the local interstellar medium in turn raises the possibility of previously unobserved Lyman alpha emissions associated with such shocks.

2. Comparing the V1 and V2 Crossing Observations

Stone, et al. [1] and at the Voyager CRS website [2], describe how the CRS telescopes are stacks of solid-state detectors, mounted so that particles can enter either end of each stack, with a guard detector surrounding each stack and coincidence logic incorporated into the data system. This logic identifies simultaneous energy deposition events in various combinations of detectors and thereby distinguishes counts caused by electrons from counts caused by positive ions. Among positive ions, it discriminates between protons, alpha particles, and heavier nuclei, as long as the guard detector is not triggered. Triggering this detector indicates that a particle came through the side of the telescope instead of from the desired field of view; thus readings from other detectors would be an incomplete or mistaken characterization of the particle, and are therefore rejected. See website [2] for more details.

Figure 2(a) shows the CRS count rates for particles with energies >0.5 MeV/nucleon (solar system cosmic rays (SSCR), abbreviated to ">0.5 MeV" for the plot labeling); particles with energies >70 MeV/nucleon (GCR, likewise abbreviated) and B magnitude from the magnetometer system for the period when the spacecraft was crossing the HP. The base-2 logarithmic scale on the left axis allows displaying both the SSCR count rate and the B magnitude in nT to show the simultaneity of the changes in the SSCR and B magnitude with each other and with the much smaller percentage changes in the GCR count rate, given by the linear scale on the right axis, as the first forward crossing occurred at about day 211 (July 29), followed by the first reverse crossing at about day 214 (August 1), the second forward on day 226 (August 13), the second reverse on day 233 (August 20) and the third and final forward on day 238 (August 25) of 2012. Green stars show the HP crossings in Figures 2-4.

Figure 2(b) shows the corresponding data for V2 near its crossing late on November 4 or early on November 5 of 2018. Due to the difficulty in processing the damaged V2 magnetometer (Burlaga, et al. [3]) readings only preliminary "Quick Look" (QL) data are now publicly available. Good-quality QL data were only posted after October 22, 2018, so the B data series starts then, while the CRS count rates from early September show how the rise in the GCR count rate signaled the impending HP crossing, much more slowly than the corresponding rises preceding the crossings seen on V1. The QL data are the best mag data available now but calibration and verification adjustments are likely.

Figure 2(a) also shows that after the final crossing on August 25 the SSCR count rate continued to decline for approximately another two weeks, stabilizing at around 2.1 after day 250. As this count rate for particles >0.5 MeV is less than the reading of around 2.6 for particles >70 MeV, evidently no particles in the energy range 0.5 - 70 MeV were being detected, so that the difference in the rates for what are actually GCRs is attributed to geometrical factors for which these raw rates are not adjusted.

Correspondingly, Figure 2(b) shows that after a decline that was far slower and more irregular than what was seen at V1, the >0.5 MeV count rate at V2 has stabilized at almost exactly 2.0, while the >70 MeV count rate is a little under 2.5, implying that V2 has reached a region with no detectable particles in the range 0.5 - 70 MeV, with nearly the same geometric factor effect on the count rates as at V1.



Figure 2(b). V2 HP-epoch solar CR (>0.5 MeV), GCR (>70 MeV), and B magnitude (QL).

Figure 3 shows how, as discussed previously by many authors, the direction of the B field observed by V1 did not change significantly during the HP crossings, although a sector boundary was crossed only a few days before the first HP crossing. By contrast, in Figure 4 the V2 QL, which has not been calibrated and verified yet, shows at the HP crossing a quick and long change of ~20 degrees in the azimuthal angle and an initial change of ~20 degrees in the polar angle later declining to ~10 degrees.

Although many other researchers will discuss these magnetometer observations in far more detail, the results in Figures 3 and 4, along with the correspondences between the particle observations in Figure 2, indicate that although many physical phenomena are associated with the HP, the HP itself is the current sheet separating the heliospheric and interstellar magnetic fields, and that the spacecraft successfully observed it, even though the change was manifested primarily as a change in field magnitude at V1 but as a change in field direction at V2. In the next section combining several recent simulation projects allows interpreting many other aspects of the observations in Figures 2-4.

3. Comparison with Simulations: HP Location Variations

Figure 5 is reproduced from Figure 5 of Washimi, et al. [4], in which they used OMNI data from 1 AU to estimate how long-term changes in the solar wind pressure may have affected the location of the HP along the trajectories of V1 and V2 since 2006, continuing the calculation to predict what might

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happen through the end of 2019. The figure shows their conclusion that in 2012 along the V1 trajectory the HP was nearly stationary, so this simulation result matches the relatively quick crossing observed by V1.



Figure 3. V1 HP-epoch magnetic observations.

However, the figure predicted that from the second half of 2017 (after completion of the paper) through the end of 2019 along the V2 trajectory the HP would be moving outward at about 2 AU/yr, so that the spacecraft, moving outward at about 3 AU/yr, would have a much slower speed relative to the HP than V1 did. This is consistent with the way that the GCR count rate increased as V2 approached the HP and the SSCR count rate decreased after V2 crossed, thus qualitatively agreeing with the observations when V1 crossed, but the count rate changes at V2 both before and after the crossing were much slower than the corresponding ones at V1. The crossing in early November, 2018, suggests that the actual HP locations in 2017-18 were about 1.5 AU farther from the Sun than the figure shows, which in view of the approximations in the model was actually a small discrepancy.

On the other hand, the observations around the crossings at both V1 and V2 showed short-term variations that are not addressed by the dynamic pressure simulation of Washimi, et al, but the plasma instability simulations of Pogorelov, et al. [5] and Borovikov, et al. [6] provide plausible hypotheses.

Figure 6 is reproduced from panel (d) of Figure 7 of [5] and also corresponds to the bottom left panel of Figure 2 of [6]. The figure shows these researchers' estimate of the field magnitude in a 2-D slice of the heliosphere plasma environment containing the Voyager trajectories (the upper diagonal line is V1 and the lower is V2) around the time of V1's crossing in 2012, with colors from blue to red representing field magnitudes from 0 to 0.7 nT. The figure indicates that the instabilities used by these authors in their simulations predict a more or less fractal structure for the HP, with wrinkles and lumps and dips on a wide range of scales.

However, since the tick marks on the horizontal and vertical axes of this figure represent increments of 10 AU, the depicted HP fluctuations are too large to be direct predictions of variations on scales that would explain the Voyager observations. They also would move too slowly, since, for example, in other panels in the figures in [5] and [6] the lobe extending in front of the V1 trajectory is little different two years later in the simulation, and in text around Figure 2 of [6] the authors expect the deepest penetrations of LISM into the heliosheath to occur on time scales of 50 - 180 years.

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We suggest that if it were possible to run comparable simulations with volume elements and time steps smaller than those that were necessary to complete these simulations with the available computational resources (which were provided by some of the largest supercomputer facilities in the world at the time) the fractal structure would be observed to continue down to the smallest simulatable scales, as is the case for many other instabilities in various types of fluids, so that the Voyager observations would be understood as resulting from smaller and faster fluctuations in the HP caused by the same instabilities as were studied by these researchers. Since neither V1 nor V2 had a trajectory close to the nose, where the Rayleigh-Taylor instability is expected to predominate [5], they probably both crossed the HP in flank regions dominated by the Kelvin-Helmholtz instability [5].





Combining these considerations with the results of [4] implies that the fluctuations around the trajectory of V1 were significantly larger than those around the trajectory of V2, since even though the HP probably was more nearly stationary overall near V1 in 2012, it fluctuated enough for V1 to observe multiple crossings, but in late 2018 and early 2019, even though the HP was probably moving outward at a substantial fraction of V2's speed, the temporary increases in the SSCR count rate at V2 in Figure 2(b) near December 1 and after December 16 suggest that for periods of several days after the crossing the HP moved closer to the spacecraft but never caught up with it. This contrast between the crossings may merely have resulted from fortuitous differences in the fractal fluctuations, or it may be connected with the crossings' being separated by about 120 AU and half a solar cycle.

4. Comparison with Simulations: Plasma Flow Effects on Cosmic Rays

The zigzag SSCR history in Figure 2(b) is taken as evidence for irregular HP motion because both 2(a) and 2(b) show that the SSCR count rates decline steeply beyond the HP and become undetectable only a few tenths of an AU away, thus raising the question of why the decline occurs. No solid bodies are present to absorb them, so in a static situation SSCR particles might be expected still to be present at greater distances from the HP, even if they had spent months or years diffusing that far. Of course, the situation is not static, as depicted in Figure 7.

Figure 7 is reproduced from Figure 2 of Opher, et al. [7], and depicts a meridional slice of results from another huge simulation (done on a system with about 2000 CPUs), depicting plasma flows

inside and outside the HP, with colors representing the field magnitudes. Figure 7 extends 200 AU latitudinally and 140 AU radially around the nose of the heliosphere and expands part of Figure 1 of [7], in which the axes give these dimensions.



Figure 5. V1 and V2 spacecraft trajectories and estimated HP locations (Washimi, et al. [4])

Figure 7 shows motions only in the radial-normal plane, but the divergence of the flows from the stagnation point also produces tangential components of motion. In the website in [8] the PLS experiment group has posted daily average V2 plasma observations from within the heliosphere up to a few days before the crossing in early November, 2018, so Figure 8 shows strong deflections of the flow from the radial in both azimuthal and polar angle that are discussed in much more detail by Richardson, et al. in [9] and many other publications. The main Faraday cup cluster of the PLS is not favorably located for observing the flows beyond the HP, so plasma data from this region are not available yet, but in [10] Richardson described how the side-facing Faraday cup D of the instrument might be able to observe the LISM plasma, and if so then this will observationally confirm the expected high degree of deflection of the LISM plasma near the HP.

Combining the LISM field magnitudes in Figures 2 - 4 with the V1 PWS plasma density estimates and with estimated pickup ion temperatures implies β values around 1 beyond the HP, quantifying the expectation of a high β in [10]. Specifically, for IBI = 0.4 - 0.7 nT (= 4 - 7 μ G, thus including field magnitudes higher than considered in [5] and [11]), as in Figures 2 - 4, the magnetic field pressure is 0.6 - 1.9 x 10⁻¹³ pascal. Correspondingly, for LISM plasma densities of 0.08 - 0.12 cm⁻³ from V1 PWS observations [12] and a mean plasma thermal energy of 3 eV, which includes pickup ions formed by the charge-exchange collisions described below in Section 5, the plasma thermal pressure would be 0.4 - 0.6 x 10⁻¹³ pascals. Comparing these ranges gives a β range of 0.25 - 1.0.

Thus, the magnetic field is sufficiently "frozen" into the plasma that the flows beyond the HP depicted in Figure 7 and perhaps observed by the PLS can be expected to transport the field with them. Then over times that are short compared to the typical time scale for cross-field diffusion the cosmic rays are carried along with the field, according to the conservation of the first adiabatic invariant. This is analogous to our description in [15] of how shocks locally stretch the LISM magnetic field so that conservation of the first adiabatic invariant causes the V-shaped GCR count rate profiles seen at V1 over weeks or months around the 3 kHz plasma wave events caused by the shocks [16].

All of this implies that as SSCRs emerge through the HP they are rapidly swept away by the LISM plasma as it flows around the HP, as shown in Figure 7, thus explaining the rapid decline in SSCR

count rate with distance from the HP. Moreover, the few that have been able to diffuse to larger distances, such as those in Figure 2(a) that were observed early in September, 2012, more than a week after the August 25 crossing, must be understood as having emerged close to the nose so that they have had time to diffuse to the distances where they were observed by the time they reached the latitude and longitude of V1. Corresponding reasoning applies to the particles observed at the low but nonzero count rates at V2 in December, 2018. (Thus, combining these considerations with those in Section 3 implies that a simulation that accounted for the SSCR fluctuations observed by V1 and V2 would combine the flow deflections of [7] with the instabilities of [5,6]. This may not yet be feasible.)



Figure 6. Estimated HP irregularities from instabilities, 2012 [5].



Figure 7. Schematic depiction of LISM and HS plasma flows near the HP [7].

The same reasoning implies that the flows within the heliosheath depicted on the right side of Figure 7 and recorded in Figure 8 should have a sweeping effect on GCRs crossing the HP from outside. This would explain at least part of the GCR count rate declines in Figure 2 with distance from the HP, (observed in reverse as the spacecraft approached the HP), mirroring the declines of the SSCR count rates beyond the HP. Figure 2 shows that the dependences were also far weaker than for the SSCRs, due at least in part to the much higher energies and consequently larger gyroradii of the GCRs, which at V1 were farther enlarged by the lower magnetic field strength in the heliosheath. On the other hand, despite the weaker dependence the higher energies of the GCRs may have contributed to slowing the plasma as it approached the HP, in a way possibly analogous to the deceleration when V2 approached the TS discussed by Florinski, et al. [17], since the fit data from [8] show that from early May to late October, 2018, the plasma speed declined irregularly from around 130 km/s to around 95 km/s. The slowing plasma speed also may be due to the piling up of plasma as in a snowplow effect.

5. Interactions in the LISM between Plasma and Neutral Atoms near the HP

The plasma flows depicted in Figure 7 also lead to a possible explanation for anomalous Lyman α observations reported by Katushkina, et al. [18]. These authors explain that, in an effort to observe the ultraviolet environment in the outer solar system, from 2003 until the instrument apparently began to malfunction in 2014 the V1 ultraviolet spectrometer (UVS) was left pointing in the same direction with respect to the spacecraft, and therefore watched a very small region of the sky upwind of the heliosphere as the spacecraft's orientation periodically changed slightly to maintain radio contact with Earth. During these years the observed Lyman α brightness consistently was significantly higher than what could be explained by the authors' model of Lyman α propagation in the solar system, which had

been well confirmed in other contexts, and the presence of an excess over a broader area of the upwind sky was shown by observations from the Alice UV spectrograph on the New Horizons spacecraft.



Figure 8. Azimuthal and polar deviations from radial flow from daily average V2 PLS velocities [8].

Figure 9 reproduces Figure 10 of [18] and compares the model to the Alice Lyman α data from the second yearly spacecraft roll at 11.3 AU from the Sun. The continuous line shows the observations, with spikes from stars that happened to be in the field of view, but between the spikes it is clear that from an ecliptic longitude of about 170 degrees all the way to 360 and wrapping around to about longitude 20 there is a consistent excess of about 20 Rayleighs (R) above the small diamonds of the model predictions. Compared to their earlier work, adding a previously unpredicted 15 - 20 R to the model also turned out to improve the agreement with the V1 UVS data from 1993 - 2003, and in a more thorough study of the Alice data Gladstone, et al. [19] also found an excess, estimating it at 40 R.



Figure 9. New Horizons Alice ultraviolet spectrograph Lyman α observations during a roll at 11.3 AU from the Sun (continuous line) and model predictions (small diamonds) [17].

Katushkina, et al. described two possible ways by which an excess could be produced. Backscatter of solar Lyman α from a thick, dense hydrogen "wall" in front of the heliosphere was one and unexpectedly high Lyman α emission from distant galaxies in these directions was the other. They probably recognized that these are not plausible mechanisms, since the Lyman α absorption studies described in Section 3 of [11] would have seen such a thick and dense hydrogen "wall", and UV light from distant galaxies is highly unlikely to correlate with the heliosphere's motion through the LISM. However, a natural explanation that they evidently did not consider could account for at least part of the excess. Charge-exchange interactions between the plasma ions and the neutral atoms of the LISM in the

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region near the HP could produce hydrogen atoms in the n=2 excited state, from which they would fall to the ground state by emitting Lyman α photons, and combining several considerations implies that sufficiently energetic charge-exchange collisions between ions and neutral atoms should be frequent enough in this region to produce significant Lyman α emission.

First, considering Figure 7 from the viewpoint of the rest frame of the LISM implies that in this context the heliosphere is plowing leftward through the LISM at 26 km/s, as determined by reconciling the IBEX and Ulysses ENA measurements [20]. Then the LISM plasma is accelerated by this interaction to flow in the way shown at left in Figure 7, but the LISM neutral atoms are unaffected by all the electric and magnetic field activity, and at a distance of roughly 120 AU the effect of the Sun's gravity is negligible, so in this frame the neutral gas has little if any bulk motion.

Nevertheless, the thermal motion of the neutral atoms is not negligible. In [20] the IBEX and Ulysses measurements were reconciled by estimating the temperature of the neutral gas in the range 7000 - 9500 K. Applying Boltzmann's Constant shows that a thermal energy of 0.75 eV corresponds to a temperature of just under 9000 K, so assuming 0.75 eV for convenience of calculation implies that a proton or a hydrogen atom with this energy is moving at about 12 km/s.

Further consideration of Figure 7 shows that the flow speed of the plasma ions following the streamlines on the left side is 26 sec θ , where θ is the angle between the streamline and the horizontal. Thus, for example, if $\theta = 45$ degrees then sec $\theta = \text{sqrt}(2)$ or approximately 1.4, for a speed of about 37 km/s. (Figure 7 is reproduced in its correct proportions, showing many streamlines on the left side at angles around 45 degrees.) The energy of a Lyman α photon is 10.2 eV, corresponding to a proton or hydrogen atom speed of about 44.3 km/s, so a head-on collision between a proton going 37 km/s and a neutral atom going 12 km/s would give a total collision speed of 49 km/s, or more than 10.2 eV for a charge-exchange collision to convert the proton into an n=2 excited atom. Of course not all collisions would be head-on, but the thermal distribution includes energies above the mean of 0.75 eV, so many slightly oblique collisions would be sufficiently energetic.



Figure 10. Comparisons between HHMS-PI simulation values (red and green lines) and Ulysses SWOOPS solar wind observations (blue lines) and SWICS PI observations (faint gray lines) [14].

Continuing this reasoning suggests that some collisions would be energetic enough to produce atoms excited to higher energy states that would then emit higher spectral lines in the Lyman series. However, Bransden and McDowell [21] report that significant numbers of atoms excited to the n=3 state are not produced until the collision energy is around 1 MeV, so this does not happen near the HP.

It is important to observe that in the aftermath of a charge-exchange collision the ion newly formed from a neutral atom of the interstellar gas would be picked up by the LISM magnetic field as it is pushed along by the advance of the heliosphere at 26 km/s with respect to the rest frame of the LISM neutral gas. Thus, it would begin gyrating around the field at a speed of 26 km/s, plus or minus the

perpendicular component of whatever thermal motion it had had at the time of the collision. Thus, as noted above in Section 4, many of these pickup ions would be expected to have gyration speeds of 26 to >30 km/s, thus contributing disproportionately to the plasma thermal pressure just beyond the HP.





In [22] by identifying corresponding events at different spacecraft and analyzing the delays between them we calculated that the shocks observed in the 3 kHz channel by the V1 plasma wave system were probably propagating through the LISM at a speed of about 69 km/s with respect to the rest frame of the LISM. Furthermore, the shock propagation speeds of around 15 AU/yr through the LISM depicted in Figures 5 and 6 of [23] correspond to speeds of around 71 km/s, agreeing remarkably well with the estimate from the delays (an observation that was omitted from the reference in [22] commending the realism of the modeling in [23]). As charge-exchange collisions between ions and neutral atoms at around 70 km/s evidently are well above the threshold for producing excited atoms, this raises the possibility, which may not have been recognized before, that shock propagation in the LISM may be associated with Lyman α emissions, and that it may be possible to observe them under sufficiently favorable conditions, in addition to the emissions from the LISM near the HP.

6. Modeling

Although we noted in [22] that the modeling in [23] was more realistic and detailed than many other studies, we believe that detailed understanding of longitudinally and latitudinally varying flows and shocks far from the Sun requires modeling from the comprehensive plasma outflow near the Sun, as provided by the Wang-Sheeley-Arge (WSA) maps of a source surface at 2.5 solar radii (below all Parker probe perihelia) instead of spacecraft data from points ≥ 1 AU. Our Hybrid Heliospheric Modeling System with Pickup Ions (HHMS-PI) is an MHD model of solar wind flow and shock propagation, and the Hakamada-Akasofu-Fry Source Surface model (HAFSS) is a simpler kinematic model.

Exemplifying our studies, Figure 10 reproduces Figure 3b of [14] (from [24]), showing the generally good agreement between a time dependent HHMS-PI simulation and Ulysses data from a 150-day period in 2003 that includes merged disturbances from the great flares that erupted around Halloween of 2003. The simulation did miss the very small SWICS PUP densities near Day 320, which may have slowed the shocks. Likewise, Figure 11 depicts a HAFSS simulation of IBEX ENA data in the 4.3 keV channel from [25], showing that HAFSS qualitatively predicted the existence of the IBEX Ribbon, although it overestimated the ENA count rates. We hope to improve on these results.

7. Concluding Remarks

Now that V2 has at last crossed the HP, it has answered some questions, but raised many others. For example, if we simply assume that the TS and HP remained where they were respectively observed by V1 and V2 then the delay calculations of Intriligator, et al. in [22] and [14] imply that a shock from the major flares in mid-September 2017 is likely to reach V2 late in August, 2019, and V1 between May and December, 2023. However, assuming constant HS thicknesses along the respective trajectories of V1 and V2 but that the TS and HP locations changed as in Figure 4 merely shifts the arrival at V2 to early September, 2019, but the time for V1 ranges from November of 2021 to April, 2022. (This

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would be consistent with how the shock predicted for early 2018 in [22] actually arrived at V1 in August 2017). All of these possible arrival times are within the expected mission lifetime until 2025, so we hope to see whether each spacecraft observes a shock from the September 2017 flares.

In this context, the discussions of pressure waves in the HS by Richardson et al. in [8] and [9] evidently provide insight into how slowly the thickness of the HS may change. It also appears worth noting that the Cassini spacecraft's INCA team reported in [26] that ENA observations indicated that the HS was about 30 AU thick along the V1 trajectory and 40 - 70 AU thick along the V2 trajectory, so that the actual HS distance traversed by each spacecraft was about 90% of the respective INCA estimate. More understanding of the heliosheath may come from further study of the Voyagers' data from this region, including whether Opher and others are right about the heliosphere being spherical.

If current hopes for the Voyagers to continue in operation and to be tracked until 2025 or longer are fulfilled then at least 6 or 7 years of informative observations of interstellar space lie ahead as the Voyagers move farther from the Sun and farther apart from each other.

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