Journal of Physics: Conference Series

**PAPER • OPEN ACCESS**

# Voyager 2 Observations Near the Heliopause

To cite this article: John D. Richardson *et al* 2020 *J. Phys.: Conf. Ser.* **1620** 012016

# Voyager 2 Observations Near the Heliopause

**John D. Richardson[1], John W. Belcher[1], Leonard F. Burlaga[2], Alan C. Cummings[3], Robert B. Decker[4], Merav Opher[5], Edward C. Stone[3]**

[1]Massachusetts Institute of Technology, Cambridge, MA 02139 USA
[2]NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3]California Institute of Technology, Pasadena, CA 91125 USA
[4]Applied Physics Laboratory, Johns Hopkins University, Laurel, MD 20723 USA
[5]Boston University, Boston, MA, USA
jdr@space.mit.edu

**Abstract**. This paper discusses plasma characteristics in the heliosheath region before the heliopause (HP), at the HP, and in the very local interstellar medium (VLISM). The Voyager 2 (V2) HP was a sharp boundary where the radial plasma currents went to background levels. The radial flow speeds derived from 53-85 keV (V1) and 28-43 keV (V2) ion data decreased about 2 years (8 AU) before the HP at V1 and V2. A speed decrease was not observed by the V2 plasma instrument until 160 days (1.5 AU) before the HP crossing when V2 entered the plasma boundary layer where the plasma density and 28-43 keV ion intensity increased. We determine the HP orientation based on the plasma flow and magnetic field data and show these observations are consistent with models predicting a blunt HP. Variations are observed in the currents observed in the VLISM; roll data from this region clearly show the plasma instrument observes the interstellar plasma and may be consistent with larger than expected VLISM temperatures near the HP.

## 1. Introduction

Voyager 2 (V2) crossed the heliopause (HP) on Nov. 5 2018 when it was 119 AU from the Sun at a heliolatitude of 31° S [1,2,3,4], close to distance the predicted by Washimi et al. [5]. The Voyager 1 (V1) plasma instrument failed in 1980, so V2 provides the first plasma data from the HP boundary regions, at the HP, and in the very local interstellar medium (VLISM) [6]. V1 crossed the HP in August 2012 at 121.7 AU [7,8,9,10] and in 2020 passed 150 AU. This paper describes the V2 observations near the HP and compares them with those from V1.

## 2. HP Overview

The V1 HP crossing was initially controversial because, although the magnetic field magnitude B and galactic cosmic ray (GCR) intensities increased and the anomalous cosmic ray (ACR) intensities decreased as predicted, the magnetic field direction did not change as was expected [1,2,3]. Plasma oscillations observed beyond the boundary showed that the electron densities were much higher than those in the heliosheath (HSH) indicating that V1 had crossed the HP [4]. V1 has remained in the VLISM since 2012.

The V2 HP crossing was similar enough to the V1 crossing that it was immediately recognized that V2 had entered the VLISM. The plasma science (PLS) instrument showed that the ion flow changed at the same time as changes were observed in B and in the GCR and ACR intensities. Figure 1 shows the currents observed in the four PLS Faraday cups [11]. The A, B, and C cup look directions lie about a cone whose central axis points towards earth; they are well-positioned to observe the outward flowing solar wind and HSH plasma. The D cup looks at a right angle to this direction and was oriented as close as possible to the expected VLISM flow direction. Figure 1 shows currents from the lowest energy channel (10-30 eV) for the A and C cups and from the lowest two (10-57 eV) for the B cup, which looks most directly into the HSH flow and thus has significant current in two channels. The A cup looks furthest from the HSH flow and has the lowest currents. Before the HP the currents in all four cups increased by a factor of 2 from day 140 to 190. This region of enhanced currents is the plasma boundary layer. The average currents decrease slowly until day 300, when they fall rapidly to background levels at the HP. The D-cup is often compromised by noise; we show only the most reliable data so the sampling rate is less but the profile shape is the same. The currents in the three sunward-looking cups go to background levels on day 309 of 2018. At this time outward flow ceases and few ions enter these detectors. The D-cup currents decrease at the HP, but not to background levels. These currents beyond the HP are the first direct measurements of the VLISM plasma.

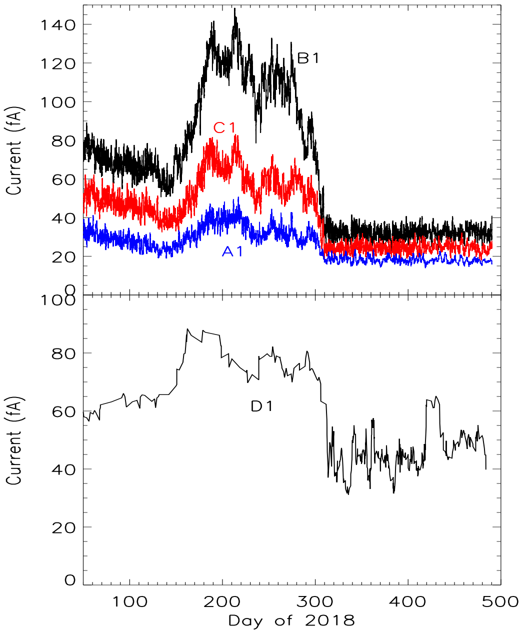

Figure 1. Currents in the sunward-looking A, B, and C cups (top) and in the sideways looking D-cup (bottom). The A, B, and C cup currents fall to background levels at the HP crossing on day 309.

We compare the two Voyager HP crossings to see which features are intrinsic to the HP boundary and which may be time and/or location dependent. Figure 2 shows that both HP crossings have a broad HP boundary region with complex structure. The V1 2012 HP crossing has an abrupt increase in the magnetic field strength B, a sharp decrease of HSH energetic particles, and an increase in the GCR counting rate. Two HP precursors were observed at V1 near days 210 and 230, with decreases in B and the energetic particle intensities and increases in the GCR counts centered on days 212 and 230 of 2012 [1,2,3]. After the HP, B remained high and steady, the HSH energetic particles disappeared, and GCR counts plateaued. Plasma wave (PWS) data confirmed the densities were high as expected in the VLISM [4]. The precursors may be flux tubes moving from the VLISM into the HSH [2].

The V2 crossing did not have precursors like those at V1. On day 309 B sharply increased, the HSH energetic particle intensity decreased, the GCR counting rate increased, and the plasma dynamic pressure and the radially outward plasma currents dropped to background levels [7,8,10]. PWS observations from days 35–55 of 2019 confirmed the density outside the HP was 0.04 cm$^{-3}$ [9].

The biggest surprise of the V1 HP crossing was that the direction of B did not change [1]. Models can explain this observation [12], but disagree on whether this lack of B rotation at V1 was a coincidence of geometry or if the rotation of the VLISM B toward the Parker spiral direction were an intrinsic HP feature. At the V2 HP crossing the direction of B again did not change [6], showing that the lack of rotation of B may be a normal HP feature.

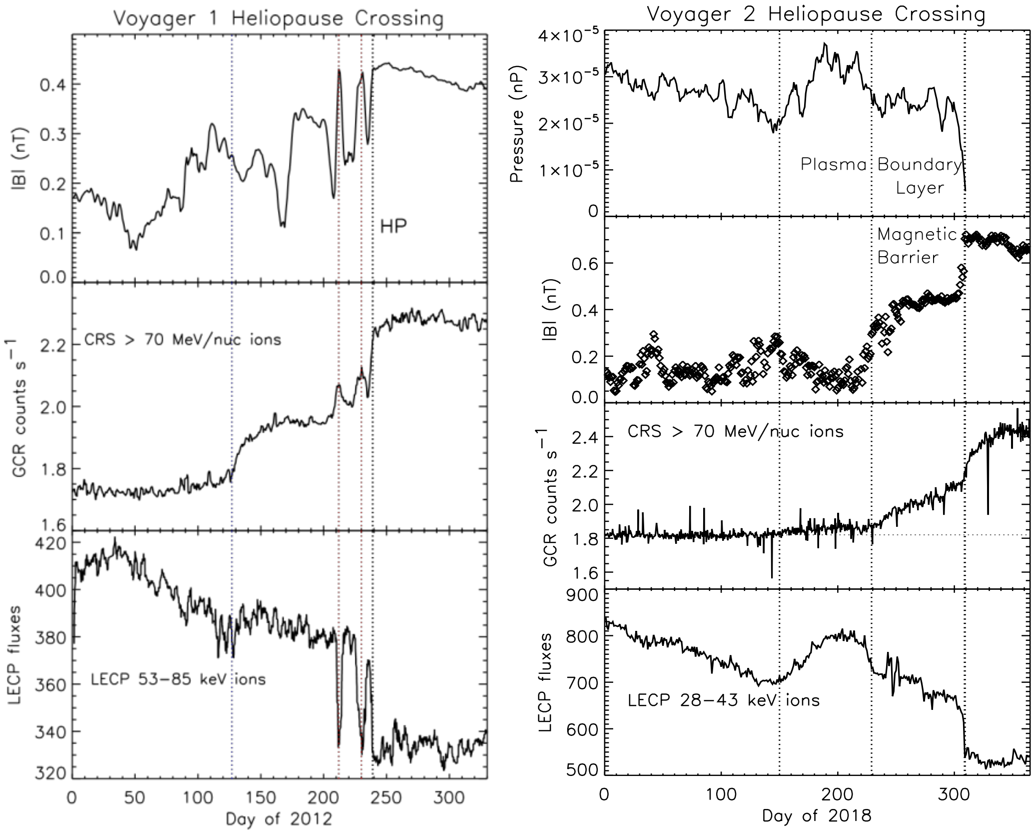

Figure 2. The V1 (left) and V2 (right) HP crossings. Left: The V1 magnetic field magnitude, the GCR count rate, and the 53-85 keV ion intensity. The dotted lines show, from left to right, the first GCR increase, two close approaches to the HP, and the HP crossing. Right: The V2 plasma dynamic pressure, the magnetic field magnitude, the GCR count rate, and the 28-43 keV ion intensity. The dotted lines show, from left to right, the beginning of the plasma boundary layer, the beginning of the magnetic barrier, and the HP.

## 3. Plasma flows and the HP orientation

Voyager data starting about two years ( ~8 AU) before both HP crossings may contain precursors of the HP. Figure 3 compares the flow speeds in the RTN coordinate system derived from LECP and CRS particle data at V1 and V2 using the Compton-Getting effect [13] and the V2 speeds reported by the PLS instrument. The V1 $V_R$ speeds are lower than those at V2 throughout the HSH and go to zero about 2 years (8 AU) before the HP. At V2, the PLS $V_R$ slowly decreases across the HSH, then drops sharply just before the HP. Starting about two years (~8 AU) before the HP, the $V_R$ derived from V2 LECP data vary between near zero and the PLS $V_R$ values, with the average LECP $V_R$ about 40 km/s below the PLS $V_R$ values. These differences are not understood, but the low $V_R$ derived from LECP data at both V1 and V2 two years and 8 AU before the HP suggests they could be related to the HP structure.

The magnitude of $V_T$ is also much larger at V2 than V1, perhaps because V1 is nearer the longitude of the HP nose. The LECP V2 $V_T$ speeds are larger than those from PLS; this difference is probably a sampling bias since the highest angle flows are outside the viewing angle of PLS [13]. The magnitude of $V_N$ decreases at both spacecraft before the HP.

The orientation of the HP at the V1 and V2 crossings may provide information on the global shape of the HP. The plasma velocity and magnetic field at the HP should be parallel to the HP boundary. We use median speed data from within 0.1 AU of the HP to calculate the angles of the HP plane for V2. We assume the LECP $V_T$ values are correct. The LECP values of $V_T$ = 139 km/s and $V_R$ = 23 km/sec give an RT angle (atan($V_R/V_T$)) of 261° for the HP. The PLS $V_R$ in this region is 49 km/s, giving an RT angle of 250°±7°; the angles in both cases signify that the HP is blunt. $V_N$ is not measured by LECP, but using the PLS $V_N$ of -23 ± 17 km/s gives a (RT)N plane angle of 9°± 6°, also in the direction indicating the HP is blunt. The (RT)N angle is defined as atan ($V_N$ /sqrt($V_R^2$ + $V_T^2$)). The observed median magnetic field angles for the same time period are 266° ± 8° in the RT plane and 19° ± 4° in the (RT)N plane; the uncertainty in the $B_R$ component is 0.06 nT and in the $B_T$ and $B_N$ components are 0.03 nT [7]. These results are in agreement given the uncertainties and are consistent with expectations of a blunt HP. The predicted magnetic field angles from a recent model (model b of [14]) gives a magnetic field angle in the RT plane of 260° ± ~3° and an (RT)N angle of 11.3° (+11°, -17°), consistent with the observations reported here.

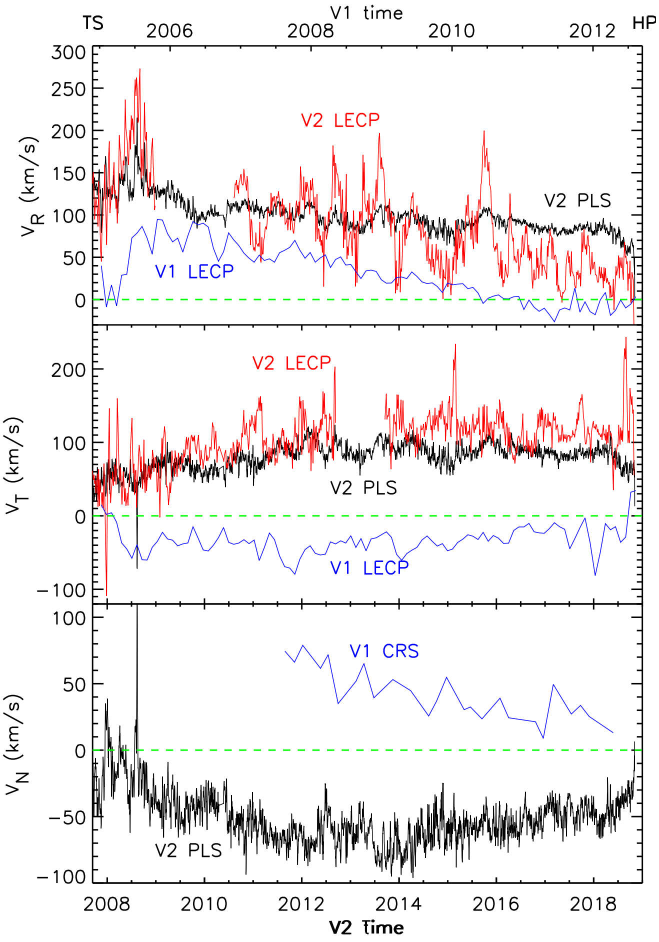

Figure 3. The HSH plasma speeds in the RTN coordinate system from PLS and LECP data for V2 and LECP and CRS data for V1. The left axis is at the termination shock and the right axis at the HP.

## 4. Plasma Boundary Layer and Magnetic Barrier

V2 provided the first plasma data in the HP region. Figures 1 and 2 show that a plasma boundary region, not observed at V1, was entered 160 days (1.5 AU) ahead of the HP. This region is identified by the enhanced PLS currents and dynamic pressure, which correspond to a plasma speed decrease of 30%, a density increase of a factor of 2, and a temperature increase of 30%, giving the 70% increase in the dynamic pressure in Fig. 2 [6]. The LECP 28-43 keV energy ion intensity in the plasma boundary region correlates well with the plasma pressure (and density). A small increase in the GCR slope was observed at the beginning of this region. No change in the magnetic field occurred at the start of the plasma boundary layer. The origin of this region is not known; compression of the plasma as it approaches the HP would increase the density, temperature, and LECP ion flux as observed, but would also cause an increase in B which was not observed.

Figure 2 shows the V1 HP crossing is preceded by a 88 day (~1.3 AU) wide region that started at day 150 of 2012 with a step increase in the GCR rates and ended at the HP crossing on day 238 with a second step increase of GCRs, an increase in B, and a dropout of low-energy ions to background levels [1,2,3]. This region probably contains open field lines that connect the solar wind and VLISM magnetic fields, allowing GCRs to enter the HSH and HSH electrons to exit.

V2 observed an increase in the slope of the GCR intensity 80 days (0.95 AU) before the HP, similar in location to the first V1 GCR increase. At V2, the GCR increase corresponded to the start of the magnetic barrier, a region of increased B not observed at V1 [1]. The average B in the magnetic barrier was ~0.40 ± 0.06 nT, significantly greater than the average B ~0.13 nT from days 1–229 of 2018 [7]. These strong fields were comparable in strength to the magnetic field in the VLISM observed by Voyager 1. Little change in the plasma or LECP ions was observed at the start of the magnetic barrier. The V2 magnetic field increased to 0.7 nT at the HP, significantly larger than the 0.4 nT field observed at V1. The larger B in the VLISM at V2 than V1 was expected, since a larger magnetic pressure in the south would move the TS position in the V2 direction inward compared to V1.

## 5. Plasma in the VLISM

PLS observed VLISM plasma directly for the first time. Although the energy and flow direction of the VLISM are at the limits of what PLS can observe, data from roll maneuvers clearly show that PLS observes the VLISM [6]. Figure 1 shows VLISM currents from the 10–30 eV energy channel of the sideways-looking PLS D-cup. PWS observations show plasma oscillations before the current increase at day 420, suggesting that this current increase is related to the shock that generates these oscillations [8]. The PLS data in the region where plasma oscillations are observed, combined with the density of 0.04 $cm^{-3}$ derived from the PWS data, show that the VLISM temperatures are larger than expected, 30,000°–50,000° K, compared to most predicted values of 15,000°–30,000° K [6]. This higher temperature is near the upper end of the range predicted by Zank et al. [15], who incorporated VLISM heating via secondary charge exchange.

Figure 4 shows the data during spacecraft rolls that clearly indicate PLS observes VLISM plasma, with the current vs. roll angle profile behaving qualitatively as expected. The data are from rolls on days 164 and 255 of 2019 and show data from two different energy channels for each roll. These data are affected by background noise; the currents shown are corrected for noise assuming a constant noise level across the roll. The dashed lines show simulations of currents during the rolls. The upper left plot shows that temperature of 54,000° K fits better than lower temperatures (37,000° and 24,000°), consistent with the higher than expected temperatures mentioned above, and the other three plots also show that 54,000° K gives a reasonable fit to the data. However, more roll data are needed to provide an estimate of the uncertainties in the noise correction procedure. After the roll on day 255 of 2019 the instrument playback was changed to give us double the time resolution during these rolls. The first two rolls with this increased time resolution were aborted due to spacecraft problems and V2 is currently in a command moratorium due to DSN scheduled downtime, but these rolls are planned to resume in late 2020 and should provide the best data to date on the plasma in the VLISM.

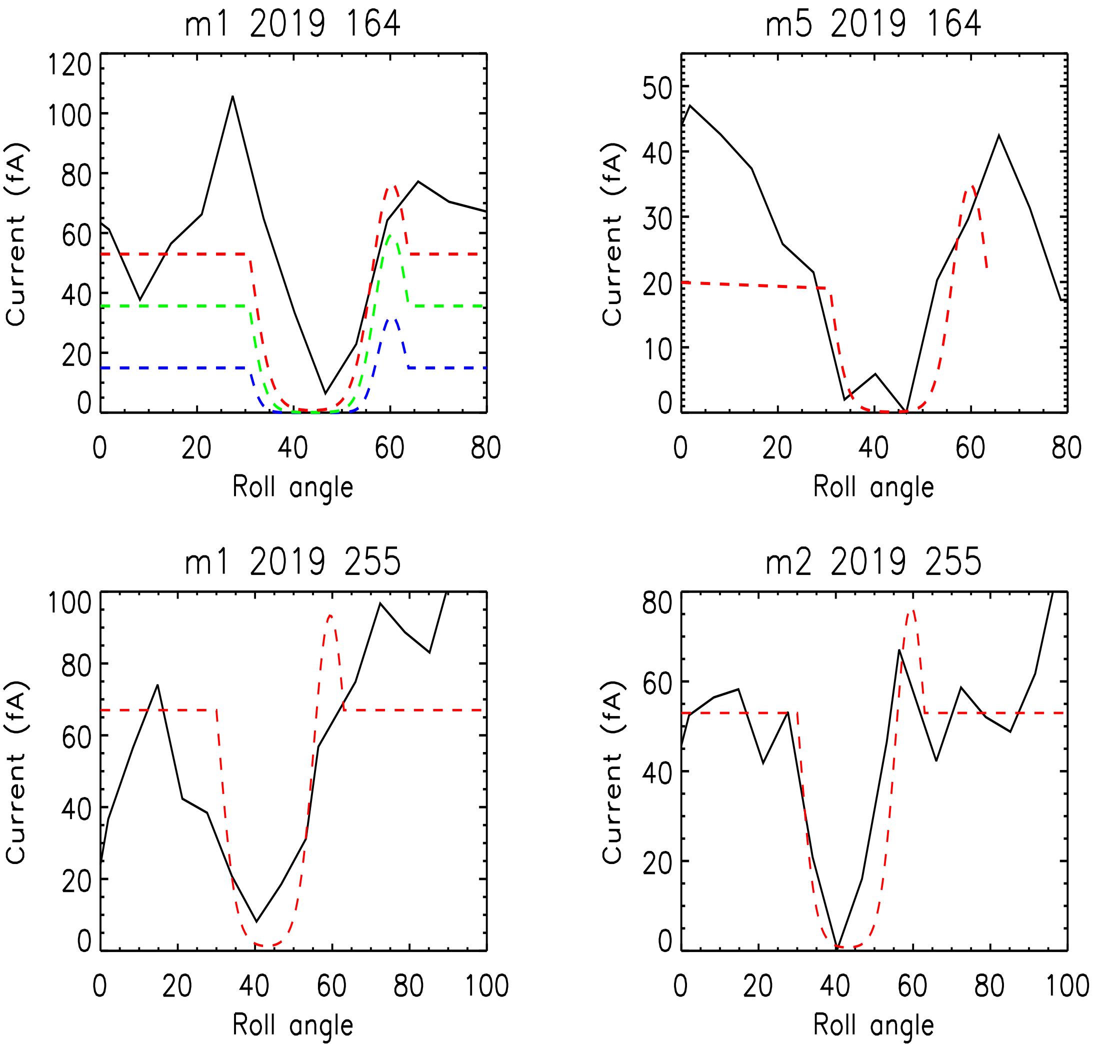

Figure 4. Observed currents in different energy ranges shown in the title of each plot [m2: 10-12 eV; m2: 12-14 eV; m5 19-22 eV) from spacecraft rolls on days 164 and 255 of 2019. The dashed lines show simulations of the expected currents during these rolls for $V_R$, $V_T$, $V_N$ = -10, 20,-10 km/s, N =0.1 cm$^{-3}$, and T = 54,000° (red), 37,000° (green), 24,000° K (blue) and in the upper left panel and 54,000° K in the other panels. As V2 rolls the PLS D cup first looks away from the VLISM flow, then nearest to the flow before the end of the roll.

## 6. Summary

This paper presents and discusses recent Voyager 2 observations near the HP. The first signs of the HP may have been changes in the speed derived from LECP data starting ~2 years (8 AU) before the HP. The PLS instrument did not see a decrease in speed until 160 days (1.5 AU) before the HP, in the newly discovered plasma boundary layer characterized by lower speeds and higher densities. The V2 HP was a sharp boundary where the radial plasma currents went to background levels. Observations of the flows and magnetic field at the HP at V2 are consistent with models predicting a blunt HP. Variations are observed in the currents observed in the interstellar medium; roll data from this region clearly show the plasma instrument observes the interstellar plasma and may be consistent with large than expect temperatures near the HP.

**Acknowledgments.** JDR was supported under NASA contract 959203 from the Jet Propulsion Laboratory to the Massachusetts Institute of Technology and NASA grant 80NSSC19K0260. RBD was supported by NASA contract NNN06AA01C. ECS and ACC were supported by NASA grant NNN12AA01C. ACC, RBD, MO, and JDR acknowledge support from NASA grant 18-DRIVE18_2-0029, Our Heliospheric Shield.

## References

[1] Burlaga, L. F. et al. *Science* **341**, 147–150 (2013)
[2] Krimigis, S. M. et al. *Science* **341**, 144–147 (2013).
[3] Stone, E. C. et al. *Science* **341**, 150–153 (2013).
[4] Gurnett, D. A., Kurth, W. S., Burlaga, L. F. and Ness, N. F. *Science* **341**, 1489–1492 (2013).
[5] Washimi, H, Tanaka, T., and Zank, G.P. *ApJ Lett*. **849**, L9 (2017).
[6] Richardson, J.D., Belcher, J.W., Garcia-Galindo, P. et al., *Nat Astron* **3,** 1019–1023 (2019).
[7] Burlaga, L.F., Ness, N.F., Berdichevsky, D.B. et al., *Nat Astron* **3,** 1007–1012 (2019).
[8] Krimigis, S.M., Decker, R.B., Roelof, E.C. et al., *Nat Astron* **3,** 997–1006 (2019).
[9] Gurnett, D.A. and Kurth, W.S. *Nat Astron* **3,** 1024–1028 (2019).
[10] Stone, E.C., Cummings, A.C., Heikkila, B.C. et al. *Nat Astron* **3,** 1013–1018 (2019).
[11] Bridge, H.S. et al., *Space Sci. Rev.*, **21**, 259-287 (1977).
[12] Pogorelov, N.V., Borovikov, S.N., Zank, G.P., and Ogino, T. *ApJ* **696**,1478-1490 (2009).
[13] Richardson, J.D. and Decker, R.B. *ApJ* **792** 126-130 (2015).
[14] Opher, M., Loeb, A., Drake, J. and Toth, G. *Nat Astron* (2020). https://doi.org/10.1038/s41550-020-1036-0
[15] Zank, G.P., Pauls, H.L.,Williams, L.L., Hall, D.T. *JGR* **101**, 21639-21655 (1996).