Pressure Waves in the Heliosheath?

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Abstract. Models predict that solar transients drive pressure waves through the heliosphere. Pressure pulses are observed near solar maximum upstream of the termination shock and in the heliosphere. These pressure pulses may generate the plasma oscillations observed in the local interstellar medium. We investigate whether the observed plasma, particle, and magnetic field observations are consistent with the presence of pressure waves. The results are mixed. The plasma density, temperature, keV, and MeV particle intensities vary in phase with similar amplitude as expected for pressure waves. The galactic cosmic rays are correlated with the plasma and particles with a ~30-day lag. However, the magnetic field and velocity show only a weak correlation with the plasma and particles.

1. Introduction
The Voyager spacecraft are making the first observations of the heliosheath and local interstellar medium (LISM). Voyager 1 (V1) was at 134 AU in March 2017 in the LISM and Voyager 2 (V2) was at 114 AU in the heliosheath. This paper provides an update of recent V2 observations and compares them with V1 observations. We also investigate whether fluctuations observed in the heliosheath are pressure waves.

2. Recent Voyager 2 Observations
Figure 1 shows 25-day running averages of V2 plasma data through early 2017 and magnetic field data through 2015 [1]. The speed at V2 continues to fluctuate between 120 and 160 km/s but has averaged about 145 km/s throughout the heliosheath; the expected slowdown is not observed [2]. The flow in the heliosheath initially rotated tailward, with the RT angle (using the standard RTN coordinate system) going from 15° after the termination shock to almost 60° in 2014, but since then it has not turned further. The RN angle increased from 5° near the termination shock to about 30° in 2013 but since then has decreased slightly. The plasma flows do not suggest that V2 is nearing the heliopause. At V1 the flow speed was near zero throughout an 8 AU stagnation region before the heliopause crossing; no signs of a stagnation region are observed at V2.

The plasma density increased in 2011, probably associated with the arrival of solar maximum at V2, and has on average remained at about 0.002 cm⁻³ with significant increases in a merged interaction region (MIR) in 2012 [3] and in a probably MIR in 2015. The temperature of the thermal protons is correlated with the density and averages about 50,000 K. The magnetic field data are also on average constant, with increases just after the termination shock and in the MIR in 2012. At V1 the magnetic field B started to increase about two years before the heliopause crossing; no evidence of such an increase is observed at V2 through 2015.
Figure 1. The magnetic field magnitude $B$, plasma speed, plasma flow angles, plasma density, and plasma temperature measured by V2 in the heliosheath.
Figure 2 extends the pressure pulse observations of Richardson et al. [4] to include 2 more years of magnetic field data. V1 crossed the heliosheath near solar minimum and saw few transients, with only one MIR in 2006 [5]. At V2 the solar wind in the outer heliosphere was dominated by MIRs in the 2001 solar maximum with pressure increases of factors of 4-10 observed 1-2 times each year [4]. The top panel of Figure 2 shows the solar wind dynamic pressure in the HSH and the monthly sunspot numbers. As solar activity increased pressure pulses were observed with a similar frequency to those observed before the TS crossing but with much lower amplitudes, usually factors of 0.5 except for one factor of three increase in 2015. The pressure increase in 2012 was a MIR with an increase in B and a decrease in the galactic cosmic ray (GCR) intensity [5]. Richardson et al. [4] suggest that pressure pulses D, E, F, and G could be MIRs based on the GCR decreases. Subsequent magnetic field data show that while D is a small MIR, E has no associated B increase [1]. We expect that the 2015 event, which has the largest pressure increase and GCR decrease, will have a B increase but analysis of these data is not yet complete.

![Figure 2](image.png)

**Figure 2.** The top panel shows the dynamic pressure in the heliosheath at V2 and the monthly sunspot number. The bottom panel shows the magnetic field magnitude and the CRS >70 MeV GCR count rates.
3. Pressure waves in the heliosheath

Several studies predict that solar transients drive pressure waves in the heliosheath [6, 7, 8, 9, 10, 11, 12]. These pressure pulses are partially transmitted and partially reflected near the heliopause. The reflected waves again encounter the termination shock, moving it inward [9, 10]. The transmitted waves drive weak shock waves into the LISM [8].

Figure 3. The profiles of B, N, keV ions, MeV ions, and GCRs in the heliosheath
We investigate the properties of the pressure pulses in Figure 3. If these events are pressure waves the thermal plasma density and temperature, particle intensities, speed, and magnetic field should all vary in phase. Figure 3 shows the V2 magnetic field, thermal plasma density, 28-43 keV ion intensity, >0.5 MeV ion intensity, and GCR intensity. This comparison is qualitative, each quantity is scaled to fit in the plot. The density N and B are 11-day running averages and the particle intensities are one-day averages. The plot covers 2009.5 through early 2017; from the termination shock crossing at 2007.7 to 2009.5 solar minimum conditions are prevalent and pressure pulses are not observed [2]. The transition from solar minimum at V2 occurs in 2011 where the plasma density and average magnetic field increase. After this time pressure pulses dominate the heliosheath.

The first MIR observed at V2 in 2012 [3] has a factor of 2 increase in B and corresponding increases in the density and all the particle intensities. The large increase in density in late 2015 corresponds to the biggest pressure pulse V2 has observed in the heliosheath, with a factor of 3 increase in pressure, increases in the particle intensities, and a GCR decrease suggesting that B also increases in this event. The smaller event at about 2013.6 has also been identified as a MIR [1] and has the same characteristics as the 2012 MIR. Increases in early 2014, in 2015 before the large event, and two in 2016 occur in all the particle data. The GCR peaks occur just before the particle peaks, suggesting they are at least partially produced by pile up in front of the increase in B.

The panels of Figure 4 compare the fluctuation amplitudes; we plot for each parameter x 25-day (1 solar rotation) averages of (x - <x>)/<x> where we average <x> over 301 days. Figure 4a compares the thermal proton density and temperature. For a pressure wave N and T should vary in phase, with Tperp (to which V2 predominantly responds) changing due to conservation of the first adiabatic invariant as B increases. The correlation coefficient is between the changes in N and T is 0.88 and peaks at zero lag. We note that N and T are derived from the same fits to PLS spectra so are not totally independent quantities, but this correlation is not seen in the supersonic solar wind, only the heliosheath.

Figure 4b compares the plasma densities and the 28-43 keV ion intensities. The low energy charged particle (LECP) experiment intensities are expected to vary slightly more than the PLS densities since the LECP ions are both compressed and heated in the pressure waves. The data show that this effect occurs before 2014; after that the fluctuations are roughly the same. The correlation coefficient is 0.60 with highest values at small lags, so these values change in phase. Figure 4c compares plasma densities with cosmic ray subsystem (CRS) >0.5 MeV ion intensities. The correlation with between N and the >0.5 MeV particles is 0.66 with a lag of 0. The keV and MeV ions are both accelerated in the heliosheath so their variations are expected to be similar, as shown in the data. The keV and MeV intensity changes have a correlation coefficient of 0.85 in this time period.

Figure 4d compares the density and CRS >70 MeV GCR intensity fluctuations. The GCRs originate outside the heliosphere and diffuse through the heliosphere. Previous work shows that GCR intensities peak before MIRs since the increased magnetic fields reduce diffusion and show Forbush decreases after the MIRs [13]. The data show that the GCR intensities increase before the density and lower-energy particle peaks. The best correlation with density is 0.61 with a 33 day lag (GCR features are observed before density features). The correlation of GCR and >0.5 MeV intensities is .85 with a 25 day lag. The magnitude of the GCR fluctuations is less than that for other particle intensities by about a factor of ten.

Figure 4e compares magnetic field and density variations. For pressure waves we expect these fluctuations to be similar. However, the plot shows that B variations are larger and more frequent than those of the plasma and particles. The correlation between B and N variations is weak, only 0.34. We have tested other correlations with B, such as dynamic pressure NV2 and VR, and these correlations are also weak. We note that magnetic field data during the large 2015-2016 variations are not yet available.
4. Discussion and Summary

We have tested the conjecture that pressure waves are important components of the structure in the heliosheath. The results are mixed. Particle intensities changes of the thermal plasma, keV energy, and MeV energy plasma are correlated, in phase, and have similar amplitudes. The thermal plasma density and temperature are highly correlated. These results are consistent with pressure waves. The GCRs are correlated with lower energy ion intensities but with a ~25 day lag, consistent with these particles being influenced by magnetic fields in pressure waves. The magnetic field, however, is only weakly correlated with the particle intensities and plasma properties. This result is not consistent with pressure waves and is not understood. We will continue these studies as more data become available.

Figure 4. Comparison of changes in density (black curves) compared to changes in other particle intensities and B (red curves). The plots of each parameter x show (x-<x>/<x> where <x> is averaged over 301 days.
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5. References

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