PLASMA WAVES IN THE VERY LOCAL INTERSTELLAR MEDIUM: A BRIEF REVIEW

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Abstract

The Plasma Wave Science instruments on the two Voyager spacecraft are providing observations of plasma waves in the very local interstellar medium. One of the most important aspects of these observations are the inferred electron densities from the identification of electron plasma oscillations and a quasi-thermal line at the plasma frequency. They provide the first and only in situ determination of the plasma density in the interstellar medium and have revealed an outward radial gradient as a large scale feature of the interstellar medium upstream of the heliopause. The presence of the electron plasma oscillations provides evidence that transients from the sun, after propagating through the heliosphere, can modulate the surrounding medium.

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1 Introduction

The two Voyager spacecraft were launched in August and September 1977, originally to make reconnaisance flybys of Jupiter and Saturn. Having carried these out successfully Voyager 2 was then targeted to Uranus and then Neptune. Meanwhile, Voyager 1, which executed a close flyby of Titan during its Saturn encounter, continued on an escape trajectory from the Sun, moving well north of the ecliptic plane and in the general direction of the so-called nose of the heliosphere, the direction from which the interstellar medium is flowing. After its Neptune encounter, Voyager 2 also continued on an escape trajectory moving well south of the ecliptic, but also in the general direction of the nose of the heliosphere. The mission was extended and renamed the Voyager Interstellar Mission (VIM).

Given that there were no targets of opportunity for the remote sensing instruments, most of them were turned off, leaving the fields and particles instruments and the ultraviolet instrument to explore the outer heliosphere and beyond. This short review focuses on observations by the Plasma Wave Science (PWS) instrument (Scarf & Gurnett, 1977). The two PWS instruments use a pair of orthogonally-extended 10-m cylindrical antennas as a balanced dipole. They have two receivers. One of them is a 16-channel spectrum analyzer covering the frequency range from 10 Hz to 56 kHz with logarithmically-spaced channels. For most of the VIM, measurements from this receiver are received as the sum of 4 measurements acquired over 16 s for each channel, effectively 16-s averages. The other receiver is a wideband waveform receiver covering 10 Hz to about 12 kHz. It digitizes the voltage at the antenna input 28,800 times per second with 4-bit resolution. An automatic gain control amplifier is used to set the signal level for optimum use of the 4-bit analog-to-digital converter. However, there was no telemetry channel available to transmit the gain to the ground, so the waveform data cannot be calibrated in an absolute sense. These data are acquired in 48-second frames consisting of 800 'lines' of 1600 samples every 60 ms and are stored on the digital tape recorder (DTR) at a rate of 115 kbps. The 1600 samples require 55.55 ms to collect, so there is a 4.44 ms gap between each 'line'. For much of the VIM, there is a mis-match between the maximum downlink rate of 1.4 kbps and the slowest DTR playback rate of 7.2 kbps. This results in only 1 of 5 'lines' of waveform data being returned. A frame of waveform data is recorded one to a few times per week. The waveform receiver on Voyager 2 stopped producing usable data in 2002. Additional information on the Voyager waveform data and their analysis is given in Kurth et al. (2023).

2 Radio emissions from beyond the heliopause

The Voyager PWS investigation of the interstellar medium actually began remotely in the early in the 1980's with the detection of radio emissions in the frequency range of ~ 1.8 to 3.6 kHz (Kurth et al., 1984). Figure 1 shows a frequency-time spectrogram of these emissions acquired from 1983 to 1997. While these data are from Voyager 1, Voyager 2 observed the same emissions. At the time, both were beyond their encounters with Saturn and at heliocentric distances of 12 or more astronomical units (AU). Critical to the detection of these very low frequency radio emissions was the fact that the solar wind plasma frequency at this distance is below about 1 kHz. The spectrogram shows radio emissions with a relatively sharp onset and a slow drift in time, ~1 kHz/yr (Kurth et al., 1987). The emissions below the power supply interference line drift much more slowly than those above 2.4 kHz.

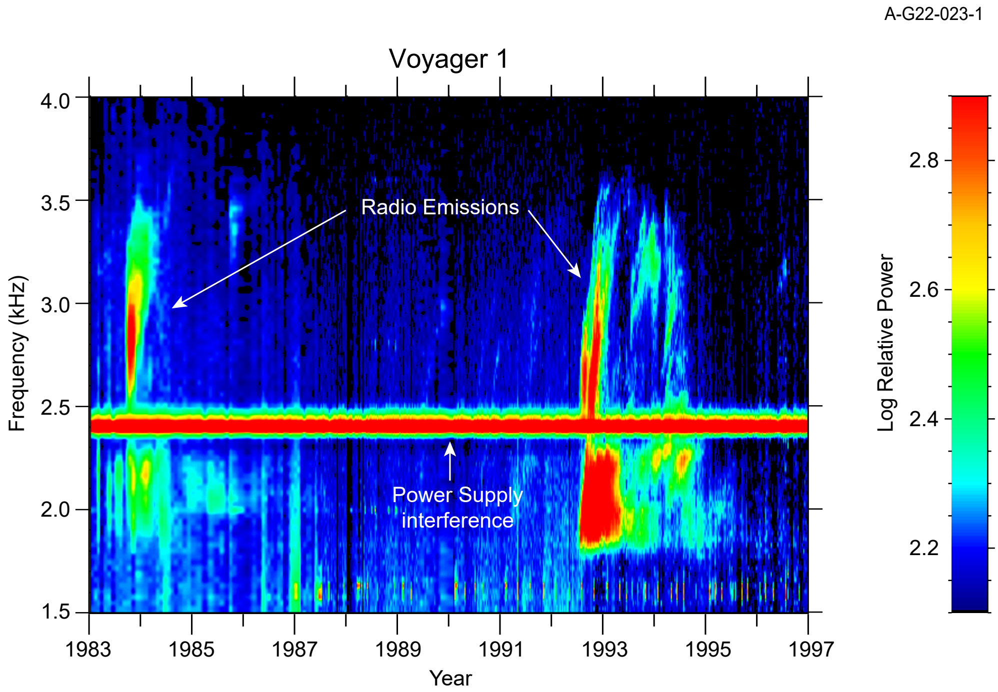

Figure 1: *Frequency-time spectrogram of low-frequency radio emissions orginating in the VLISM. The relative amplitudes of waves are displayed using the color bar on the right.*

Gurnett et al. (1993) provided the first relatively complete explanation for the low-frequency radio emissions and that explanation remains basically correct, today. These two radio emission events followed the two largest Forbush decreases on record at the time, by 412 and 408 days, respectively, for the radio events beginning in 1983 and 1992, strongly suggesting that solar activity is ultimately the trigger for them. This means the transients that propagate out from the Sun and evolve into merged interaction regions and even global merged interaction regions, eventually reach the heliopause. Part of this disturbance is transmitted through the heliopause and into the very local interestellar medium (VLISM). As the shock propagates, it accelerates electrons that form a bump-on-tail distribution that is unstable to electron plasma oscillations, much like in the electron foreshock of a planetary bow shock. The plasma oscillations can then mode convert, probably through a nonlinear interaction, creating ordinary mode radio emissions. The radio emissions can propagate into lower density plasmas and eventually be detected in the heliosphere. The rising tones mean the shocks move into increasing plasma densities, exciting higher frequency plasma oscillations, hence radio emissions, as the shock moves outward. The electron plasma frequency is related to the electron density by $f_{pe} = 8980\sqrt{n_e}$ where f_{pe} is in Hz and n_e is in cm^{-3}. Using the range of the radio emission frequencies of 1.8 to 3.6 kHz, and assuming the conversion of plasma oscillations to radio emissions takes place at f_{pe}, then the observations in Figure 1 give the electron densities at the source in the interstellar medium between 0.04 and 0.16 cm^{-3}.

Gurnett et al. (1993) used a time-of-flight argument based on the $\sim$ 400-day delay from the Forbush decreases to the radio emission onset of the two events in Figure 1 to estimate the distance to the heliopause to be in the range of 116 to 177 AU. Most of the uncertainty in this determination was due to various estimates of the speed of the solar transients based on the timing of the passage of them past Voyagers 1 and 2 and Pioneers 10 and 11. Another significant source of uncertainty had to do with the propagation speed of a shock through the heliosheath and the thickness of the heliosheath, which at the time were based soley on modeling.

So, given the observations in Figure 1, the approximate distance to the heliopause was known and the electron density in the interstellar medium just beyond the heliopause was known. Further, the radio emissions are evidence that the Sun can influence the very local interstellar medium. The confirmation would be in the detection of electron plasma oscillations beyond the heliopause, should Voyager be in the right place at the right time.

3 Plasma waves in the VLISM

3.1 Electron plasma oscillations

It wasn't until 2013 when Voyager 1 had entered the VLISM for the Gurnett et al. (1993) predictions to be confirmed (Gurnett et al., 2013). In this paper, two instances of electron plasma oscillations (in late 2012 and spring of 2013) were reported. These can be seen early in Figure 2. The plasma frequencies for these two events at $\sim$ 2.2 kHz and 2.6 kHz, respectively, correspond to electron densities of 0.06 cm^{-3} and 0.08 cm^{-3}. These densities are of the order 50 times greater than those measured by the Voyager 2 plasma instrument in the heliosheath and provided the final argument that Voyager 1 had, indeed, crossed the heliopause on 25 August 2012 at a distance of 121.6 AU. At that point the rates of galactic cosmic rays jumped and the rates of solar wind energetic particles dropped as observed by the Voyager 1 Cosmic Ray Science instrument (Stone et al., 2013) and the Low Energy Charged Particle instrument (Krimigis et al., 2013). There had been considerable discussion about the boundary crossing since the expected rotation of the magnetic field from a solar orientation to an interstellar orientation was not observed (Burlaga et al., 2013).

While the Voyager 2 PWS no longer has a functional wideband waveform receiver, it does have the capability to detect plasma oscillations with its spectrum analyzer. These data were used by Gurnett & Kurth (2019) to confirm the crossing of the heliopause by Voyager 2 and to establish the VLISM electron density at Voyager 2 just beyond the heliopause at 119 AU was similar to that observed by Voyager 1. Given the rather coarse frequency resolution of the Voyager spectrum analyzer, Gurnett & Kurth (2019) determined the density to be 0.039 cm^{-3} but with an uncertainty between 0.0347 and 0.0454 cm^{-3}.

A second plasma oscillation event was detected by Voyager 2 (Kurth & Gurnett, 2020) at a distance of 124.2 AU and was used to establish a radial gradient in the direction of

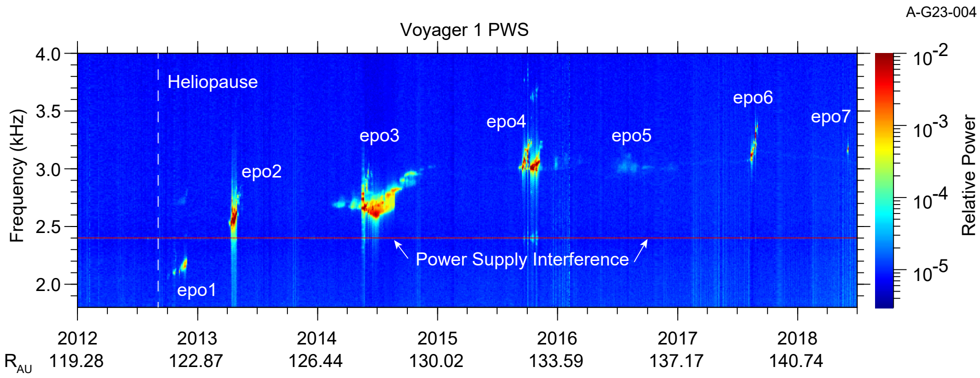

Figure 2: *Voyager 1 electron plasma oscillation events through June 2018.*

Voyager 2 that was very similar to that reported from Voyager 1 observations. Given that the two spaceraft are separated by some 70° on the sky and are at distances well over 100 AU, these observations allow one to conclude the radial gradient is a large-scale feature of the VLISM at least in the general direction of the nose of the heliosphere.

A third, very brief electron plasma oscillation event was observed by Voyager 2 on 23 May, Day 143, 2021 at a distance of 127.1 AU. Figure 3 shows the observations for this event. Here, we show three of the spectrum analyzer channels centered at 1.78, 3.11, and 5.62 kHz. The solid black areas show average electric field values and the line above the black area represents peak values. The May 2021 event lasted no more than a day. (The gaps in Figure 3 are due to incomplete tracking coverage by the Deep Space Network. Voyager 2 is only in view of the complex in Canberra, Australia.)

3.2 Weak emission line at f_{pe}

By using special signal processing techniques, Ocker et al. (2021) were able to detect a very faint, narrowband line in the Voyager 1 waveform measurements acquired after about 2016. This line was observed to connect some of the more recent plasma oscillation events and was more-or-less continuously present. This discovery enables a more continuous determination of f_{pe}, hence, electron density. Other processing capabilities have been developed to detect this line (c.f. (Burlaga et al., 2021) and (Kurth et al., 2023)). The bottom panel of Figure 4 shows a frequency-time spectrogram with a gray-scale stretch designed to reveal this line. Note that the plasma oscillation events are highly saturated with this dynamic range.

Gurnett et al. (2021) showed that a Maxwellian distribution with a temperature of 7000 K plus a kappa distribution with $\kappa = 1.53$ could produce a quasi-thermal noise line at f_{pe} intense enough to be observed by Voyager 1. Meyer-Vernet et al. (2022) suggested that a full kappa distribution as described by Gurnett et al. (2021) would contribute excessive pressure to the VLISM and argued that just a small population of fast electrons could result in the an observable quasi-thermal line. The presence of the line provides a

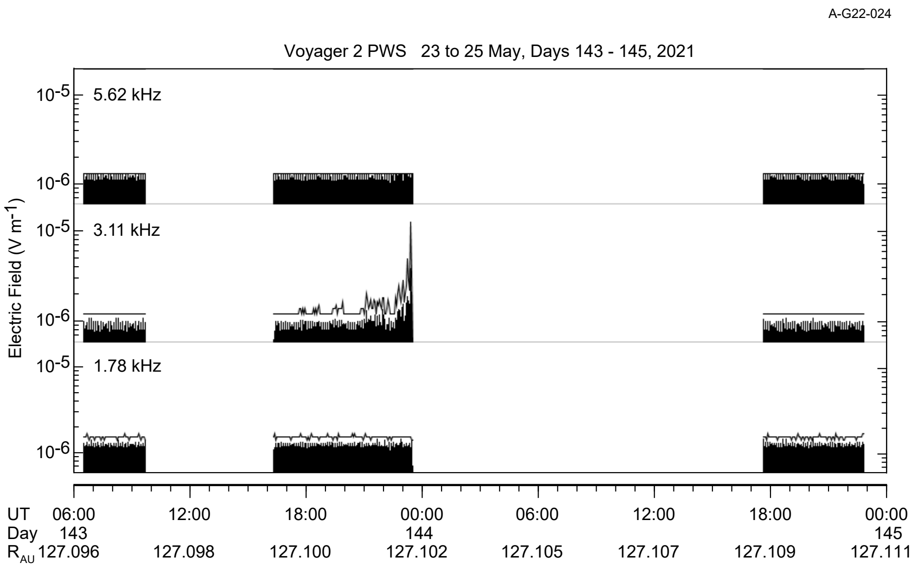

Figure 3: *Voyager 2 detection of an electron plasma oscillation event in 2021.*

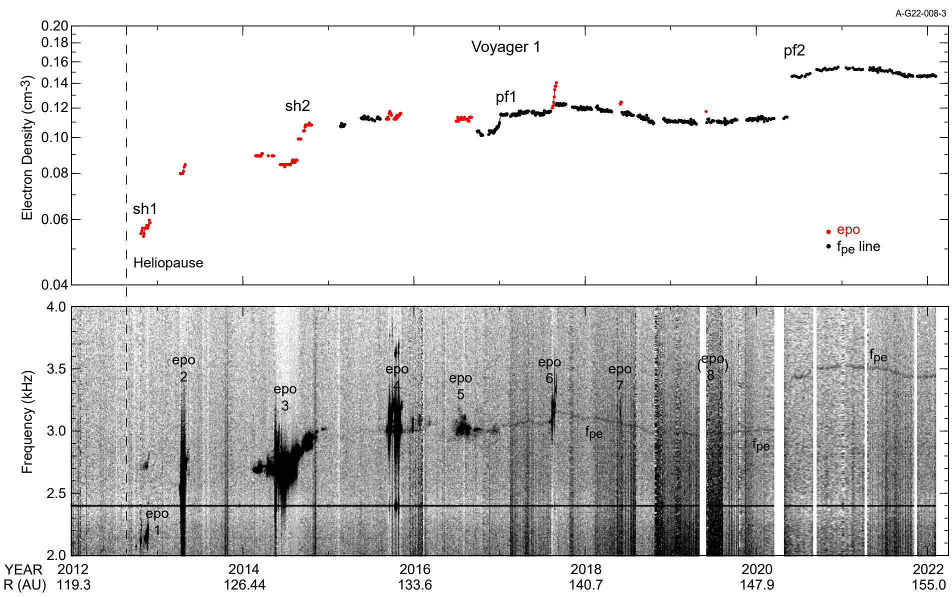

Figure 4: *(top) Electron densities inferred from the frequency of electron plasma oscillations (red) and the quasi-thermal line (black) at f_{pe}. (bottom) Long-term spectrogram of plasma waves measured by the Voyager 1 wideband receiver. The notations sh1, sh2, pf1, and pf2 denote the times of shocks and pressure fronts discussed by Burlaga et al. (2021).*

quasi-continuous measure of the electron density in the VLISM, a much-needed quantity given there is no functional plasma instrument on Voyager 1. We should say that 'quasi-continuous' in this usage refers to the fact that the waveforms are only sampled one to a few times per week.

Using the above relation of the electron plasma frequency to the electron density, it is straightforward to derive the electron density along Voyager 1's trajectory as shown in the top panel of Figure 4.

4 Discussion and conclusion

The detection of electron plasma oscillations and, more recently, the weak line at the electron plasma frequency represent the only in situ observations that provide the electron density in the VLISM. As a fundamental property of this medium, its importance cannot be overstated. The plasma wave observations from both Voyager PWS instruments have provided a first in situ look at the structure of the plasma just beyond the nose of the heliosphere. Figure 5 is an updated illustration from Kurth & Gurnett (2020) that includes the three Voyager 2 events superposed on other measurements of the plasma density made by both Voyagers and including densities from the Voyager 2 plasma instrument in the heliosheath. The major result is that both Voyagers observe a similar radial gradient in the upstream direction from the heliopause, despite being separated by some 70° on the sky.

This radial gradient is also evident in greater detail in the top panel of Figure 4 using the Voyager 1 observations of both electron plasma oscillations and the quasi-thermal line at f_{pe}. As foretold by the radio emissions observed deep in the heliosphere decades ago, the gradient extends from about 0.04 to 0.016 cm^{-3}. Superposed on what might be considered an asymptotic rise to the upper limit of this range are a number of abrupt jumps in the density. Some of these are associated with shocks and pressure fronts identified in the magnetometer observations by Burlaga et al. (2021). In fact, the most recent event, pf2 in Figure 4, is responsible for a significant fraction of the rise in density.

The fact that Voyager 1 observed approximately one plasma oscillation event per year through about 2019 (Figure 4) and Voyager 2 observed the events at a similar pace, would seem at odds with the simple picture in Figure 1 with one major event on the time scale of a solar cycle. However, there is evidence for weaker radio emission events in the wideband observations in the heliosphere that are not as prominent as the events beginning in 1983 and 1992. For example, close inspection of Figure 1 shows some weaker events between 1989 and 1992 as well as in 1996. Another event in 2002 was reported by Gurnett et al. (2003). So, one might conclude that the events in 1983 and 1992 were standouts for their intensity, duration, and complexity. However, the recent observations of plasma oscillation events suggest an ongoing train of disturbances that persist after their evolution and merging in the outer heliosphere extending over time scales approaching a solar cycle.

We conclude by emphasizing the insight gained of the VLISM through the observation of radio and plasma waves. These represent the only Voyager observations that provide electron density measurements beyond the heliopause and have revealed the structure of the plasma density in the interstellar medium just upstream of the heliopause and its response to solar transients.

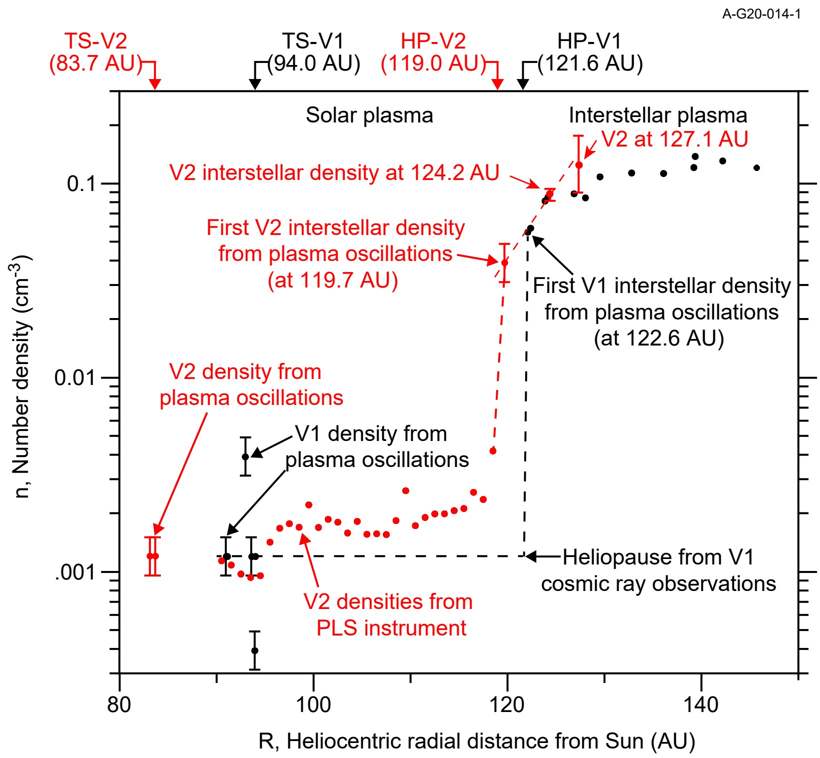

Figure 5: *A summary of electron densities in the VLISM and evidence for a large-scale radial density gradient, after Kurth & Gurnett (2020). The measurements with error bars are all from the frequency of electron plasma oscillations observed using either Voyager 1 or 2 PWS spectrum analyzers. The red dots without error bars are from the Voyager 2 plasma instrument. The black dots are from the Voyager 1 PWS. After the heliopause, these are taken from waveform measurements, hence, have very small errors compared to those from the spectrum analyzer observations.*

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