Plasma waves associated with the termination shock

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Abstract. Voyager 1 crossed the termination shock of the heliosphere on December 16, 2004 and provided our first opportunity to examine this unique boundary and associated processes. A common wave phenomenon that is often observed upstream of shocks in the solar wind are Langmuir waves, or electron plasma oscillations. Langmuir waves were observed sporadically by Voyager 1 for nearly a year prior to the termination shock crossing. The Langmuir waves are thought to be produced by a bump-on-tail electron distribution consisting of beams of electrons coming from the shock, and are usually produced by a velocity selection effect caused by the convection of the solar wind. In fact, evidence for such electron beams was found in conjunction with Langmuir waves observed on the day prior to the termination shock crossing. Voyager 2, which trails Voyager 1 in heliocentric distance by about 19 AU, is now approaching the termination shock and promises a second opportunity with which to observe the region near this boundary. We assess the usefulness of Langmuir waves as a predictor of an impending shock crossing, using the Voyager 1 experience as a guide.

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INTRODUCTION

Kurth and Gurnett [1] suggested that Langmuir waves (electron plasma oscillations) might be observed prior to Voyager crossing the termination shock and that a broadband burst of electrostatic wave turbulence might be observed at the crossing, itself. As noted by Gurnett and Kurth [2] , the upstream Langmuir waves, were, indeed found preceding the shock crossing. However, due to the crossing itself occurring during a data gap, the existence of broadband wave turbulence at the shock is yet to be verified.

In this paper, we review the case for Langmuir waves upstream of the termination shock and the observations obtained by Voyager 1. A fundamental purpose for the Kurth and Gurnett [1] publication was to provide some guidance as to the utility of plasma wave measurements as indicators of an imminent termination shock crossing. As will be discussed, the Voyager 1 Langmuir wave observations spanned a range of time of about 10 months prior to the crossing, hence, did not provide a very reliable predictor of an imminent crossing. However, in retrospect, the solar wind pressures derived from the Voyager 2 plasma instrument now suggest that for a significant portion of 2004 the termination shock was moving outward with Voyager 1, in effect, chasing it. Hence, it is likely that Voyager 2 detections of Langmuir waves in conjunction with in situ plasma pressure measurements may be used more effectively to predict the crossing.

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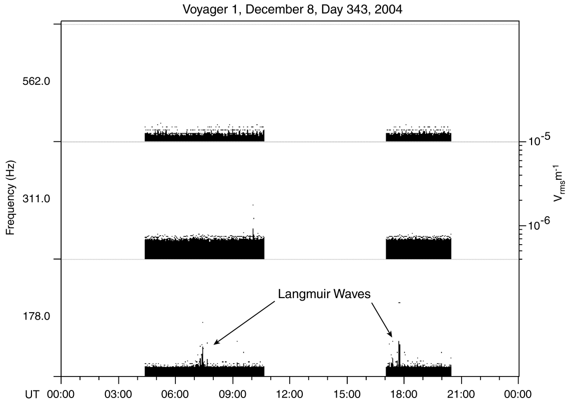

FIGURE 1. Voyager 1 observations of Langmuir waves on December 8, Day 343, 2004.

OBSERVATIONS

The observations of upstream Langmuir waves were obtained by the Voyager 1 16-channel spectrum analyzer portion of the plasma wave science instrument (see Scarf and Gurnett [3] for a detailed instrument description). In the mode used for the outer heliosphere, a spectrum is acquired every 4 seconds and four of the logarithmically-compressed amplitudes are summed for each frequency channel providing a 16-second 'average' for each channel. Since the log compression is not exactly logarithmic, and in fact, has a linear range at low amplitudes, the 'average' is not mathematically well-defined. Nevertheless, the net result is a spectrum every 16 seconds.

The Voyager plasma wave instrument is susceptible to a number of sources of narrow-band bursty interference that might be mistaken for Langmuir waves. We have examined an extensive set of observations for such interference. For every significant burst of noise we have searched the onboard sequence for events which might cause interference. From this information, we developed an algorithm to exclude measurements at times of events which have been shown to produce interference at various frequencies. Thruster firings may show up more or less at random as these occur sporadically to keep the space-craft pointed at Earth. To avoid this source of potential interference, we have removed measurements above background that do not persist for four spectra (64 seconds). After this filtering process, we are confident that remaining narrowband noise bursts have a high probability of being due to naturally-occurring phenomena and not spacecraft interference. It should be noted that most of the interference is relatively low in amplitude compared to many of the magnetospheric emissions observed by Voyager throughout its mission. However, the amplitudes of the upstream emissions were expected to be relatively close to the limit of detectability of the instrument [1], hence, any interference can potentially mask the natural emissions.

Figure 1 is an example of the observations of upstream waves and shows three of the Voyager 1 spectrum analyzer channels for a period during December 8, Day 343, 2004.

TABLE 1. Upstream wave events observed by Voyager 1 [2]

Day of 2004	Radial Distance (AU)	Frequency (Hz)	Max. Intensity (μV/m)
042–043	91.0	311	2.0
054-057	91.1	311	1.2
242–245	93.0	562	1.1
311–312	93.7	311	1.3
343	94.0	178	1.3
350	94.1	178–311	1.7

Clear evidence of narrowband bursty emissions can be seen in the 178 Hz channel near 07:15 and 17:40 UT. That these emissions, typically, only appear in one channel and not the surrounding channels is evidence of their narrowband nature, although narrowband signals near the midpoint between two successive channels can, in principle, appear in both channels.

Table 1 lists the upstream events observed in the 10 months or so preceding the termination shock crossing [2] which evidently occurred on day 351 (December 16) 2004. The first of these events occurred over the interval February 11–15 (days 042–043) 2004. Prior to the February event, there were basically no clearly evident examples of such wave activity for several years. A final event was observed on December 15, day 350, just before a day-long data gap and is shown in Gurnett and Kurth [2]. After the data gap, the spacecraft was in the heliosheath, on the other side of the termination shock [4] [5] [6].

Figure 2 is an adaptation of an illustration given by Kurth and Gurnett [1] illustrating the amplitude of Langmuir waves associated with planetary bow shocks as a function of heliocentric radial distance with the addition of the amplitudes observed for the termination shock upstream events. For reference, we have included a line representing the energy density in the solar wind as a function of distance. Gurnett et al. [7] pointed out that the intensity of Langmuir waves in the inner heliosphere observed by Helios scaled as this quantity. Note that while the events are somewhat below the range of intensities predicted, they are not unreasonably low and, more to the point, they are in the same range of amplitudes as waves observed upstream of interplanetary shocks in the distant heliosphere.

Langmuir waves associated with shocks in the heliosphere are believed to be driven by unstable distributions of electrons known as ‘bump-on-tail’ distributions. These distributions have a region in velocity space where $df/dv > 0$. While it is not impossible for such an unstable beam to exist in the upstream plasma, directly, Filbert and Kellogg [8] pointed out that the convection of the solar wind acts as a velocity selector which guarantees such a positive slope in the beam distribution. That is, if one assumes a broad distribution of energetic electrons coming from a point at which the magnetic field is tangent to the shock surface, the solar wind will convect the beam electrons as they move along the magnetic field. At a given point in the electron foreshock, only electrons above a given critical energy can reach the point; less energetic electrons will have convected downstream. The resulting distribution will show a bump above the critical

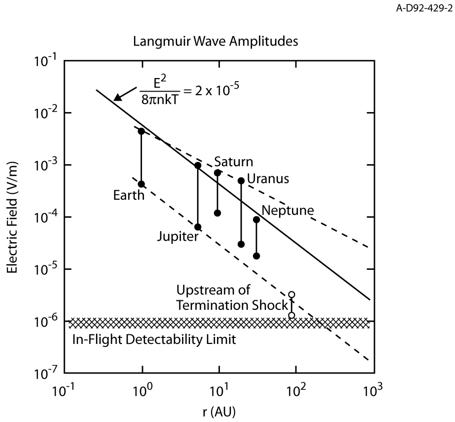

FIGURE 2. Comparison of extrapolated Langmuir wave amplitudes upstream of planetary bow shocks as a function of heliocentric radial distance with observed intensities upstream of the termination shock.

energy (velocity).

Decker et al. [2005] showed evidence for electron beams moving sunward at the time of the Langmuir wave observations on December 15 (day 350). Figure 3 shows evidence for the anisotropic beam of electrons in the energy range of 0.35 to 1.5 MeV at the times of the observed waves. As indicated by the inset describing the sectors, anisotropies with fluxes greatest in sector 3 would be indicative of a beam directed toward the sun. The electron spectra do not show the positive slope in velocity space, which likely occurs at lower energies, possibly much lower energies. Hence, it is likely the energetic electrons are the high energy tail of the beam. We have examined electrons in this same energy range at the times of the other wave events listed in Table 1 but have not found similar distributions that might be indicators of electrons accelerated at the shock. Because the electrons in Figure 3 are likely at much higher energies than those expected to drive the Langmuir waves, the search needs to be expanded to lower energies, an effort which is ongoing.

DISCUSSION

The observations of Langmuir waves upstream of the termination shock confirms a prediction by Kurth and Gurnett [1993] that such waves ought to be observable and would serve to indicate that a crossing might occur in the not-so-distant future. However, Kurth and Gurnett, based on evidence from planetary foreshocks and Langmuir waves associated with type III bursts, suggested that unstable beams can propagate for distances of order 1 AU. They attempted to estimate how much warning this might provide for an impending termination shock crossing. However, they implicitly assumed a stationary shock to arrive at estimates of the order of a few weeks depending on the deviation of the magnetic field from its normal Parker orientation. In reality, the Voyager 1 observations of upstream waves were spread over approximately 10 months, which is not very useful

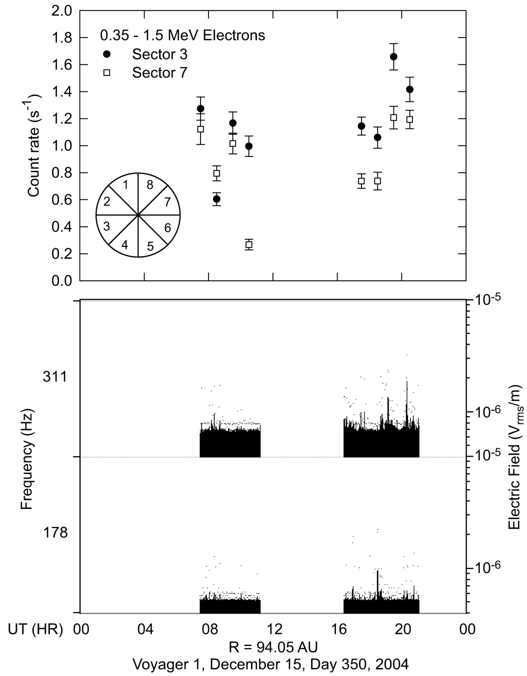

FIGURE 3. Anisotropic distributions of 0.35 - 1.5 MeV electrons observed by the LECP instrument as the plasma wave instrument observed upstream Langmuir waves just prior to the termination shock crossing.

from the point of an operational response, e.g. obtaining additional tracking by the Deep Space Network.

However, in retrospect, additional information is available from the solar wind plasma pressure which helps to interpret the upstream waves. As shown in Figure 4, Richardson et al. [9] have used the average pressure to estimate the distance of the termination shock. In fact, during a good part of 2004 the pressure was increasing, hence, the termination shock was likely moving outwards, perhaps just ahead of Voyager 1. We have added red dots to the dashed line representing the trajectory of Voyager 1 in Figure 5 at times when the upstream waves were observed. These are times when the distance to the shock may have been quite small. The specific trajectory of the termination shock in Figure 4 is likely not accurate in detail, as Voyager 2 was separated from Voyager 1 during this time by some 100 AU. Obviously, the termination shock trace actually intersects that of Voyager 1 in 2003 long before the observed crossing. Nevertheless, the upstream wave observations suggest that the termination shock was close to Voyager 1 early in 2004 before receding, qualitatively similar to the variations seen in Figure 4.

Therefore, we suggest that (a) having local solar wind plasma measurements on Voyager 2 will improve the detailed knowledge of the motion of the termination shock

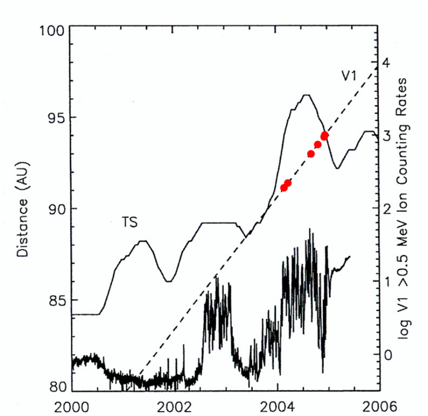

FIGURE 4. Plot of locations of Langmuir Wave activity on the Voyager 1 trajectory (red dots) with an estimate of the location of the termination shock based on averaged Voyager 2 solar wind pressures. After Richardson et al. [9]

in the vicinity of Voyager 2 as it approaches the shock and (b) observations of upstream waves when the solar wind dynamic pressure is not increasing should suggest that a shock crossing is imminent, within a few weeks as opposed to several months. Likewise, if the pressure is increasing, then the likelihood of a crossing in the near term is diminished.

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REFERENCES

1. W. S. Kurth, and D. A. Gurnett, *J. Geophys. Res.* **98**, 15,129–15,136 (1993).
2. D. A. Gurnett, and W. S. Kurth, *Science* **309**, 2025–2027 (2005).
3. F. L. Scarf, and D. A. Gurnett, *Space Sci. Rev.* **21**, 289–308 (1977).
4. L. F. Burlaga, N. F. Ness, M. H. Acuna, R. P. Lepping, J. E. P. Connerney, E. C. Stone, and F. B. McDonald, *Science* **309**, 2027–2029 (2005).
5. R. B. Decker, S. M. Krimigis, E. C. Roelof, M. E. Hill, T. P. Armstrong, G. Gloeckler, D. C. Hamilton, and L. J. Lanzerotti, *Science* **309**, 2020–2024 (2005).
6. E. C. Stone, A. C. Cummings, F. B. McDonald, B. C. Heikkila, N. Lal, and W. R. Webber, *Science* **309**, 2017–2020 (2005).
7. D. A. Gurnett, R. R. Anderson, F. L. Scarf, and W. S. Kurth, *J. Geophys. Res.* **83**, 4147–4152 (1978).
8. P. C. Filbert, and P. J. Kellogg, *J. Geophys. Res.* **84**, 1369–1381 (1979).
9. J. D. Richardson, C. Wang, E. C. Stone, and F. B. McDonald, "Plasma observations from Voyager 2," in *Proc. Solar Wind 11 – SOHO 16 "Connecting Sun and Heliosphere"*, edited by B. Fleck, and T. H. Zurbuchen, ESA SP 592, ESA, Noordwijk, 2005, pp. 379–382.