JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 98, NO. A9, PAGES 15,129–15,136, SEPTEMBER 1, 1993

Plasma Waves as Indicators of the Termination Shock

W. S. KURTH AND D. A. GURNETT

Department of Physics and Astronomy, University of Iowa, Iowa City

The plasma wave receivers on the Voyager spacecraft will likely provide indicators of both the actual crossing of the termination shock as well as precursors of the shock crossing. Langmuir waves are commonly observed in the electron foreshock regions associated with planetary bow shocks; hence we expect to observe similar emissions ahead of the termination shock. Since the electron foreshock can extend considerable distances upstream of the termination shock, the detection of these waves can provide as many as several weeks warning that a crossing of the termination shock is imminent. Electrostatic turbulence associated with planetary bow shocks themselves is also an expected feature of the solar wind termination shock and will provide an important signature with which to identify the shock and to provide information on its thickness and fundamental processes. Since this turbulence is collocated with the shock, it cannot provide any advanced warning of the shock. Both upstream Langmuir waves and electrostatic wave turbulence can often be found in conjunction with interplanetary shocks, although the generally weaker nature of these shocks often leads to weaker plasma wave signatures than observed at planetary bow shocks. We demonstrate with Voyager observations that the amplitudes expected for each of these phenomena are well within the range of detectability by the Voyager plasma wave receiver even for termination shock distances exceeding 100 AU.

INTRODUCTION

As the Voyager and Pioneer spacecraft achieve greater heliocentric radial distances, currently ~50 and 56 AU, respectively for Voyager 1 and Pioneer 10, interest increases in identifying the termination shock, where it is thought that the supersonic solar wind becomes subsonic. While the consensus seems to be that a shock will exist, probably in the radial distance range of 60–150 AU, the character of the shock is poorly understood. It is worthwhile to consider what indications might be available via instruments on board the spacecraft which would indicate the actual crossing of the shock, provide some precursor or warning that a shock crossing was imminent, or provide information on the essential physics governing the formation of the shock. The Voyager spacecraft carry plasma wave receivers which promise to make a substantial contribution to these three objectives.

In this paper we concentrate on actual indicators of the shock crossing and precursors which the Voyager plasma wave receiver might provide. Owing to the great uncertainties in the type of shock which might be encountered, for example, whether cosmic rays play an important role in its formation or not, it is perhaps more profitable at present to concentrate on the indicators of the shock and leave the detailed physics of the interaction for such time as actual observations are available.

The plasma wave receiver can detect at least three signatures which may be relevant to the termination shock. First, it is likely that Langmuir waves (also called electron plasma oscillations) will be observed well upstream of the shock and could provide a useful warning of an impending shock crossing. Second, the shock itself will likely be characterized by a rather thick region of electrostatic turbulence that should be readily apparent in the plasma wave data. Third, observations of a low-frequency radio emission in the frequency range of ~2–3 kHz have been made since about 1983 [*Kurth et al.*, 1984; *Kurth and Gurnett*, 1991]; by some theories the termination shock may be responsible for the generation of these waves.

The low-frequency radio emissions will not be discussed in detail in this paper. These emissions are described in a number of other papers and their possible relationship to the termination shock is a subject of considerable discussion [*Kurth*, 1993]. The association of the source of these waves with the termination shock, however, remains quite speculative; it is more likely that the crossing of the termination shock will tell us more about the true source of the waves than the observations can now tell us about the shock. Further, there is considerable reason to suspect that these waves are trapped in the heliospheric cavity and execute numerous reflections before being detected by Voyager [*Czechowski and Grzedzielski*, 1990]. Hence the information they carry about their source is indirect, at best. We should point out that given the Fermi-scattering model for the upward drift of the transient component of these waves, the emissions do suggest an ultimate plasma frequency for the outer wall of the heliospheric cavity of ~3.5 kHz, or a plasma density of ~0.15 cm^{-3}, and also provide a scale size for the cavity of ~100 AU; these results are actually independent of where the waves are generated since they only rely on the propagation of the emissions after generation. Even if the low-frequency emissions are being generated at the termination shock, they are observable from most locations in the outer heliosphere and therefore do not provide a very useful warning of an impending crossing. Also, they are often not observable; hence for extended periods of time no information is provided. The best opportunity for this situation to improve is if the proposed triggering of these emissions [*McNutt*, 1988; *Grzedzielski and Lazarus*, 1993] is demonstrated to be reliable. In this case the time of flight of the triggers can be used to determine the distance to the source (not necessarily the termination shock) to the extent that the velocity of the trigger is known.

The most beneficial observations provided by the Voyager

Paper number 93JA01176.
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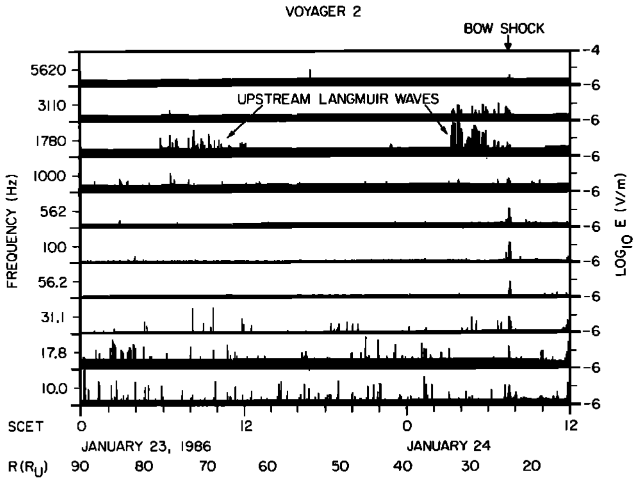

Fig. 1. Langmuir waves and broadband electrostatic emissions associated with the Uranian bow shock. The Langmuir waves can be seen 0.01 AU upstream of the shock, but the geometric constraints requiring magnetic connection to the shock are quite severe for the Voyager 2 local noon approach to Uranus. The broadband noise at the shock is likely a combination of ion-acoustic and whistler modes.

plasma wave receivers will likely be of Langmuir waves upstream of the shock. We estimate that these waves will be visible for a considerable time prior to the actual shock crossing and may therefore provide a basis for advancing the Voyager team, Deep Space Network, and the spacecraft to a relatively high state of preparedness for the impending shock crossing.

We will briefly discuss the electrostatic turbulence at the shock. These waves will provide a very accurate indicator of the shock crossing. They will not be useful if the crossing occurs while the spacecraft is not being tracked. The expected duration of the signature is much less than the round-trip light travel time from the spacecraft, hence, the detection of this signature will not provide any warning of the crossing. However, these waves are reliable indicators of the shock crossing and can be used in conjunction with other observations to verify that a shock was crossed and to assess the duration of the crossing.

We preface this work with the caveat that we are using planetary bow shocks and interplanetary shocks as the basis for a model for the termination shock. We do not profess to understand the detailed nature of the termination shock, especially if it is strongly modified by cosmic rays, as has been suggested by *Jokipii* [1990]. We assume, however, that the microphysical processes in the termination shock will be very similar to those studied in depth at the Earth's bow shock and studied to a lesser degree at interplanetary shocks and the bow shocks of the outer planets. Specifically, we assume that (1) the shock acts as a "source" of energetic electrons which can stream into the upstream solar wind and form a bump-on-tail distribution which is unstable to Langmuir waves, and (2) the shock itself will be the site of appropriate jumps in the interplanetary medium parameters of bulk speed, density, temperature, and magnetic field intensity which conspire at other shocks to generate a broadband spectrum of wave turbulence. Even in the extreme case of a cosmic-ray-modified shock, it is generally speculated that there will be a "subshock" imbedded in a larger-scale transition which is similar to other solar wind shocks. We also appeal to the logic that the model for the acceleration of the anomalous component of the cosmic ray spectrum requires that the termination shock have enough similarity to other solar wind shocks that acceleration can occur. It follows from our choice of a shock model that we will not be able to unambiguously distinguish between the termination shock and interplanetary shocks via the plasma wave observations, alone. However, we will suggest other observations which might contribute to resolving such an ambiguity.

In Figures 1 and 2 we provide Voyager observations of the plasma waves associated with the Uranian bow shock and an interplanetary shock, respectively. Both illustrations show the amplitude of wave activity in several of the Voyager spectrum analyzer channels as a function of time. For a description of the Voyager spectrum analyzer, see *Scarf and Gurnett* [1977]. The solid black area in each panel represents the average electric field strength as a function of time and the peak value measured during each averaging interval is represented as a line over the averages. For most of these observations, there is little difference between the peak and average values. The averaging intervals are 144 and 76 s for Figures 1 and 2, respectively. Figure 1 shows the 10 channels on Voyager 2 covering the range from 10 Hz to 5.62 kHz for a 36-hour interval. The broadband spike seen across all channels at ~0730 spacecraft event time (SCET) is due to the electrostatic turbulence at the Uranian bow shock. The bursty emissions in the 1-, 1.78-, and 3.11-kHz channels are electron plasma oscillations or Langmuir waves. In Figure 2 a slightly smaller spectral range is shown from Voyager 1 culminating in the crossing of an interplanetary shock at about 2310 SCET at a heliocentric radial distance of about 46.1 AU. Again, the shock is demarcated by a broadband pulse seen over the entire frequency range displayed. Langmuir waves are seen sporadically in the 1.0-kHz channel for several hours prior to the shock crossing. We caution that similar sporadic bursts are often seen in the Voyager data in the 178- and 311-Hz channels, which we believe are due to various spacecraft activities; naturally occurring bursty emissions in these channels will be difficult to distinguish from the spacecraft sources.

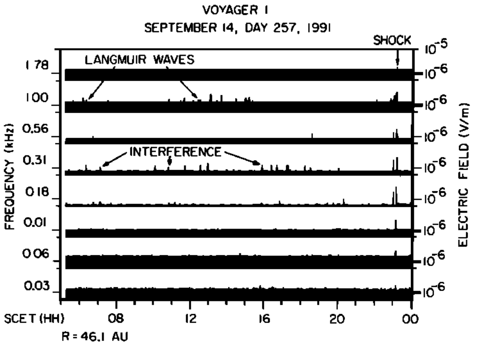

Fig. 2. Recent Voyager 1 observations of Langmuir waves and broadband turbulence associated with an interplanetary shock at ~46.1 AU. The upstream waves are seen as much as 0.2 AU from the shock, and the broadband turbulence is quite similar to that observed at planetary bow shocks in the outer heliosphere.

LANGMUIR WAVES AS ADVANCED INDICATORS OF AN IMPENDING SHOCK CROSSING

As is indicated in the introduction and in Figures 1 and 2, the region upstream of both planetary bow shocks and sometimes interplanetary shocks can be identified by the presence of narrowband, bursty Langmuir wave emissions. Such upstream wave activity has proven to be a reliable indicator of an impending crossing of planetary bow shocks at each of the Voyager planetary encounters, in some cases providing as much as a day's warning. For the Uranian shock shown in Figure 1 the Langmuir waves start more than one day before the shock crossing. On the other hand the warning time can be as little as a few minutes, as was the case at the Voyager 1 crossing of the Saturnian bow shock [*Gurnett et al.*, 1981]. Hence the possibility of detecting such wave activity upstream of the termination shock provides the possibility that we might have some warning that the termination shock crossing is imminent. We will demonstrate that such wave activity is highly likely and that it is conceivable that as much as several weeks warning could be provided by the detection of these emissions.

Langmuir waves associated with planetary bow shocks have been the subject of numerous studies [cf. *Scarf et al.*, 1971; *Filbert and Kellogg*, 1979] and a general understanding of the phenomenon is well accepted. Basically, the shock acts as a source of energetic electrons by either reflection or acceleration. Some of these energetic electrons can be directed into the upstream region from the shock, forming the electron foreshock. This population of electrons moving in the upstream direction creates a bump-on-tail distribution in the upstream solar wind, which is a combination of the normal solar wind electrons with the backstreaming electrons superimposed. Figure 3 shows a schematic of this distribution. The positive slope in the distribution function is unstable to Langmuir waves; hence the electron foreshock is characterized by intense electrostatic Langmuir waves. The same mechanism applies as well to interplanetary shocks and, according to our assumed model, should apply to the termination shock.

Two requirements must be met before Langmuir waves upstream of a shock can be detected. First, the waves must be of sufficient amplitude that the receiver can detect them. Since the Voyager receiver's noise level is of order 1 μV/m, this implies the Langmuir waves must be greater than this intensity to be observed. We believe that Langmuir waves associated with a termination shock within a few hundred AU should be of sufficient intensity to be detectable. The primary support for this is in the amplitude of Langmuir waves detected upstream of planetary bow shocks in the outer heliosphere. Figure 4, adapted from *Macek et al.* [1991*a*, *b*], shows the observed levels of upstream Langmuir waves at Earth, Jupiter, Saturn, Uranus, and Neptune. Even though there are only limited observations from the outer planets, it seems reasonable to expect that an empirical extrapolation of the trend to the vicinity of 100 AU would yield a reliable range of intensities to be expected near 100 AU. We have indicated a reasonable extrapolation of these amplitudes by extending dashed lines through the limiting points plotted for the Earth and the outer planets. These are set by Earth and Uranus on the high side and Earth and Jupiter on the low side. The area between these two lines remains well above the level of detectability with Voyager 1 until well beyond 100 AU as indicated by the cross-hatched region near 1 μV/m. A range of limits is implied by the finite thickness of this cross-hatched region because the level of detectability has a weak dependence on frequency and is somewhat variable depending on spacecraft interference. We use background levels in the frequency range of ~100 Hz–1 kHz recently determined from in-flight data to set this range of detectability.

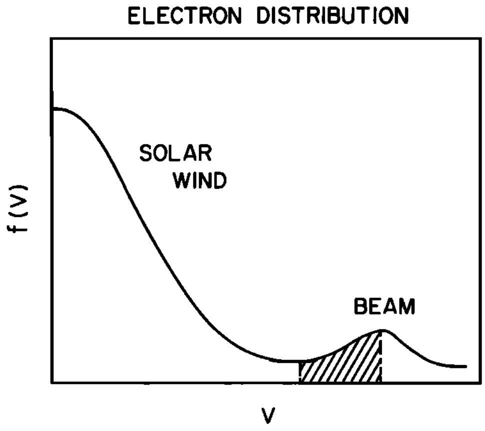

Fig. 3. A schematic representation of a bump-on-tail electron distribution expected upstream from the termination shock. For phase velocities in the range of the hatched region this distribution is unstable to Langmuir waves.

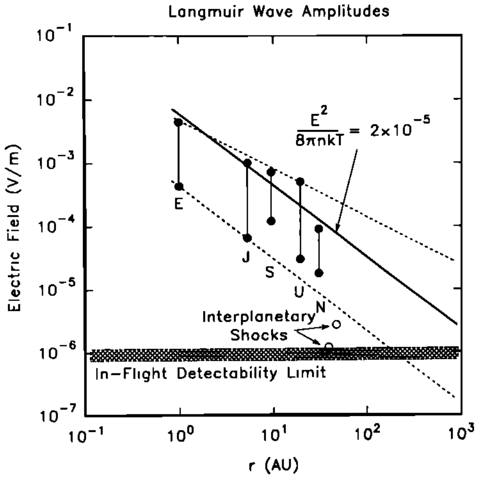

Fig. 4. The observed ranges of Langmuir wave intensities in the foreshocks of the Earth and outer planet magnetospheres adapted from *Macek et al.* [1991*a*]. These intensities easily extrapolate to detectable values for a termination shock within a few hundred astronomical units.

Other evidence that Langmuir waves will be at detectable levels in the outer heliosphere includes an empirical variation of Langmuir wave intensities due to solar flare electrons in the inner heliosphere reported by *Gurnett et al.* [1980]. The electric fields from the inner heliospheric observations vary as $r^{-\alpha}$, where α is 1.4 ± 0.5 and yield values near 100 AU in the range of 0.1–6 μV/m. Gurnett et al. also estimate the electric field at saturation as a function of r. They suggest that the ratio of the electric field energy density to the plasma energy density $E^2/8\pi nkT$ should be a constant at saturation.

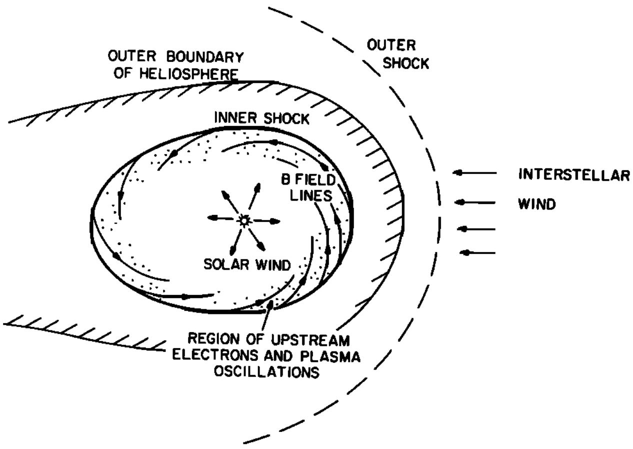

Fig. 5. A schematic drawing of the heliosphere showing a region just inside the termination shock which is likely characterized by Langmuir wave activity which could be detected by Voyager. While the thickness of this electron foreshock region is magnified in this drawing, it is reasonable to expect that it could have a scale size of the order of 1 AU.

On the basis of the observations of Langmuir waves associated with type III radio bursts, they estimate that

$$\frac{E^2}{8\pi nkT} \approx 2 \times 10^{-5}. \tag{1}$$

Since the electron density n varies as $1/r^2$ and the temperature T varies as $(1/r)^{2/7}$ [*Hundhausen*, 1972], then E should vary as approximately $r^{-1.14}$. The saturation amplitude at 100 AU, then, would be ~30 μV/m. The solid line in Figure 4 labeled with (1) comes directly from the empirical saturation intensity determined by *Gurnett et al.* [1980] at 1 AU and extrapolated to larger heliocentric distances using the $r^{-1.14}$ variation suggested therein. Since some of the outer planet bow shock-related Langmuir waves exceed this, one might conclude that either the empirically derived saturation amplitude near 1 AU is low or that the radial distance dependence should be weaker or both. The latter would be most likely due to a deviation in the temperature dependence on r from the Hundhausen model. The fact that Langmuir waves are also observable upstream of some interplanetary shocks at large heliocentric distances such as the one at 46 AU in Figure 2 also lends credence to the view that termination shock-associated Langmuir waves should be detectable. We have indicated with open circles the peak amplitudes of interplanetary shock-associated Langmuir waves in Figure 4. These are considerably weaker than the waves associated with the planetary bow shocks, and we attribute this to the fact that interplanetary shocks are generally weaker than those observed ahead of the dayside planetary magnetospheres.

The second requirement to be met in order for Voyager to be able to observe Langmuir waves upstream of the termination shock is a geometric constraint. That is, the spacecraft must be magnetically connected to the shock. In the case of a spacecraft approaching a planetary bow shock this geometric constraint can be quite severe. This is especially true for an approach trajectory near local noon in the outer heliosphere where the nominal Parker spiral field configuration makes it highly unlikely that connection should occur until the spacecraft is very close to the shock. In fact, this is probably the reason Voyager 1 at Saturn observed Langmuir waves for only 3 min prior to crossing the shock. Fortunately, however, this geometric constraint is very easy to meet with respect to the termination shock because all field lines eventually connect to the shock (except for situations involving magnetic loops or other closed field topologies). Figure 5 is a schematic representation of the region just upstream of the termination shock which is likely to be characterized by detectable levels of Langmuir wave activity. (The region is sketched with a disproportionally large thickness in order to highlight it.) The only remaining question concerns how far upstream the waves might be detected. It is this distance, and the relative velocity between the shock and the spacecraft, which will determine how much warning of the shock crossing the detection of these waves will provide.

The thickness of the foreshock region depends on how far along the magnetic field the unstable electron distribution can propagate and the competition between the electron beam velocity in the solar direction and the convection of the solar wind into the shock. This competition depends on the electron energy and pitch angle as well as the angle between the shock normal and the magnetic field, θ_{BN}. We know from studies of the generation of solar type III radio bursts that unstable distributions of solar flare electrons can propagate at least 1 AU from the sun and perhaps much further. Evidence of this can be implied from recent Ulysses observations of type III bursts and associated Langmuir waves out to distances of 2.5 AU [*Reiner et al.*, 1992]. We also have observed foreshock electrons from the Earth's bow shock with ISEE 3 as much as 200 R_E or 0.01 AU from the shock. We believe that at greater distances it is very difficult to know whether observed Langmuir waves are associated with the shock as opposed to solar electrons due to irregularities in the field orientation at such large scale lengths. In the relatively quiet outer heliosphere, it is entirely possible these electron beams can propagate much more than 1 AU. Therefore, if the field were radial, it would be reasonable to expect to observe Langmuir waves 1 AU or more from the termination shock. The obvious difficulty, however, is that the average field orientation is almost purely azimuthal according to the Parker model.

Figure 6 shows a very simple planar geometry which serves to illustrate the considerations relevant to determining the thickness of the electron foreshock region. For this simple derivation we assume that the thickness is much smaller than the radius of curvature of the termination shock. This would seem to be reasonable in the absence of large waves or other deformations of the shock surface and we use the planar geometry. We also take note of observations of large deviations from the nominal Parker orientation of the magnetic field as observed by Voyager (N. F. Ness,

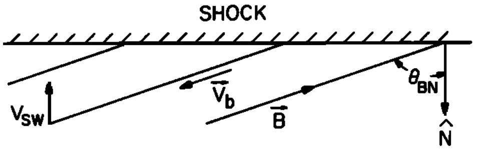

Fig. 6. A simple planar geometry for the termination shock useful in estimating the foreshock thickness (see text).

personal communication, 1992). In fact, there is a large probability of observing deviations from the nominal orientation by 45° or even more. It is clear in Figure 1 that the magnetic field must have been nearly radial for Voyager to have been magnetically connected to the Uranian bow shock from its location near noon, local time, when the spacecraft was a long distance from the shock.

Given a value of θ_{BN}, all that is required to determine the thickness of the electron foreshock region is to examine the competition between the electron beam's sunward velocity component and the convection velocity of the solar wind, under the simplifying assumption that the electron beam propagates a total of 1 AU along the field.

Using the geometry detailed in Figure 6, it is straightforward to estimate the thickness of the foreshock region and, more importantly, the amount of warning the detection of Langmuir waves might provide under ideal conditions. In Figure 6, θ_{BN} is the angle between the shock normal and the magnetic field (without regard to whether the sector is inward or outward). The solar wind is assumed to be moving radially with a speed v_{sw}, and the electron beam associated with the shock is assumed to be moving parallel to **B** with speed v_b. That is, we have assumed a pitch angle for the beam electrons of 0°. This derivation can be normalized for other pitch angles if v_b is used for the parallel component of the velocity. It is clear that the component of v_b directed away from the shock is offset by v_{sw} and that for the case where these two velocity components are equal and opposite, the beam electrons never escape from the shock since they are convected into it as fast as they are directed away from it. For this critical beam velocity v_c the foreshock thickness is zero and

$$v_{sw} = -v_b \cos \theta_{BN} \tag{2}$$

or

$$v_b = v_c = -v_{sw} \cos^{-1} \theta_{BN}. \tag{3}$$

Then, for $v_b > v_c$, the velocity of the beam electrons toward the Sun, perpendicular to the shock surface $v_{\perp b}$ is

$$v_{\perp b} = v_b \cos \theta_{BN} - v_{sw}. \tag{4}$$

We shall assume that the beam electrons can travel 1 AU parallel to **B** without disruption of a bump-on-tail distribution, though we believe this is likely a lower limit to the total distance the beams can travel. If we assume the shock is at rest with respect to the Sun and it is only the radial velocity of the spacecraft $v_{s/c}$ which carries it through the shock, then it is straightforward to calculate the amount of warning time provided by detecting the first upstream waves T_w

$$T_w = \frac{v_{\perp b} T_b}{v_{s/c}} \tag{5}$$

where T_b is the time it takes the beam to move 1 AU along the magnetic field (T_b = 1 AU/v_b).

Figure 7 is a plot of the nominal warning time the observation of Langmuir waves might provide of a shock crossing assuming a shock which is stationary in the rest frame of the Sun (i.e., we only consider the radial velocity of the spacecraft), a straight and uniform magnetic field between the spacecraft and the shock, beam electrons in a range of energies as high as 20 keV with pitch angles of 0° (for simplicity), and a solar wind speed of 400 km/s. This plot shows that for a nominal θ_{BN} near 90°, the foreshock thickness is very small; hence the warning time is quite short. However, for even modest field deviations toward the radial direction, electron energies of several keV will allow a foreshock thickness of a sizable fraction of an AU, which would require several weeks for Voyager to traverse. We conclude that under favorable field orientations and modest expectations for the energy of the beam electrons, Voyager could detect Langmuir waves associated with the termination shock for a period of up to weeks prior to crossing the shock.

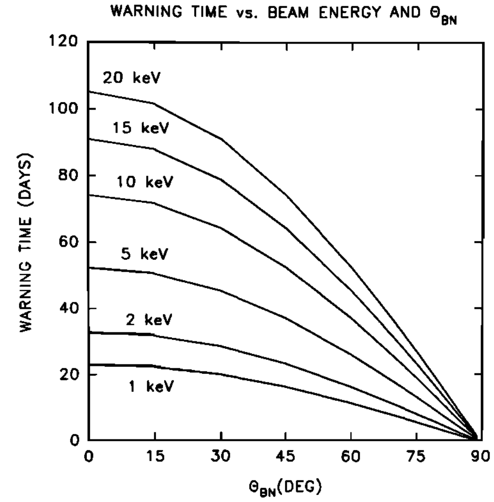

Fig. 7. Estimated shock crossing warning time provided by the detection of Langmuir waves for various values of θ_{BN} and electron beam energies. We have assumed that the termination shock is at rest in the solar frame, a solar wind speed of 400 km/s, 0° pitch angle, and a uniform magnetic field in the vicinity of the termination shock.

The picture is complicated considerably when the stationary shock and uniform field assumptions are removed. If the shock can move radially at speeds of the order of 100 km/s as suggested by *Suess* [1990], then the warning times must be shortened by the ratio of the approaching shock velocity to the radial spacecraft velocity. Typically, this could reduce the warning times in Figure 7 by as much as a factor of 10. Also, given that the field direction is not constant and can change dramatically over times scales of hours in the outer heliosphere (N. F. Ness, personal communication, 1992), Voyager could find itself alternately inside and outside of the electron foreshock.

Instead of expecting several weeks of constant Langmuir wave observations, the rotations of the field and the potentially large radial motions of the shock mean that Voyager would see an increasing rate of occurrence of Langmuir waves as the shock approached, perhaps over the time period of several weeks. As the shock gets closer, it becomes more likely the various geometrical constraints are met and the occurrence rate of the upstream waves becomes larger, or alternately, the emissions become more continuous.

On the basis of our experience in detecting Langmuir waves associated with interplanetary shocks in the solar wind, we believe it will be possible to differentiate between the approach of the termination shock and interplanetary shocks in some cases. The Langmuir wave activity preceding the interplanetary shock in Figure 2 endures for a period of <1 day. This is the longest period of upstream wave activity we have observed to date with Voyager in the outer heliosphere. If the model of a rather thick foreshock region, which varies considerably over time is correct, we should see increasing upstream wave activity with numerous cessations over a considerable time period, perhaps as long as weeks. The wave activity would come and go, and we would not see an accompanying interplanetary shock, unless by coincidence. Should the periods of Langmuir wave activity correlate well with periods when the field has turned radial, this would be consistent with a thickening of the foreshock with decreasing θ_{BN}. Given such a set of observations, we might conclude that the wave activity is associated with an extended termination shock foreshock region and not an interplanetary shock. Obviously, signatures in other Voyager detectors, such as a general rise in the intensity of anomalous cosmic rays, would be useful in adding support to the evidence provided by the upstream wave activity.

We expect Langmuir wave activity upstream of the termination shock, but not downstream [cf. *Cairns and Gurnett*, 1992]. Hence one might conclude that there would be evidence of the crossing due to the cessation of upstream wave activity if it were punctuated by broadband wave turbulence at the shock as discussed below. Should a cessation of upstream wave activity occur during a tracking gap, however, there would be no way of telling from only the plasma wave data that the shock had been traversed during the tracking gap since Voyager may have simply moved out of the foreshock region due to the rotation of the field from near radial to near azimuthal. In either case, evidence of downstream conditions (such as subsonic flow and a sustained increase in magnetic field strength) would be essential to verify that the spacecraft was in a subsonic solar wind expected on the downstream side.

ELECTROSTATIC TURBULENCE AT THE TERMINATION SHOCK

Both the Uranian bow shock and interplanetary shock examples shown in Figures 1 and 2 show very clear signatures of the shock in the form of a broadband pulse of turbulence. This turbulence is a durable and ubiquitous feature of collisionless shocks in space plasmas [cf. *Fredricks et al.*, 1968; *Rodriguez and Gurnett*, 1975; *Scarf et al.*, 1987; *Moses et al.*, 1990]. The detailed physics involved in the generation of this spectrum is not fully understood, however, it is likely that a number of wave modes may contribute. In particular, in the frequency range of the Voyager observations shown in Figures 1 and 2 it is likely that the waves are ion-acoustic-like and therefore electrostatic in nature. (Voyager has only an electric antenna; hence it is generally not possible to directly determine whether an emission is electrostatic or electromagnetic.) At lower frequencies there is evidence that whistler-mode waves make up part of the spectrum. This is especially apparent at the Earth's bow shock where both electric and magnetic observations are available [*Rodriguez and Gurnett*, 1975]. In the outer heliosphere where the electron cyclotron frequency can be below the Voyager plasma wave receiver's lowest-frequency channel (10 Hz), the whistler mode spectrum is expected to be at frequencies that are too low to be detected.

We consider the broadband wave turbulence to be an extremely reliable indicator of a collisionless shock. The Voyager plasma wave receivers have detected this kind of turbulence at virtually every planetary bow shock crossing and certainly for every dayside crossing where the angle between the v_{sw} and the shock normal $\hat{n}$ is small [cf. *Scarf et al.*, 1979; *Gurnett et al.*, 1981, 1986, 1989]. The only questionable detections are a small number of outbound shocks along the flanks of the Uranian magnetosphere where either the Voyager magnetometer or plasma science teams reported evidence for the shock [*Ness et al.*, 1986; *Bridge et al.*, 1986]. In each of these exceptional cases where no clear wave signature of the shock was observed, there was an apparent disagreement between the magnetometer and plasma teams' identification of the shock; either there was a shock reported by only one of these teams or there was a substantial disagreement in the crossing time of more than several minutes. In all cases where there was a clear shock signature in both the magnetometer and plasma observations within a few minutes of each other, the plasma wave receiver observed a clear signature of the broadband wave turbulence. It may be that there are shocks which were too thin for the wave instrument's temporal resolution to detect or even that there could be a shock with no wave signature at all. Until the discrepancies between the times of shocks reported by the plasma and magnetometer teams are resolved for the shocks along the flanks of the Uranian magnetosphere, it is not possible to draw any definitive conclusions; the explanation of this small set of poorly identified shocks with no apparent wave signatures may become a moot point.

It is not the case that interplanetary shocks are always identifiable by their plasma wave signature. In fact, electrostatic waves associated with interplanetary shocks in the outer heliosphere are seldom observed. We believe this is explained by the fact that interplanetary shocks are usually weak compared to the dayside planetary bow shocks. Given that the termination shock fluctuates about some average distance, at least half of the time one would expect the termination shock to be moving toward the Sun and likely be a strong shock. It is possible that the interaction of the termination shock moving outward, in the same direction as the bulk flow, would be weaker and less likely to generate an observable plasma wave signature.

The intensity of the electrostatic wave signatures at the Uranian and Neptunian bow shocks are ~20–40 dB above the receiver background. It is not clear how these amplitudes might be extrapolated to larger heliocentric radial distances, but we can take an empirical approach to this problem similar to the one used for estimating the intensities of Langmuir waves in the previous section. In Figure 8 we have plotted observed ranges of intensities for wave turbulence at each of the planetary bow shocks. We have used all of the dayside (inbound) shock crossings observed by the Voyagers at the outer planets and published terrestrial shock spectra [*Rodriguez and Gurnett*, 1975]. For the outer planets we selected the most intense 1-min averaged spectrum among all of the observed shocks. For this spectrum the lower point for a given planet represents the average spectral density at the frequency of maximum intensity. The upper points are determined from the peak value obtained during the 1-min averaging interval. For Earth the upper point represents the intensity at the maximum of the most intense peak spectrum obtained by Rodriguez and Gurnett and the lower point represents the intensity at the maximum of the most intense average spectrum. In all cases we have tried to avoid the low-frequency peak which is most likely due to whistler-mode emissions since the 10-Hz lower frequency limit of the Voyager receiver normally precludes the detec-

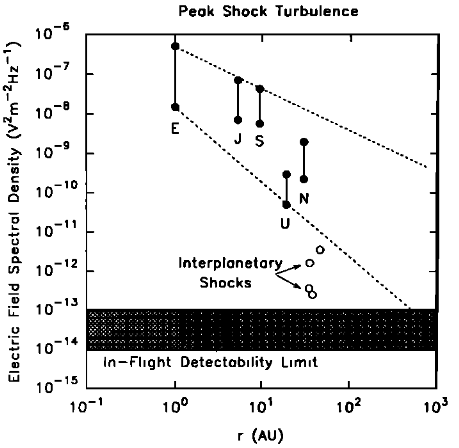

Fig. 8. A plot of the peak planetary bow shock turbulence as a function of heliocentric distance used to estimate a likely range of intensities which might be expected in the termination shock. It is clear that detectable levels of shock turbulence can be expected even if the termination shock is several hundred astronomical units from the Sun.

tion of the whistler-mode component of the shock spectrum in the outer heliosphere where the magnetic field strength is of the order of 0.1 nT.

As was done in Figure 4, we have sketched in Figure 8 upper and lower limits to the range of values represented by the planetary bow shock spectra by using the maximum points for Earth and Saturn and the minimum points for Earth and Uranus and extending these lines to larger heliocentric distances. The in-flight level of detectability is again indicated. In units of spectral density this range is somewhat larger than that indicated in Figure 4 (which uses units of electric field strength) because of the differing filter bandwidths used in the receiver. To first order, the bandwidth is a constant percentage of the center frequency, hence, is greater at higher frequencies; the higher frequency channels are, therefore, somewhat more sensitive to a broadband signal. It is clear from the peak shock spectra determined at planetary bow shocks shown in Figure 8 that easily detectable levels of turbulence will be encountered at the termination shock should it be within several hundred AU of the Sun.

We have also plotted the spectral densities of a few interplanetary shocks in Figure 8 for comparison. These are clearly detectable out to 46 AU but fall below the range implied by the peak planetary bow shock spectra. As discussed above, we believe this is a natural consequence of the interplanetary shocks being generally weaker than bow shocks. It is also important to remember that the planetary bow shock spectra were selected to be the most intense examples.

The observations of wave turbulence at the termination shock will aid in the identification of the shock and the duration of the turbulence may be useful in determining the thickness of the structure, although the lack of any a priori information about the shock's velocity may make such a determination problematic. The duration of the electrostatic turbulence at the dayside bow shocks of the outer planets demonstrate a trend for increasing thicknesses at larger heliocentric radial distances, likely reflecting the increasing scale sizes in the outer heliosphere, most notably the ion Larmor radius. At Neptune the signature lasted for about 10 min and, given a shock which is stationary in the solar frame of rest, corresponds to some 10^4 km. It is not unreasonable to expect a turbulence signature at the termination shock of several tens of minutes provided the relative velocity between Voyager and the shock is primarily due to the spacecraft's motion away from the Sun. On the other hand, some estimates suggest that the shock could be moving in response to variations in the solar wind ram pressure at speeds as high as one third of the solar wind velocity or of the order of 100 km/s.

Given the very weak magnetic field in the outer heliosphere (of the order of 0.1 nT (N. F. Ness, personal communication, 1992)) and the fact that the Voyager 1 plasma instrument is severely handicapped due to a prior failure, it will be very useful to have the plasma wave signature in addition to the magnetic field signature to increase confidence in any potential shock identification.

The detection of the shock-associated plasma wave turbulence, however, will not be useful in providing any forewarning of the shock's arrival, since the turbulence and the shock are collocated and since the duration of the shock signature is likely to be significantly shorter than the round-trip light time to the spacecraft (~12 hours at 50 AU). However, the initial detection of the shock will establish its position very accurately at one instant in time and should therefore provide much more useful estimates of the shock's position based on analyses of variations in the solar wind ram pressure. It should be possible to predict a second crossing to some degree of accuracy should the pressure increase and reverse the velocity of the shock and cause it to move back over the spacecraft. Whether the accuracy of such a prediction will be good enough to be of practical value in preparing for additional shock observations is unknown at this time. Voyager Project estimates are that ~1 to 2 weeks are required to prepare a command sequence and to set up additional tracking coverage, if such additional coverage is possible. It is also considered reasonable to maintain an elevated level of tracking for a period of about a week, but this is highly dependent on the specific tracking conflicts which are encountered at the time increased coverage is desired.

SUMMARY AND CONCLUSIONS

We have demonstrated that plasma wave phenomena are likely to be important for providing advanced warning of the approach of the termination shock to the Voyager spacecraft and also for identifying the shock, itself. On the basis of extensive observations of planetary bow shocks and interplanetary shocks, it is entirely reasonable to expect that Langmuir waves will characterize the region upstream of the shock and, hence, provide some advanced warning of the shock crossing. Further, one or more wave modes will likely demarcate the shock itself such as ion-acoustic waves. In each case we have argued, primarily on the basis of examples from the bow shocks of the outer planets and extremely distant interplanetary shocks, that the expected amplitude of the waves are well within the range of detectability with the Voyager plasma wave receivers. Each phenomena should exhibit waves with electric field intensities of the order of a few microvolts per meter or more.

The wave turbulence associated with the shock is a local phenomenon and will not provide any advanced warning of the crossing of the boundary unless the duration would exceed the round-trip light time to the spacecraft, of the order of 12 hours, which is highly unlikely based on the thickness of outer planet bow shocks. The upstream Langmuir waves, however, should exist in an extensive electron foreshock region which could provide up to several weeks of warning, provided regions with field orientations having a substantial radial component and a termination shock with a small velocity with respect to the spacecraft. In the likely event that the shock velocity is high, as high as 100–200 km/s, the warning time could decrease considerably. The inward and outward motion of the shock in response to temporal variations in the solar wind pressure and the observed variations in the magnetic field orientation are expected to result in a period of sporadic upstream wave activity which increases in continuity as the shock is approached. As the shock is crossed, the upstream waves will disappear, and the shock itself will be observed via the broadband noise associated with the shock. Should these transitions occur during a tracking gap, it will be difficult to conclude that a shock crossing has taken place on the basis of the wave data alone, but comparisons with energetic particle and magnetic field observations should help to clarify the situation.

As part of a general effort within the Voyager Project to enhance the scientific return of an encounter with the termination shock, we have provided algorithms to the project that should help to identify both Langmuir waves and shock-associated broadband wave turbulence in the data stream acquired from the spacecraft. These algorithms are designed to identify upstream waves and shock noise associated with planetary bow shocks and interplanetary shocks, so we expect them to also respond to interplanetary shocks, which they do. These, however, are also of scientific interest in their own right and do not detract from the termination shock search. As time goes on, we can work with the project to minimize the number of "false alarms," most of which currently are associated with interference from onboard activities. Other Voyager teams are providing similar algorithms to search for other indicators of the termination shock which might allow some forewarning or at least alert the science team that a shock has been crossed. Even if the first crossing is missed via a telemetry gap, it is generally believed that the shock position will vary over time and perhaps several crossings will eventually be experienced by each spacecraft, thereby increasing the probability that in situ observations of the termination shock will be obtained.

Acknowledgments. This research was supported by the National Aeronautics and Space Administration through Contract 959193 with the Jet Propulsion Laboratory.

The Editor thanks two referees for their assistance in evaluating this paper.

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D. A. Gurnett and W. S. Kurth, Department of Physics and Astronomy, University of Iowa, Iowa City, IA 52242.

(Received October 29, 1992;
revised December 8, 1992;
accepted November 18, 1992.)