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On the amplitude of intense Langmuir waves in the terrestrial electron foreshock

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Abstract. Waveforms of large-amplitude Langmuir oscillations were recorded by the Wind spacecraft in the Earth's upstream electron foreshock region. We present some statistics of the waveforms and discuss them in the context of various saturation mechanisms. In particular, it is found that the value of $E_{\text{peak}}/E_{\text{rms}}$ is not large, as previously suggested, and that the largest-amplitude Langmuir waveforms are generally somewhat sinusoidal and lack structure on small spatial scales. The measured probability distribution of electric field amplitude and dimensionless energy suggest that some stochastic process may play a role in wave generation. The values of dimensionless energy needed to arrest Langmuir wave collapse occur with very small probability and the value of $E_{\text{peak}}/E_{\text{rms}}$ for large fields suggests that, statistically, Langmuir wave collapse is not an important process in the terrestrial foreshock.

Introduction

Despite many years of observational and theoretical work, the generation and saturation of Langmuir waves in the solar wind upstream of the Earth's bow shock remains an interesting, even controversial, problem. The flux of accelerated solar wind electrons upstream from the bow shock is thought to generate a beam-like "cut-off" distribution due to time-of-flight effects [*Filbert and Kellogg*, 1979]; this should exist irrespective of, and in addition to, other processes which may generate beams near the foreshock-solar wind boundary (e.g., fast Fermi processes [*Wu*, 1984; *Leroy and Mangeney*, 1984]). This beam is then unstable to Langmuir waves as well as beam modes [e.g., *Cairns*, 1989]. The fast Fermi process, which operates most efficiently at quasi-perpendicular shocks, has been shown to generate an energetic ring beam [*Krauss-Varban and Burgess*, 1991] and ring beams can generate Langmuir waves as well as electromagnetic radiation [*Kainer and MacDowall*, 1996].

There are various proposed saturation mechanisms for the Langmuir waves. In the strong turbulence scenario, the electric field pressure of the wave modifies the ambient plasma, thereby changing the dispersion properties of the wave. This definition of strong turbulence incorporates such effects as the modulational instability, reactive parametric decay instability, and Langmuir soliton collapse. *Goldman* [1984], *Melrose* [1991], and *Robinson* [1997] offer good reviews of these mechanisms. The electrostatic decay scenario involves the decay of a Langmuir wave into another, oppositely directed Langmuir wave and a sound wave (denoted $L \rightarrow L' + S$). Electrostatic decay occurs as both phase coherent (termed "reactive parametric decay" or "stimulated backscatter") and random-phase (often just called "electrostatic decay") variants. These processes have been studied by many authors [e.g., *Cairns and Melrose*, 1985]. *Robinson and Cairns* [1995] recently calculated maximum field values in planetary foreshocks based on the solar wind variation of the threshold parameters for electrostatic decay and found consistency with the various observations. They predict threshold field values at Earth of about $E_{L0} \approx 30$ mV/m but allow for momentary overshoots of up to $\approx 3E_{L0}$. The modulational (or oscillating two-stream) instability involves the decay of Langmuir waves to a standing solution of a cubic Schrödinger equation [e.g., *Nishikawa*, 1968]; in this scenario, the interaction is mediated by a zero frequency wave, so no large low-frequency component need be present. More generally, the *Zakharov* [1972] equations describe these effects as well as the self-focusing, which leads to spatial collapse of the waveform. Langmuir wave collapse is thought to occur when the ponderomotive force dominates; in this case, the wave field becomes localized on scales of $L \sim (10 - 20)\ \lambda_d$ before damping on the electrons. Langmuir wave collapse has been reported in the Jovian foreshock [*Thiessen and Kellogg*, 1993] and in the interplanetary

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solar wind [*Kellogg et al.*, 1992] using the fast envelope sampler (FES) instrument on Ulysses. However, *Cairns and Robinson* [1992b; 1995] have suggested that these observations are inconsistent with Langmuir wave collapse.

These mechanisms depend on the dimensionless wave energy

$$W = \frac{\epsilon_0 E^2}{n\, k_b T_e} \quad (1)$$

as an important parameter. In particular, the modulational instability and Langmuir wave collapse require long wavelengths such that $\Delta k\, \lambda_d \ll W^{1/2}$. In the limit that $W \gg m/M$ the ion inertia may not be ignored in the Zakharov equations and the "supersonic" limit is obtained. In this case, the rate of spatial collapse is slowed relative to the adiabatic limit $W \ll m/M$. The crossover point from subsonic to supersonic collapse is proportional to m/M but may actually be a bit larger [e.g., *Robinson*, 1997].

The previous generation of plasma wave receivers typically relied on a swept frequency analyzer to determine spectral density and hence amplitude of plasma waves. Since the waves are known to be spikey and evolving, this has permitted some speculation as to the true amplitude of the waves. In particular, *Robinson and Newman* [1991] proposed that the intense Langmuir waves observed upstream by IMP 6 and ISEE 1 were actually in a state of wave packet collapse. They argued that the integration time of these spectral density measurements had reduced the true amplitude and scale size of the measurements.

In this paper, we show unambiguously that $E_{\rm peak}/E_{\rm rms}$ is small for upstream Langmuir waves. We also calculate W for several hundred Langmuir waveforms; it is shown that when the amplitude is large, the Langmuir waves generally have a smooth waveform and do not appear to be spatially localized on scales of $\sim 10\lambda_d$. The probability distribution of both E and W are calculated and are consistent with that predicted by the stochastic growth theory for solar type III bursts as applied to the electron foreshock.

Wind Observations

The Wind spacecraft was launched on November 1, 1994, and has made a series of Earth orbits as staging to its nominal position at the L1 equilibrium point upstream. The data presented here are from the time domain sampler (TDS) instrument of the WAVES experiment [*Bougeret et al.*, 1995]. The TDS samples various combinations of the electric field antennas and search coil magnetometers at sample speeds up to 120,000 samples per second. The sampled signal is returned as a signed logarithm allowing for 90 dB of dynamic range from threshold values near 80 μV (RMS). The data presented here are all taken on the X antenna, a wire dipole, whose tip-to-tip length is 100 m; the TDS was sampling at 120,000 samples per second with a low pass filter at 50 kHz to reduce frequency aliasing. The TDS instrument samples waveforms continuously and returns the events above a certain hardware threshold amplitude (typically ~ 0.05 mV/m) with the peak centered in an interval of 2048 points. For the data presented here, the events are buffered and telemetered by a last-in/first-out algorithm; this allows for good statistical work. In March 1996, the TDS was put into an instrument mode where a "quality" factor is applied to sort events in the buffer. These data are not reported here.

When Wind is in the terrestrial foreshock, the TDS may return hundreds of events per day. The fast sampling rate allows full resolution of the plasma frequency in the solar wind. For a solar wind speed of 400 km/s, each sample represents about 3 m of solar wind convection. The Debye length is about 10 m in the solar wind. Since each TDS event is $2048/(120,000\ {\rm s}^{-1}) \approx 17$ ms long, this represents about 7 km or 700 λ_d of convected solar wind.

Langmuir Waves

Figure 1 shows Langmuir waveforms sampled in the electron foreshock on August 4, 1995. An initial results paper showing Wind observations of upstream Langmuir waves and waves at the bow shock has been published [*Kellogg et al.*, 1996]. The panels are arranged in order of decreasing field amplitude. It can be seen that the larger amplitude events have smoother, well formed envelopes. The waveforms in Figures 1d and 1e are fairly weak and have choppier envelopes. This is a general trend and is consistent with the observation by *Etcheto and Faucheux* [1984] that the largest-amplitude waves have a smaller bandwidth.

Langmuir wave events were chosen from 6 days of data: December 2, 3, 11, and 14, 1994, and August 4 and 22, 1995. These are days when Wind made several passes through the electron foreshock region and large amplitude waves are observed near the plasma frequency. Also, these days show relatively little emission due to solar radio bursts in the frequency range of the instrument. The RMS field is calculated using the 2048 samples of each event and ISTP key parameter data are interpolated onto the time tag of each Langmuir wave event. This provides estimates of plasma density and temperature at each of the observations. The key parameter plasma data are from the Solar Wind Experiment (SWE) experiment on Wind [*Ogilvie et al.*, 1995]; the data are provided, typically, at intervals of 92 seconds in CDF format by the ISTP Central Data Handling Facitility (CDHF) [*Mish et al.*, 1995]. Using the density, we then include only events whose peak frequency lies between 0.95 and 1.35 times the local plasma frequency and whose peak amplitude is above 0.5 mV/m. The frequency constraint should exclude most of the beam mode waves and second harmonic

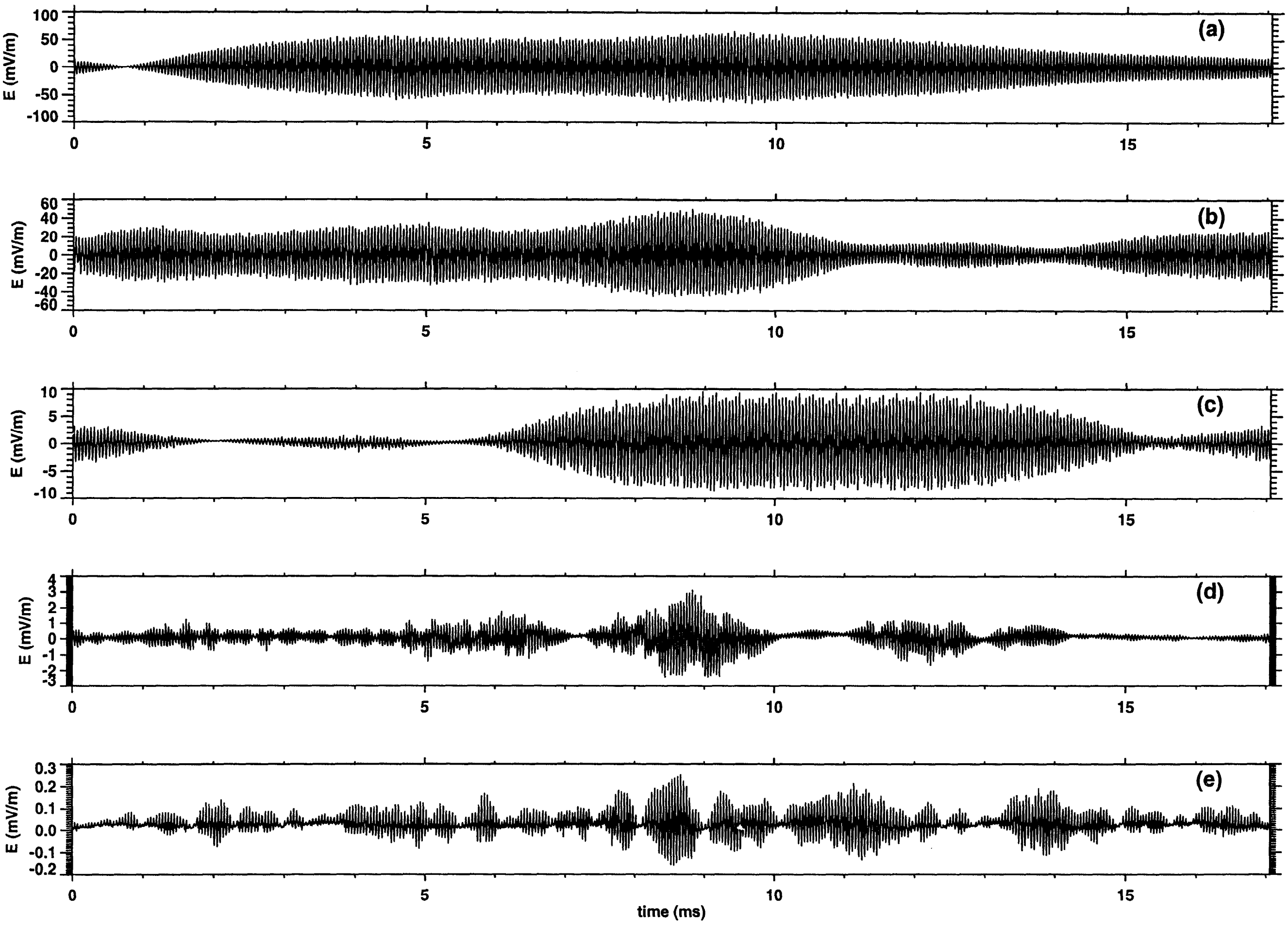

Figure 1. Typical Langmuir waveforms of various amplitudes. Panels (a), (b), and (c) show large amplitude Langmuir waves; these are have very smooth envelopes. Weaker Langmuir wavepackets, panels (d) and (e), tend to be broken up and patchy.

emission; at $f \approx 1.35\ f_{pe}$, we expect the Langmuir waves to be damped with $k\lambda_d \approx 0.5$. Also, events are only included whose peak frequency lies below 35 kHz in order to minimize the effect of the instrument low-pass filter. It is well known [e.g., *Filbert and Kellogg*, 1979; *Etcheto and Faucheux*, 1984] that the largest-amplitude Langmuir waves occur near the solar wind-foreshock boundary. For this analysis, we have not filtered our data spatially; however, the intensity of these events requires that they be sampled near the boundary field line. A study of the spatial dependence is forthcoming.

Figure 2 is a scatterplot of $E_{\rm peak}/E_{\rm rms}$ as a function of $E_{\rm peak}$. It can be seen that the largest amplitude Langmuir waves have relatively small values of $E_{\rm peak}/E_{\rm rms}$; these may approach $\sqrt{2}$ as would be the case for a perfect sine wave. Indeed, if one assumes a sine waveform modulated by a Gaussian envelope and sampled for a finite time 2T about the peak, the theoretical value of $E_{\rm peak}/E_{\rm rms}$ is

$$\frac{E_{peak}}{E_{rms}} = (\frac{1}{2T}\int_0^{2T} dt\ \sin^2 \omega_0 t\ e^{-2[(t-T)/\tau]^2}\ )^{-1/2} \quad (2)$$

where ω_0 is the carrier frequency of the wave, τ is the width of the packet and $2T$ is the sample length. This relationship is shown numerically integrated in Figure 3 . A wave packet with a scale size of $l \sim 10\lambda_d$ would have a transit time of roughly $\tau \approx 10\lambda_d/v_{sw} \approx 0.25$ ms; assuming a 20-kHz plasma wave gives $\chi = \omega\tau \approx 30$. From Figure 3, this gives an $E_{\rm peak}/E_{\rm rms}$ value of about 6. This is larger than our observed value for the large-amplitude events and more consistent with the values for the smaller amplitude, broken up wavepackets. If large-amplitude, small-scale structures were important in the data, one would expect an increase in $E_{\rm peak}/E_{\rm rms}$ at large values of E_{peak}. A very similar result can be obtained using a hyperbolic secant envelope as would be predicted in soliton theory. Note that a large value of $E_{\rm peak}/E_{\rm rms}$ could be due to multiple well-formed envelopes though these would have to have much shorter timescales. The value of $E_{\rm peak}/E_{\rm rms}$ cannot be taken alone as a collapse criterion; however, it is true that small values correspond to waves that are more sinusoidal.

Robinson and Newman [1991] argued that previous observations of Langmuir wave amplitudes in the foreshock [*Filbert and Kellogg*, 1979; *Anderson et al.*, 1981;

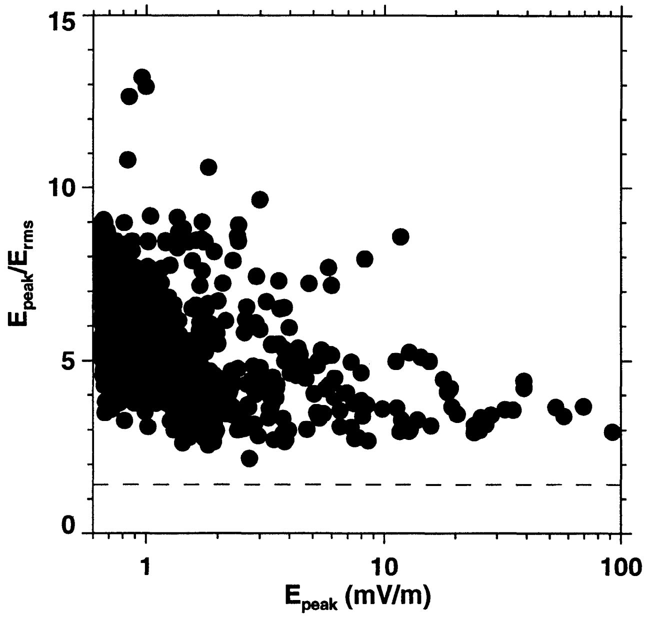

Figure 2. $E_{\text{peak}}/E_{\text{rms}}$ against E_{peak}. The largest-amplitude waves have relatively small values of $E_{\text{peak}}/E_{\text{rms}}$. Instrumental effects are not systematically reducing large amplitudes. The dotted line is at $\sqrt{2}$.

Etcheto and Faucheux, 1984] from the IMP 6 and ISEE 1 spacecraft were systematically underestimated due to instrumental effects. The University of Minnesota Plasma Wave Experiment on IMP 6 returned electric field values integrated over 100 ms and reported maximum amplitudes near 70 mV/m [*Filbert and Kellogg*, 1979]. The relaxation sounder on ISEE 1 averaged together 7 records of 16 ms each for each reported field value. Using this instrument, *Etcheto and Faucheux* [1984] reported RMS amplitudes of $\sim$ 3 mV/m near the foreshock edge. Both of these instruments sample within a relatively small bandwidth and integrate over many cycles of the Langmuir waves. This prompted *Robinson and Newman* [1991] to interpret the results in

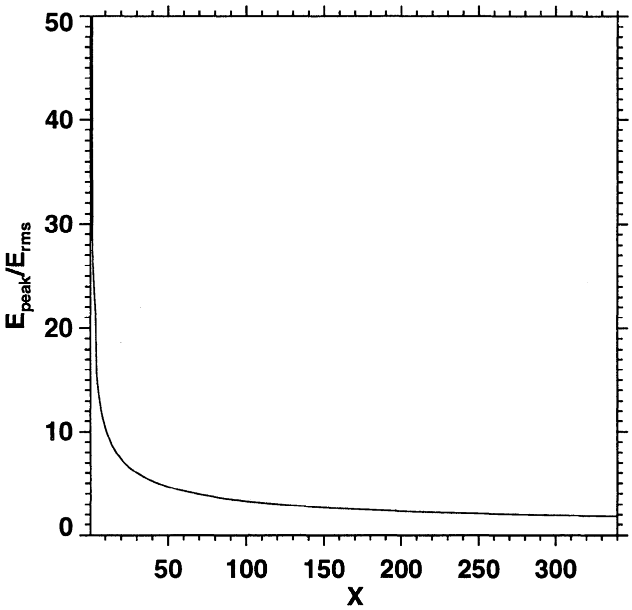

Figure 3. $E_{\text{peak}}/E_{\text{rms}}$ of a Gaussian modulated sine wave as a function of the Gaussian width X = $\omega_0\tau$ (equation (2)) in a finite sample of length 2T. Narrow, localized wavepackets will produce larger values of $E_{\text{peak}}/E_{\text{rms}}$.

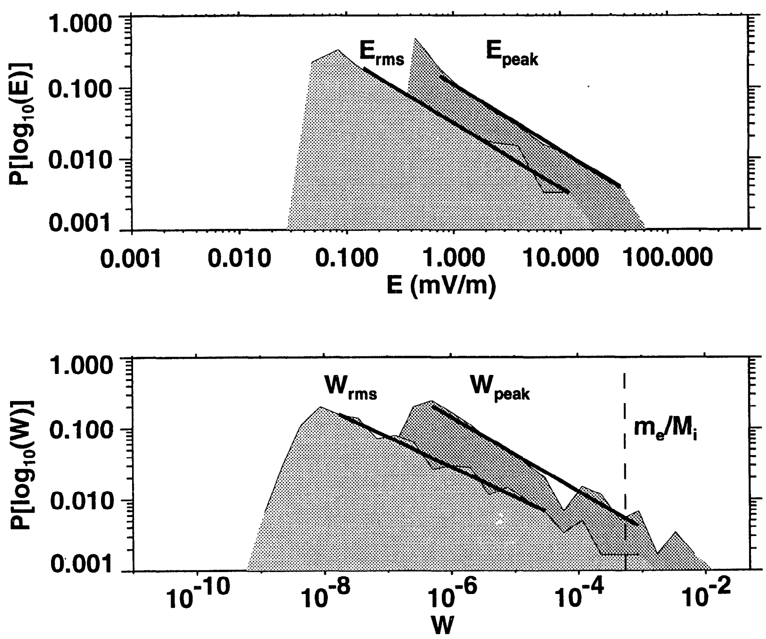

Figure 4. Probability distributions of logged electric field amplitude and dimensionless wave energy. The distributions of peak and RMS amplitude exhibit a $1/E$ form; this may be consistent with a stochastic growth scenario. Dimensionless wave energies (peak and RMS) are distributed as roughly $1/W^{1/2}$ with a slight enhancement above $W_{\text{peak}} \sim m/M$.

the context of Langmuir wave collapse, assuming that these instruments were averaging away large amplitudes on short scales. A structure of size L convecting with the solar wind would be reduced in amplitude by a fraction $L/v_{sw}\Delta t$ in a measurement cycle that averages over Δt. For collapsed Langmuir waveforms of size $L \sim 20\lambda_d$ and $v_{sw} \approx 400\ km/s$, this fraction is $L/v_{sw}\Delta t \approx 1/200$ for IMP 6 and 1/250 for the ISEE 1 sounder. Assuming this effect, and a similar one for finite frequency measurements, *Robinson and Newman* [1991] predict collapsing waveforms with peak amplitudes up to 2 V/m and scale lengths of $l \sim (10 - 20)\lambda_d$. Figure 1, showing fully resolved Langmuir waves, and the peak-to-RMS relationship (Figure 2) do not support this picture. The largest-amplitude waveforms are generally more sinusoidal and have relatively small values of $E_{\rm peak}/E_{\rm rms}$. Here $E_{\rm rms}$ is calculated on each TDS event with an integration time of 17.0667 ms; a longer integration time would, of course, reduce the RMS amplitude.

In Figure 4, the probability distribution of amplitudes and dimensionless wave energy (equation (1)) is shown as calculated from 842 events plotted as P[log$_{10}$(E)] and P[log$_{10}$(W)]. While the lower amplitude/energy end of the scale reflects our choice of threshold, the upper end shows a particular form. In the top panel are the peak and RMS amplitude distributions. The log probability distribution falls off as roughly P[log$_{10}$(E)] $\sim E^{\delta}$ with δ = -0.99 for peak field amplitudes above $\sim$ 1 mV/m. Similarly, the distribution of RMS fields has δ = -0.91 for field amplitudes above $\sim$ 0.1 mV/m.

Recent work [*Cairns and Robinson*, 1997] suggests that this form of the probability distribution is consistent with the stochastic growth theory of type III solar radio bursts [*Robinson*, 1992]. The stochastic growth theory proposes that waves grow, from a marginally stable beam, when the beam interacts with density fluctuations in the solar wind and becomes briefly unstable. Quantitatively, this is achieved by assuming that the process is Markovian and the wave growth (or number of e-foldings) G is a normally distributed random variable. Since G is proportional to log$_e$(E), this distribution can be shown to have the steady state form of a parabola in P[log(E)] versus log(E) [*Robinson*, 1992]. Our data are not binned with respect to spatial position in the foreshock; therefore we are averaging over different growth conditions. This results in a convolution of parabolas that gives the form P[log(E)] $\sim E^{-1}$; *Cairns and Robinson* [1997] have found a similar result in the ISEE 1 data.

Figure 4b shows the peak and RMS dimensionless energy distributions for the same electric field values as Figure 4a. The values of n_p and k_bT_i are taken from the SWE key parameter data. We assume $n_e = n_p$ and $T_e = 3/(\gamma - 1)\ T_i$ with $\gamma = 3$. These distributions show a power law form, P[log$_{10}$(W)] $\sim W^{\delta}$, as well with δ = -0.49 for the peak values and δ = -0.41 for the RMS values. This is consistent with the amplitude distributions.

It can be seen that some of the largest events approach the supersonic limit of the Zakharov equations $W > m/M$. Figure 1 above, however, shows that these large-amplitude wave fields do not show evidence of small-scale, intense structure. Indeed, given that the collapse rate is impeded in the supersonic limit, one would expect statistically to find a relative enhancement in the population of collapsing structures far above $W = m/M$.

Discussion

We find that the peak-to-RMS value of intense plasma waves in the electron foreshock is not large. This is in disagreement with the analysis of *Robinson and Newman* [1991], who suggested that instrumental effects in previous experiments masked the large-amplitude and short scale length of Langmuir wavepackets and inferred that large-amplitude waves are probably in a state of collapse. This is not to say that collapsing waveforms cannot play a role in foreshock wave saturation, only that the bulk of the intense upstream Langmuir waves are not in this state and, indeed, collapsing waveforms have probably not yet been observed in the terrestrial electron foreshock. However, the large-amplitude, sinusoidal waveforms may be part of the plasmon condensate needed to precipitate collapse. The spread in $E_{\rm peak}/E_{\rm rms}$ for smaller peak field values is in some ways equivalent to the observation, by *Etcheto and Faucheux* [1984], that the bandwidth of the large-amplitude waves is smaller. If these large-amplitude waves are indeed evolving by some reactive plasma instability (e.g., parametric decay) then as they affect the particle velocities, they should broaden in bandwidth and pass over to the resistive regime [e.g., *Melrose*, 1991].

Histograms of electric field amplitude show the form P[log$_{10}$(E)] $\sim E^{-1}$ as predicted by the stochastic growth theory of type III radio sources [*Robinson*, 1992] when applied to the foreshock (P. Robinson, personal communication, 1996). The form P[log$_{10}$(E)] $\sim E^{-1}$ is produced when the data are obtained from a wide range of foreshock parameters; local P[log$_{10}$(E)] measurements show the parabolic shape associated with a normal distribution [*Cairns and Robinson*, 1997]. It may be that Langmuir waves in the foreshock grow to saturation in a similar way, encountering patches of instability due to varying solar wind conditions. Alternatively, it could be that variations in the beam itself produce stochastic growth. If the beam acceleration mechanism is fast Fermi in nature [*Krauss-Varban and Burgess*, 1991], randomly varying connectivity or shock tangent angle could distribute growth randomly on a given field line, resulting in the measured distribution.

As mentioned previously, the above results have not been analyzed with respect to spatial location. Previous analyses have shown the dependence of Langmuir wave intensity on distance from the solar wind-foreshock boundary. The cutoff beam speed in time-of-flight models [*Filbert and Kellogg*, 1979] depends on this distance and the distance from the shock tangent point. In practice, it is most likely this beam speed that is the important parameter for wave growth [*Goldman et al.*, 1996] and we are continuing the analysis with respect to cutoff beam speed; this work will be published later. As noted above, the TDS flight software is more sensitive to large-amplitude events; since March 1996, the largest events are telemetered preferentially. Preliminary analysis shows that the very largest events can be highly structured on quite small scales (tens of Debye lengths); still, these events are rare and do not represent the bulk of the foreshock Langmuir wave activity. The present analysis represents a random selection of wave events above the hardware threshold (roughly 0.05 mV/m).

If Langmuir wave collapse were observed near its final stage, where $W \sim (k\ \lambda_d)^2$, then the expected scale of the collapsed waveform, $L \sim 20\ \lambda_d$ [*Robinson and Newman*, 1991], implies $W \sim 0.1$. Our probability distribution of W (Figure 4) shows that such an observation would occur with very small probability. It may be that resistive or reactive electrostatic decay dominates as a saturation mechanism for solar wind Langmuir waves.

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References

Anderson, R. R., G. K. Parks, T. E. Eastman, D. A. Gurnett, and L. A. Frank, Plasma waves associated with energetic particles streaming into the solar wind from the Earth's bow shock, *J. Geophys. Res.*, *86*, 4493, 1981.

Bougeret, J.-L., et al., WAVES: The radio and plasma wave investigation on the Wind spacecraft, *Space Sci. Rev.*, *71*, 231, 1995.

Cairns, I. H., and D. B. Melrose, A Theory for the $2f_{pe}$ radiation upstream of the Earth's bow shock, *J. Geophys. Res.*, *90*, 6637, 1985.

Cairns, I. H., Electrostatic wave generation above and below the plasma frequency by electron beams, *Phys. Fluids B*, *1*, 204, 1989.

Cairns, I. H., and P. A. Robinson, Theory for low-frequency modulated Langmuir wave packets, *Geophys. Res. Lett.*, *19*, 2187, 1992a.

Cairns, I. H., and P. A. Robinson, Strong Langmuir turbulence at Jupiter, *Geophys. Res. Lett.*, *19*, 1069, 1992b.

Cairns, I. H., and P. A. Robinson, Inconsistency of Ulysses millisecond Langmuir spikes with wave collapse in type III radio sources, *Geophys. Res. Lett.*, *22*, 3437, 1995.

Cairns, I. H., and P. A. Robinson, First test of stochastic growth theory for Langmuir waves in Earth's foreshock, *Geophys. Res. Lett.*, *24*, 369, 1997.

Etcheto, J. and M. Faucheux, Detailed study of electron plasma waves upstream of the Earth's bow shock, *J. Geophys. Res.*, *89*, 6631, 1984.

Filbert, P. C., and P. J. Kellogg, Electrostatic noise at the plasma frequency beyond the Earth's bow shock, *J. Geophys. Res.*, *84*, 1369, 1979.

Goldman, M. V., Strong turbulence of plasma waves, *Rev. Mod. Phys.*, *56*, 709, 1984.

Goldman, M. V., D. L. Newman, J. G. Wang, and L. Muschietti, Langmuir turbulence in space plasmas, *Phys. Scr.*, *T63*, 28, 1996.

Kainer, S., and R. J. MacDowall, A ring beam mechanism for radio wave emission in the interplanetary medium, *J. Geophys. Res.*, *101*, 495, 1996.

Kellogg, P. J., K. Goetz, R. L. Howard, and S. J. Monson, Evidence for Langmuir wave collapse in the interplanetary plasma, *Geophys. Res. Lett.*, *19*, 1303, 1992.

Kellogg, P. J., S. J. Monson, K. Goetz, R. L. Howard, J.-L. Bougeret, and M. L. Kaiser, Early Wind observations of bow shock and foreshock waves, *Geophys. Res. Lett.*, *23*, 1243 1996.

Krauss-Varban, D., and D. Burgess, Electron acceleration at nearly perpendicular collisionless shocks 2. Reflection at curved shocks., *J. Geophys. Res.*, *96*, 143, 1991.

Leroy, M. M., and A. Mangeney, A theory of energization of solar wind electrons by the Earth's bow shock, *Ann. Geophys.*, *2*, 449, 1984.

Melrose, D. B., Collective plasma radiation processes, *Annu. Rev. Astron. Astrophys.*, *29*, 31, 1991.

Mish, W. H., J. L. Green, M. G. Reph, and M. Peredo, ISTP science data systems and products, *Space Sci. Rev.*, *71*, 815, 1995.

Nishikawa, K., Parametric excitation of coupled waves, II, Parametric plasmon-photon interaction, *J. Phys. Soc. Jpn.*, *24*, 1152, 1968.

Ogilvie, K. W., et al., SWE, A comprehensive plasma instrument for the Wind spacecraft, *Space Sci. Rev.*, *71*, 55, 1995.

Robinson, P. A., Clumpy Langmuir waves in type III radio sources, *Sol. Phys.*, *139*, 147, 1992.

Robinson, P. A., Nonlinear wave collapse and strong turbulence, *Rev. Mod. Phys.*, in press, 1997.

Robinson, P. A., and I. H. Cairns, Maximum Langmuir fields in planetary foreshocks determined from the electrostatic decay threshold, *Geophys. Res. Lett.*, *22*, 2657, 1995.

Robinson, P. A., and D. L. Newman, Strong plasma turbulence in the Earth's electron foreshock, *J. Geophys. Res.*, *96*, 17,733, 1991.

Thejappa, G., D. Lengyel-Frey, R. G. Stone, and M. L. Goldstein, Evaluation of emission mechanisms at ω_{pe} using Ulysses observations of type III bursts, *Astrophys. J.*, *416*, 831, 1993.

Thiessen, J. P., and P. J. Kellogg, Langmuir wave decay and collapse in the Jovian foreshock, *Planet. Space Sci.*, *41*, 823, 1993.

Wu, C. S., A fast Fermi process: Energetic electrons accelerated by a nearly perpendicular bow shock, *J. Geophys. Res.*, *89*, 8857, 1984.

Zakharov, V. E., Collapse of Langmuir waves, *Sov. Phys. JETP*, *35*, 908, 1972.

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