Observations of Foreshock Langmuir Waves by the Cluster Wideband Data Plasma Wave Receiver
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Abstract

The Wideband Data (WBD) Plasma Wave Receiver, which is a part of the Cluster Wave Experiment Consortium (WEC), provides high-resolution measurements of waveform electric and magnetic fields in selected frequency bands up to 577 kHz. Continuous waveforms are transmitted to a DSN ground station in a 220 kbit/s real-time mode, making the Cluster Wideband Data Plasma Wave Receiver an excellent instrument for studying Langmuir waves in Earth's foreshock region. We will discuss the statistics of the amplitudes of foreshock Langmuir waves observed by Cluster. We will also describe the characteristics of the observed electric field waveforms, and how the properties of the Langmuir waves depend on the spacecraft location within the foreshock region and on upstream solar wind conditions. We will examine the relevance of our Langmuir wave observations to various growth mechanisms and instabilities, such as the modulational instability and stochastic growth theory.

The Electron Foreshock

- The foreshock is a region upstream from Earth's bow shock that is magnetically connected to the bow shock.

- The electron foreshock contains electrons that have been reflected at the bow shock. Upstream of the foreshock boundary, no electrons from the bow shock are observed.

  - Electrons streaming from the bow shock are convected downstream by the **v** x **B** electric field in the solar wind. This produces a beam-like, time-of-flight electron distribution with a higher energy bump on the tail of the distribution function [Filbert and Kellogg, J. Geophys. Res., 84, 1369, 1979].

- The Langmuir waves observed in Earth's foreshock are thought to be generated by instabilities due to the electron beams propagating into the foreshock along the magnetic field lines from the bow shock.

  - Waves are usually observed at the plasma frequency and the second harmonic of the plasma frequency, but waves at frequencies up to the fifth harmonic have been reported in ISEE 1 data [Cairns, J. Geophys. Res., 91, 2975, 1986]. The Langmuir waves often shift above and below the plasma frequency far away from the foreshock boundary [Fuselier et al., J. Geophys. Res., 90, 3935, 1985].

Determining Location Within the Foreshock

- The boundary of the foreshock is determined by the location of the solar wind magnetic field line that is tangent to the bow shock. A method of determining a spacecraft's location within the foreshock was described by Cairns et al. [J. Geophys. Res., 102, 24,249, 1997].

- Assume that $\mathbf{B}_{sw} = (B_x, B_y, B_z)$ and $\mathbf{V}_{sw} = (-V_{sw}, 0, 0)$ in GSE coordinates. We rotate about the X GSE axis by an angle α so that $B_{z'} = 0$. In the new coordinate system,

$$\begin{aligned} x' &= x \\ y' &= y\cos\alpha + z\sin\alpha \\ z' &= -y\sin\alpha + z\cos\alpha \\ B_{yz} &= \sqrt{B_y^2 + B_z^2} \\ \sin\alpha &= B_z / B_{yz} \\ \cos\alpha &= B_y / B_{yz} \end{aligned} \tag{1}$$

  If the spacecraft coordinates are $(x_{obs}, y_{obs}, z_{obs})$ in GSE coordinates, then $x'_{obs} = x_{obs}$ and y'_{obs} and z'_{obs} are given by the above relations.

- We will use a paraboloid in GSE coordinates to represent the bow shock

$$x = a_s - b_s\left(y^2 + z^2\right) \tag{2}$$

where a_s is the shock standoff distance from Earth, and b_s determines the perpendicular scale of the shock. Nominal values of the scaling parameters from Cairns et al. [J. Geophys. Res., 100, 47, 1995] are $a_s = 13.7\ R_E$ and $b_s = 0.0223\ R_E^{-1}$ for an average solar wind ram pressure of 1.8 nPa. The coordinate rotation described in (1) maintains the paraboloid form of the bow shock model, with the substitution of the primed positions in (2).

- In the plane of the spacecraft at z'_{obs}, the point where the solar wind magnetic field is tangent to the model bow shock is

$$\begin{aligned} x'_t &= a_s - b_s\left(y'^2_t + z'^2_{obs}\right) \\ y'_t &= \cos\theta_{bu} / \left(2b_s \sin\theta_{bu}\right) \\ z'_t &= z'_{obs} = Z_\perp \end{aligned} \tag{3}$$

where $\theta_{bu} = \cos^{-1}(\mathbf{V_{sw}} \bullet \mathbf{B_{sw}})/(V_{sw}B_{sw})$ is the angle between the solar wind velocity and the solar wind magnetic field.

- If we transform into a reference frame in the (x', y') plane that has its origin at the tangent point, we can specify the spacecraft's location in the foreshock by $(D_f, R, Z_\perp)$ where

$$\begin{aligned} D_f &= x'_{test} - x'_{obs} \\ x'_{test} &= x'_t - \frac{B_x}{B_{yz}}\left(y'_t - y'_{obs}\right) \\ R &= -\left(x'_{obs} - x'_t\right)\cos\theta_{bu} + \left(y'_{obs} - y'_t\right)\sin\theta_{bu} \end{aligned} \tag{4}$$

In the set of relations given by (4), x'_{test} gives the x' coordinate on the tangent magnetic field line corresponding to the y' coordinate of the observing spaceraft, y'_{obs}. R gives the coordinates parallel to the solar wind magnetic field.

- The coordinates (D_f, R, $Z_\perp$) are illustrated in the drawing below.

Cluster WBD Langmuir Wave Observations on March 26, 2002

- Two time periods when Cluster WBD Plasma Wave Receiver data were available in Earth's foreshock were selected for this presentation. The first time interval is March 26, 2002 from 01:04:27 to 03:50:57 UT. Data were available from spacecraft 2, 3, and 4 during this time period.

- Intense waves near the plasma frequency (30-40 kHz) were observed by all three spacecraft until approximately 01:53 UT. After this time, Cluster was located close to the tangent point and moved in and out of the foreshock. Cluster entered the magnetosheath at 03:19 UT.

- The figures for March 26, 2002 show the spacecraft location in the foreshock for selected time periods, a spectrogram from all three spacecraft, and sample electric field waveforms.

  - Typical Langmuir wave electric field amplitudes in Earth's foreshock are on the order of a few mV/m or less.

Cluster WBD Langmuir Wave Observations on February 17, 2002

- On February 17, 2002 Cluster WBD Plasma Wave Receiver data were available from spacecraft 3 and 4 between 09:13:06 UT and10:13:55 UT. Waves near the plasma frequency (25-35 kHz) were observed during this entire time period.

- The WBD receiver gain is determined by a set of four amplifiers that provide various gains in 5 dB increments up to 75 dB. The gain control can operate in either a manual or auto-ranging mode. For the auto-ranging mode, the gain update rate is programmable from 0.1 to 27 s in increments of 0.1 s. On February 17, 2002, the receiver on spacecraft 4 was run with the gain manually set to zero, allowing us to consistently observe waveforms with amplitudes at the maximum range of the instrument without clipping of the peaks. On spacecraft 3, the amplification was determined by the automatic gain control (update rate 0.1 s).

- The figures for February 17, 2002 show the spacecraft location in the foreshock for selected time periods, a spectrogram from both spacecraft and sample electric field waveforms.

Dependence of Langmuir Wave Amplitudes on Location in the Foreshock

- The statistics of the waveform amplitudes were examined for March 26, 2002 and February 17, 2002. The raw waveform data were checked to eliminate clipped waveforms and waveforms with amplitudes below a selected digitization noise threshold.

- The following figures show scatter plots of the maximum electric field amplitudes for each 0.005 s waveform snapshot plotted against the foreshock coordinates D_f and R. The red trace represents the average electric field amplitudes in 0.5 R_E bins of the D_f and R spacecraft coordinates. $D_f = 0$ and $R = 0$ mark the position of the point where the solar wind magnetic field is tangent to the bow shock.

- The largest electric field amplitudes were observed near the foreshock boundary. The sharp drop-off in the amplitudes indicates the actual position of the foreshock boundary. The observations show that the simple bow shock model for average solar wind conditions correctly determined the foreshock boundary to within a few R_E during these time periods.

Stochastic Growth Theory

- We are investigating various mechanisms that have been proposed to explain the observed characteristics of Langmuir waves in Earth's foreshock. In this presentation, we will discuss stochastic growth theory.

- Stochastic growth theory considers the behavior of waves subject to a randomly varying growth rate.

    - Spatial inhomogeneities and time-varying perturbations in the plasma cause the appearance of regions of positive and negative growth rate.

    - Waves propagating through these regions grow at a rate that fluctuates randomly around the mean. At marginal stability, this leads to a random walk in the logarithm of the wave energy density.

    - Perturbations to the marginally stable state can be externally imposed, due to temporal variations, due to propagation through a spatially inhomogeneous medium or energy source, or generated by a feedback mechanism that allows the waves to affect the energy source.

- For a general formulation of stochastic growth theory that does not incorporate the microphysics of any specific wave instabilities, see Robinson [Phys. Plasmas, 5, 1466-1479, 1995].

Stochastic Growth of Langmuir Waves in Earth's Foreshock Region

- Stochastic growth theory can be used to predict probability distributions for Langmuir wave amplitudes and wave energy densities. According to Cairns and Robinson [Phys. Rev. Lett., 82, 3066, 1999], the amplitude probability distribution is Gaussian in log E

$$P(\log E) = \left(\sigma\sqrt{2\pi}\right)^{-1} e^{-\left(\log E - \mu\right)^2/2\sigma^2} \qquad (5)$$

  In the above relation, μ and σ are the average and standard deviation of log E.

- Cairns and Robinson [Geophys. Res. Lett., 24, 369, 1997] found the observed ISEE 1 electric field amplitude probability distribution P(log E) was Gaussian in log E for an approximately constant spacecraft location relative to the foreshock boundary, in agreement with the prediction of stochastic growth theory.

- For periods with a large variation in the spacecraft location relative to the foreshock, Cairns and Robinson found P(log E) was a power law $P(\log E) \propto E^{-0.8\pm0.3}$.

  - Using Wind TDS data, Bale et al. [J. Geophys. Res., 102, 11,281, 1997] found $P(\log E) \propto E^{-0.99}$.

- Cairns and Robinson interpreted the power law result as the convolution of a spatially varying P(log E) distribution with a probability distribution describing the spacecraft residence time at a given distance from the foreshock boundary.

- We constructed probability distributions for the electric field waveform amplitudes observed by the Cluster WBD Plasma Wave Receiver on March 26, 2002, and February 17, 2002. We divided the amplitude range from 0.001 mV/m to 40 mV/m into 50 bins and determined the percentage of waveforms in each bin. This was done first for all values of D_f, and then for 1 R_E bins in D_f. The results were fit to the Gaussian function predicted by stochastic growth theory. Data from February 17, 2002 were also fit to a power law for comparison.

  - A reasonably good fit to the function predicted by stochastic growth theory was found in many cases, however large deviations from a Gaussian distribution often occurred at very low and very high electric field amplitudes.

Summary of Cluster WBD Foreshock Langmuir Wave Observations

- Our results are consistent with studies of Langmuir waves in the foreshock conducted using data from Wind and ISEE 1 [Bale et al., J. Geophys. Res., 102, 11,281, 1997;Cairns and Robinson, Geophys. Res. Lett., 24, 369, 1997].

    - The largest amplitude waveforms are more sinusoidal and do not vary much on short time scales, while lower amplitude waves tend to occur in bursty packets.

    - The largest amplitude waves are observed near the boundary of the foreshock.

    - The probability distributions for the waveform amplitudes are sometimes consistent with the predictions of stochastic growth theory.

- Further investigations of Langmuir waves in Earth's foreshock using data from the Cluster WBD Plasma Wave Receiver will include studies of other physical processes. The theory of strong Langmuir turbulence can be used to describe the process of Langmuir collapse, which is associated with the modulational instability and the oscillating two-stream instability (OTSI). The random-phase variation of electrostatic decay ($L \rightarrow L' + S$) may also be important for Langmuir waves in Earth's foreshock.