Characteristics of a Langmuir Soliton Observed in a Solar Type III Burst

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Abstract. We present the high time resolution in situ observations of a Langmuir wave packet obtained by the STEREO WAVES experiment in the source region of a solar type III radio burst. This wave packet is unique in the sense that it occurs as an intense localized one-dimensional magnetic field aligned wave packet with peak intensity well in excess of the threshold for the oscillating two stream instability (OTSI), soliton formation and related strong turbulence processes. Most importantly, the measured half-width of this wave packet is approximately equal to the expected half-width of a Langmuir soliton with the same peak intensity as that of the wave packet. Furthermore, a density cavity is created by the ponder-motive force of this wave packet as expected of a Langmuir soliton. These findings indicate that the observed wave packet is most likely a Langmuir soliton formed as a result of the balance between the non-linearity related self-compression and the dispersion related spreading. We discuss the implication of these observations for theories of solar type III radio bursts.

1. Introduction
In a recent paper [14], we have reported the results of our search for Langmuir solitons in the high time resolution in situ wave data obtained by the STEREO WAVES experiment [2] in the source regions of 10 solar type III radio bursts. This search has yielded the identification of several localized magnetic field aligned one dimensional strongly turbulent wave packets as Langmuir solitons. In this paper, we describe the characteristics of one of those events.

In the subsonic limit, the electric field $E(Z, T)$ and the corresponding density perturbation $\delta n_e / n_e$ of the one dimensional Langmuir soliton can be described as [5]:

\begin{align*}
E(Z, t) &= \frac{E_t}{\cosh[k_0(Z - ut)]} \exp[i(k_L Z - \omega t)] \\
\delta n_e &= \frac{W_L}{n_e T_e} \frac{n_e}{n_e T_e}
\end{align*}
where \( Z \) is the longitudinal coordinate, \( t \) is the time, \( k_0 \) is the wave number and \( u \) is the velocity of the soliton. The frequency and wave numbers are defined as [5]

\[
\omega = \omega_{pe} + \frac{3}{2} \lambda^2_{De} (k_L^2 - k_0^2) \omega_{pe}
\]

\[ k_0 = \lambda^{-1}_{De} \sqrt{\frac{W_L}{6 n_e T_e}}. \]

Here \( \frac{W_L}{n_e T_e} = \epsilon_0 E_t^2 \) is the normalized peak energy density (\( E_t \) is the peak amplitude of the wave packet, \( \epsilon_0 \) is the dielectric constant, \( n_e \) and \( T_e \) are the electron density and temperature, respectively), \( \lambda_{De} \) is the Debye length, \( k_L \) is the wave number of the Langmuir wave and \( f_{pe} = \frac{\omega_{pe}}{2\pi} \) is the electron plasma frequency. The velocity of the soliton \( u \) is defined as

\[
u = \frac{\partial \omega}{\partial k_L} = 3 \omega_{pe} \lambda^2_{De} k_L. \]

The half-power width \( L_E \) is related to the peak amplitude \( E_t \) of the soliton as

\[
L_E \approx \frac{2.6}{k_0} \approx \lambda_{De} \sqrt{\frac{40 n_e T_e}{W_L}}, \]

which is obtained from the relation

\[
\frac{E}{E_t} = \frac{1}{\cosh(k_0 Z)} = \frac{1}{2}. \]

Thus, any observed localized wave packet of peak amplitude \( E_t \) can be identified as the Langmuir soliton, if its half-power width \( L_T \) is comparable to \( L_E \) as given in equation (6).

2. Observations

In Figure 1, we present the dynamic spectrum of a local type III radio burst and its associated in situ waves, observed by the STEREO WAVES experiment [2]. The emission drifting fast from \( \approx 14 \text{MHz} \), all the way to \( \approx 26 \text{kHz} \) is the type III radio burst. Using its fast negative frequency drift, we estimate the velocity of the electron beam responsible for this event as \( v_b \approx 0.37c \) (\( c \) is the velocity of light). We identify the non-drifting emissions seen in the 11-15 kHz interval as the Langmuir waves. The time domain sampler (TDS) of the STEREO WAVES experiment has resolved these Langmuir waves into several wave packets. In the left panel of Figure 2, we present the X, Y and Z electric field components of one of such wave packets in the spacecraft frame. We have transformed these field components into the magnetic field aligned coordinate system, whose X-, Y- and Z-axes are aligned along the \( \vec{b}, \vec{b} \times \vec{v} \),
Figure 2. (left) The X- Y- and Z- components of one of the type III associated Langmuir wave packets in spacecraft frame, and (right) the parallel and perpendicular electric field components with respect to the magnetic field. The unit vectors of magnetic field and solar wind velocity used in the coordinate transformation are $\vec{b} = [0.43176, 0.81756, -0.37836]$ and $\vec{v} = [0.98834, -0.049404, 0.14406]$, respectively.

and $\vec{b} \times (\vec{v} \times \vec{b})$, respectively. Here $\vec{b}$ and $\vec{v}$ are the unit vectors of the magnetic field ($\vec{B}$) and solar wind velocity ($v_{sw}$), respectively. These are provided by the STEREO IMPACT magnetic field [1] and STEREO PLASTIC [3] experiments, respectively. Here, we use $\vec{b} = [0.43176, 0.81756, -0.37836]$ and $\vec{v} = [0.98834, -0.049404, 0.14406]$ as given in aten.igpp.ucla.edu/forms/stereo/. In the right panel of Figure 2, we present the field components in the B-aligned coordinate system. Since the peak amplitude of the parallel component $\approx 58.1298 \text{ mV/m}$ is larger than those of the perpendicular components $\approx 7.6 \text{ mV/m}$ and $\approx 24.6 \text{ mV/m}$, we consider this wave packet as the one-dimensional field aligned wave packet. We have used TDS data to study non-linear processes in solar radio bursts [9, 10, 11, 12, 13, 14, 15]. Previously, we have used the Ulysses observations for similar studies [6, 7, 8].
Thus, the measured half-width

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These values yield the half-width of the wave packet as

$\tau_{0.5} \approx 8.08 \text{ ms}. By assuming that the observed wave packet is stationary in the solar wind, $\tau_{0.5}$ measured in the spacecraft frame can be translated into half-width $L_\tau$ of the wave packet in the solar wind frame using the relation

$L_\tau = \tau_{0.5} v_{sw} \cos \theta. \quad (10)$

The STEREO/PLASTIC experiment [3] has measured the solar wind speed as $v_{sw} \approx 628.6 \text{ kms}^{-1}$, and the angle between the solar wind and magnetic field $\theta$ as $\sim 70^\circ$. These values yield the half-width of the wave packet as $L_\tau \approx \tau_{0.5} v_{sw} \cos \theta \approx 100 \lambda_{De}$. Thus, the measured half-width $L_\tau \approx 100 \lambda_{De}$ is very close to the expected half-width

$L_E = \lambda_{De}(40n_{De}E_{\perp})^{1/2} \sim 107 \lambda_{De}. This indicates that the observed wave packet most
Figure 3. (a) The time profile of the total electric field $E_t = \sqrt{E_X^2 + E_Y^2 + E_Z^2}$ (the $\frac{1}{2}$-power duration of $8.076 \text{ ms}$ is equivalent to the spatial scale of $\sim 100 \lambda_{De}$), and (b) the observed time profiles of the $\frac{W_L}{n_e T_e}$ and its associated density cavity $\frac{\delta n_e}{n_e}$, which show that $\frac{1}{2}$-power spatial scales are $\sim 65 \lambda_{De}$ and $\sim 35 \lambda_{De}$, respectively.

likely is the Langmuir soliton formed as a result of cancellation of non-linearity related compression by the dispersion related spreading. If this is true, the ponderomotive force of this wave packet should create a density cavity. As shown in equation (2) the depth of this cavity $\frac{\delta n_e}{n_e}$ should be equal to $\sim \frac{W_L}{n_e T_e}$. To verify this, in Figure 3b, we present the observed time profiles of the $\frac{W_L}{n_e T_e}$ and its associated density cavity $\frac{\delta n_e}{n_e}$. The density fluctuations are measured using the spacecraft potential as shown in [4, 14, 15].

Figure 3b shows that $\frac{1}{2}$-power spatial scales of the $\frac{W_L}{n_e T_e}$ wave packet and density cavity $\frac{\delta n_e}{n_e}$ are $\sim 65 \lambda_{De}$ and $\sim 35 \lambda_{De}$, respectively. Furthermore, as seen in Figure 3b, the $\frac{W_L}{n_e T_e} \sim 3.5 \times 10^{-3}$ agrees reasonable well with $\frac{\delta n_e}{n_e} \sim 2.8 \times 10^{-3}$. Thus, the observed density cavity is most likely created by the ponderomotive force of the observed wave packet. In [14], we have identified 17 Langmuir wave packets as Langmuir solitons. In Figure 4, we plot the measured half-widths ($L_T$) versus their expected half-widths ($L_E$), which shows an excellent correlation with correlation
coefficient of $\sim 0.98$. This provides unambiguous evidence for Langmuir solitons in type III solar bursts.

4. Conclusions
We have presented the observations of an intense localized one dimensional magnetic field aligned Langmuir waveform obtained by the STEREO WAVES experiment in the source region of a local solar type III radio burst. The theories predict that the bump-on-tail distributions of electron beams propagating along the magnetic field excite one-dimensional field aligned Langmuir wave packets. The observations presented in this study represent one of such wave packets. Our analysis has revealed that (1) the peak intensity and short spatial scale of this wave packet easily satisfy the threshold condition for excitation of OTSI and related strong turbulence processes, and (2) the observed wave packet represents the Langmuir soliton formed as a result of OTSI. Thus, the observations presented in this study well confirm that the OTSI and related strong turbulence processes play significant roles in the stabilization of the electron beam as well as excitation of solar radio emissions at the fundamental and higher harmonics of the electron plasma frequency, $f_{pe}$.

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6. References
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