Langmuir Solitons in Solar Type III Radio Bursts: STEREO Observations

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Received 2018 February 16; revised 2018 July 23; accepted 2018 July 23; published 2018 September 5

Abstract

The source regions of solar type III radio bursts are regions of very intense Langmuir wave packets excited by the bump-on-tail distributions of energetic electrons accelerated during solar flares. We report the high time resolution observations of some of these wave packets, which provide unambiguous evidence for Langmuir solitons formed as a result of oscillating two-stream instability (OTSI), since (1) they occur as intense localized one-dimensional magnetic field aligned wave packets, (2) their measured half-widths and peak amplitudes are inversely correlated with each other, so that the narrower the wave packet is, the greater its amplitude; this inverse correlation is the characteristic feature of Langmuir solitons formed as a result of balance between the nonlinearity related self-compression and dispersion related broadening of the wave packets, (3) their FFT spectra contain peaks corresponding to sidebands and low frequency enhancements in addition to pump Langmuir waves, whose frequencies and wave numbers satisfy the resonance conditions of the four-wave interaction known as the OTSI, and (4) they are accompanied by their ponderomotive force induced density cavities. The implication of these observations for theories of solar radio bursts is discussed.

Key words: Sun: flares – Sun: radio radiation

1. Introduction

The purpose of this paper is to report the detection of Langmuir solitons by the time domain sampler (TDS) of the STEREO WAVES experiment (Bougeret et al. 2008) in the source regions of solar type III radio bursts. Langmuir waves excited by the bump-on-tail distributions of electron beams accelerated during solar flares are known to be responsible for these bursts (Ginzburg & Zheleznyakov 1958; Gurnett & Anderson 1977; Lin et al. 1981, 1986). When the intensities of these one-dimensional Langmuir wave packets exceed certain thresholds, theory predicts that they form quasi-stationary self-compressed intense localized wave packets called Langmuir solitons as a result of balance between the nonlinear effect of self-compression and the oppositely acting dispersion induced broadening (Vedenov & Rudakov 1964; Rudakov 1972; Zakharov 1972; Rudakov & Tsytovich 1978). Langmuir solitons are argued to play a very important role in the disruption of the resonance between the Langmuir waves and the electron beam, so that the bump-on-tail distribution of energetic electrons can survive over large distances against the quasi-linear relaxation (Papadopoulos et al. 1974; Galeev et al. 1977; Gorev et al. 1977; Goldman 1983). Because of their large peak intensities, Langmuir solitons are also predicted to be very efficient emitters of electromagnetic waves at the fundamental as well as at higher harmonics of the electron plasma frequency, \( f_{pe} \) (Galeev & Krasnoselskikh 1976; Galeev & Krasnoselskikh 1978; Papadopoulos & Freund 1978; Goldman et al. 1980).

From early on, the in situ wave measurements have shown that Langmuir waves occur as bursty field structures in space environments (Gurnett & Anderson 1977; Kellogg et al. 1992). A comprehensive review of Langmuir wave observations across the heliosphere can be found in Briand (2015). The high time resolution in situ wave observations obtained by the ULYSSES and GALILEO spacecraft in the source regions of solar type III radio bursts have provided evidence for several nonlinear processes (Gurnett et al. 1993; Thejappa et al. 1993, 1995, 1999, 2003; Hospodarsky & Gurnett 1995; Thejappa & MacDowall 1998; Nulsen et al. 2007). The much superior high time resolution in situ wave data from the TDS of the STEREO WAVES experiment (Bougeret et al. 2008) have given us a unique opportunity to identify the signatures of several interesting weak as well as strong turbulence processes in type III bursts (Ergun et al. 2008; Kellogg et al. 2009; Malaspina & Ergun 2008; Henri et al. 2009; Malaspina et al. 2010, 2011; Graham et al. 2012a, 2012b, 2014a, 2014b; Thejappa et al. 2012a, 2012b, 2012c, 2013a, 2013b). It was reported that one of these type III burst associated Langmuir wave packets provides evidence for the four-wave interaction called the oscillating two-stream instability (OTSI; Thejappa et al. 2012c). The trispectral analysis techniques enabled Thejappa et al. (2012a) to show that the spectral components of this wave packet are coupled to each other with a high degree of phase coherency as expected of OTSI. Graham et al. (2012a) argued that the OTSI may not be a viable process for this event because of its three-dimensional nature. However, Thejappa et al. (2013a) have confirmed the findings of Thejappa et al. (2012c) by showing that the parallel as well as perpendicular components of this wave packet contain the spectral signatures of OTSI. Thejappa et al. (2012b) have reported the evidence for OTSI in the high time resolution observations of Langmuir wave packets associated with three different type III events, and have argued that the OTSI probably is a commonly occurring phenomenon in type III bursts.

The searches for Langmuir solitons have also been conducted in the in situ high time resolution wave data obtained in solar type III bursts (Kellogg et al. 1992; Thejappa et al. 1999) as well as in Earth’s foreshock regions (Kellogg et al. 1999). In one of these studies, Thejappa et al. (1999) reported the evidence for Langmuir envelope solitons in the
data obtained by the *Ulysses* URAP Fast Envelope Sampler (Stone et al. 1992) in the source regions of type III radio bursts. However, in that study, the widths of the wave packets were estimated by assuming that the solar wind velocity and magnetic field vectors were parallel to each other, since the data were not available.

Langmuir solitons are of interest for many branches of plasma physics, which include the beam-plasma systems, plasma chemistry, plasma heating, study of evolution of plasma turbulence, anomalous transfer processes, and particle acceleration (see, for example, Lonnregen 1983; Hasegawa 1985) as well as for a variety of astrophysical situations (Gurnett et al. 1981; Pelletier et al. 1988). The topic of Langmuir solitons has been the focus of several theoretical (Rudakov 1972; Zakharov 1972; Krasnoselskikh & Sotnikov 1977; Rudakov & Tyutovich 1978; Thornhill & ter Haar 1978), numerical (Nicholson et al. 1978; Dergyiayev et al. 1980; Robinson 1997), and experimental investigations (Kim et al. 1974; Wong et al. 1974; Wong & Quon 1975; Antipov et al. 1978; Cheung et al. 1982; Nezlin 1993; Vyacheslavov et al. 2002). Solitons in general are considered to be the fundamental objects in nonlinear wave theory, theoretical physics, and even in theoretical bio- and neuro-physics (Rebbi 1979; Zakharov et al. 1980; Newell 1985).

In this paper, we report the results of our recent search for Langmuir solitons in the high time resolution in situ wave data obtained by the TDS of the *STEREO* WAVES experiment in the source regions of 10 solar type III radio bursts. This has resulted in the identification of several localized magnetic field aligned one-dimensional strongly turbulent wave packets, which are unique in the sense that (1) their measured half-widths agree very well with the expected half-widths of Langmuir solitons, (2) they are accompanied by the density cavities created probably by their ponderomotive forces, and (3) their spectra contain signatures of the four-wave interaction called the OTSI. We present the observations of these wave packets and argue that most probably they correspond to Langmuir solitons formed as a result of OTSI. In Section 2, we briefly describe the form of Langmuir solitons, and in Sections 3 and 4, we present the observations, and the discussion and conclusions, respectively.

### 2. Forms of Langmuir Solitons

In the subsonic limit, the electric field $E(Z, t)$ and the corresponding density perturbation $\frac{\delta n_e}{n_e}$ of the one-dimensional Langmuir soliton can be described as (Rudakov & Tyutovich 1978; Nezlin 1993):

$$E(Z, t) = \frac{E_t}{\cosh[k_0(Z - ut)]} \exp[i(k_0Z - \omega t)] \quad (1)$$

$$\frac{\delta n_e}{n_e} = \frac{W_L}{n_e T_e}, \quad (2)$$

where $Z$ is the longitudinal coordinate, $t$ is the time, and $k_0$ and $u$, respectively, are the wave number and velocity of the soliton. The frequency and wave number of oscillations of the soliton are defined as (Nezlin 1993)

$$\omega = \omega_{pe} + \frac{3}{2} \lambda_{De}^2 (k_0^2 - k_0^2) \omega_{pe} \quad (3)$$

Here $\frac{W_L}{n_e T_e}$ 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, $k_0$ is the wave number of the Langmuir wave, and $f_p = \frac{\omega_{pe}}{2\pi}$ is the electron plasma frequency. The velocity of the soliton $u$ is usually assumed to be zero (Kellogg et al. 1999). The half-width $L_E$ is related to the peak amplitude $E_t$ of the Langmuir soliton as

$$L_E \approx \frac{2.6}{k_0} \approx \lambda_{De} \left(\frac{40 n_e T_e}{W_L}\right)^{1/2}. \quad (5)$$

This relationship is obtained from Equation (1) by writing the ratio of the half-power amplitude to peak amplitude of the soliton as

$$\frac{E_E}{E_t} = \frac{1}{\cosh(k_0Z)} \approx \frac{1}{2}. \quad (6)$$

This implies that any Langmuir wave packet of peak amplitude $E_t$ can be identified as the Langmuir soliton, if its measured half-width $L_{1/2}$ is comparable to the expected half-width $L_E$ of the Langmuir soliton of peak intensity $E_t$ as given in Equation (5).

### 3. Observations

The observations consist mainly of the high time resolution waveforms of Langmuir waves captured by the TDS of the *STEREO* WAVES experiment (Bougeret et al. 2008) in the source regions of type III solar radio bursts. The high time resolution voltage differences $V_x$, $V_y$, and $V_z$ returned by the TDS, are usually converted into the wave electric field components $E_x$, $E_y$, and $E_z$ in the spacecraft frame using the transformation matrix given by Bale et al. (2008). In the following, we describe the high time resolution observations of Langmuir waves associated with one of the local type III bursts.

In Figure 1, we show the dynamic spectrum of a typical solar type III radio burst and its associated in situ wave activity, obtained by the high- and low frequency receivers of the *STEREO A* WAVES experiment. Here, the fast drifting emission band from $\approx 16$ MHz to $\approx 26$ kHz corresponds to the type III radio burst, and the nondrifting bursty emissions in the 19–22 kHz range correspond to the Langmuir waves. The TDS has resolved these Langmuir wave bursts into 43 intense waveforms. Each of these waveforms contains 16,384 samples, acquired at a rate of 250,000 samples per second (a time step of 4 μs for a total duration of 65 ms). After examining all these wave packets, we have identified one of them as the probable Langmuir soliton, since (1) it is a localized one-dimensional magnetic field aligned wave packet with a single peak, (2) its peak intensity $E_t$ satisfies the threshold conditions for OTSI and related strong turbulence processes, (3) its spectrum contains the signatures of OTSI, and (4) it is accompanied by the ponderomotive force induced density cavity. In the following, we describe the characteristics of this wave packet, and show that its measured half-width $L_{1/2}$ is approximately equal to that
of the expected half-width $L_E$ of the Langmuir soliton of peak amplitude $E_r$.

### 3.1. Physical Characteristics

In Figure 2, we present the waveforms of the $E_X$, $E_Y$, and $E_Z$ components of this unique TDS event. The peak amplitudes (in spacecraft coordinates) of these components are $27.8 \text{ mV m}^{-1}$, $40.4 \text{ mV m}^{-1}$, and $7.5 \text{ mV m}^{-1}$, respectively. These $E_X$, $E_Y$, and $E_Z$ components are subsequently transformed from the spacecraft into more useful magnetic field ($B$) aligned coordinate system, whose $X$, $Y$, and $Z$-axes are assumed to be aligned along the $b$, $b \times v$, and $b \times (v \times b)$, respectively. The unit vectors of the solar wind velocity $v$ and the magnetic field $b$ are provided by the STEREO PLASTIC (Galvin et al. 2008) and the STEREO IMPACT magnetic field (Acuna et al. 2008) experiments, respectively. In this study, we use $b = (-0.60747, -0.79512, 0.005553)$ and $v = (0.9917, -0.12865, 0.0060756)$ as given in aten.igpp.ucla.edu/forms/stereo/.

In Figure 3, we present the field components of this wave packet in the B-aligned coordinate system, where the top panel shows the parallel component $E_b$ and the middle and bottom panels show the perpendicular components $E_{\perp,1}$ and $E_{\perp,2}$, respectively. The peak amplitudes of these field components $E_b \approx 48.6 \text{ mV m}^{-1}$, $E_{\perp,1} \approx 6.7 \text{ mV m}^{-1}$, and $E_{\perp,2} \approx 8.9 \text{ mV m}^{-1}$ show that the inequalities $E_b \gg E_{\perp,1}$ and $E_b \gg E_{\perp,2}$ are easily satisfied for this wave packet. This suggests that this wave packet is mostly a one-dimensional magnetic field aligned wave packet.

Here, we note that Langmuir wave packets captured by the TDS in the source regions of type III bursts are mostly one-dimensional in nature with $E_b \gg E_{\perp,1}$ and $E_b \gg E_{\perp,2}$. This is consistent with the spectrum of waves excited by the one-dimensional electron beam propagating along the open solar wind magnetic field lines. As discussed by Smith et al. (1979), the growth rate of the beam-plasma instability $\gamma_b$ can be written as:

$$\gamma_b = \frac{\pi}{2} \frac{n_b}{n_e} \frac{v_b}{\Delta v_b} \omega_{pe} \cos^2 \Psi,$$

where $n_b$ is the beam density, $v_b$ is the beam speed, $\Delta v_b$ is the velocity spread in the beam, and $\Psi$ is the angle between the wave vector $k$ and the magnetic field $B$. From this expression, it is clear that $\gamma_b$ is maximum when $\Psi \approx 0$ and it rapidly decreases to zero for $\Psi \approx \frac{\pi}{2}$, i.e., field aligned waves grow much faster in comparison with those of off-angle waves. Smith et al. (1979) have shown that the beam-plasma instability is confined to a narrow cone with an open angle less than 7° about the direction of the magnetic field, i.e., one can consider that the spectrum is one-dimensional. Here, we note that although the wave packet presented in Figures 2 and 3 is strictly not a one-dimensional wave packet, with constraints of a single spacecraft’s observations, we assume that the inequalities $E_b \gg E_{\perp,1}$ and $E_b \gg E_{\perp,2}$ best reflect the one-dimensional nature of the wave packet. However, there exist some exceptions, where the wave packets do occur as two- and three-dimensional field structures. For example, the wave packet presented in Thejappa et al. (2012c) is a three-dimensional wave packet with $E_b \sim E_{\perp,1}$ and $E_b \sim E_{\perp,2}$. 

![Figure 1. Dynamic spectrum of a local type III radio burst (fast drifting emission from $\approx 16 \text{ MHz}$ down to $\approx 26 \text{ kHz}$) and associated Langmuir waves (nondrifting emissions in the frequency interval $19–22 \text{ kHz}$).](image-url)
As seen from Figure 4, the time profile of total electric field $E_t = \sqrt{E_x^2 + E_y^2 + E_z^2}$ clearly shows that this is an intense localized wave packet with peak amplitude $E_t \approx 49$ mV/m. This yields the normalized peak energy density as $\frac{E_t}{E_{T_e}} \approx 7.7 \times 10^{-4}$. Here, for the electron temperature $(T_e)$, we have assigned a typical value of $10^5$ K since the measurements of $T_e$ are not available, and by assuming that the intense peak (L) in the spectrum of the parallel component $E_{\|}$ corresponds to Langmuir waves excited at the local electron plasma frequency, $f_{pe} \approx 20$ kHz (Figure 5(a)), we have estimated the electron density as $n_e \approx 5 \times 10^6$ m$^{-3}$ using the relation $f_{pe}$ [Hz] = $9n_e^{-1/2}$. These values yield the Debye length as $\lambda_{De} = 697/n_e^{-1/2} \approx 9.8$ m.

The modified dispersion relation of an intense Langmuir wave can be written as

$$\omega_L = \omega_{pe} + \frac{3}{2}(k_L \lambda_{De})^2 \omega_{pe} = \frac{W_i}{2n_e T_e} \omega_{pe},$$

where $k_L$ is the wave number of Langmuir waves. From Equation (8), the threshold condition for OTSI can be written as (Zakharov 1972)

$$\frac{W_i}{n_e T_e} > (k_L \lambda_{De})^2.$$  \hspace{1cm} (9)

If the Langmuir waves correspond to beam-excited Langmuir waves, we can estimate $k_L$ by using the speeds of the electron beam derived from the frequency drift $df$ of the type III event. If we assume that the electron density of the solar wind $n_e$ (m$^{-3}$) is given by the Radio Astronomy Explorer (RAE) density model (Fainberg & Stone 1971):}

$$n_e = n_0 r^{-a},$$  \hspace{1cm} (10)

where $n_0 = 5.52 \times 10^{13}$, $a = 2.63$, and $r$ is the solar altitude (in units of $R_{\odot}$), and the type III burst is excited at the second
harmonic of the electron plasma frequency, $f_{pe}$, by the electron beam traveling along the spiral magnetic field lines with a velocity $\beta$ (units of velocity of light $c$), we can express the frequency drift of the type III burst in terms of the velocity of the corresponding electron beam as (Papagiannis 1970)

$$\frac{df}{dt} = -\frac{a\beta c}{2(1 - \beta \cos \phi)R_c(81 \times 10^{-6})^{1/3}f^{(a+2)/a}},$$

where $c$ is the velocity of light, $\phi$ is the angle of exciter direction to Sun-Spacecraft line, and $f$ is the midpoint of frequency interval $df$.

Using the frequency drift of the type III burst presented in Figure 1, we have estimated the beam speed $v_b$ as $\sim 0.37c$, where it is assumed that the path length traveled by the electron beam is increased by a factor of $\alpha = 1.7$ (Lin et al. 1973; Alvarez et al. 1975; Fokker 1984) due to pitch angle scattering. This yields the wave number and wavelength of Langmuir waves as $k_L = \frac{2\pi}{\lambda_L} \approx 1.1 \times 10^{-3} \text{ m}^{-1}$ and $\lambda_L \approx 583\lambda_{De}$, respectively, and $k_L\lambda_{De} \approx 1.1 \times 10^{-2}$. Thus, the threshold condition (9) is easily satisfied, since $\frac{W_L}{n_eT_e} \approx 7.7 \times 10^{-4}$ and $(k_L\lambda_{De})^2 \approx 1.2 \times 10^{-4}$ estimated for $k_L \sim 1.1 \times 10^{-3} \text{ m}^{-1}$ and $\lambda_{De} = 9.8 \text{ m}$. Here, we note that if the Langmuir waves correspond to condensate formed as a result of induced scattering or electrostatic decay (ESD) of beam-excited Langmuir waves into daughter Langmuir and ion sound waves, the threshold for OTSI and soliton formation can be written as (Zakharov 1972)

$$\frac{W_L}{n_eT_e} \geq \frac{m_e}{m_i},$$

where $m_e$ and $m_i$ are the electron and ion masses, respectively. This condition is also easily satisfied for the current event, since $\frac{W_L}{n_eT_e} \approx 7.7 \times 10^{-4}$ and $\frac{m_e}{m_i} \approx 5.5 \times 10^{-4}$.

### 3.2. Spectral Characteristics

To examine the spectral characteristics of this wave packet, we have computed the FFT spectrum of its parallel component $E_p$. The logarithmic spectrum in a narrow frequency interval of $19-21 \text{ kHz}$, presented in Figure 5(a) clearly shows an intense peak (L) corresponding to the beam-excited Langmuir waves at $f_{pe} \approx 20 \text{ kHz}$, and two sidebands, corresponding to the spectral peaks (D) and (U) at $\approx 19.7 \text{ kHz}$ and $\approx 20.3 \text{ kHz}$, respectively. The linear spectrum from $0$ to $0.8 \text{ kHz}$ presented in Figure 5(b) shows the low frequency wave activity below $\approx 500 \text{ Hz}$ with a peak around $60 \text{ Hz}$, probably corresponding to ion sound waves.

The spectral peaks corresponding to sidebands with accompanying low frequency enhancement are the expected spectral signatures of OTSI, which arises as a result of coupling of two Langmuir waves with frequencies and wave numbers ($f_L, k_L$) with the up- and down-shifted sidebands with ($f_U, k_U$) and ($f_D, k_D$) via a purely growing ion sound mode with ($f_S, k_S$). We can identify the observed spectral peaks with the modes involved in OTSI, if they satisfy the following frequency, wave number, and phase matching conditions:

$$2f_L = f_D + f_U,$$
$$2k_L = k_D + k_U,$$
$$2\phi_L = \phi_D + \phi_U,$$

where, the subscripts L, D, and U correspond to the beam-excited Langmuir wave, down- and up-shifted sidebands, respectively.

The frequency matching condition $2f_L = f_D + f_U$ is easily satisfied, since the frequency shifts $\Delta f$ of the down- and up-shifted sidebands are symmetric with respect to the Langmuir wave pump, being $\approx 300 \text{ Hz}$ and $\approx 300 \text{ Hz}$, respectively. Here, the frequency differences $\Delta f = |f_L - f_{LD}|$ are also in good agreement with the frequency of the ion sound waves of $<500 \text{ Hz}$. The wave numbers of the ion sound waves can be estimated as $k_S\lambda_{De} \approx 0.08$ by substituting the observed values $f_S = 300 \text{ Hz}$, $\nu_w = 527 \text{ km s}^{-1}$, and $\cos \theta \approx 0.5$ in the expression for the Doppler shift, $k_S = \frac{2\pi n_w}{\nu_w \cos \theta}$, where $\theta$ is the angle between the electric field and the solar wind vectors. Thus, we obtain $k_{UD} \approx k_S$, since $k_L\lambda_{De} \approx 1.1 \times 10^{-2}$ is much less than $k_S\lambda_{De} \approx 0.08$. This implies that the matching condition $k_{UD} = k_L \pm k_S$ is also satisfied. Here, we note that in one of our earlier studies (Thejappa et al. 2012b), using the trispectral analysis techniques, we have shown that the phase coherence condition (15) is also well satisfied for this event. Thus, the frequency, wave number, and phase coherence matching conditions of OTSI are easily satisfied, for this event, which implies that the spectral peaks seen in the FFT spectrum of the wave packet (Figure 5(a)) probably correspond to the beam-excited Langmuir wave and daughter products of OTSI.
As far as the linear spectrum presented in Figure 5(b) is concerned, it shows four peaks at \( \sim 60 \) Hz, \( \sim 137 \) Hz, \( \sim 200 \) Hz, and \( \sim 300 \) Hz with powers of \( \sim 1.5 \times 10^{-2} \) (mV m\(^{-1}\)) Hz\(^{-1}\), \( \sim 3.5 \times 10^{-3} \) (mV m\(^{-1}\)) Hz\(^{-1}\), \( \sim 1.0 \times 10^{-3} \) (mV m\(^{-1}\)) Hz\(^{-1}\), and \( \sim 1.8 \times 10^{-3} \) (mV m\(^{-1}\)) Hz\(^{-1}\), respectively. These values are much higher than the respective base level powers, which are \( \sim 1.7 \times 10^{-3} \) (mV m\(^{-1}\)) Hz\(^{-1}\) at 60 Hz and \( \sim 7.5 \times 10^{-4} \) (mV m\(^{-1}\)) Hz\(^{-1}\) in the frequency range from 100 to 300 Hz. This suggests that the spectral enhancements seen below 500 Hz in Figure 5(b) are real. Although the waves corresponding to spectral peak at 300 Hz satisfy the resonance conditions of OTSI, with the observational constraints in the estimation of the frequencies, we cannot rule out the involvement of the ion sound waves corresponding to other spectral peaks, especially to the intense peak at \( \sim 60 \) Hz in OTSI.

Here, we note that the spectral enhancements corresponding to sidebands in Figure 5(a) are not as sharp as those presented in Thejappa et al. (2012c). This may be due to different conditions in the source regions of these type III bursts. However, the spectra of some of the wave packets identified as the probable Langmuir solitons in the present study exhibit relatively sharper spectral peaks. In Figure 6, we present one of such spectra. This spectrum is that of the Langmuir wave packet associated with the local type III event of 2010 September 12. In Figure 6(a), we present the logarithmic spectrum in a narrow frequency interval of 23–27 kHz. This narrow spectrum clearly shows an intense peak (L) corresponding to the beam-excited Langmuir wave at \( \approx 20.0 \) kHz, and D and U correspond to the down-shifted sideband at \( \approx 19.7 \) kHz, and up-shifted sideband at \( \approx 20.3 \) kHz, respectively. These values are much higher than the respective base level powers, which are \( \sim 1.7 \times 10^{-3} \) (mV m\(^{-1}\)) Hz\(^{-1}\) at 60 Hz and \( \sim 7.5 \times 10^{-4} \) (mV m\(^{-1}\)) Hz\(^{-1}\) in the frequency range from 100 to 300 Hz. This narrow spectrum clearly shows an intense peak (L) corresponding to the beam-excited Langmuir waves at \( f_{pe} \approx 25.2 \) kHz, and two spectral peaks (D) and (U) at \( \approx 24.9 \) and \( \approx 25.4 \) kHz, respectively. In Figure 6(b), we present the linear spectrum of this event from 0 to 0.5 kHz. This linear spectrum clearly shows an enhancement in low frequency wave activity below \( \approx 500 \) Hz. Notable in this linear spectrum are the peak around 200 Hz and a general enhancement below \( \sim 140 \) Hz with peaks at \( \sim 100 \) Hz and \( \sim 40 \) Hz. We note that these low frequency spectral peaks are real, since the observed powers are much higher than the base level power of 6
In this case also, the frequency matching condition $2f_{\text{L}} \sim f_{\text{D}} + f_{\text{U}}$ is easily satisfied, since the frequency shifts $\Delta f$ of the down- and up-shifted sidebands are relatively symmetric with respect to the Langmuir wave pump, being $\approx 300\,\text{Hz}$ and $\approx 200\,\text{Hz}$, respectively. With experimental uncertainties, the frequency differences $D = |f_{\text{LU}}|$ are in good agreement with the frequency of the ion sound waves of $<500\,\text{Hz}$. The wave numbers of the ion sound waves can be estimated as $k_{\text{S}} \lambda_{\text{De}} \approx 4.5 \times 10^{-2}$ by substituting the observed values $f_{\text{L}} = 300\,\text{Hz}$, $v_{\text{sw}} = 463\,\text{km s}^{-1}$, and $\cos \theta \approx 0.67$ in the expression for the Doppler shift, $k_{\text{S}} = \frac{2\pi f_{\text{L}}}{v_{\text{sw}} \cos \theta}$. Since $k_{\text{L}} \lambda_{\text{De}} \approx 1.0 \times 10^{-2}$ is much less than $k_{\text{S}} \lambda_{\text{De}} \approx 4.5 \times 10^{-2}$, we obtain $|k_{\text{LU},\text{D}}| \approx |k_{\text{S}}|$. This implies that the matching condition $k_{\text{LU}} = k_{\text{L}} \pm k_{\text{S}}$ is also satisfied. Thus, the frequency and wave number matching conditions of OTSI are easily satisfied for this event. Here, we have used the beam speed $v_{\text{b}} \sim 2.2c$ obtained from the estimated frequency drift of the type III burst with the help of Equation (11).

Here we note that in addition to frequency and wave number matching conditions (Equations (13)–(15)), the amplitudes of the sidebands D and U and the pump Langmuir wave L should probably also satisfy certain conditions in the case of OTSI. These conditions may be obtained by solving the appropriate wave kinetic equations, which is beyond the scope of the present study. Here we also note that (1) the amplitude of anti-Stokes mode (U) in Figure 5(a) is lower by 2 orders of magnitude in comparison with that of the Stokes mode (D), which in turn is less than the amplitude of the Langmuir wave pump by 2 orders of magnitude, and (2) the D and U peaks in Figure 6(a) are much weaker than the central peak L.

### 3.3. Ponderomotive Force Induced Density Cavities

In the following, we examine whether the observed wave packet is associated with any ponderomotive force induced density cavity as expected of a Langmuir soliton (Equation (2)). In the present case, since the inequality $\approx 10^{-3}$ (mV m$^{-1}$) Hz$^{-1}$. In this case also, the frequency matching condition $2f_{\text{L}} \sim f_{\text{D}} + f_{\text{U}}$ is easily satisfied, since the frequency shifts $\Delta f$ of the down- and up-shifted sidebands are relatively symmetric with respect to the Langmuir wave pump, being $\approx 300\,\text{Hz}$ and $\approx 200\,\text{Hz}$, respectively. With experimental uncertainties, the frequency differences $D = |f_{\text{LU}}|$ are in good agreement with the frequency of the ion sound waves of $<500\,\text{Hz}$. The wave numbers of the ion sound waves can be estimated as $k_{\text{S}} \lambda_{\text{De}} \approx 4.5 \times 10^{-2}$ by substituting the observed values $f_{\text{L}} = 300\,\text{Hz}$, $v_{\text{sw}} = 463\,\text{km s}^{-1}$, and $\cos \theta \approx 0.67$ in the expression for the Doppler shift, $k_{\text{S}} = \frac{2\pi f_{\text{L}}}{v_{\text{sw}} \cos \theta}$. Since $k_{\text{L}} \lambda_{\text{De}} \approx 1.0 \times 10^{-2}$ is much less than $k_{\text{S}} \lambda_{\text{De}} \approx 4.5 \times 10^{-2}$, we obtain $|k_{\text{LU},\text{D}}| \approx |k_{\text{S}}|$. This implies that the matching condition $k_{\text{LU}} = k_{\text{L}} \pm k_{\text{S}}$ is also satisfied. Thus, the frequency and wave number matching conditions of OTSI are easily satisfied for this event. Here, we have used the beam speed $v_{\text{b}} \sim 2.2c$ obtained from the estimated frequency drift of the type III burst with the help of Equation (11).
Figure 7. Time profiles of the normalized peak energy density \( \frac{W_t}{n_e T_e} \) of the wave packet of Figure 2 and its associated density cavity \( \frac{\Delta n_e}{n_e} \). The \( \frac{1}{\epsilon} \)-power temporal widths of \( \sim 5.3 \text{ ms} \) and \( \sim 2.14 \text{ ms} \) of the wave packet and associated density cavity are equivalent to the spatial scales of \( \sim 142 \lambda_{De} \) and \( \sim 64 \lambda_{De} \), respectively, for the solar wind velocity of \( v_{sw} = 526 \text{ km s}^{-1} \), the angle \( \theta \approx 120^\circ \) between \( b(E) \) and \( n_e \), and the Debye length \( \lambda_{De} = 9.8 \text{ m} \).

\[
\frac{W_t}{n_e T_e} > (k_l \lambda_{De})^2
\]
is easily satisfied, one can see from Equation (8) that \( \omega_{k_l} < \omega_{pe} \), and, therefore, the Langmuir wave packet is trapped inside the self-generated density cavity. The depth of this density cavity \( \frac{\Delta n_e}{n_e} \) created by the ponderomotive force of the Langmuir wave packet should be approximately equal to \( \frac{W_t}{n_e T_e} \). The \( \frac{\Delta n_e}{n_e} \) and the observed spacecraft potential \( \delta \Phi_{sc} [\text{V}] \) are related to each other as (Kellogg et al. 2009; Henri et al. 2011)

\[
\delta \Phi_{sc} [\text{V}] = \frac{1}{T_{ph} [\text{eV}]} \delta \Phi_{sc} [\text{V}],
\]

where \( T_{ph} = 3 \text{ eV} \) is the photoelectron temperature. The \( \delta \Phi_{sc} \) is the change in the spacecraft voltage, measured by the \( X \), \( Y \), and \( Z \) antennas in the frequency band from 100 to 2000 Hz. In Figure 7, we superpose the time profiles of \( \frac{W_t}{n_e T_e} \) and \( \frac{\Delta n_e}{n_e} \). The density shows three types of fluctuations. The fluctuations that show variations in the range from \( \sim 2 \times 10^{-4} \) to \( \sim 3 \times 10^{-4} \) away from the wave packet probably correspond to background density fluctuations. The fluctuations that contain deep cavities in the wings of the wave packet with values \( \sim 8 \times 10^{-4} \) and \( \sim 1 \times 10^{-3} \) are probably related to the wave packet, even though the exact relationship is not clear at this time. The density cavity, which shows a temporal coincidence with the wave packet with \( \frac{\Delta n_e}{n_e} \approx 6.5 \times 10^{-4} \) is probably the density cavity created by the ponderomotive force of the wave packet. As seen from Figure 7, the observed \( \frac{1}{\epsilon} \)-power width of this density cavity \( \sim 64 \lambda_{De} \) is less than that of the wave packet \( \sim 142 \lambda_{De} \).

Here, we have used the Equation (17) to convert the \( \frac{1}{\epsilon} \)-power temporal widths of the wave packet and corresponding density cavity into respective spatial scales. With experimental constraints involved in the measurements of density fluctuations, this is a reasonably good agreement. Here, we note that even in the laboratory experiments (Antipov et al. 1978), usually, the solitons are broader than the corresponding density cavities, and each of these solitons is associated with more than one density cavity. Thus the spectral evidence for OTSI, the inequality \( \frac{W_t}{n_e T_e} \gg \frac{\Delta n_e}{n_e} \), and the temporal coincidence of the density cavity with the wave packet suggest that (1) this density cavity is probably created by the Langmuir soliton of peak energy density of \( \frac{W_t}{n_e T_e} \), and (2) this cavity may not be one of the pre-existing density cavities.

To compare the low frequency waves presented in Figure 5(b) with density fluctuations \( \frac{\Delta n_e}{n_e} \) presented in Figure 7, we present in Figure 8 the corresponding frequency spectra. Here, one should note that the units are in V m\(^{-1}\) unlike those used in all other plots. This is because as seen from Equation (16), the \( \frac{\Delta n_e}{n_e} \) is obtained from the observed spacecraft potential \( \delta \Phi_{sc} (\text{V}) \). Furthermore, since \( \frac{\Delta n_e}{n_e} \) is estimated using Equation (16) in a narrow frequency band from 100 to 2000 Hz, in Figure 8(b) we show its spectrum only from 100 to 500 Hz. As seen in Figure 8, the spectral peaks of the \( E_l \) of the wave packet in this frequency range agree very well with those of \( \frac{\Delta n_e}{n_e} \). This suggests that the density fluctuations corresponding to spectral peaks in Figure 8(b) probably correspond to OTSI excited ion sound waves. As far as the spectral peak at \( \sim 60 \text{ Hz} \) in Figure 5(b) is concerned, it does not correspond to any density fluctuations presented in Figure 7. This is because Equation (16) limits the estimation of \( \frac{\Delta n_e}{n_e} \) to 100–2000 Hz frequency range. However, this does not rule out the link between the waves corresponding to spectral peak at \( \sim 60 \text{ Hz} \) (Figures 5(b) and 8(a)) and density fluctuations.

### 3.4. Measured and Predicted Half-widths

As seen from Figure 4, the half-power duration \( \tau_{0.5} \) of the wave packet is \( \approx 8.46 \text{ ms} \). If we assume that the observed wave packet is stationary in the solar wind, this half-power duration \( \tau_{0.5} \) measured in the spacecraft frame can be converted into the half-width \( L_{1/2} \) of the wave packet in the solar wind frame using the relation

\[
L_{1/2} = \tau_{0.5} v_{sw} \cos \theta,
\]

where \( v_{sw} \) is the solar wind speed and \( \theta \) is the angle between the solar wind velocity and the electric field vector. In the present case, the observed values obtained by the STEREO PLASTIC (Galvin et al. 2008) and the STEREO IMPACT magnetic field (Acuna et al. 2008) experiments are \( v_{sw} \approx 525.7 \text{ km s}^{-1} \) and \( \theta = 120^\circ \), where \( \theta \) is between the solar wind velocity and the magnetic field vectors. Since the observed wave packet is the one-dimensional magnetic field aligned wave packet, this angle can be considered as the angle between the solar wind velocity and the electric field. Thus, we obtain \( L_{1/2} \approx \tau_{0.5} v_{sw} \cos \theta \approx 227 \lambda_{De} \) for \( \tau_{0.5} \approx 8.46 \text{ ms} \), \( v_{sw} \approx 526 \text{ km s}^{-1} \), \( \theta \approx 120^\circ \), and \( \lambda_{De} \approx 9.8 \text{ m} \). As far as the expected half-width
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3.5. Larger Data Set

The TDS has captured 412 Langmuir wave packets during 10 local type III bursts. In Figure 9, we present the histogram of the peak intensities of these wave packets. This histogram shows that it is a skewed distribution. A distribution is usually called skewed right if, as in this histogram, the right tail (larger values) is much longer than the left tail (small values). After a detailed examination of all these wave packets, we have selected 17 of them as the probable candidates for Langmuir solitons. For a wave packet to be qualified as a possible Langmuir soliton, it should satisfy the following conditions: (1) it should be a localized wave packet with a single prominent peak, (2) it should be a one-dimensional magnetic field aligned wave packet with \( \frac{W_1}{n_T} \gtrsim 227 \lambda_{De} \) and \( \frac{W_1}{n_T} \gtrsim 7.7 \times 10^{-4} \), (3) it should satisfy the threshold condition for OTSI and associated Langmuir soliton formation: (a) \( \frac{W_1}{n_T} \gtrsim (\Delta k_1 \lambda_{De})^2 \), (b) \( \frac{W_1}{n_T} \gtrsim (k_1 \lambda_{De})^2 \), and (c) \( \frac{W_1}{n_T} \gtrsim m_e / m_i \), (4) its spectrum should contain the signatures of OTSI, namely, the spectral peaks corresponding to sidebands and low frequency ion sound waves in addition to pump Langmuir wave, which satisfy the relevant resonance conditions, and (5) it should be accompanied by a density cavity with \( \frac{\delta n}{n_0} \lesssim \frac{W_1}{n_T} \).

In Figure 9, we have overlaid the distribution of the identified Langmuir solitons on the histogram of the wave packet power spectrum.
packets observed during the 10 type III events. The blue shows the distribution of these solitons. This comparative histogram clearly shows the subpopulation of solitons in the data. This subpopulation is in the tail of the histogram, i.e., the solitons correspond mostly to very intense wave packets of the distribution. Thus only a small fraction of the observed wave packets can be identified as Langmuir solitons. The majority of TDS events (red in the histogram) are relatively weaker wave packets with a variety of shapes and structures. As seen from this histogram, there are several events with peak intensities equal to or greater than those of the identified solitons. These events are also not selected because of their complex shapes, structures, and spectra.

In Table 1, we present the observed characteristics of the identified Langmuir solitons. As seen from this table, only the event observed on 2013:06:21 at 03:54:35.8411 does not show spectral signatures of OTSI, although it satisfies all other conditions. This may be because the intensities of sidebands and ion sound waves are below the background levels. For these wave packets, we have estimated the peak normalized energy densities $\frac{W_L}{n_e T_e}$, the expected half-widths $L_E$ and the half-power widths $L_{1/2}$ using their measured peak intensities $E_n$, electron densities $n_e$ derived using the fact that the most intense peaks in their FFT spectra correspond to Langmuir waves, half-power durations $\tau_{0.5}$, and, respective solar wind velocities $v_{sw}$ and angles $\theta$ between the solar wind and the magnetic field vectors. For electron temperature $T_e$, we have assigned a typical value of $\sim 10^5$ K for all the events.

In Figure 10, we plot the expected widths $L_E$ estimated by assuming that observed wave packets are the one-dimensional Langmuir solitons (where the peak normalized energy densities $\frac{W_L}{n_e T_e}$ of the wave packets are used) versus the half-widths $L_{1/2}$ estimated directly from the corresponding measured half-power durations $\tau_{0.5}$, solar wind speeds $v_{sw}$ and the angles $\theta$ between the solar velocity and magnetic field vectors. As seen from this plot, the agreement between $L_E$ and $L_{1/2}$ is excellent with the correlation coefficient of 0.98. This indicates that $L_{1/2} \approx L_E$, which is equivalent to the inverse correlation between $\sqrt{\frac{W_L}{n_e T_e}}$ and $L_{1/2}$. This suggests that the larger the amplitude is, the narrower the wave packet, as expected of Langmuir solitons. Here we note that in Figure 10 we have used only 17 events because only these events enabled us to unambiguously estimate $L_{1/2}$ from the measured $\tau_{0.5}$. Because of the complicated shapes, we could not estimate $\tau_{0.5}$ for the rest of the events. Therefore, we could not include them in this plot. As far as the origin of these wave packets is concerned, solitary as well as nonsolitary wave packets probably correspond to beam-excited waves. For a variety of reasons, such as the beam velocity and density, and other conditions in the ambient plasma, these wave packets probably show different characteristics. However, based on these observations, we cannot exactly pinpoint the origin of these different kinds of wave packets.

Since, we have used a value $T_e = 10^5$ K for all 17 events due to lack of electron temperature measurements, it would have introduced some error in Figure 10. Therefore, in Figure 11, we plot $E_n^{-1}$ versus $L_{1/2}$, where $L_{1/2}$ and $E_n$ are in units of m and Vm$^{-1}$, respectively. Figure 11 also shows that $E_n$ and $L_{1/2}$ are inversely correlated as expected of Langmuir solitons with a correlation coefficient of $\approx 0.91$. This confirms the inverse correlation seen in Figure 10. Thus, the characteristics of the observed wave packets agree very well with the expected characteristics of Langmuir solitons.

4. Discussion and Conclusions

We have presented the results of our recent search for Langmuir solitons in the high time resolution in situ wave data obtained by the TDS of the STEREO WAVES experiment in the source regions of 10 local solar type III radio bursts. In these data, we identified 17 unique intense localized one-dimensional magnetic field aligned Langmuir wave packets as probable candidates for the Langmuir solitons. The theories of solar type III bursts predict that the bump-on-tail distributions of electron beams propagating along the coronal and interplanetary magnetic fields excite one-dimensional magnetic field aligned Langmuir wave packets. The waveforms identified in this study represent such wave packets.

Our analysis has revealed that the peak intensities of these wave packets easily satisfy the threshold condition for excitation of OTSI and related strong turbulence processes. For verification of the threshold condition, we have used the wave numbers $k_i$ derived from the beam speeds obtained from the negative frequency drifts of the type III bursts. As expected from such strongly turbulent wave packets, with the help of spectral analysis, we have found that 16 out of 17 wave packets exhibit the characteristic signatures of OTSI, namely, a resonant peak at $f_{pe}$, Stokes and anti-Stokes peaks at $f_{pe} \pm f_s$, and a low frequency enhancement below $f_S$, where $f_{pe}$ and $f_S$ are the electron plasma and ion sound frequencies, respectively. We have shown that these spectral components easily satisfy the frequency and wave number resonance conditions of the OTSI type of four-wave interaction. It is interesting to note that none of the wave packets contain spectral signatures of the ESD, i.e., the decay of the beam-excited Langmuir wave into a daughter Langmuir wave and an ion sound wave. This suggests that the Langmuir wave packets presented in this study probably correspond to the waves excited directly by the electron beam, i.e., they may not correspond to the condensate...
Table 1
Characteristics of Langmuir Solitons Captured by the STEREO Spacecraft in the Source Regions of Solar Type III Radio Bursts

| Date          | Time        | A/B | $E_i$ (mV m$^{-1}$) | $T_{0.5}$ (ms) | $f_{pe}$ (kHz) | $\lambda_{De}$ (m) | $V_{sw}$ km s$^{-1}$ | $\cos \theta$ | $\frac{mL}{n_i\lambda}$ | $L_E$ ($\lambda_{De}$) | $L_{1/2}$ ($\lambda_{De}$) | OTSI | $\frac{\delta n}{n_i}$ |
|---------------|-------------|-----|-------------------|---------------|--------------|-------------------|----------------------|--------------|-----------------|---------------------|-------------------------|------|-----------------|
| 20090718      | 02:42:17.159 | A   | 49.02             | 8.5           | 20.0         | 9.8               | 525.68               | 0.5           | $7.7 \times 10^{-4}$ | 227                | 227                     | Y    | $6.5 \times 10^{-4}$ |
| 20100912      | 08:19:31.214 | A   | 27.35             | 11.7          | 25.18        | 7.8               | 462.73               | 0.67          | $1.5 \times 10^{-4}$ | 513                | 465                     | Y    | $2.9 \times 10^{-4}$ |
| 20111219      | 13:42:21.529 | A   | 43.30             | 8.06          | 27.48        | 7.15              | 346.57               | 0.78          | $3.22 \times 10^{-4}$ | 353                | 305                     | Y    | $2.7 \times 10^{-4}$ |
| 20111219      | 13:47:14.92  | A   | 35.14             | 10.11         | 16.60        | 11.83             | 376.3                | 0.74          | $5.8 \times 10^{-4}$ | 263                | 238                     | Y    | $2.5 \times 10^{-4}$ |
| 20111219      | 13:53:46.131 | A   | 41.36             | 8.0           | 19.15        | 10.25             | 374.30               | 0.78          | $6 \times 10^{-4}$  | 258                | 229                     | Y    | $6.7 \times 10^{-4}$ |
| 20120211      | 22:29:16.198 | B   | 62.84             | 8.82          | 14.11        | 13.91             | 481.75               | 0.48          | $2.6 \times 10^{-3}$ | 125                | 145                     | Y    | $3.5 \times 10^{-4}$ |
| 20130607      | 19:34:25.725 | A   | 60.47             | 8.08          | 11.54        | 17                | 629                  | 0.33          | $3.5 \times 10^{-3}$ | 107                | 100                     | Y    | $2.8 \times 10^{-4}$ |
| 20130621      | 03:53:9.49   | B   | 32.91             | 9.84          | 12.71        | 15.45             | 521.47               | 0.67          | $8.65 \times 10^{-4}$ | 215                | 202                     | Y    | $3 \times 10^{-4}$   |
| 20130621      | 03:53:30.393 | B   | 38.05             | 9.46          | 12.57        | 15.6              | 521.47               | 0.67          | $1.2 \times 10^{-3}$ | 184                | 211                     | Y    | $1.9 \times 10^{-4}$ |
| 20130621      | 03:53:55.725 | B   | 48.39             | 9.5           | 12.70        | 15.3              | 522.45               | 0.58          | $1.9 \times 10^{-3}$ | 215                | 202                     | Y    | $4 \times 10^{-4}$   |
| 20130621      | 03:54:35.811 | B   | 46.48             | 7.24          | 12.82        | 15.35             | 538.29               | 0.52          | $1.7 \times 10^{-3}$ | 154                | 133                     | N    | $6 \times 10^{-4}$  |
| 20130621      | 03:55:1.639  | B   | 50.70             | 8.33          | 12.79        | 15.45             | 538.29               | 0.52          | $2.03 \times 10^{-3}$ | 140                | 153                     | Y    | $9.5 \times 10^{-4}$ |
| 20130704      | 22:15:19.401 | A   | 28.66             | 9.3           | 13.20        | 14.88             | 564.44               | 0.74          | $6.1 \times 10^{-4}$ | 257                | 261                     | Y    | $2.4 \times 10^{-4}$ |
| 20130704      | 22:43:36.733 | A   | 72.14             | 6.83          | 13.69        | 14.35             | 627.94               | 0.31          | $3 \times 10^{-3}$  | 105                | 93                      | Y    | $7.8 \times 10^{-4}$ |
| 20130807      | 10:46:27.18  | B   | 38.26             | 11.0          | 16.25        | 12.08             | 432                  | 0.61          | $7.15 \times 10^{-4}$ | 236                | 241                     | Y    | $7.1 \times 10^{-4}$ |
| 20140629      | 12:52:57.299 | A   | 60.76             | 9.93          | 24.42        | 8.0               | 372.18               | 0.48          | $8 \times 10^{-4}$  | 224                | 219                     | Y    | $3 \times 10^{-4}$   |
| 20140821      | 12:13:11.389 | B   | 31.22             | 15.77         | 22.41        | 8.73              | 358                  | 0.33          | $2.5 \times 10^{-4}$ | 377                | 401                     | Y    | $2.3 \times 10^{-4}$ |
formed as a result of ESD or induced scattering. Moreover, we have discovered that these wave packets are accompanied by density cavities, with depths \( d = W / n_T \), approximately equal to the normalized peak energy densities of the wave packets \( W_{\perp} / n_T \), as expected of Langmuir solitons.

Finally, we have shown that these localized one-dimensional wave packets are unique in the sense that they show high degrees of agreement between their measured half-widths \( L_{1/2} \) obtained from the observed temporal widths \( \tau_{0.5} \), solar wind velocity \( v_w \), and the angle \( \theta \) between the solar wind and magnetic field vectors, and the expected widths \( L_{E} \) of Langmuir solitons of peak amplitudes equal to those of the wave packets. This agreement is a clear indication that the observed wave packets correspond to Langmuir solitons in which the spreading of the wave packets due to dispersion is balanced by the self-focusing due to nonlinearity. This also suggests that the more localized the wave packet or the larger the spread in the wave vector space, the greater the nonlinearity must be and hence the peak intensity.

There are two kinds of solitons: (1) envelope solitons with \( L_{1/2} > \lambda \) and \( W_{\perp} / n_T < (k_L \lambda_{De})^2 \) and (2) Langmuir solitons with \( L_{1/2} < \lambda \) and \( W_{\perp} / n_T > (k_L \lambda_{De})^2 \). In the case of an envelope soliton, since \( \omega_L > \omega_p \), it is not trapped inside the density cavity. On the other hand, the Langmuir soliton is trapped inside the self-generated density cavity, since \( \omega_L < \omega_p \). Therefore, the observed characteristics \( L_{1/2} < \lambda \) and \( W_{\perp} / n_T > (k_L \lambda_{De})^2 \) and \( L_{1/2} \simeq L_E \) indicate that the observed wave packets correspond to Langmuir solitons formed as a result of OTSI. The width of a stable Langmuir soliton should be less than the wavelength of the Langmuir wave \( \lambda \).

Here, we should mention that the formation of solitons is the initial state of strong Langmuir turbulence. Although in one-dimensional approximation, these solitons are expected to be stable, they are known to be unstable for transverse perturbations especially in the case of weak magnetic fields with \( f_{ce} < f_p \) (Rypdal & Juul Rasmussen 1989; Hadzievski et al. 1990; Newman et al. 1994; \( f_p \) is the electron cyclotron frequency). The observed inequalities \( E_{\perp} \gg E_{L,1} \) and \( E_{\parallel} \gg E_{L,1} \) probably indicate that these wave packets are in the initial state of this soliton instability, i.e., these field structures, whose half-widths range from \( \sim 93 \lambda_{De} \) to \( \sim 465 \lambda_{De} \) are still very close to the stable state of one-dimensional solitons. As a result of soliton instability, these wave packets will eventually undergo rapid spatial collapse to very localized intense three-dimensional wave packets. The three-dimensional wave packet presented in our previous study (Thejappa et al. 2012c) is probably one of such wave packets. Theoretically, it is shown that (Robinson 1991; Melatos & Robinson 1993 once these wave packets collapse to spatial scales of the order of \( \sim 20 \lambda_{De} \) the transit time damping suddenly sets in and leads to the complete absorption of the collapsing fields, i.e., burnt-out empty density cavities will be left behind. We have not found any such three-dimensional wave packets in the present data set.

In conclusion, we have clearly demonstrated that the Langmuir wave packets presented in this study provide what is believed to be the first observational evidence for the quasi-stable one-dimensional magnetic field aligned Langmuir solitons formed as a result of OTSI in the source regions of solar type III radio bursts. We have also demonstrated that these solitons are most probably trapped inside the self-generated density cavities. The implication of these findings is that the strong turbulence processes, such as the OTSI and Langmuir solitons play important roles for stabilization of the electron beams as well as emission of the fundamental and higher harmonic electromagnetic waves, which are the long-standing unresolved issues in solar radio astronomy.

The SWAVES instruments include contributions from the Observatoire de Paris, University of Minnesota, University of California, Berkeley, and NASA/GSFC. G.T. acknowledges the support from the NASA STEREO and WIND projects. We thank the anonymous referee for valuable comments, which clarified ideas and presentation.
