Observational Evidence for the Parametric Decay in a Solar Type III Radio Burst

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Abstract. The STEREO spacecraft has provided new observational evidence for the parametric interaction, known as the electrostatic decay instability in the source region of a solar type III radio burst. The in situ high time resolution wave observations show that Langmuir waves often occur as intense one dimensional magnetic field aligned beat type of wave packets, with spectra containing peaks at $f_{pe}$, $f_{pe} - f_S$ and $f_S$, corresponding to the beam excited Langmuir waves ($L$), and respectively to the daughter Langmuir ($L'$) and ion sound ($S$) waves generated as a result of the electrostatic decay instability (ESD) $L \rightarrow L' + S$. Most probably, the beat pattern is due to beating between $L$ and oppositely directed $L'$, and the beat frequency corresponds to ion sound frequency. The implication of these observations for theories of solar type III radio bursts is discussed.

1. Introduction

The STEREO WAVES experiment [2] is equipped with a high resolution receiver called the time domain sampler (TDS), designed primarily for the study of Langmuir and other low frequency waves. The rapid simultaneous sampling of three orthogonal antennas allows the study of waveforms, their distortions, and, through ground-based Fourier analysis, a frequency determination which is far more accurate than any possible on-board filter analysis system. The in situ high time resolution wave observations from the TDS have made it possible to positively identify and study several important non-linear plasma processes, in a wide variety of space environments [3, 6, 10, 12], especially in type III and type II solar radio bursts [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27].

The purpose of this paper is to report some new TDS in situ wave observations, which show that Langmuir waves often occur as one-dimensional magnetic field aligned beat-type waveforms, and to show that they provide new evidence for one of the extremely important non-linear process called the electrostatic decay (ESD) instability. We show that the velocity of the electron beam derived from the resonance conditions of ESD agrees very well with that derived from the drift rate of the type III radio burst,
and, the wave-wave merging of beam-excited Langmuir waves with those of counter-streaming daughter Langmuir waves excited during the ESD appears to be the excitation mechanism for the second harmonic emission. Here, we should note that the evidence for ESD, presented in this study provides additional support for those observations, previously reported in other studies [5, 7, 8, 11, 9, 15, 16]. In section 2, we describe the observations, and in section 3, we present the discussion and conclusions.

2. Observations

In Figure 1, we present the dynamic spectrum of a local solar type III radio burst and its associated in situ waves, observed by the STEREO WAVES experiment [2]. The emission drifting fast from ≈14 MHz, all the way to 2f_{pe} ≈ 32 kHz is the local type III radio burst, where f_{pe} is the electron plasma frequency. Since the frequencies of the type III bursts depend on the radially decreasing electron density n_e, they occur at lower frequencies at later times. The non-drifting emissions in the 16 to 24 kHz frequency range probably correspond to Langmuir waves generated by the solar flare electron beam. These waves show substantial frequency spread of ≈ 8 kHz, which can be interpreted in terms of nonlinear frequency broadening. Using the fast negative frequency drift, we can estimate the velocity of the electron beam v_b responsible for the type III burst to lie in the range ≈ (0.1 – 0.3)c (c is the velocity of light) [19].

TDS has resolved the Langmuir waves into several wave packets, some of which happen to occur as beat-type waveforms. In Figure 2a, we present the X, Y and Z electric field components of one of such beat-type of wave packets in the spacecraft frame. As seen from these waveforms, the wave activity is confined mainly to ≈ 20 ms in the center of the wave packet. The peak amplitudes of these X-, Y- and Z-components are ≈ 37.5 mVm⁻¹, ≈ 16.1 mVm⁻¹ and ≈ 16.9 mVm⁻¹, respectively.

In order to interpret these observations in a meaningful way, we have transformed the field components from the spacecraft into the magnetic field aligned coordinate system, whose X-, Y- and Z-axes are aligned along \( \vec{b} \), \( \vec{b} \times \vec{v} \), 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 (\( \vec{v}_{sw} \)), respectively. In this study, we use \( \vec{b} = [0.812459, 0.4066909, -0.4185185] \) and \( \vec{v} = [0.99278, -0.10437, -0.059174] \), provided respectively by the IMPACT magnetic field [1] and PLASTIC [4] experiments of the STEREO spacecraft. In Figure 2b, we present the waveforms of these field components in the B-aligned coordinate system, which show the beat patterns in the \( E_{||} \) as well as in both \( E_{\perp 1} \) and \( E_{\perp 2} \) components. Since the peak amplitude of the parallel component ≈ 40.7022 mVm⁻¹ is much larger than those of the perpendicular components ≈ 6.1 mVm⁻¹ and ≈ 9.7 mVm⁻¹, this wave packet can be considered as
Figure 2. (a) The X-, Y- and Z- components of one of the type III associated Langmuir wave packets in spacecraft frame, and (b) the parallel and perpendicular electric field components of this wave packet with respect to the magnetic field. The unit vectors of magnetic field and solar wind velocity used in the coordinate transformation are \( \hat{b} = [0.812459, 0.4066909, -0.4185185] \) and \( \hat{v} = [0.99278, -0.10437, -0.059174] \), respectively. 

The time profile of the total electric field, \( E_t = \sqrt{E_x^2 + E_y^2 + E_z^2} \), presented in Figure 3a clearly shows that it steeply rises starting from \( \sim 25 \) ms, by reaching the maximum of \( 42.079 \) mV/m at \( \sim 30 \) ms, and subsequently falls steeply to the background level at \( \sim 45 \) ms. The intense fluctuations seen in \( E_t \) reflect the beat pattern of the wave packet. The \( \tau_e \)-width of this wave packet is \( \sim 17.2 \) ms. By assuming that the observed wave packet is stationary in the solar wind, \( \tau_e \) measured in the spacecraft frame can be translated into \( \tau_e \)-spatial width \( L_\tau \) of the wave packet in the solar wind frame using the relation

\[
L_\tau = \tau_e v_{sw} \cos \theta, \tag{1}
\]

where \( \theta \) is the angle between the solar wind and the wave vector of the wave packet. In the present case, \( \theta \) is the angle between the solar wind velocity and the magnetic field since this event is the one dimensional magnetic field aligned wave packet. During this event, the STEREO PLASTIC experiment [4] has measured the solar wind speed \( v_{sw} \) as \( \sim 347.66 \) kms\(^{-1}\). For \( \cos \theta \sim 0.79 \), \( v_{sw} \sim 347.66 \) kms\(^{-1}\), \( \lambda_{De} \sim 14.5 \) m and \( \tau_e \sim 17.2 \) ms,
we obtain $L_e \sim 325 \lambda_{De}$, where $\lambda_{De}$ is the Debye length.

We have estimated the electron density $n_e$ as $\sim 3.4 \times 10^6$ m$^{-3}$ using the measured $f_{pe}$ of $\sim 16.6$ kHz (see the FFT spectrum of the $E_\parallel$-component presented in Figure 3b). We assign a typical value of $1.5 \times 10^5$K for the electron temperature and assume that $T_e \sim 3T_i$, where $T_i$ is the ion temperature; the measurements of $T_e$ are not available. We estimate the Debye length, $\lambda_{De} = 69T_i^{1/2}n_e^{-1/2} \sim 14.5$ m, and the relative peak energy density $\frac{W_L}{n_e T_e} = \frac{\epsilon_0 E^2_{m}}{2n_e T_e} \approx 1.1 \times 10^{-3}$ ($E_t = 42.079$ mVm$^{-1}$, $n_e = \sim 3.4 \times 10^6$ m$^{-3}$ and $T_e = 1.5 \times 10^5$ K), where, $\epsilon_0 = 8.85 \times 10^{-12}$ Fm$^{-1}$ is the permittivity of free space. The STEREO Impact Magnetic Field Experiment [1] has provided the ambient magnetic field $B \sim 9.07$ nT, which yields the electron cyclotron frequency $f_{ce}$ of $\sim 254$ Hz and $f_{ce}/f_{pe} \sim 1.5 \times 10^{-2}$. This suggests that the ambient plasma can be considered as an isotropic medium, since $f_{ce} << f_{pe}$. We summarize these observed values in Table 1.

3. Discussion
The beat type of waveforms presented in Figure 2 are generated most probably as a result of beating between two identical waves with similar amplitudes with slightly different frequencies. In order to verify this, we have computed the FFT spectrum of the parallel component ( $E_\parallel$ ) of the wave packet. In the top panel of Figure 3b, we present the logarithmic spectrum in the frequency range from 15 to 18 kHz, which clearly exhibits two sharp emission peaks at $\sim 16.6$ kHz and $\sim 16.3$ kHz, with difference in the frequencies ($\Delta f$) of $\sim 300$ Hz, which is the beat frequency of the wave packet. This also shows that the amplitude of the 16.6 kHz peak is slightly higher than that of the 16.3 kHz peak. The linear spectrum in the frequency range from 0 to 1 kHz (bottom panel of Figure 3b) also shows a clear peak at $f_{Ls} \sim 300$ Hz, which is equal to the difference in the frequencies of high frequency spectral peaks $\Delta f$. Thus, the most probable non-linear interaction which can generate an oppositely propagating wave with similar amplitude with a slightly lower frequency is the parametric decay of beam excited Langmuir waves into a daughter Langmuir and ion sound waves. This is also referred to as the electrostatic decay instability (ESD). Thus the spectral peak $L$ at 16.6 kHz probably corresponds to the beam-excited (pump) Langmuir wave, and the spectral peaks $L$ and $S$ at 16.3 kHz and at $\sim 300$ Hz correspond to the oppositely propagating daughter Langmuir and ion sound waves generated as a result of ESD.

The dispersion relations of the Langmuir and ion sound waves are:

$$\omega_L = \omega_{pe}(1 + \frac{3}{2}k_L^2\lambda_{De}^2)$$ (2)

$$\Omega = qc_s,$$ (3)

where $\omega_{pe} = 2\pi f_{pe}$, $k_L$ and $q$ are the wave numbers of the Langmuir and ion sound waves, respectively, $c_s = \sqrt{K_B (T_e + 3T_i)/m_i}$ is the speed of the ion sound waves, $K_B$ is the Boltzmann constant, and $m_i$ and $m_e$ are ion and electron masses, respectively. For $T_e = 3T_i = 1.5 \times 10^5$ K, we estimate $c_s \sim 5 \times 10^4$ ms$^{-1}$. The dispersion relation of the daughter Langmuir wave ($L'$) can be written as:

$$\omega_{L'} = \omega_{pe}(1 + \frac{3}{2}k_{L'}^2\lambda_{De}^2).$$ (4)
The resonance conditions relevant for ESD are:

\[ \vec{k}_{L'} = \vec{k}_L - \vec{q}, \]  
\[ \omega_{L'} = \omega_L - \Omega. \]  

If we substitute dispersion relations (2) and (3) into equations (5) and (6), we obtain

\[ k_{L'}^2 = k_L^2 - qk_0, \]  
where the parameter

\[ k_0 = \frac{2\omega_{pe}c_s}{3v_{Te}^2} \]  
depends only on the ambient electron density and electron and ion temperatures. In the present case, we obtain \( k_0 \simeq 7.7 \times 10^{-4} \) m\(^{-1}\) for \( f_{pe} = 16.6 \) kHz, \( c_s = 5 \times 10^4 \) ms\(^{-1}\) and

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 17.172 ms is equivalent to the spatial scale of \( \sim 325\lambda_{De} \)), and (b) The FFT spectrum of \( E_{||} \) component of the wave packet of Figure 2b; Here the top panel shows the logarithmic spectrum in 15 - 18 kHz range, where the spectral peaks (\( L \)) and (\( L' \)) correspond probably to beam excited Langmuir waves and daughter down-shifted Langmuir waves excited as a result of the electrostatic decay instability (ESD), and the bottom panel shows the linear spectrum in the 0 - 1 kHz frequency range, where the peak at \( f_{IS} \sim 300 \) Hz corresponds to ion sound waves excited as a result of ESD.
$v_{Te} = 2.13 \times 10^6$ ms$^{-1}$. Using equation (5), we can write:

$$k^2_L = k^2_L + q^2 - 2qk_L \cos \phi,$$

(9)

where $\phi$ is the angle between $\vec{k}$ and $\vec{q}$. By substituting equation (7) in (9), we obtain

$$2k_L \cos \phi = q + k_0.$$  

(10)

For $\cos \theta \sim 1$, i.e., for the maximum possible values of $q$, this equation takes the form

$$k_L = \frac{1}{2}(q + k_0).$$

(11)

The wave numbers of ion sound waves can be estimated as:

$$q = \frac{\Omega}{v_{sw} \cos \psi + c_s},$$

(12)

where the $\psi$ is the angle between the ion sound velocity and the solar wind velocity. If we assume that the $\vec{q}$ is aligned along the ambient magnetic field, we obtain $q \simeq 5.8 \times 10^{-3}$ m$^{-1}$ for $\Omega = 2f_{IS}$ with $f_{IS} \simeq 300$ Hz , $v_{sw} \simeq 347.7$ km$s^{-1}$ and $\cos \psi \simeq 0.79$. Thus for $k_0 \simeq 7.6 \times 10^{-4}$ m$^{-1}$, and $q \simeq 5.8 \times 10^{-3}$ m$^{-1}$, we obtain $k_L \simeq 3.3 \times 10^{-3}$ m$^{-1}$ and $v_b = \frac{\omega_{pe}}{k_L} \sim 0.11c$. This velocity agrees with those velocities derived from the measured drift rate of the type III burst of $\sim (0.1 - 0.3)c$.

The threshold condition for ESD can be written as [16]:

$$\frac{W_L}{n_T e} \geq \frac{4\Gamma_L \Gamma_s}{\omega_{pe} \Omega},$$

(13)

where $\Gamma_L$ and $\Gamma_s$ are the damping rates of Langmuir and ion sound waves, respectively. We can estimate $\frac{\Gamma_L}{\omega_{pe}^2}$ using the observed peak energy density of the wave packet using the expression [13]:

$$\frac{\Gamma_L}{\omega_{pe}^2} = \frac{W_L}{(n_T e m_e (\Delta v_b)^2/2\pi)},$$

(14)

where $\Delta v_b$ is the velocity dispersion in the beam. For the current event, we can estimate its peak energy density $W_L = \frac{\pi e k^2}{2}$ as $\sim 7.8 \times 10^{-15}$ J. This yields the relative growth rate of Langmuir waves $\frac{\Gamma_L}{\omega_{pe}^2} \sim 4.9 \times 10^{-5}$ for the observed $n_T e \simeq 3.4 \times 10^6$ m$^{-3}$, and $\Delta v_b \sim 0.2v_b$ and $v_b \sim 0.3c$. The relative damping rate of ion sound waves can be written as [14]:

$$\frac{\Gamma_s}{\Omega} = \left(\frac{\pi}{2}\right)^{1/2}[0.32 \frac{T_e}{T_i} \exp(-\frac{T_e}{2T_i}) + \left(\frac{m_e}{m_i}\right)^{1/2}].$$

(15)

For $T_e = 1.5 \times 10^5$ K and $T_e = 3T_i$, we obtain $\frac{\Gamma_s}{\Omega} \sim 0.3$. Thus the observed $\frac{W_L}{n_T e}$ of $1.1 \times 10^{-3}$ of the wave packet is well above the threshold $\frac{4\Gamma_L \Gamma_s}{\Omega \omega_{pe}^2}$ of $\sim 5.9 \times 10^{-5}$.

Here one should note that since the daughter Langmuir waves generated during ESD are directed against the beam excited Langmuir waves, they can easily coalesce with the beam excited Langmuir waves and yield the second harmonic radio emissions.
Table 1. Plasma and Wave Parameters

| Parameters                                      | 2011 December 19       |
|------------------------------------------------|------------------------|
| Electron Density, \( n_e \) \( \text{m}^{-3} \) | \( 3.4 \times 10^9 \)  |
| Magnetic Field, \( B \) (nT)                    | 9.07                   |
| Electron Cyclotron Frequency (Hz)              | 254                   |
| Solar wind velocity, \( v_{sw} \) \( \text{km} \text{s}^{-1} \) | 347.66                |
| Electron Temperature, \( T_e \) (K)            | \( 1.5 \times 10^5 \)  |
| Electron Ion Temperature Ratio, \( T_e/T_i \)  | 3                     |
| Debye length, \( \lambda_{De} \) (m)          | 14.5                  |
| Electron plasma frequency, \( f_{pe} \) (kHz)  | 16.6                  |
| \( \vec{b} \)                                  | (0.812459, 0.4066909, -0.4185185) |
| \( v_{sw} \)                                   | (0.99278, -0.10437, -0.059174) |
| Beam velocity, \( v_b \)                       | (01 - 0.3)c            |
| Beam width, \( \Delta v_b \)                   | \( \sim 0.1 - 0.2 \)  |
| \( \vec{E} \) mV/ m (Spacecraft Frame)        | (37.5, 16.1, 16.9)     |
| \( \vec{E} \) mV/ m (\( \vec{B} \)-aligned Frame) | (40.7, 6.1, 9.7)      |
| Peak wave amplitude, \( E_t \) (mVm\(^{-1}\))  | 42.1                  |
| Normalized energy density, \( W_L/n_eT_e \)     | \( 1.1 \times 10^{-3} \) |
| \( (f_1, f_2) \) (kHz)                         | (16.6, 16.3)          |
| \( f_S \) (kHz)                                | 0.3                   |

4. Conclusions

This study has clearly shown that the Langmuir waves often occur as one dimensional magnetic field aligned wave packets in the source region of a solar type III radio burst, which is consistent with our previous observations [17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27]. The most striking feature of the wave packets presented in this study is that most of them occur as the beat-type of waveforms, which is indicative of beating between two equally intense oppositely propagating waves with slightly different frequencies. This study has shown that the observed beat pattern is consistent with the predictions of parametric interaction called the electrostatic decay instability, which is the decay of beam excited Langmuir wave directed radially outward into a oppositely propagating daughter Langmuir wave and a low frequency ion sound wave. As expected by this process, the spectra of these wave packets contain peaks corresponding to outward propagating beam excited Langmuir waves, oppositely propagating daughter Langmuir waves and ion sound waves. The frequency and wave number resonance conditions, required by the electrostatic decay instability (ESD) are shown to be easily satisfied for these modes. The speeds of the electron beams derived using these conservation relations agree reasonably well with those obtained from the frequency drift rates of solar type III radio bursts.

Thus, the observed beat-type of wave packets provide unambiguous evidence for the electrostatic decay instability in the source regions of type III radio bursts, even though the strong turbulence processes such as the oscillating two stream instability, Langmuir solitons and Langmuir collapse are generally observed in many other events.
The implication of these observations is that for some type III radio bursts, the ESD plays a very critical role in the stabilization of the electron beam so that it can travel very large distances as well as in excitation of electromagnetic waves at the second harmonic of the electron plasma frequency, $f_{pe}$.

5. Acknowledgment

The SWAVES instruments include contributions from the Observatoire of Paris, University of Minnesota, University of California, Berkeley, and NASA/GSFC. G. T. acknowledges the NASA STEREO and Wind projects for the financial support.

References

[1] Acuna, M. H. et al., 2008, Space Sci. Rev., 136, 203
[2] Bougeret, J. L. et al. 2008, Space Sci. Rev., 136, 487
[3] Ergun, R. E., et al. 2008, Phys. Rev. Lett., 101(5), doi:10.1103/PhysRevLett.101.051101
[4] Galvin, A. B. et al. 2008, Space Sci. Rev., 136, 437
[5] Graham, D. B., & Cairns, I. H. 2013, J. Geophys. Res., 118, 3968
[6] Graham, D. B., Cairns, I. H., & Malaspina, D. M. 2014, J. Geophys. Res., 119, 723
[7] Garnett, D. A., Hospodarsky, G. B., W. S. Kurth, W. S., Williams, D. J., & Bolton, S. J., 1993, J. Geophys. Res., 98, 5631.
[8] Henri, P., Briand, C., Mangeney, A., Bale, S. D., Califano, F., Goetz, K., & Kaiser, M., 2009, J. Geophys. Res., 114, A03103, doi:10.1029/2008JA013738.
[9] Hospodarsky, G. B., & Garnett, D. A., 1995, Geophys. Res. Lett., 22, 1161.
[10] Kellogg, P. J., Goetz, K., Monson, S. J., Bale, S. D., Reiner, M. J., and Maksimovic, M. 2009, J. Geophys. Res., 114, A02107, doi:10.1029/2008JA013566
[11] Lin, R. P., Levedahl, W. K., Lotko, W., D. A. Garnett, D. A., & Scarf, F. L., 1986, Astrophys. J., 308, 954
[12] Malaspina, D. M., & Ergun, R. E. 2008, J. Geophy. Res., 113, A12108
[13] Melrose, D. B., Dulk, G. A., & Cairns, I. H. 1986, Astron. Astrophys., 163, 229
[14] Robinson, P. A., Rev. Mod.Phys., 1997, 69, 507.
[15] Thejappa, G., & MacDowall, R. J., 1998, Astrophys. J., 498, 465.
[16] Thejappa, G., MacDowall, R. J., Scime, E. E., & J. E. Littleton, J. E., 2003, J. Geophys. Res., 108, 1139.
[17] Thejappa, G., MacDowall, R. J., Bergamo, M., and Papadopoulos, K. 2012a, Astrophys. J., 747, L1
[18] Thejappa, G., MacDowall, R. J., and Bergamo, M. 2012b, Geophys. Res. Lett., 39, LXXXX, doi:10.1029/2012GL051017
[19] Thejappa, G., MacDowall, R. J., and Bergamo, M. 2012c, J. Geophys. Res. , 117, A08111, doi:10.1029/2012JA017695
[20] Thejappa, G., MacDowall, R. J., and Bergamo, M. 2013a, Ann. Geophys., 31, 1417-1428
[21] Thejappa, G., MacDowall, R. J., and Bergamo, M. 2013b, J. Geophys. Res. , 118, 114, doi:10.1002/jgra.50441
[22] Thejappa, G., and MacDowall, R. J. 2018a, Astrophys. J., 864:122, http://doi.org/10.3847/1538-4357/aad5e4
[23] Thejappa, G., and MacDowall, R. J. 2018b, Astrophys. J., 862:75, https://doi.org/10.3847/1538-4357/aaca3b
[24] Thejappa, G., & MacDowall, R. J., 2019a, Journal of Physics: Conference Series, 1332, 012016, doi:10.1088/1742-6596/1332/1/012016
[25] Thejappa, G., & MacDowall, R. J., 2019b, Astrophys. J., 864, 122
[26] Thejappa, G., & MacDowall, R. J., 2020a, J. Geophys. Res., (in press)
[27] Thejappa, G., & MacDowall, R. J., 2020b, Astrophys. J., (submitted)