AN IMPROVED MODEL FOR NONLINEAR GENERATION OF TYPE III SOLAR RADIO BURSTS

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Abstract

An improved model of the fundamental plasma emission of type III solar radio bursts is presented. We consider the nonlinear conversion of a traveling Langmuir pump wave into an electromagnetic wave via either convective or absolute hybrid modulational instabilities, resulting from the coupling of two wave triplets. The properties of these four-wave hybrid modulational instabilities are studied using the observed interplanetary parameters.

Nonlinear wave-wave interactions involving Langmuir waves (L), electromagnetic waves (T) and ion-acoustic waves (S) are related with type III solar radio bursts [1, 2, 3]. Traditionally, type III events are interpreted in terms of three-wave processes $L \rightarrow T \pm S$ and $L \rightarrow L \pm S$ [4, 5, 6, 7, 8]. Three-wave electromagnetic or electrostatic three-wave decay/fusion instabilities turn out to be oversimplified descriptions of nonlinear interaction. Recent studies indicated that hybrid parametric instabilities, involving nonlinear coupling of two or more wave triplets, are easily produced by a Langmuir pump wave [9, 10, 11]. In particular, Chian & Rizzato [13, 14] demonstrated that the ponderomotive interaction of hybrid (electromagnetic-electrostatic) parametric instabilities can occur during active experiments in space and laser-plasma experiments in laboratory.

In this paper, we study the nonlinear generation of type III solar radio bursts by a four-wave *hybrid* (coupled electromagnetic and electrostatic) modulational instability, $L \rightarrow T + L + S$, driven by a traveling Langmuir pump wave.

The nonlinear coupling of Langmuir waves, electromagnetic waves and ion-acoustic waves is governed by the generalized Zakharov equations [9, 10, 11, 12]. The *hybrid* nature of coupled high-frequency *electromagnetic* and *electrostatic* waves is evident in equation (1) of Ref. [12].

A traveling Langmuir pump wave $\mathbf{E}_0(\omega_0, \mathbf{k}_0)$ can excite two types of four-wave hybrid modulational instabilities [9, 11]: $L_0 \rightarrow T^+ + L^- + S$ and $L_0 \rightarrow T^- + L^+ + S$, respectively, provided the following frequency and wave-vector matching conditions are fulfilled

$$\omega_\alpha^- \approx \omega_0 - \omega^*, \qquad \omega_\alpha^+ \approx \omega_0 + \omega, \qquad \mathbf{k}_\alpha^\mp = \mathbf{k}_0 \mp \mathbf{k}, \tag{1}$$

where ω and $\mathbf{k}$ are the frequency and wave vector of the low-frequency ion mode, respectively, $\alpha =$ T or L, with $|\mathbf{k}_T^\mp| \ll (|\mathbf{k}_0|, |\mathbf{k}_L^\mp|)$ and $|\mathbf{k}| \approx |\mathbf{k}_0|$, the asterisk denotes the complex conjugate. We shall focus on the process $L_0 \rightarrow T^+ + L^- + S$ since it generates an upconverted anti-Stokes electromagnetic wave ($\omega_T^+ = \omega_0 + \omega$) which can readily leave the source region. In the presence of a large-amplitude traveling Langmuir wave, the two wave triplets $L_0 + S \rightarrow T^+$ and $L_0 \rightarrow L^- + S$ are actually coupled to each other, resulting in a hybrid modulational instability, as depicted in Fig. 1.

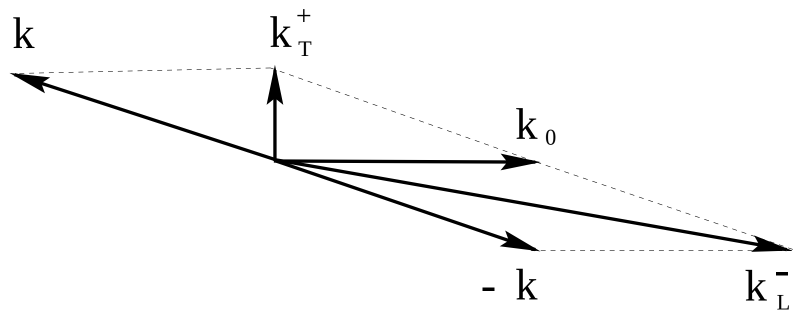

Figure 1. Geometry of wave-vector matching conditions for the hybrid modulational instability $L_0 \rightarrow T^+ + L^- + S$

The nonlinear dispersion relation for the process $L_0 \rightarrow T^+ + L^- + S$ can be derived from a Fourier analysis of the generalized Zakharov equations [12], making use of the phase-matching conditions (1), which yields

$$D_S(\omega, \mathbf{k}) = \Lambda[1/D_T^+(\omega^+, \mathbf{k}_T^+) + 1/D_L^{-*}(\omega^-, \mathbf{k}_L^-)], \tag{2}$$

where $\Lambda = e^2 k_S^2 |\mathbf{E}_0|^2/(m_e m_i)$, $D_S(\omega, \mathbf{k}) = \omega^2 + i\nu_S\omega - v_S^2 k^2$, $D_T^+(\omega^+, \mathbf{k}_T^+) = (\omega_0 + \omega)^2 + i\nu_T(\omega_0 + \omega) - c^2(\mathbf{k}_0 + \mathbf{k})^2 - \omega_p^2$, and $D_L^-(\omega^-, \mathbf{k}_L^-) = (\omega_0 - \omega^*)^2 + i\nu_L(\omega_0 - \omega^*) - \gamma_e v_{th}^2(\mathbf{k}_0 - \mathbf{k})^2 - \omega_p^2$. We assume $\mathbf{k}_T$ perpendicular to $\mathbf{k}_0$. Making the resonant approximation for the high-frequency electromagnetic and Langmuir waves, equation (2) becomes

$$\omega^2 + i2\nu_S\omega - \mu\tau k_0^2 = \frac{\mu\tau k_0^2 W_0}{4}\left[\frac{1}{\omega + \frac{3}{2}k_0^2 - \frac{1}{2}(c/v_{th})^2 k_T^2 + i\nu_T} - \frac{1}{\omega - \frac{9}{2}k_0^2 + i\nu_L}\right], \tag{3}$$

where $\mu = m_e/m_i$, $\tau = (\gamma_e T_e + \gamma_i T_i)/T_e$, $W_0 = \epsilon_0|\mathcal{E}_0|^2/(2n_0 K T_e)$ is the normalized energy density of the Langmuir pump wave, $\mathbf{E}_0 = 1/2 \quad \mathcal{E}_0 exp \quad i(\mathbf{k}_0 \cdot \mathbf{r} - \omega_0 t) + c.c.$, $\lambda_D = [\epsilon_0 K T_e/(n_0 e^2)]^{1/2}$ and we have introduced the normalizations $\omega/\omega_p \rightarrow \omega$ and $\mathbf{k}\lambda_D \rightarrow \mathbf{k}$.

The three-wave electromagnetic fusion instability $L_0 + S \rightarrow T^+$ is obtained from equation (2) by treating the daughter Langmuir wave off-resonant ($D_L^- \neq 0$), giving $D_S D_T^+ = \Lambda$. Under the assumption of resonant ion-acoustic wave ($\omega = v_S k + i\Gamma, \Gamma \ll v_S k \equiv \omega_S$), the threshold is $W_{th} \geq 8\nu_T\nu_S v_S/(\mu\tau k_0)$ and growth rate $\Gamma = [\mu\tau k_0 W_0/(8v_S)]^{1/2}$. This instability operates when $k_0 > (2/3)(\mu\tau)^{1/2}$.

The full dispersion relation (3) contains both convective and absolute hybrid modulational instabilities. Under the assumption of purely growing low-frequency ion mode ($\omega = i\Gamma$), the minimum threshold is $W_{th} = 4(\nu_T\nu_L)^{1/2}$ which is independent of ν_S, and the growth rate is

$$\Gamma = (k_0/2^{1/2})\{[9\mu\tau W_0 + (\frac{81}{4}k_0^2 - \mu\tau)^2]^{1/2} - [\frac{81}{4}k_0^2 + \mu\tau]\}^{1/2} \tag{4}$$

where the relation $k_T = \sqrt{12} \; v_{th} k_0/c$ was imposed. This instability operates when $k_0 < (1/3){W_0}^{1/2}$.

Equation (3) is solved numerically using the typical parameters of interplanetary type III events [1]. For a given k_0, we vary k_T to find the point where the growth rate is maximum.

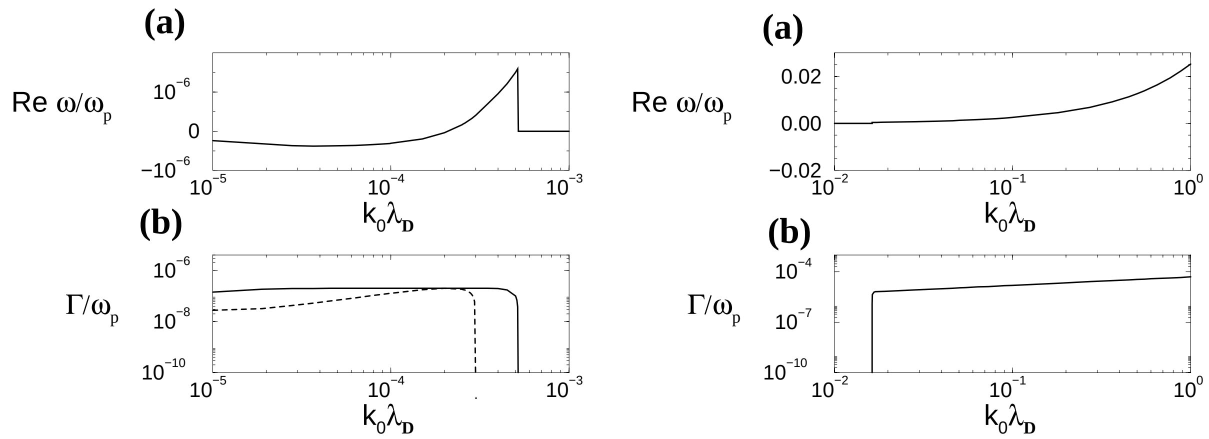

Figure 2. The real wave frequency (a) and maximum growth rate (b) of the convective hybrid modulational instability for small k_0 (on the left), and large k_0 (on the right); $W_0 = 8 \times 10^{-7}$, $T_e = 5T_i$ and $v_{th} = 1.8 \times 10^6$ m/sec.

Figure 3 displays this maximum growth rate (Γ) and the corresponding real part of frequency (Re ω) as a function of k_0. Figure on the left shows the result for $k_0 < (1/3)W_0^{1/2}$. We call this region the absolute regime, since Re $\omega \approx 0$. Figure on the right shows the result for $k_0 > (2/3)(\mu\tau)^{1/2}$. In this region the instability is convective, Re $\omega = \omega_S \neq 0$. For strong Langmuir pump ($W_0 = 0.1$) discussed by Akimoto[9], the absolute and convective regimes merge into a single wideband unstable region.

In order to compare the four-wave hybrid modulational instability with the three-wave electromagnetic fusion instability, we plot in Fig. 3 the growth rate as a function of k_T for a fixed value of k_0. The hybrid modulational instability presents a higher growth rate and wider bandwidth than the three-wave electromagnetic fusion instability.

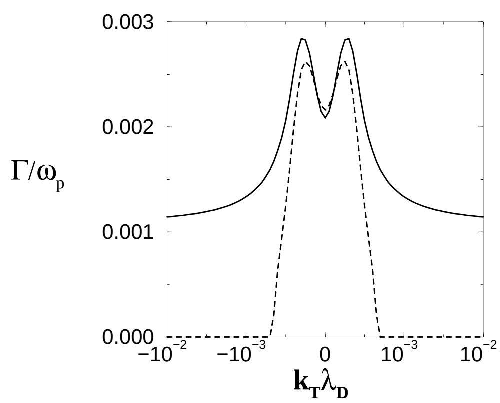

Figure 3. The growth rate of the hybrid modulational instability (solid line) and the electromagnetic fusion instability (dashed line); $W_0 = 8 \times 10^{-2}$, $T_e = 5T_i$, $v_{th} = 1.8 \times 10^6$ m/sec and $k_0\lambda_D = 0.0506$.

Beam-driven Langmuir waves have $k_0 \approx k_b = \omega_p/v_b$, where v_b is the electron beam velocity. For the two interplanetary type III events reported by Lin et al. [1], the condition $k_0 > (2/3)(\mu\tau)^{1/2}$ is satisfied. Hence, the beam-driven Langmuir waves operate in the convective regime. The beam-driven Langmuir waves may subsequently cascade to lower wave numbers through successive forward and backward scatterings if $k_b \gg (m_e/m_i)^{1/2} = 0.0233$. Alternatively, direct scattering of k_b to lower wave numbers can occur if $k_b \geq (m_e/m_i)^{1/2}$ [15]. As the result of the above scattering processes, Langmuir wave energy is built up in the region $k_0 \approx 0$ leading to the formation of Langmuir wave condensate. According to Fig. 2 (left), Langmuir waves in the condensate state can emit radio waves via the absolute hybrid modulational instabilities. In the condensate state, nucleated collapse of Langmuir waves can take place; evidence of such phenomenon in the solar wind was seen by Kellogg et al. [16].

In conclusion, we have shown that the four-wave hybrid modulational instability provides a more accurate description of the fundamental plasma emission of type III solar radio bursts. The nonlinear conversion of Langmuir waves into radio waves occurs via a convective instability for large Langmuir pump wave numbers, and via absolute instabilities for small Langmuir pump wave numbers. For a given Langmuir pump wave energy level, the growth rate of the convective instability is higher than the growth rate of the absolute instabilities. However, in the convective regime the radio waves can propagate out of the source region before reaching sufficiently large amplitudes, whereas in the absolute regime the radio waves can grow to higher amplitudes in the localized source region until nonlinear saturation sets in. Hence, both convective and absolute hybrid modulational instabilities are likely to contribute to the generation of type III solar radio bursts.

Acknowledgments

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