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NONLINEAR GENERATION OF THE FUNDAMENTAL RADIATION OF INTERPLANETARY TYPE III RADIO BURSTS

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ABSTRACT

A new generation mechanism of interplanetary type III radio bursts at the fundamental electron plasma frequency is discussed. It is shown that the electromagnetic oscillating two-stream instability, driven by two oppositely propagating Langmuir waves, can account for the experimental observations. In particular, the major difficulties encountered by the previously considered electromagnetic decay instability are removed.
Subject headings: plasmas — Sun: radio radiation — Sun: solar wind

Interplanetary type III radio bursts are a type of solar radio emission produced by energetic electron streams, accelerated either in solar flares or in active storm regions, that penetrate the solar corona and the interplanetary medium, up to distances of 1 AU and even beyond (Gurnett and Frank 1975; Goldman 1983; Lin *et al.* 1986). As electron streams move away from the Sun, Langmuir waves are excited due to a beam-plasma instability. The Langmuir waves then interact with low-frequency density fluctuations to generate fundamental radiation with frequencies near the local electron plasma frequency. Alternatively, the Langmuir waves can interact with each other to emit harmonic radiation with frequencies near twice the local electron plasma frequency.

Previous theoretical studies usually interpret low-frequency (below 1 MHz) type III emission as second harmonic (Ginzburg and Zheleznyakov 1958; Papadopoulos and Freund 1978; Goldman, Weatherall, and Nicholson 1980; Kruchina, Sagdeev, and Shapiro 1981). However, these theories cannot properly explain the characteristic delay between the onset of the local radio emission and the onset of both the Langmuir waves and the associated energetic electron beams. This inconsistency can be resolved if the low-frequency radio emission is interpreted as fundamental radiation generated much closer to the Sun. Recent experimental observations indicate that interplanetary type III emission is indeed dominated by fundamental radiation from burst onset to peak (Kellogg 1980; Dulk, Steinberg, and Hoang 1984).

Various mechanisms have been suggested for generating solar fundamental radiation. These include induced scattering of Langmuir waves off ion clouds (Ginzburg and Zheleznyakov 1958); direct mode conversion due to propagation and tunneling of Langmuir waves through an inhomogeneous plasma (Ginzberg and Zheleznyakov 1959); incoherent (random phase) coalescence of Langmuir waves with low-frequency waves (Kaplan and Tsytovich 1968); supersonic collapse of strongly turbulent Langmuir wave packets (Goldman, Weatherall, and Nicholson 1980); conversion of Langmuir waves by density fluctuations produced by strong turbulence (Kruchina, Sagdeev, and Shapiro 1981); and electromagnetic decay instability (Cairns 1984; Lin *et al.* 1986; Melrose and Goldman 1986).

In this *Letter*, we consider an electromagnetic oscillating two-stream instability, driven by two oppositely propagating Langmuir waves, which has not yet been discussed in the context of solar fundamental radiation. It is well known that the head-on colescence of two Langmuir waves can generate second harmonic radiation (Ginzburg and Zheleznyakov 1958; Smith 1975; Melrose 1980; Goldman 1983). We demonstrate, in the present *Letter*, that two countertraveling Langmuir waves can interact with low-frequency density perturbations to produce fundamental radiation. In particular, we show that the electromagnetic oscillating two-stream instability may account for the spacecraft observations of interplanetary type III radio bursts. Moreover, the major difficulties associated with the previously considered electromagnetic decay instability are removed.

Several coherent (fixed phase) parametric processes can convert intense Langmuir waves into electromagnetic waves near the fundamental electron plasma frequency. The processes $L \to T \pm S$ involve the decay/fusion (Lashmore-Davies 1974; Shukla *et al.* 1983) of a Langmuir wave (L) into an electromagnetic wave (T) through a parallel/antiparallel propagating ion-acoustic wave (S); these are called electromagnetic decay/fusion instabilities (EDI/EFI), respectively. The processes $L \to T \pm S^*$ involve the coupling of two oppositely directed Langmuir waves ($L^{\pm}$) with purely growing density perturbations (S^*) to produce two electromagnetic waves ($T_{\pm}$) traveling in opposite directions; these are called electromagnetic oscillating two-stream instabilities (EOTSI). The process $L + S^* \to T$ has previously been studied by Lashmore-Davies (1974) using a normal mode formalism which is valid only for interactions involving normal modes. In this *Letter*, we present a unified formulation of EOTSI, EDI, and EFI, including strongly turbulent regimes in which quasi-reactive modes are excited.

The electromagnetic oscillating two-stream instability is operative provided two distributions of Langmuir waves are present in the wave-wave interaction region: beam-generated forward Langmuir waves (L^+) and secondary backward Langmuir waves (L^-). This implies the need of some processes which cause the L^+-waves to be scattered into the backward direction. A number of plausible mechanisms for producing such required spectral modification of Langmuir waves, involving wave-wave interaction or scattering off density irregularities, have been investigated in connection with the second-harmonic radiation (Goldman 1983). Some of these mechanisms may provide the source for the L^--waves required for driving EOTSI.

The coupled wave equations (Lashmore-Davies 1974; Shukla *et al.* 1983) that describe the coherent generation of electromagnetic waves by intense Langmuir waves via ponderomotive coupling with ion acoustic waves are given by

$$\left(\frac{\partial^2}{\partial t^2} - c^2\nabla^2 + \omega_p^2\right)\boldsymbol{E}_T = -\frac{\omega_p^2}{n_0}(n\boldsymbol{E}_L)_T , \qquad (1)$$

$$\left(\frac{\partial^2}{\partial t^2} - c_s^2\nabla^2\right)n = \frac{\omega_p^2\epsilon_0}{2m_i\omega_L\omega_T}\nabla^2\langle \boldsymbol{E}_L \cdot \boldsymbol{E}_T\rangle , \qquad (2)$$

where $\omega_p = (n_0 e^2/m_e \epsilon_0)^{1/2}$; $v_{\rm th} = (KT_e/m_e)^{1/2}$; $c_s = (KT_e/m_i)^{1/2}$; $\langle\ \rangle$ denotes the fast time average; the subscripts L and T refer to Langmuir and transverse electromagnetic waves, respectively; $(\ )_T$ refers to the projection in the direction of $\boldsymbol{E}_T$; and the quasi-neutrality approximation $n_e \approx n_i \equiv n$ for slow time scale density perturbations was assumed.

Consider the pump field consisting of two oppositely propagating Langmuir waves, $\boldsymbol{E}_L = \mathscr{E}_0^+ + \mathscr{E}_0^-$, with $\mathscr{E}_0^+ = \frac{1}{2}\boldsymbol{E}_0^+ \exp i(\boldsymbol{k}_0 \cdot \boldsymbol{x} - \omega_0 t) + \text{c.c.}$, $\mathscr{E}_0^- = \frac{1}{2}\boldsymbol{E}_0^- \exp i(-\boldsymbol{k}_0 \cdot \boldsymbol{x} - \omega_0 t) + \text{c.c.}$; and the density perturbations, $n = \frac{1}{2}n \exp i(\boldsymbol{k} \cdot \boldsymbol{x} - \omega t) + \text{c.c.}$ The beating of the pump field and density perturbations gives rise to induced electromagnetic waves, with the following combination of frequencies and wave vectors: $\boldsymbol{E}_-^+(\omega_0 - \omega, \boldsymbol{k}_0 - \boldsymbol{k}) = \boldsymbol{E}_0^+$-pump driven Stokes mode, $\boldsymbol{E}_+^+(\omega_0 + \omega, \boldsymbol{k}_0 + \boldsymbol{k}) = \boldsymbol{E}_0^+$-pump–driven anti-Stokes mode, $\boldsymbol{E}_-^-(\omega_0 - \omega, -\boldsymbol{k}_0 - \boldsymbol{k}) = \boldsymbol{E}_0^-$-pump–driven Stokes mode and $\boldsymbol{E}_+^-(\omega_0 + \omega, -\boldsymbol{k}_0 + \boldsymbol{k}) = \boldsymbol{E}_0^-$-pump–driven anti-Stokes mode.

The parametric processes $L \to T + S^*$ (EOTSI) and double EDI can be described by the coupling of the pump field with the $\boldsymbol{E}_0^+$-pump–driven Stokes mode $\boldsymbol{E}_-^+$, the $\boldsymbol{E}_0^-$-pump–driven anti-Stokes mode $\boldsymbol{E}_+^-$, and the associated density perturbations. In this case, the Fourier-transformed coupled wave equations, determined from equations (1) and (2), are

$$D_-^+(\omega_-^+, \boldsymbol{k}_-^+)E_-^+ = \frac{\omega_p^2}{2n_0}n^*E_0^+ , \qquad (3)$$

$$D_+^-(\omega_+^-, \boldsymbol{k}_+^-)E_+^- = \frac{\omega_p^2}{2n_0}nE_0^- , \qquad (4)$$

$$D(\omega, \boldsymbol{k})n = \frac{\omega_p^2\epsilon_0 k^2}{4m_i\omega_L\omega_T}(E_0^+E_-^{+*} + E_0^{-*}E_+^-) , \qquad (5)$$

where $D_-^+(\omega_-^+, \boldsymbol{k}_-^+) = (\omega_0 - \omega)^2 - c^2(\boldsymbol{k}_0 - \boldsymbol{k})^2 - \omega_p^2$, $D_+^-(\omega_+^-, \boldsymbol{k}_+^-) = (\omega_0 + \omega)^2 - c^2(\boldsymbol{k}_0 - \boldsymbol{k})^2 - \omega_p^2$, $D(\omega, \boldsymbol{k}) = \omega^2 - c_s^2k^2$; the pump and induced transverse electric fields are taken to be approximately collinear, which is a valid assumption for the wavevector kinematics to be considered in this *Letter*. From equations (3)–(5), we obtain the dispersion relation

$$D(\omega, \boldsymbol{k}) = \Lambda^+/D_-^+(\omega_-^+, \boldsymbol{k}_-^+) + \Lambda^-/D_+^-(\omega_+^-, \boldsymbol{k}_+^-) , \qquad (6)$$

where $\Lambda^\pm = (\epsilon_0\omega_p^4k^2|E_0^\pm|^2)/(8m_in_0\omega_L\omega_T)$. Note that, in general, $\Lambda^\pm$ contains angular factors $(\boldsymbol{e}_0 \cdot \boldsymbol{e}^\pm)^2$ which become unity if the collinear assumption is made. This means that the resulting emission is in an essentially dipole pattern about $\boldsymbol{k}_0$. In the absence of the E_0^--pump ($\Lambda^- = 0$), equation (6) describes the EDI driven by a traveling Langmuir wave (Shukla *et al.* 1983). For simplicity, we set $\Lambda^+ = \Lambda^- \equiv \Lambda$ (i.e., a standing pump). Making the resonant approximation for high-frequency modes, equation (6) can then be rewritten as

$$(\omega^2 - c_s^2k^2)(\omega^2 - \delta^2) = \delta\Lambda/\omega_T , \qquad (7)$$

where $\delta = \omega_T - \omega_0$ and $\omega_-^+ = \omega_+^- = [\omega_p^2 + c^2(\boldsymbol{k}_0 - \boldsymbol{k})^2]^{1/2} \equiv \omega_T$.

Double EDI is excited if $\delta < 0$. Combining the condition $\delta < 0$ with linear dispersion relations shows that $k_T < (3^{1/2}v_{\rm th}/c)k_0$, which for nonrelativistic plasmas implies $k_T \ll k_0$ and $\boldsymbol{k} \approx \boldsymbol{k}_0$, thus in agreement with the usual EDI kinematics (Shukla *et al.* 1983; Cairns 1984; Lin *et al.* 1986). The resulting solutions describe a pair of unstable ion acoustic waves propagating in opposite directions, with two associated electromagnetic waves also traveling in opposite directions (nearly perpendicular to $\pm\boldsymbol{k}_0$ respectively) but having the same frequency (Fig. 1*a*). Two pump regimes of double EDI can be distinguished: weak and strong. In the weak pump regime ($|\omega|^2 \approx c_s^2k^2 \equiv \omega_I^2$), the nonlinear growth rate is $\Gamma_{\rm NL} = (\omega_p\omega_I W/32)^{1/2}$, where $W = \epsilon_0|E_0|^2/n_0KT_e$. Apart from a numerical factor, this expression recovers the result obtained previously for EDI (Shukla *et al.* 1983; Lin *et al.* 1986). In the strong pump regime ($|\omega|^2 \gg c_s^2k^2$), the density perturbations are quasi-reactive modes, and the maximum growth rate is $\Gamma_{\rm NL} = (3^{1/2}/4)(\omega_p c_s^2k^2W/4)^{1/3}$. This modified EDI is excited when $W \gg 32\mu^{1/2}k_0\lambda_D$, where $\mu = m_e/m_i$ and $\lambda_D = (\epsilon_0 kT_e/n_0e^2)^{1/2}$.

Next let us examine the process $L \to T + S^*$ (EOTSI). Assuming a solution $\omega = i\Gamma_{\rm NL}$ in equation (7), we obtain

$$(\Gamma_{\rm NL}^2 + k^2c_s^2)(\Gamma_{\rm NL}^2 + \delta^2) = \delta\Lambda/\omega_T , \qquad (8)$$

which shows that the instability is possible if $\delta > 0$, namely, $k_T > (3^{1/2}v_{\rm th}/c)k_0$. The wavevector kinematics for this modulational instability is fairly similar to double EDI, $k_T \ll k_0$ and $\boldsymbol{k} \approx \boldsymbol{k}_0$ (Fig. 1*a*), which is very different from the usual modulational instabilities wherein more stringent conditions such as $\boldsymbol{k}_0 \to 0$ or $\boldsymbol{k} \perp \boldsymbol{k}_0$ are required. Two regimes of EOTSI can be identified: subsonic and supersonic. In the subsonic regime ($\Gamma_{\rm NL}^2 \ll c_s^2k^2$), the maximum growth rate, obtained when $\delta = \Gamma_{\rm NL}$, is $\Gamma_{\rm NL} = \omega_p W/16$. In the supersonic regime ($\Gamma_{\rm NL}^2 \gg c_s^2k^2$), the maximum growth rate, $\Gamma_{\rm NL} = (\omega_p c_s^2k^2W/16)^{1/3}$, is obtained when $\delta = \Gamma_{\rm NL}$. This supersonic instability is excited when $W \gg 16\mu^{1/2}k_0\lambda_D$.

The parametric processes $L + S^* \to T$ (EOTSI) and double EFI can be described by the coupling of the pump field with the $\boldsymbol{E}_0^+$-pump–driven anti-Stokes mode $\boldsymbol{E}_+^+$, the $\boldsymbol{E}_0^-$-pump driven Stokes mode $\boldsymbol{E}_-^-$, and the associated density pertur-

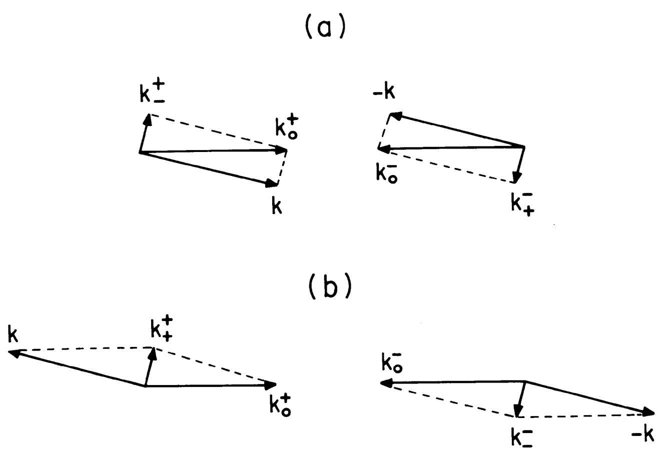

FIG. 1.—The geometry of wavevector matching condition for (*a*) $L \to T + S^*$ (EOTSI) and double EDI, $k_T \ll k_0$ and $\boldsymbol{k} \approx \boldsymbol{k}_0$; (*b*) $L + S^* \to T$ (EOTSI) and double EFI, $k_T \ll k_0$ and $\boldsymbol{k} \approx -\boldsymbol{k}_0$. In the figure, $\boldsymbol{k}_0^\pm$ = wavevectors of pump Langmuir waves, $\pm\boldsymbol{k}$ = wavevectors of ion acoustic waves, and wavevectors of electromagnetic waves are defined as $\boldsymbol{k}_-^+ = \boldsymbol{k}_0^+ - \boldsymbol{k}$, $\boldsymbol{k}_+^- = \boldsymbol{k}_0^- + \boldsymbol{k}$, $\boldsymbol{k}_+^+ = \boldsymbol{k}_0^+ + \boldsymbol{k}$, and $\boldsymbol{k}_-^- = \boldsymbol{k}_0^- - \boldsymbol{k}$.

bations. In this case, the Fourier-transformed coupled wave equations, obtained from equations (1) and (2), are

$$D_+^+(\omega_+^+, \mathbf{k}_+^+)E_+^+ = \frac{\omega_p^2}{2n_0} nE_0^+ , \tag{9}$$

$$D_-^-(\omega_-^-, \mathbf{k}_-^-)E_-^- = \frac{\omega_p^2}{2n_0} n^*E_0^- , \tag{10}$$

$$D(\omega, \mathbf{k})n = \frac{\omega_p^2 \epsilon_0 k^2}{4m_i \omega_L \omega_T} (E_0^{+*}E_+^+ + E_0^- E_-^-) , \tag{11}$$

where $D_+^+(\omega_+^+, \mathbf{k}_+^+) = (\omega_0 + \omega)^2 - c^2(\mathbf{k}_0 + \mathbf{k})^2 - \omega_p^2$, $D_-^-(\omega_-^-, \mathbf{k}_-^-) = (\omega_0 - \omega)^2 - c^2(\mathbf{k}_0 + \mathbf{k})^2 - \omega_p^2$, $D(\omega, \mathbf{k})$ is as defined before, and the wavevector kinematics in this case requires $k_T \ll k_0$ and $\mathbf{k} \approx -\mathbf{k}_0$ (Fig. 1*b*). From equations (9)–(11), we get the dispersion relation

$$D(\omega, \mathbf{k}) = \Lambda^+/D_+^+(\omega_+^+, \mathbf{k}_+^+) + \Lambda^-/D_-^-(\omega_-^-, \mathbf{k}_-^-) , \tag{12}$$

where $\Lambda^{\pm}$ are as given previously. In the absence of the E_0^--pump ($\Lambda^- = 0$), equation (12) describes the EFI driven by a traveling Langmuir wave (Lashmore-Davies 1974). Setting $\Lambda^+ = \Lambda^- \equiv \Lambda$, equation (12) then reduces exactly to equation (7) with $\omega_+^+ = \omega_-^- = [\omega_p^2 + c^2(\mathbf{k}_0 + \mathbf{k})^2]^{1/2} \equiv \omega_T$. The results for this case follow exactly the same results obtained before.

The theoretical results can be summarized as follows:

1. EDI/EFI are essentially three-wave processes in which a Langmuir wave excites an electromagnetic wave and a traveling ion acoustic wave, whereas EOTSI is a four-wave process in which two Langmuir waves excite two electromagnetic waves by means of forced, localized, density perturbations.

2. EDI/EFI are convective, whereas EOTSI is absolute since it is a purely growing instability.

3. EDI/EFI are essentially down-conversion ($\omega_T < \omega_0$) processes except when large-frequency mismatch is induced, whereas EOTSI is necessarily an up-conversion ($\omega_T > \omega_0$) process; in fact, the conditions $\delta \lesseqgtr 0$ can provide useful information on the range of electromagnetic wave frequency that each instability can generate: $\omega_p < \omega_T$ (EDI/EFI) $< \omega_c$ and $\omega_c < \omega_T$ (EOTSI), where $\omega_c = \omega_p(1 + 3v_{\rm th}^2/v_b^2)^{1/2}$ and $v_b =$ electron beam velocity.

4. The dissipative threshold for EDI/EFI, obtained by including the damping terms in equation (7), is $W_0 \gtrsim 32\Gamma_I \Gamma_T/\omega_I \omega_p$, which depends on the damping rates of both ion acoustic (Γ_I) and electromagnetic waves (Γ_T), whereas the minimum threshold for EOTSI, $W_0 \gtrsim 16\Gamma_T/\omega_p$, is independent of the damping rate of density perturbations.

The electromagnetic waves generated by the electromagnetic oscillating two-stream instability, as well as EDI/EFI, may provide a natural source for interplanetary type III radio bursts near the fundamental electron plasma frequency. In a recent paper, Lin *et al.* (1986) presented the interplanetary data from *ISEE 3* spacecraft at 1 AU that indicate strong evidence for occurrence of nonlinear wave-wave interactions associated with type III emission. Experimental observations in support of parametric processes are, in brief, (1) close temporal correlation of the low-frequency bursts with the intense Langmuir wave spikes; (2) the electric field of the correlated low-frequency bursts appears to increase linearly with the Langmuir wave amplitude; and (3) the wavenumbers of low-frequency modes are comparable to the Langmuir wave numbers. All the above features are intrinsic properties of EOTSI, as well as EDI/EFI, discussed in this paper. Observations 1 and 2 are evident from the nonlinear ion acoustic wave equation (2), whereas observation 3 is the kinematics condition upon which all three parametric processes are based.

Lin *et al.* (1986) used two sets of interplanetary parameters to show that the threshold for EDI (same as EFI) is about $W_0 \approx 10^{-11}$, which is clearly exceeded by the observed Langmuir wave levels, $W_{\rm max} \approx 10^{-6}$ and 10^{-8}, respectively. Since the threshold for EOTSI is, within a factor ω_I/Γ_I, of the order of the threshold for EDI and $\omega_I/\Gamma_I \approx 10$ for the interplanetary plasma, we conclude that the observed Langmuir wave amplitudes associated with type III emission certainly exceed the threshold for EOTSI.

The observed Langmuir wave levels are below the conditions for exciting either supersonic EOTSI or modified EDI/EFI, since for interplanetary data (Lin *et al.* 1986) the excitation condition of quasi-reactive mode instabilities is $W \gg 10^{-3}$. Hence, the observed Langmuir wave amplitudes in the interplanetary medium lie in the regimes of either subsonic EOTSI or normal EDI/EFI. It should be remarked, however, that the existence of microstructures in the distribution of type III electrons may cause Langmuir wave to reach levels considerably higher than those observed (Melrose and Goldman 1987); thus, some of the more intense Langmuir spikes may be strong enough to excite quasi-reactive mode instabilities. The parameters for the 1979 March 11 event (Lin *et al.* 1986) yields a nonlinear growth rate $\Gamma_{\rm NL} \approx 10^{-2}$ s for subsonic EOTSI. This growth rate can be greatly enhanced in the presence of microstructures (Melrose and Goldman 1987) in the solar wind.

The EDI interpretation of type III emission presented by Lin *et al.* (1986) encountered two major difficulties: (1) EDI is essentially a down-conversion process; hence the fundamental radiation is easily absorbed in surrounding regions of slightly higher plasma density; and (2) EDI is convective; thus the waves excited can propagate out of the unstable region before reaching sufficiently large amplitude. These two difficulties are removed by EOTSI since (1) EOTSI is necessarily an up-conversion process; hence the fundamental radiation can readily propagate in the surrounding plasma; and (2) EOTSI is absolute; thus the waves grow indefinitely in the localized region until some nonlinear effects saturate the instability.

In conclusion, we have shown that the electromagnetic oscillating two-stream instability is a likely source of interplanetary type III fundamental radiation. This instability may be applied to other plasma emission processes such as the fundamental radiation upstream of planetary bow shocks (Chian 1987) and pulsar radio emission (Chian and Kennel 1983).

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