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Parametric Instability Driven by Weakly-Trapped Particles in Nonlinear Plasma Waves

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This paper presents a new parametric instability mechanism caused by a distribution f_T of particles trapped in the potential wells of a wave-train. This mechanism is intended to describe a nonlinear instability in Trivelpiece-Gould [TG] waves[1, 2], and could also be a destabilizing factor in a range of nearly-collisionless nonlinear plasma waves. The theory is compared to particle in cell [PIC] simulations of TG waves.

Many plasmas exhibit parametric instabilities, in which longer-wavelength "daughter waves" grow on a shorter-wavelength nonlinear "pump" wave. The instability has been observed in laser-plasma experiments,[3, 4] in tokamaks[5, 6] and other magnetic confinement devices[7, 8], and in nonneutral plasmas[1, 2, 9], and studied in theory and simulation for many years in a range of scenarios.[10–15] Here we consider a novel instability mechanism caused by particles trapped in, and carried along by, the fields of the pump wave. The instability mechanism is quite simple and fairly general, and may therefore be applicable to a range of nonlinear wave phenomena in which particles are trapped in the wave.

The mechanism applies to waves with a nearly acoustic dispersion relation, $\omega(k) \approx ck$, in which the pump wave decays to daughter waves of the same type (i.e. on the same branch of the dispersion relation). This case describes experiments[1, 2] involving large amplitude Trivelpiece-Gould plasma waves[16, 17] traveling axially along a non-neutral plasma column. Under these circumstances, it has been previously shown that the classic three-wave theory of parametric instability,[10] based on ideal fluid equations, is inapplicable; and that in fact ideal fluid theory predicts that the pump wave is stable at all amplitudes.[18] We show that parametric instability arises when "weakly-trapped" particles are included in the theory. We compare to PIC simulations, which observe parametric instability only when such weakly-trapped particles are present, at a growth rate consistent with the new theory.

The instability mechanism is as follows. Consider a nonlinear pump wave with amplitude A , wavenumber k and phase speed u .[19] The growth of daughter waves with wavenumber $k/2$ and speed close to u (the most unstable case) corresponds to a slow relative motion of the pump wave peaks; pairs of adjacent peaks approach one-another and recede from neighboring pairs. Any particles trapped between the approaching peaks of the pump wave are adiabatically heated, while any particles trapped between receding peaks are cooled.

This heating and cooling would normally produce restoring forces that stabilize the relative motion of the peaks. However, some weakly-trapped particles are heated enough to become untrapped, and these particles are then retrapped and cooled between receding peaks (an untrapped particle moving toward a receding peak can reflect from it and lose energy, becoming trapped). The net effect of this detrapping and retrapping is to change the sign of

the restoring force, producing a trapped particle force that *amplifies* the modulations.

A simplified model for this process applies to pump waves made up of a chain of soliton-like potential peaks, each separated by a large wavelength L compared to their width. Each potential well in the chain has a trapped particle distribution $f_T(v)$ (Fig. 1a). Consider the trapped particle distributions $f_1(v)$ and $f_2(v)$ in adjacent wells. Initially, both f_1 and f_2 equal f_T . In the instability, the two adjacent peaks that trap f_1 slowly reduce their separation by δL . The next peaks recede from one-another by the same distance δL (Fig. 1b). This motion is replicated along the wavetrain, creating a periodic structure with period $2L$ (the daughter wave, with twice the pump wavelength).

Trapped particles are adiabatically compressed in the first well, and $f_1(v)$ changes from $f_T(v)$ to $f_T(vL_1/L) \equiv f_1^{final}(v)$, where $L_1 = L - \delta L$. The density change for these particles is $\delta n_1 = 2 \int_0^{v_s} dv (f_1^{final} - f_T)$ where v_s is the separatrix speed, given in terms of the peak height E_s by $mv_s^2/2 = E_s$. Taylor expansion to first order in δL and integration by parts gives the density change as

$$\delta n_1 = 2 \frac{\delta L}{L} \int_0^{v_s} dv (f_T(v) - f_T(v_s)). \quad (1)$$

If $f_T(v_s) = 0$, the density change in the compression is positive. However, for weakly-trapped particles with a distribution satisfying $f_T(v_s) \geq f_T(v)$ for $|v| < v_s$, δn_1 is *negative* under compression. This occurs because particles escape the potential well as they are heated (Fig. 1b).

The trapped-particle distribution $f_2(v)$ between the receding peaks can be analyzed the same way. This distribution changes from $f_T(v)$ to

$$f_2^{final}(v) = \begin{cases} f_T(vL_2/L), & 0 < v < v_s L/L_2 \\ f_T(2v_s - vL_2/L), & v_s L/L_2 < v < v_s \end{cases} \quad (2)$$

where $L_2 = L + \delta L$. The second form for f_2 is from particles retrapped from the other well.

The total kinetic energy change $\delta E_T = \delta E_1 + \delta E_2$ for these trapped particles is

$$\delta E_T = 2 \int_0^{v_s} dv \frac{mv^2}{2} (L_1 f_1^{final} + L_2 f_2^{final} - 2L f_T(v)), \quad (3)$$

After Taylor-expansion and integration by parts, one finds that δE_T is second-order in δL (as expected since $\pm \delta L$

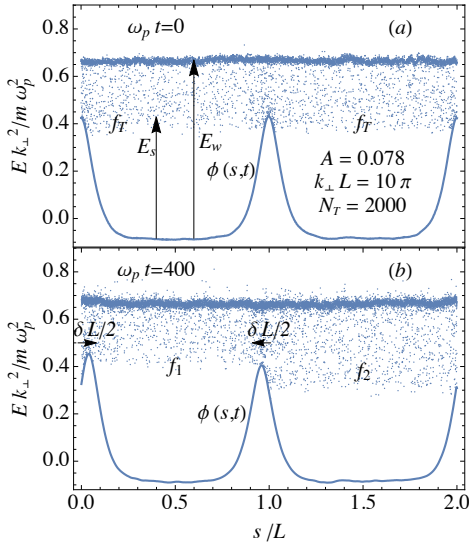


FIG. 1: PIC simulation showing energy versus position in a TG wave with trapped particles, at two times.

must give the same energy change): $\delta E_T = -\beta \delta L^2$, where

$$\beta = \frac{6}{L} \int_0^{v_s} d v m v^2 (f_T(v_s) - f_T(v)). \quad (4)$$

For a weakly-trapped distribution with $\beta > 0$ the process reduces the kinetic energy of the trapped particles. This energy change can drive the instability.

An approximate expression for the decay instability growth rate can now be found by treating the wavetrain as a chain of solitons. A soliton's energy E_0 is a function of its speed u . Adjacent solitons change velocities by $+\delta u$ and $-\delta u$ respectively, where $\delta u = (1/2)d\delta L/dt$. Then the energy change per pair is $\delta E_0 = \alpha(\delta u)^2$ where $\alpha = \partial^2 E_0 / \partial u^2 > 0$ is the ‘‘inertial mass’’ of a soliton. This energy change is due to work done by trapped particles, and energy conservation $\delta E_0 + \delta E_T = 0$ implies the ODE

$$\alpha(\delta \dot{L}/2)^2 - \beta(\delta L)^2 = 0. \quad (5)$$

This ODE yields an exponential growth rate Γ for $\delta L(t)$ given by $\Gamma = 2\sqrt{\beta/\alpha}$. (There is also an exponentially-decaying solution with decay rate Γ .) The growth rate in this model is proportional to the square root of the number of trapped particles, and instability occurs for any number of trapped particles, no matter how small (provided that $\beta > 0$, i.e. the distribution is weakly-trapped).

This simple model can be made somewhat more realistic by noting that, in the ideal fluid model of nonlinear TG waves, interacting solitons repel (the solitons are elevated density regions of like-sign charge)[18]. The repulsion adds a restoring energy $\kappa(\delta L)^2$ per pair to the energy of the chain of solitons, and hence to Eq. (5):

$$\alpha(\delta \dot{L}/2)^2 + \kappa(\delta L)^2 - \beta(\delta L)^2 = 0, \quad (6)$$

which implies the growth rate is modified to

$$\Gamma = 2\sqrt{(\beta - \kappa)/\alpha}. \quad (7)$$

Now instability requires that the trapped particle fraction must be sufficiently large to overcome the natural repulsion between wave potential/density peaks.

A more general kinetic theory of the instability applies to waves of any amplitude or wavelength, and treats the system as a cold fluid plus a weak tail distribution that includes trapped particles. Neglecting tail particles, the nonlinear wave is assumed to be a steady solution of the cold fluid equations[18] with density $n(s)$, fluid velocity $V(s)$ and potential $\phi(s) = \hat{G}n$ as seen in the wave frame, where \hat{G} is the Green's function operator for Poisson's equation. The tail particles are treated as a perturbation. The tail distribution function f_T is assumed to evolve adiabatically in the wave potential. The initial tail distribution is a function of particle energy, $f_T = f_T(E)$ where $E = m v^2/2 + \phi(s)$, and v is particle velocity in the wave frame. Collisionless adiabatic theory implies that changes in the tail distribution, caused by changes $\delta\phi(s, t)$ in the wave potential, are

$$\delta f_T(s, v, t) = \frac{\partial f_T}{\partial E} (\delta\phi(s, t) - \langle \delta\phi \rangle(E, t)), \quad (8)$$

where $\langle \cdot \rangle$ is an average along a particle trajectory in phase space holding energy E fixed.[20]

The cold fluid evolves according to fluid equations coupled to the tail particles via the wave potential. The perturbed fluid velocity $\delta V(s, t)$ and density $\delta n(s, t)$ follow linearized continuity and momentum equations,

$$\frac{\partial}{\partial t} \begin{pmatrix} \delta n \\ \delta V \end{pmatrix} + \frac{\partial}{\partial s} \begin{pmatrix} V \delta n + n \delta V \\ V \delta V + \delta\phi_F/m \end{pmatrix} = -\frac{\partial}{\partial s} \begin{pmatrix} 0 \\ \delta\phi_T/m \end{pmatrix}. \quad (9)$$

Here we have broken the perturbed wave potential $\delta\phi$ into two pieces, a fluid portion $\delta\phi_F \equiv \hat{G}\delta n$ and a portion $\delta\phi_T \equiv \hat{G}\delta n_T$ arising from the tail density $\delta n_T = \int d v \delta f_T$, using Eq. (8) for δf_T .

To analyze stability of solutions to Eqs. (9), consider the eigenmodes of the equation. Let $\psi_0(s) \equiv (\delta n_0(s), \delta V_0(s))$ be a complex vector eigenfunction of Eq. (9) with no tail particles ($\delta\phi_T = 0$). That is, ψ_0 satisfies

$$i\omega_0\psi_0 = \hat{L} \cdot \psi_0, \quad (10)$$

with a linear matrix operator $\hat{L} \equiv \frac{\partial}{\partial s} \begin{pmatrix} V & n \\ \hat{G}/m & V \end{pmatrix}$, where ω_0 is the eigenfrequency.

The operator \hat{L} is anti-Hermitian with respect to a matrix inner-product: for any two eigenfunctions ψ_1 and ψ_2 , $[\psi_1, \hat{L} \cdot \psi_2] = -[\psi_2, \hat{L} \cdot \psi_1]^*$, where

$$[\psi_1, \psi_2] = \int d s \psi_1^* \cdot \begin{pmatrix} \hat{G}^\dagger & mV \\ mV & mn \end{pmatrix} \cdot \psi_2, \quad (11)$$

and where \hat{G}^\dagger is the left Green's function operator defined as $\delta\phi = \delta n \hat{G}^\dagger$. The anti-Hermitian property of \hat{L} implies that[21] (i) all eigenfrequencies are real; (ii) ψ_0^* is also an

eigenfunction with eigenfrequency $-\omega_0$; (iii) $[\psi_0, \psi_0^*] = 0$ provided $\omega_0 \neq 0$. Result (i) implies that steady traveling wave solutions to the cold fluid equations are stable, from which it follows that three-wave theory for parametric instability[10] cannot apply to this system, conclusions found via a more circuitous route in Ref. 18.[22]

Furthermore, Eq. (11) implies that $[\psi_0, \psi_0]$ is real and is equal to four times the eigenmode energy δE_0 :

$$[\psi_0, \psi_0] = 4\delta E_0 = \int ds \{nm|\delta V_0|^2 + mV(\delta n_0 \delta V_0^* + \delta V_0 \delta n_0^*) + \delta n_0 \delta \phi_0^*\}, \quad (12)$$

where $\delta \phi_0 \equiv \hat{G} \delta n_0$ is the eigenmode potential. [Reality of δE_0 follows from the symmetry $\int ds \delta n_1 \hat{G} \delta n_2 = \int ds \delta n_2 \hat{G} \delta n_1$ for any δn_1 and δn_2 .]

The effect of the tail particles can now be handled with degenerate perturbation theory, assuming that the fraction of tail particles is small. Including these particles, an eigenmode $\psi \equiv (\delta n, \delta V)$ of Eq. (9), with frequency ω , satisfies

$$i\omega\psi = \hat{L} \cdot \psi + \hat{C} \cdot \psi, \quad (13)$$

where $\hat{C} \cdot \psi \equiv \partial/\partial s(0, \delta \phi_T/m)$ is treated as a small perturbation. Then the most unstable eigenmode will be perturbed away from the unperturbed pair (ψ_0, ψ_0^*) that have the smallest frequencies $(\omega_0, -\omega_0)$. In degenerate perturbation theory, we write $\psi = a\psi_0 + b\psi_0^* + \Delta\psi$, where $[\psi_0, \Delta\psi] = [\psi_0^*, \Delta\psi] = 0$, and where $\Delta\psi$ is small. Substituting for ψ in Eq. (13), using Eq. (10) and its complex conjugate, and dropping the small term $\hat{C} \cdot \Delta\psi$ yields

$$i\omega(a\psi_0 + b\psi_0^* + \Delta\psi) = i\omega_0(a\psi_0 - b\psi_0^*) + \hat{L} \cdot \Delta\psi + a\hat{C} \cdot \psi_0 + b\hat{C} \cdot \psi_0^*. \quad (14)$$

Taking inner products of this equation with respect to ψ_0 and ψ_0^* , the $\Delta\psi$ terms vanish and one obtains two coupled homogeneous equations for the coefficients a and b , which can be written in matrix form as $\mathbf{M} \cdot (a, b) = (0, 0)$. Setting the determinant of the matrix \mathbf{M} to zero determines the eigenfrequency ω as $\omega^2 = \omega_0^2 - (X + X^*)\omega_0 + |Y|^2 - |X|^2$, where $X = i[\psi_0, \hat{C} \cdot \psi_0]/[\psi_0, \psi_0]$ and $Y = i[\psi_0, \hat{C} \cdot \psi_0^*]/[\psi_0, \psi_0]$. Since X and Y are small the $|Y|^2 - |X|^2$ term can be dropped, and to first order in the tail density the eigenfrequency is

$$\omega^2 = \omega_0^2 - 2X\omega_0, \quad (15)$$

where we take X real (this is shown later). Instability occurs when $X > \omega_0/2$. The coefficient X can be directly related to the tail distribution. Using Eqs. (11) and (12),

$$X = i \frac{\int ds (V \delta n_0^* + n \delta V_0^*) \partial \delta \phi_T / \partial s}{4\delta E_0} = -\omega_0 \frac{\int ds \delta n_0^* \delta \phi_T}{4\delta E_0} = -\omega_0 \frac{\int ds \delta \phi_0^* \delta n_T}{4\delta E_0}, \quad (16)$$

where we integrated by parts and used the complex conjugate of the continuity equation (the first element of

Eq. (10)), and the final form employed symmetry of the Green's function. The tail density δn_T is obtained by integrating over δf_T given by Eq. (8):

$$\delta n_T(s) = \int dv \frac{\partial f_T}{\partial E}(E) (\delta \phi_0(s) - \langle \delta \phi_0 \rangle(E)), \quad (17)$$

where for simplicity we have dropped $\delta \phi_T$ on the right hand side, keeping only the potential $\delta \phi_0 = \hat{G} \delta n_0$ from the fluid density δn_0 in the eigenmode. We can do this because $\delta \phi_T \ll \delta \phi_0$, since the tail particle density is assumed small. Applying Eq. (17) to Eq. (16) yields

$$X = \frac{\omega_0}{4\delta E_0} \int ds dv \frac{\partial f_T}{\partial E} (|\langle \delta \phi_0 \rangle|^2 - |\delta \phi_0(s)|^2). \quad (18)$$

Thus, the coefficient X is real, and proportional to the fraction of tail particles.

We can now connect Eq. (15) to the previous expression for the growth rate, Eq. (7). In that simplified model we treated the wavetrain as a chain of weakly-interacting solitons. As one soliton moves by $\delta L/2$ and the next moves by $-\delta L/2$, the wave potential change in each soliton is $\delta \phi_0(s) = \pm(1/2)\delta L \partial \phi(s)/\partial s$ where $\phi(s)$ is the equilibrium soliton potential. This potential is mainly local to each soliton, and therefore the $|\delta \phi_0(s)|^2$ term in Eq. (18) is negligible compared to $|\langle \delta \phi_0 \rangle|^2$. As shown in Ref. 20, the bounce-average of $\delta \phi_0$ is then given by $\langle \delta \phi_0 \rangle = \pm m v^2 \delta L/L$ for trapped particles (those with speed $|v| < v_s$), and is zero for untrapped particles, where the upper (lower) sign is for compressing (expanding) potential wells. Applying this to Eq. (18) and integrating in v and in s over one pair of wells (of length $2L$) yields $2\omega_0 X = (\omega_0 \delta L)^2 \beta / \delta E_0$ where β is given by Eq. (4). Here we have used $E = m v^2/2$, $\partial f_T / \partial E = (1/m v) \partial f_T / \partial v$, and have performed an integration by parts in v . Substituting for $2\omega_0 X$ in Eq. (15) and again taking $\delta E_0 = \alpha(\delta u)^2$ where $|\delta u| = \omega_0 \delta L/2$ is the change in soliton speed, results in the growth rate $\Gamma = \sqrt{4\beta/\alpha - \omega_0^2}$, which is equivalent to Eq. (7).

We now compare this theory of parametric instability to PIC simulations of a nonlinear TG wave. The simulations are in the wave frame, using periodic boundary conditions with period $2L$, with $N = 10^6$ particles of charge e and mass m . The Poisson equation relating density to potential in these 1D simulations is $\partial^2 \phi / \partial s^2 - k_\perp^2 \phi = -4\pi e^2 n$, where k_\perp is the perpendicular wavenumber of the waves[2, 18], a free parameter in the simulations; in Fig. 1 $k_\perp L = 10\pi$. The initial particle distribution in the wave frame (where particles are flowing to the left with mean speed u) is nearly a delta-function at energy E_w above the potential minimum. The resulting density and fluid velocity create a large amplitude wave with $A = 0.078$, stationary in this frame. To this distribution $N_T = 2000$ tail particles are added, distributed uniformly in phase space between energies from E_w down to $E_m = 0.9E_s$ (Fig. 1a). This creates a population of about 400 trapped particles.

In Fig. 1b the distribution is shown at time $\omega_p t = 400$, where $\omega_p = \sqrt{4\pi e^2 n_0/m}$ is the plasma frequency. The

wave peaks have moved spontaneously and trapped particles have been heated in the left well, causing them to become untrapped and then retrapped in the right well, where trapped particles are cooled to lower energy. The change $\delta L(t)$ in the distance between wave peaks increases exponentially with time[24], and an exponential fit gives the growth rate for the instability.

Figure 2 displays growth rates versus the number N_T of tail particles (with f_T the same functional form as described above) for two amplitude and k_\perp values. The dots are growth rates measured in simulations. The solid lines are Eqs. (15) and (18). The fluid wavefunctions

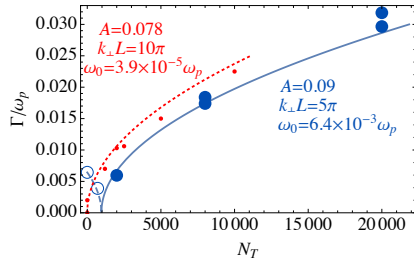


FIG. 2: Growth rates in simulations (points) and from Eq. (15) (lines) versus number of tail particles, for two cases: red: a very nonlinear wave (ϕ shown in Fig. 1) and blue: a less nonlinear wave (see Fig. 3)

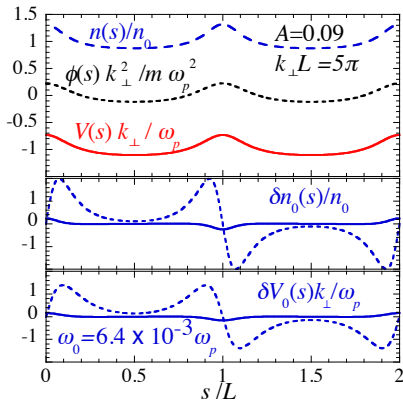


FIG. 3: Top: Density, potential and velocity in the cnoidal wave used for the blue data in Fig 3. Bottom: Least-stable fluid eigenmode. Solid:real; dashed: imaginary

$n(s)$, $V(s)$, $\phi(s)$, the eigenfunction $\psi_0 = (\delta n_0, \delta V_0)$, and the

frequency ω_0 are evaluated using the methods described in Ref.18 ; see Fig. 3 for examples. For the more nonlinear wave (red data) ω_0 is quite small and the simple "chain-of-solitons" model provides a growth rate estimate, $\Gamma = 2\sqrt{\beta/\alpha}$ with β given by Eq. (4). One can show[18] that for large-amplitude TG solitons $\alpha \approx 16m n_0/k_\perp$, with $n_0 = N/(2L)$. For uniform $f_T \approx N_T/(4L(v_w - v_m)) \equiv f_{T0}$ when $v_m < |v| < v_w$ (where $v_w = \sqrt{2E_w/m} = 1.22\omega_p/k_\perp$ and $v_m = \sqrt{2E_m/m} = 0.96\omega_p/k_\perp$), $\beta/\alpha \approx (4/16)(f_{T0}/N)k_\perp v_m^3$. This gives $\Gamma = 0.16\sqrt{N_T/N}\omega_p$, within 30% of Eq. (15). For the weaker wave (blue data) the open symbols are below the instability threshold. In these cases $\delta L(t)$ oscillated at the plotted rates, rather than exponentially increasing. The blue dashed curve is the frequency predicted by Eq. (15).

These simulations varied the number of tail particles N_T (proportional to the trapped particle number) holding the functional form of f_T fixed, but in other simulations (not shown) the tail distribution was modified, taking $E_m > E_s$, so that there were no trapped particles. No instability was observed for any N_T , as the new theory predicts.

The parametric instability discussed in this paper arises from a novel effect: when compressed by a growing daughter wave, weakly-trapped particles "change sides" by becoming detrapped and then retrapped, and thus amplify the compression. The growth rate scales roughly as the square root of the trapped particle fraction. Two versions of the theory were presented: a chain-of-solitons model and a novel kinetic theory; and the theories were compared to PIC simulations. The simulations and theory are for traveling waves, but we have also observed similar growth rates for standing waves of relevance to previous experiments[1, 2]. Future work will extend the theory to standing waves and compare to simulations and experiments. The new theory may also be relevant to other plasma waves such as BGK states[25] and electron acoustic waves[9, 26], where trapped particles play a central role in the wave dynamics; ion acoustic waves, where trapped particles have been observed to affect parametric decay[14]; and waves in other systems such as 2-D nearly-inviscid fluids, where exchange of vorticity across moving flow separatrices (for example, in nonlinear Kelvin waves[27–29]) may have similar consequences to the effects considered here.

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