KINETIC SELF-ORGANIZATION: A CASE OF STIMULATED RAMAN SCATTERING

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Recent papers on complexity and self-organization (*SO*) in plasmas [1] have revealed profound underlying structure in complex and seemingly irregular plasma phenomena. It was postulated that the following key points govern the *SO* in an open nonlinear far-from-equilibrium system: 1. External pumping of free energy; 2. Global instability development; 3. Anomalous dissipation and entropy production; 4. Entropy expulsion. The above concept was successfully applied in studies of different phenomena of the macro-scale *MHD* and micro-kinetic *SO* in plasmas.

In this paper we concentrate at an open convective weakly confined model of a stimulated Raman backscattering [2-4]. Detailed analysis of spatio-temporal patterns in a *fluid* model has revealed a growing complexity as the pump increases [2], reflected in a quasi-periodic transition to spatio-temporal chaos via an intermittent route. However, due to turbulence related anomalous dissipation, *SO* to a state of reduced complexity should be expected. To emulate the realistic entropy balance we introduce a *hybrid* three-wave interaction (*3WI*) model which includes a phenomenological kinetic dissipation via particle trapping and wave breaking [5].

Stimulated Raman scattering involves parametric coupling of the electromagnetic (*EM*) pump to the electron plasma wave (*epw*) and scattered *EM* wave. We study a nonlinear evolution of a resonant Raman three-wave backscattering in a bounded weakly dissipative plasma. Based on recent advances in a general comprehension of complexity in plasmas due to Sato et al. [1] it became obvious that fluid model [2] fails short in accounting for the physically realistic entropy balance. It is a purpose of this study to introduce a plausible entropy inventory by a phenomenological modeling of anomalous kinetic dissipation consistent with particle simulation.

In a bounded, uniform, completely ionized plasma the spatio-temporal evolution of Raman-coupled waves is governed by the following partial differential equations [2]:

$$\frac{\partial a_0}{\partial \tau} + V_0 \frac{\partial a_0}{\partial \xi} = -a_1 a_2,\ \ \frac{\partial a_1}{\partial \tau} - V_1 \frac{\partial a_1}{\partial \xi} = a_0 a_2^*,\ \ \frac{\partial a_2}{\partial \tau} + V_2 \frac{\partial a_2}{\partial \xi} + \gamma a_2 + i\sigma |a_2|^2 a_2 = \beta_0^2 a_0 a_1^*, \qquad (1)$$

where the normalized coordinates are: $\tau = \omega_0 t$, $\xi = x/L$; a_i and V_i are normalized, slowly varying complex amplitudes and group velocities of a pump (0), backscattered wave (1) and *epw* (2), respectively. The quantity β_0 is a relative pump strength, the ratio between the electron quiver velocity in the pump and the speed of light, and v_{th} is the electron thermal velocity. The self-modal cubic term in the *epw* equation appears as a phase shift due to nonlinear detuning of a large amplitude plasma wave.

We introduce a phenomenological hybrid–*3WI* simulation model. The set of *3WI* equations will be solved simultaneously with model equations for hot and bulk plasma heating. In this way effective damping $\gamma = \gamma(t)$ and the electron bulk temperature $T_b = T_b(t)$ appear as dynamical variables, in distinction to a standard model [2] that assumes a constant plasma background. To emulate basic kinetic effects missed by the original fluid *3WI* model (1), we include a generation of hot electrons that are trapped and accelerated in large amplitude plasma waves. As a consequence, we shall account the suppression of Raman instability by hot electrons through a linear Landau damping effect. We further assume that the effective damping of plasma waves is due to both linear Landau and nonlinear term, related to bulk electron acceleration via trapping and plasma wave breaking.

We start by assuming that the electron distribution function consists of thermal (bulk) and hot components [4]. Taking into account the continuity equation for hot electrons, and after performing the spatial average, one readily gets the equation for the hot electron generation:

$$\frac{dn_h(t)}{dt} = \frac{n_b(L,t)}{L} \int\limits_{v_{ph}-v_{tr}(L,t)}^{v_{ph}+v_{tr}(L,t)} v f_b(v,t) dv - \alpha n_h(t). \tag{2}$$

where n_b is bulk electron density, f_b is bulk distribution function, v_{ph} is *epw* phase velocity and v_{tr} is trapping velocity. The loss term comes due to electrons which escape through open plasma boundaries ($\alpha = v_{ph}/L$ for a free streaming or $\alpha = 2v_{ph}/L$ for a Maxwellian flow). The rate of plasma wave energy dissipation through linear and nonlinear processes is given by

$$2\gamma(t)W(t) = 2\gamma_{Landau}^{hot} W(t) + \frac{n_b(L,t)}{2L} \int\limits_{v_{ph}-v_{tr}(L,t)}^{v_{ph}+v_{tr}(L,t)} (mv^2) v f_b(v,t) dv, \tag{3}$$

where an integral term gives a nonlinear contribution to plasma wave dissipation, determining the value of γ_{nl}, and $W(t)$ is spatially averaged *epw* energy.

Finally, we derive the equation for the *epw* energy balance starting from a general energy conservation law. The equation for the thermal energy variation is obtained in the form:

$$\frac{d}{dt}\left[n_b(t)T_b(t)\right] = 2\gamma W(t) - \frac{d}{dt}\left[n_h(t)T_h(t)\right] - \frac{1}{L} k (S_{th} + S_h - S_q) \Big|_0^L, \tag{4}$$

where, we have introduced S_{th}, S_h and S_q for the averaged energy fluxes for thermal, hot and ambient electrons, respectively. The electron transport coefficient k in (4) characterizes the rate of the system openness.

We assume a model with boundaries open to electromagnetic waves and plasma electrons and write a total electron current at the boundary as an algebraic sum of the outgoing and the incoming components: $J_{tot} = J_{th} + J_h - n_q v_0$, where $n_q v_0$ stands for a return current of ambient electrons streaming into a plasma layer.

We started the simulation with plasma parameters: the electron density is 10% of the critical density, the initial electron temperature is $0.5keV$, the plasma length $L = 100c/\omega_0$ and the pump $\beta_0 = 0.026$.

We take the electron transport coefficient k to be the main control parameter and plot the reflection coefficients, hot electron density and bulk temperature vs. time. By changing k from a strongly confined closed system ($k = 0.001$) to an open system with k close to unity (0.95), the system experiences different saturated – longtime behavior (Fig. 1). In the former case (inhibited transport), after transient pulsations reflectivity saturates to a zero steady-state, due to a complete Raman suppression caused by quick raise and saturation in n_h and T_b. For $k = 0.05$ we discover a bifurcation to a new state of *kinetic SO* [1]. Structural instability transits to a quasi-periodic dynamical state, observed readily in trains of temporal pulses in the reflectivity as well as hot electron population with strong quasi-periodic pulsations. On the other hand, the bulk temperature, after its initial growth exhibits strong sawtooth oscillations. By further exploring a parameter space for an open system ($k = 0.95$) we find a striking transition to a quasi-periodic dynamics interrupted by chaotic bursts pointing to an intermittent nature of this regime.

Although phenomenological rather than rigorous, our hybrid-*3WI* model self-consistently accounts for the entropy production and expulsion for both thermal and supra-thermal electrons. In this way longtime saturation in the open model with anomalous kinetic dissipation reveals a generic connection of self–organization at particle–kinetic (micro) and wave–fluid (macro) scales.

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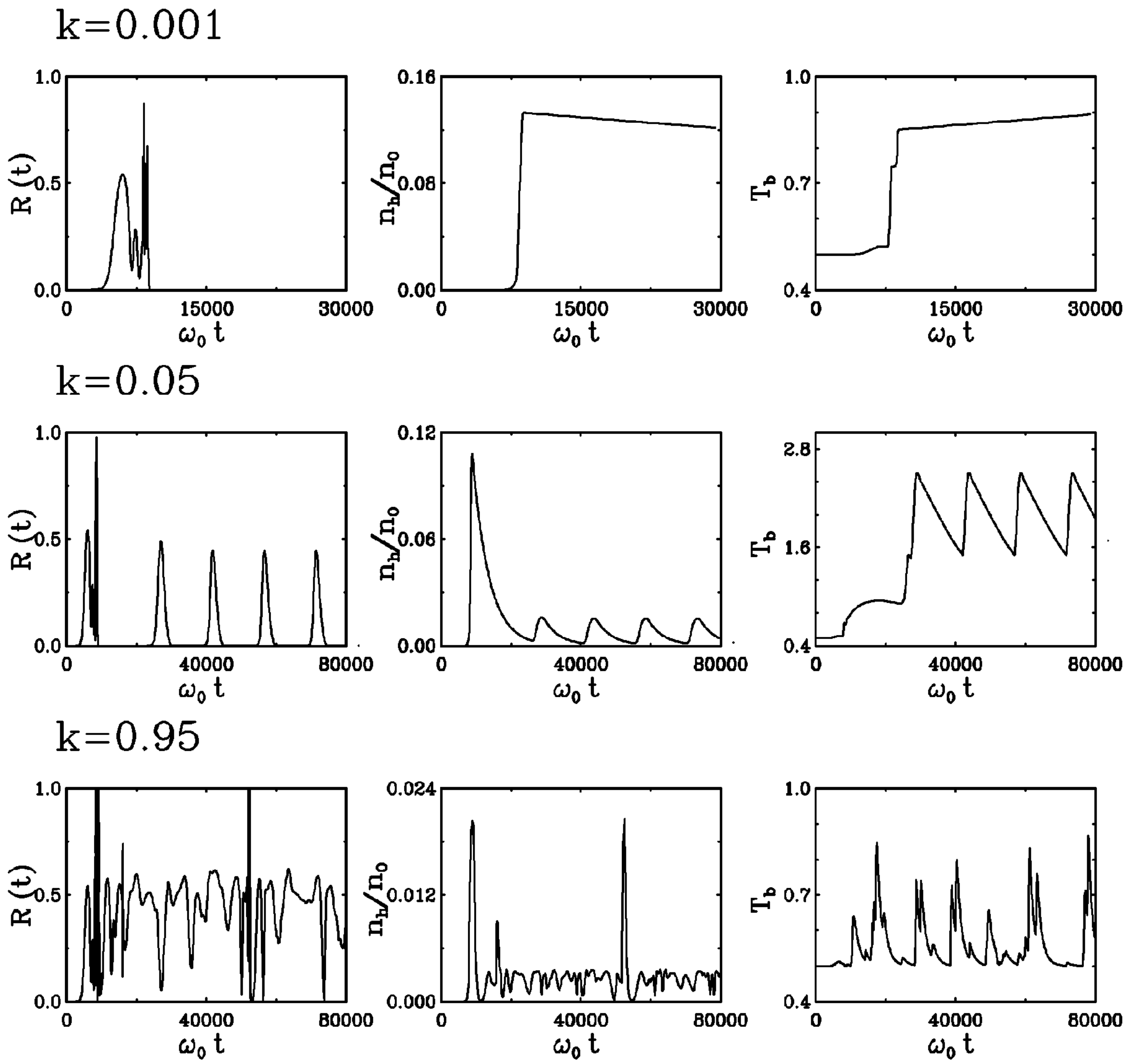

Figure 1. Time evolution of the Raman reflectivity, hot electron density and bulk temperature for different values of transport parameter k

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