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On Kinetic Complexity in a Three-Wave Interaction

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ABSTRACT

A stimulated Raman scattering in a plasma represents a resonant three-wave interaction which involves the nonlinear coupling of an electromagnetic pump into a scattered electromagnetic wave plus an electron plasma wave. In this paper, we concentrate on a nonlinear evolution of stimulated Raman backscattering in an open convective weakly confined model. In recent fluid simulations, rich spatio-temporal complexity that exhibits a transition to intermittency and chaos was revealed. However, this model has failed to account for a realistic entropy balance due to an anomalous dissipation. We introduce a hybrid-three-wave interaction model to include a phenomenological kinetic dissipation due to particle trapping and plasma wave breaking. Furthermore, we propose an open plasma model with realistic current-free boundaries to compare with a closed-isolated case. Under a continual free energy supply we vary a transport parameter to study a kinetic self-organization. In simulations, macro and micro scale complexities develop, which saturate and get attracted to definite dynamical states, such as: quasi-steady, quasi-periodic and intermittent ones. At this point, an important consistency of above findings with a general scenario of a self-organization in plasmas can be claimed.

Keywords: nonlinear waves, self-organization, complexity, Raman instability

1. INTRODUCTION

In seminal papers on complexity and self-organization in plasmas, by Sato et al. /1-2/, profound underlying structure in complex and seemingly irregular plasma phenomena was revealed. It was postulated that following key points govern self-organization 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, as a working hypothesis, was successfully applied in studies of markedly different phenomena of the macro-scale MHD and micro-kinetic self-organization in plasmas. For a continual pumping of free energy and efficient excess entropy removal, generic self-organization to an intermittent state was predicted. As a striking feature of a kinetic self-organization, creation of a super ion-acoustic double layer was discovered. However, to single out this unique phenomenon, under entropy expulsion conditions; a novel sophisticated open boundary particle simulation model was developed /1/.

In this paper, we concentrate on an open convective weakly confined model of a stimulated Raman backscattering. In fluid simulations, rich spatio-temporal complexity, which exhibits transition to intermittency and chaos following a quasi-periodic route was revealed by some of these authors /3/. Detailed analysis of spatio-temporal patterns, examining the partition of energy among coherent structures has revealed growing complexity as the pump increases. However, based on general advancements in studies of complexity /1/; it is understood that due to turbulence related anomalous dissipation; self-organization to a state of reduced complexity should be expected. To emulate the effect of entropy balance we shall introduce a hybrid- three-wave interaction model to include a phenomenological kinetic dissipation via particle trapping and wave breaking

2. BACKGROUND

A resonant nonlinear three-wave interaction, as a physical concept, is a paradigmatic phenomenon which has found applications in hydrodynamics, acoustics, nonlinear optics and plasma physics. More generally, nonlinear coupled oscillator models are generic to various problems in physics, biology, chemistry, etc. /4-6/. Stimulated scattering in a plasma, represents a wide class of three-wave interactions related to nonlinear coupling of a finite amplitude electromagnetic pump wave to the electrostatic plasma (electron or ion) wave and the scattered electromagnetic wave /7/. Assuming that resonant matching between frequencies and wavenumbers is satisfied, pump parametrically excites the stimulated growth of the daughter waves from their thermal noise level. Stimulated Raman scattering involves parametric coupling of the electromagnetic (EM) pump to the electron plasma wave and scattered EM wave /8/. Various applications in laboratory: radio-frequency and laser driven plasmas, as well as in space and astrophysical plasmas were attempted /8-11/. We discuss a nonlinear evolution of a resonant Raman three-wave backscattering in a bounded weakly dissipative plasma. Generally taken, the invariants point to an onset of non-stationarity for conditions of imperfect phase matching. Studies of spatio-temporal complexity in a fluid model of stimulated Raman backscattering in a bounded weakly dissipative plasma were attempted by Škoric et al. /3/ This analysis of an open convective weakly confined model has revealed a quasi-periodic transition to spatio-temporal chaos via an intermittent route. A continual increase in complexity with a control parameter (e.g. pump strength) was predicted by this fluid model, thus establishing its place in a growing family of paradigmatic physical phenomena that display an intermittent route to spatio-temporal chaos /6/. However, based on recent advances in a general comprehension of complexity in plasmas due to Sato et al. /1-2/ it became obvious that the above fluid model fails short in accounting for the physically realistic entropy balance. Namely, the effects of anomalous dissipation and plasma heating and subsequent entropy expulsion, were lacking. It is a purpose of this study to introduce a plausible entropy inventory by a phenomenological modeling of anomalous kinetic dissipation derived from particle simulation. In long saturated regimes, we seek for intermittent evolution, generic to an open system under a continual energy supply /1/

3. ANOMALOUS REGIMES

Extensive studies of nonlinear stimulated Raman backscattering have been performed by analytics, fluid and particle simulations /3,8-11/. Under strongly driven conditions, Raman instability exponentiates until arrested by nonlinear and dissipative effects. The saturation comes, basically through pump depletion and/or higher fluid as well as kinetic nonlinearities related to electron trapping and plasma wave breaking /7-8/. While pump depletion is readily included in fluid modeling, later effects are inherently kinetic ones. However, after more than two decades of intensive particle simulation studies, nonlinear Raman scattering is understood to posses relatively clear, albeit anomalous overall features /8/. As a result of electron trapping and breaking of large plasma waves a hot tail- supra-thermal electron population is generated. The corresponding velocity of hot (fast) electrons roughly equals the phase velocity of the electron plasma wave Once born, hot electrons efficiently Landau damp freshly excited plasma waves to suppress the growth of the Raman instability. As a general feature, two temperature Maxwellian electron distribution is recorded, for the thermal (bulk) and supra-thermal (hot tail) electrons. Energy exchange leads to an increase of the bulk temperature at the expense of plasma wave dissipation However, actual details of this overall scenario, are determined by wave turbulence and the electron transport, both influenced strongly by boundary and other plasma conditions. This qualitative understanding of anomalous Raman features have enabled useful scaling relations and semi-empirical formulae, typically extracted from the averaged (time and shot) short-run data. Therefore, a general comprehension of dynamical regimes, critical parameters and signatures of long saturated states still seem to be lacking. Scenarios, often appear nontransparent and inconclusive, likely due to a number of variable parameters and inconsistent modeling (number of particles, boundaries, noise, etc.). Generally taken, a longtime saturation (e.g. > 10.000 plasma wave periods) does not appear to be assessable to even high performance particle simulation due to a required computer time and numerical limitations of the scheme involving large number of particles. It is this situation that has motivated us to address a problem of anomalous Raman in a longtime evolution. We shall study a question of possible self-organization to saturated states using a general concept of complexity in plasmas in a system open to an environment. Firstly, we develop a phenomenological hybrid-fluid model to try to emulate basic physics of anomalous Raman as a precursor to state-of-the-art particle simulation with open boundaries, planned for the future /12/.

4. A COUPLED MODE MODEL

Stimulated Raman backscattering in a plasma is a paradigm of a three-wave parametric process whereby a strong electromagnetic wave (0-pump) decays into an electron plasma wave (2) and backscattered wave (1) downshifted in frequency. This process obeys a resonant matching condition for wave frequencies and wavenumbers, in a form

$$\omega_0=\omega_1+\omega_2 , \qquad \text{and} \qquad k_0=k_1+k_2 .$$

We consider a coupled three-wave interaction (3WI) model. In one-dimensional case, which is of major importance, the linear parametric Raman backscatter growth rate is given by

$$\gamma_0 \approx \beta_0 \alpha^{1/2} / 2(1-\alpha)^{1/2} \omega_0 \quad ; \qquad \alpha \equiv \omega_{pe} / \omega_0 = \sqrt{n_0 / n_{cr}}$$

is the ratio between the electron plasma frequency and the frequency of the pump. In a bounded, uniform, completely ionized plasma, the spatio-temporal evolution of coupled waves is governed by the following set of partial differential equations /3/

where the dot and the prime signs designate partial temporal and spatial derivatives,

$$\dot{a}_0 + V_0 a_0' = -a_1 a_2 \qquad (1)$$

$$\dot{a}_1 - V_1 a_1' = a_0 a_2^* \qquad (2)$$

$$\dot{a}_2 + V_2 a_2' + \gamma a_2 + i\sigma |a_2|^2 a_2 = \beta_0^2 a_0 a_1^* \qquad (3)$$

respectively; given in normalized coordinates

$$\tau = \omega_0 t, \quad \xi = x / L \quad ; \quad where \quad a_j(\xi, \tau)$$

are normalized, slowly varying complex amplitudes of a pump (0), backscattered wave (1) and plasma wave density perturbation (2), respectively; with each of the waves satisfying the linear dispersion relation.
The group velocities of the waves are:

$$V_0 = c^2 k_0 / \omega_0^2 L, \quad V_1 = c^2 k_1 / \omega_0 \omega_1 L, \quad V_2 = 3 v_T^2 k_2 / \omega_0 \omega_{pe} L,$$

with a plasma wave damping rate given by γ. Damping of the light waves is neglected. The quantity β_o is a relative pump strength, the ratio between the electron quiver velocity in the pump and the speed of light, and v_T is the electron thermal velocity.

An important feature of the system is the self-modal cubic term in the plasma wave equation It appears as a phase shift due to nonlinear detuning of a large amplitude plasma wave /8/ A time-only version of (1-3) was studied in detail, and it was shown to exhibit bifurcation to a low-dimensional chaos under restricted conditions. The spatially extended model, that is of a more physical significance, has recently revealed rich complexity related to a low-dimensional as well as spatio-temporal chaos. The system (1-3) was solved in space-time for standard initial and boundary conditions In the steady-state, for zero phase shift, the system predicts well known elliptic-function solutions, together with a set of (Manley-Rowe) conserved quantities /3-4/. However, with a nonzero phase shift ($\sigma>0$) , for finite boundary conditions, invariants are broken A violation of the steady-state condition, thus points to a nonstationary Raman saturation. The subsequent evolution exhibits a quasi-periodic route to low-dimensional intermittency to finally result in a fully developed spatio-temporal chaos, in this fluid model (1-3). However, we note that chaotic dynamics is related to plasma wave breaking followed at a kinetic level, by a strong nonlinear electron acceleration In turn, hot electrons Landau-damp freshly driven plasma waves to suppress and strongly alter Raman instability and possibly limit the level of kinetic complexity. To perform studies in this direction we shall 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 that way, effective damping $\gamma=\gamma(t)$ and the electron temperature $T=T(t)$ in 3WI, appear as dynamical variables, in distinction to a standard model that assumes a constant plasma background Therefore, we expect to emulate dissipative effect on longtime Raman saturation and kinetic self-organization in an open system

5. KINETIC -HYBRID SCHEME

We chose to simulate conditions relevant to anomalous Raman saturation in an Open system, i.e. allowing an energy exchange between an interaction region and the plasma environment. To emulate basic kinetic effects missed by the original fluid 3WI model (1-3), we propose a phenomenological "hybrid" scheme by including generation of hot electrons, that are trapped and accelerated in large amplitude plasma waves. Assuming that a part of plasma wave energy is transferred to electrons that are resonant with the forward propagating plasma wave, we numerically solve hot electron generation equation together with a 3WI set (1-3) As a consequence, we shall account the suppression of Raman instability by hot electrons through a linear Landau damping effect We further assume that effective damping (γ- term) of plasma waves is due to both *linear* Landau and *nonlinear* term- related to electron acceleration via trapping and plasma wave breaking. Finally, we add a simple energy balance equation to model bulk heating via the redistribution of the absorbed energy between bulk (thermal) and hot (supra-thermal) electrons. We believe that, although rather straightforward, our work appears to be a rare attempt to treat a rather complex, inherently kinetic regime of anomalous Raman by a simple fluid-based model Simplifying the electron transport to spatially averaged dynamics we introduce a hybrid -coupled mode scheme that includes effects of both thermal and hot electrons on Raman instability. Open boundaries are carefully accounted for, thus enabling us to model conditions of both, current-free and inhibited electron transport. We plan to check our model performance against particle

simulation data in order to try close fits by adjusting free parameters in a hybrid scheme. In that way, we expect to be able to address a longtime Raman saturation in an open system, an important question that is not accessible to even high performance particle simulations /8/.
We start by assuming the electron distribution function, for thermal (bulk) and hot components; to be bi-Maxwellian, /7-8/.

$$F(x,t,v) = n_h(x,t)f_h(v) + n_b(x,t)f_b(v)\,, \qquad (4)$$

where, n_h and n_b ($>> n_h$) stands for *hot* and *bulk* electron density, respectively.
We assume that the total hot electron current includes a source term due to trapped resonant electrons (in the thermal Maxwellian tail); therefore, we write

$$j_h(x,t) = \int_{hot} vF(v)dv = n_h(x,t)\int_{-\infty}^{+\infty} vf_h(v)dv \quad + n_b(x,t)\int_{V_\phi - V_{tr}}^{V_\phi + V_{tr}} vf_b(v)dv$$

where, v_ϕ is the plasma wave phase velocity and v_{tr} – stands for average velocity of resonant electrons (with $v \sim v_\phi$) trapped in a trough of a large amplitude plasma wave /4/.
Equation of continuity for hot electrons is written in a standard form, as

$$\frac{d}{dt}n_h(x,t) \equiv \frac{\partial}{\partial t}n_h(x,t) + \quad div\, j_h = 0$$

or, after performing the spatial average, as

$$<\ldots\ldots.>_L \equiv \frac{1}{L}\int_0^L (\ldots)dx$$

where $n_h(t)$ is hot electron density averaged over the plasma length-L, according to

$$\frac{d}{dt}n_h(t) \quad + \frac{1}{L}j_h(x,t)\,\Big|_0^L \quad = 0$$

Using the electron current one readily gets equation for the hot electron generation

$$\frac{dn_h(t)}{dt} = \frac{n_b(L,t)}{L}\int_{V_\phi - V_{tr}(L,t)}^{V_\phi + V_{tr}(L,t)} v\,f_b(v,T)\,dv \quad - \alpha\, n_h(t)\,, \qquad (5)$$

We note that $v_{tr}(0,t)=0$, due to the boundary condition for a plasma wave. The loss term is due to electrons which escape through open plasma boundaries; with $\alpha = a\, v_{hot}/L$, and $a \sim 2$, for a free streaming Maxwellian flow.
We now proceed to evaluate the effective damping rate in the plasma wave equation (3)
We assume that a total damping is due to both, *linear* Landau and *nonlinear* (trapping and wave breaking) effects, namely : $\gamma = \gamma_{Landau} + \gamma_{NL}$; where for the Landau term we shall use a formula, known in the literature /4,8/.
Further, we introduce the spatially integrated plasma wave energy density, through

$$W(t) = \frac{1}{L}\int_0^L (|E(x,t)|^2 / 8\pi)\, dx$$

The rate of plasma wave energy dissipation through linear and nonlinear processes, is

$$2\gamma(t)\,W(t) = 2\gamma_L(t)\,W(t) \;+\; \frac{n(L,t)}{2L}\int_{V_\phi - V_{tr}(L,t)}^{V_\phi + V_{tr}(L,t)} m\,v^2 v\, f_b(v)dv\,, \qquad (6)$$

where an integral term, gives a nonlinear contribution to plasma wave dissipation, determining the value of γ_{NL}
Finally, we derive the equation for the energy balance for the plasma wave, the thermal and hot electron component; by starting from a general conservation law (w_i- energy ; s_i- energy flux)

$$\frac{d}{dt}[\sum_i w_i(x,t)] = \frac{\partial}{\partial t}[\sum_i w_i\ ] + div\,[\sum_i s_i(x,t)\,] = 0$$

For spatially averaged (integrated) quantities, one has to evaluate the energy flux at open boundaries

$$\frac{d}{dt}\sum_i W_i(t) \;+\; \frac{1}{L}\sum_i s_i(x,t)\,\Big|_0^L = 0$$

For our system: the plasma wave, thermal and hot component: $W_i(t) = W - E_T - E_h$ the electron energy densities are simply $E_T = n_b T$ and $E_h = n_h T_h$; and the average energy flux, is given by $S_T = (+,-)\, v_T E_T$ and $S_h = (+,-)\, v_h E_h$. Typically, the average energy flux for the Maxwellian should be modified by a factor ~ (0 - 0.64), as a heuristic model of the highly complex electron energy transport /8/. The (+,-) sign, indicates the flux direction at the plasma boundary (at x= 0 , L).

By using above expressions, the equation for the thermal energy variation is given as:

$$\frac{d}{dt}\big[n_b(t)T(t)\big] = 2\gamma\, W(t) - \frac{d}{dt}\big[n_h(t)T_h(t)\big] \;\; - \frac{1}{L}\big\{S_T + S_h - S_Q\big\}\Big|_0^L\,, \qquad (7)$$

where, we have introduced S_Q as the return flux of fresh ambient particles through an *open* plasma boundary (vide infra).

6. OPEN BOUNDARY MODEL

We introduce a model with boundaries *open* to electromagnetic waves and plasma electrons. Furthermore, we shall allow a free transport between an interaction region and a large surrounding plasma environment For electrons which escape from an interaction layer (length-L), fresh ambient electrons are re-injected in order to preserve the plasma quasi -neutrality. Accordingly, a longtime Raman saturation will be observed under conditions of physically more realistic *current-free* boundaries.

We briefly sketch a straightforward procedure. We shall write a total electron current at the boundary as an algebraic sum of the outgoing and the incoming components $\mathbf{J_{tot}} = \mathbf{J_{out}} - \mathbf{J_{in}}$; with $\mathbf{J_{out}} = \mathbf{J_T} + \mathbf{J_h}$, for thermal and hot electron terms, respectively. We further write, $\mathbf{J_{in}} = \mathbf{n_Q v_0}$; where $(\mathbf{n_Q v_0})$ stands for a return current of ambient electrons streaming into a plasma layer. By taking the total current at the boundary to be zero, one readily evaluates $\mathbf{J_{in}}$ in terms of the thermal and hot components. The energy flux carried by ambient electrons (with the temperature-T_0) is simply $\mathbf{S_Q \sim J_{in} T_0}$, making the calculation of the loss term in the heat balance equation an easy task.
In further studies, we shall refer to the above model as the *Open* one, in distinction to the *Closed* model with an electron transport inhibited by a build up of a space charge The latter case corresponds to e.g. plasma-vacuum boundary, with the energy flux (S), coefficient, so called flux limit, restricted to low values (typically, ~ 0.01 –0.04). As for the Maxwellian with an open boundary this factor maximizes at ~0.64; one should expect a wide range of dynamical regimes between these two extreme transport cases.

7. KINETIC SELF-ORGANIZATION

We briefly analyze Raman complexity obtained in hybrid simulations. We chose parameters of the "standard case" studied in depth in a fluid 3WI model (vide supra) /3/. Initial plasma parameters: the electron density is 0.1 of the critical density, the electron temperature is 0.5 keV and the plasma length- L= 100 c/ω_0 .We take the electron transport coefficient- **k** to be the main control parameter. We apply a continual pumping to observe different saturated states for an Open and Closed (isolated) system. Typically, we plot the Reflection and Transmission coefficient in time, as well as the evolution of hot electron density (T_{hot} ~ 22 keV) and bulk temperature. To illustrate the spatio-temporal nature of Raman complexity we also plot the plasma wave profile. We fix the pump equal to 0.0253. For two cases of an Open (k=0.5) and Closed (k=0.07) system, after transient pulsations reflectivity saturates to a quasi steady- state. As expected, the transmittivity follows the similar scenario. However, while for an Open system reflectivity saturates around high- finite values; in a strongly confined-Closed system, reflectivity quickly drops to zero due to a complete Raman suppression (figs. 1-2). More precise insight into a phase dynamics finds out that, while the Closed system saturates to an exact steady-state ("fixed point"), in the Open case, small periodic oscillations ("limit cycle") are present. Moreover, in a latter case, moderate hot electron population, which is locked to a finite-plasma wave as a source of hot electrons, saturates to a quasi steady-state. In distinction, in a Closed system, hot density is high and nonstationary, typically an order of magnitude higher than above, rapidly generated during an abrupt dissipation of Raman driven plasma waves (fig.3). It gradually relaxes in later times, due to a convective cooling through the boundaries. Similar to a hot population, important difference exists in a bulk temperature evolution (fig.4). In an Open system, temperature saturates to a quasi steady-state, moderately above an initial/ambient one. This is due to a continual energy input via kinetic dissipation balanced by efficient convection losses. In a Closed system, rapid and large temperature rise is observed, to

reach its maximum by halting Raman instability, later to experience slow cooling through strongly inhibited boundaries (fig. 4a).
Further, we carefully vary a control parameter -k to study generic structural bifurcations along the route to complexity (figs. 5-8) For k= 0.05, in our system, we discover a bifurcation to a new state of kinetic *self-organization* /1/ Structural instability transits to a *quasi-periodic* dynamical state, observed readily in a train of temporal pulses in the reflectivity and transmitivity. Hot electron population follows, with strong quasi-periodic pulsations peaked around 20% of the initial electron density On the other hand, the bulk temperature, after its initial growth, exhibits strong saw-teeth oscillations somewhat reminiscent of those observed in tokamak plasmas. By further exploring a parameter space for an Open system (k=0 9), we find a transition to a quasi-periodic dynamics interrupted by chaotic bursts. Closer insight into the attractor space, finds irregular portion of the dynamics, pointing to an *intermittent* nature of this regime. Indeed, hot electrons are intermittently ejected in a form of intense jet spikes, as a striking feature of this type of kinetic self-organization (fig 7). Bulk temperature follows an intermittent scenario, by exhibiting QP –fluctuations, somewhat above its initial value (fig.8). To illustrate, we also plot the plasma wave profile (fig.9), in order to reveal a genuine spatio-temporal nature of an intermittent regime as compared to regular dynamical regimes of the steady-state and QP type /3,6/. We further show a transition to complexity by plotting a phase space attractor for the hot electrons (fig 10). By varying a transport parameter k (0 7-0 9) a gradual onset of complexity and chaos is revealed, starting with typical "stretching and folding" features of the periodic trajectories We believe that our findings appear to be a first indication of a generic intermittent scenario in a kinetic self-organization of anomalous Raman instability 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, rich transient Raman complexity, gradually gets self-organized and attracted to definite saturated dynamical states, such as: the quasi-steady, the quasi-periodic and intermittent one. Moreover, we observe a self-consistent evolution and coexistence of both fluid and kinetic complexities, as a striking example of an interplay between the macro and micro scale self-organization in a plasma.
At this point, we may note that, at least qualitatively, one is able to claim a consistency with the *working hypothesis* and *general scenario* of *Self-organization* put forward by T. Sato et al. /1/ As a next step, we plan to upgrade a hybrid model to possibly treat wave-breaking dominated Raman saturation related to a strong pumping. However, to continue, we expect an important justification of the above hypothesis on anomalous Raman saturation, by the state-of- the- art open boundary particle simulation, currently under development /12/.

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FIGURE CAPTIONS

Figure 1
Time evolution of the Raman reflectivity for transport parameter –k corresponding to (a) Closed model (inhibited transport; k=0.07) and (b) Open model (k=0.5).

Figure 2
Time evolution of the Raman transmittivity for transport parameter –k corresponding to (a) Closed model (inhibited transport; k=0.07) and (b) Open model (k=0.5). Note, that for (a), in a long saturation, R+T=1, due to a suppressed Raman instability.

Figure 3
Hot electron density variation in time, related to figures 1-2 ; (a) k=0.07 and (b) k=0.5.

Figure 4
Bulk temperature variation in time, related to figures 1-2 ; (a) k=0.07 and (b) k=0.5.

Figure 5
Time evolution of the Raman reflectivity showing a complexity of the (a) quasi-periodic (k=0.05) and (b) intermittent type (k=0.9).

Figure 6
Time evolution of the Raman transmittivity showing a complexity of the (a) quasi-periodic (k=0.05) and (b) intermittent type (k=0.9).

Figure 7
Hot electron density variation in time related to figures 5-6; (a) k=0.05 and (b) k=0 9; exhibiting strong quasi-periodic-(a) and intermittent-(b) pulsations.

Figure 8
Bulk temperature evolution in time related to figures 5-6;(a) k=0.05 and (b) k=0.9.

Figure 9
Spatio-temporal profile of the electron plasma wave for different k values showing a route to complexity, from a steady-state via quasi-periodicity to intermittency. Note, different scales on the vertical axis; case k=0.07, corresponds to a suppressed instability

Figure 10
Phase diagrams of the hot electron temporal evolution. Onset of complexity is connected to typical features of "stretching and folding" of periodic orbits gradually leading to an intermittent and chaotic attractor.

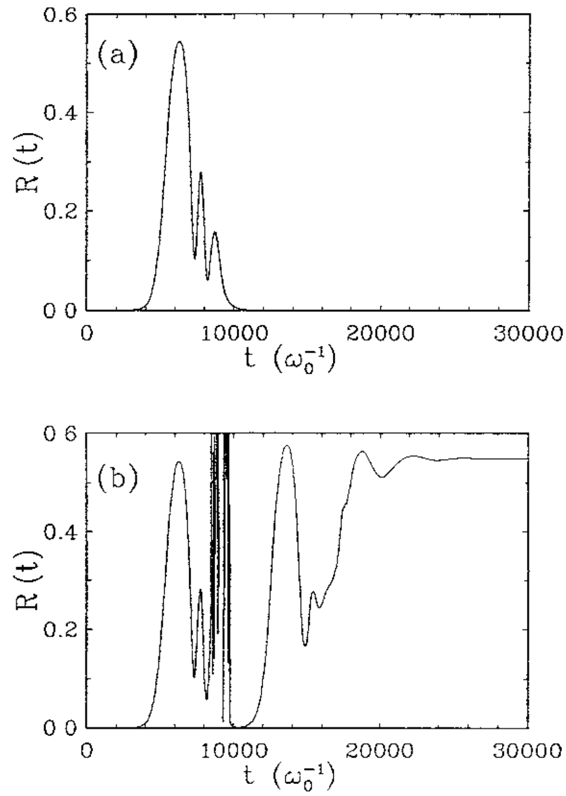

Fig. 1

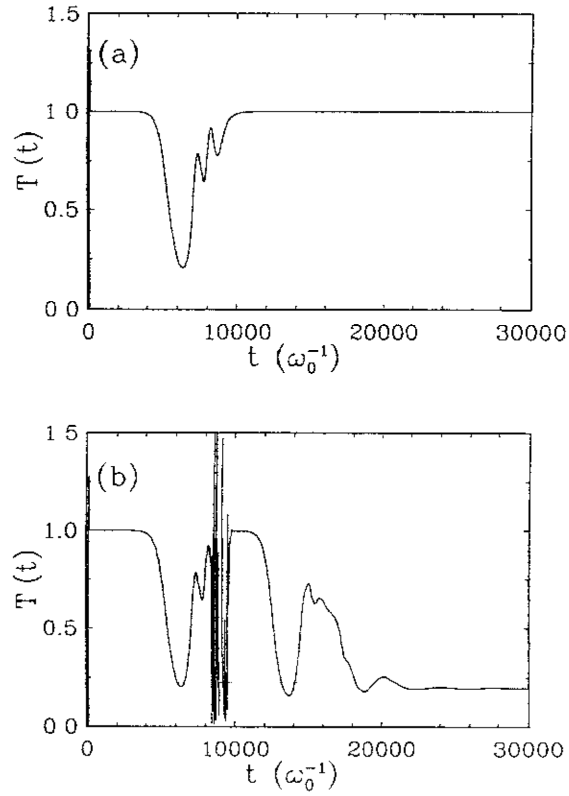

Fig. 2

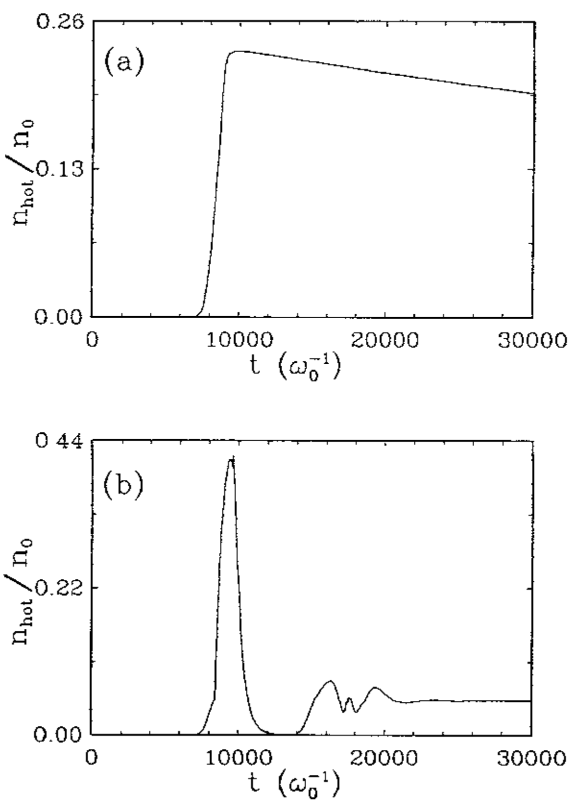

Fig. 3

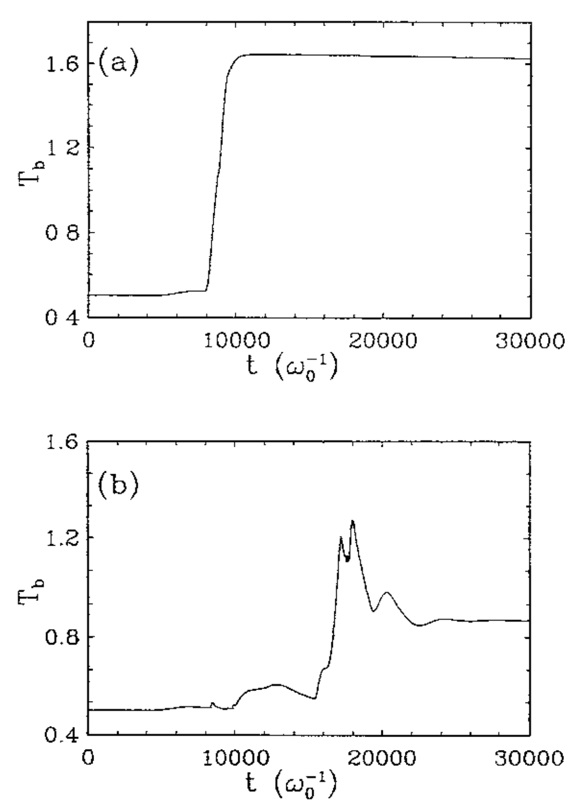

Fig. 4

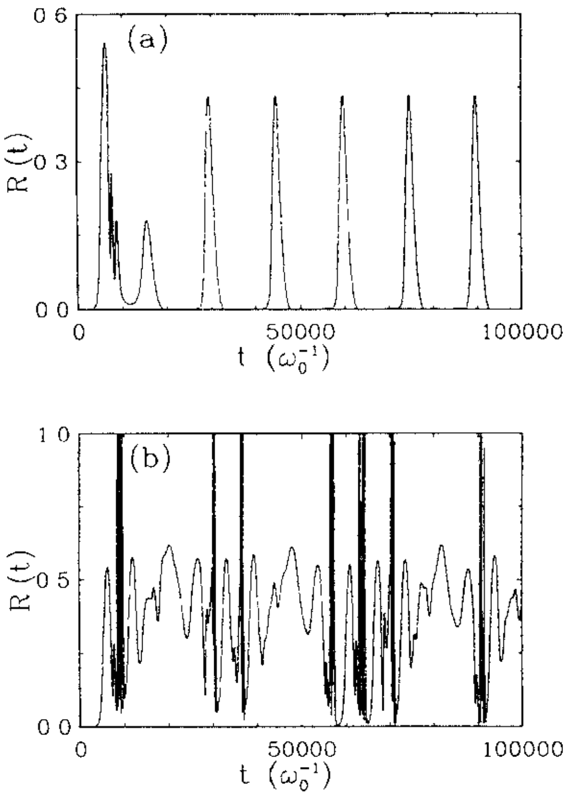

Fig. 5

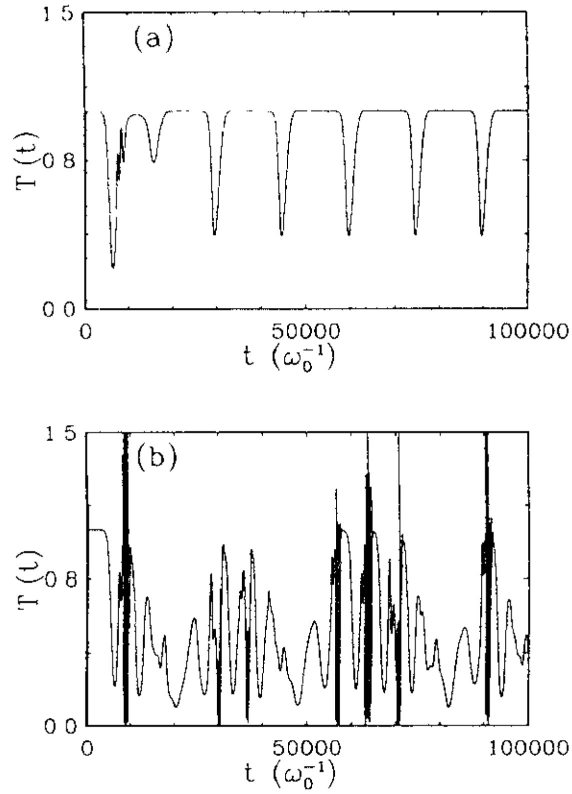

Fig. 6

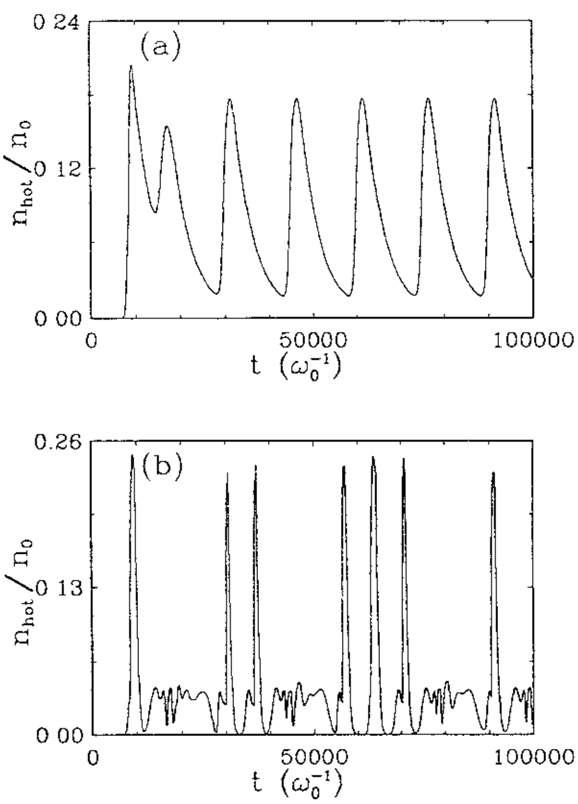

Fig. 7

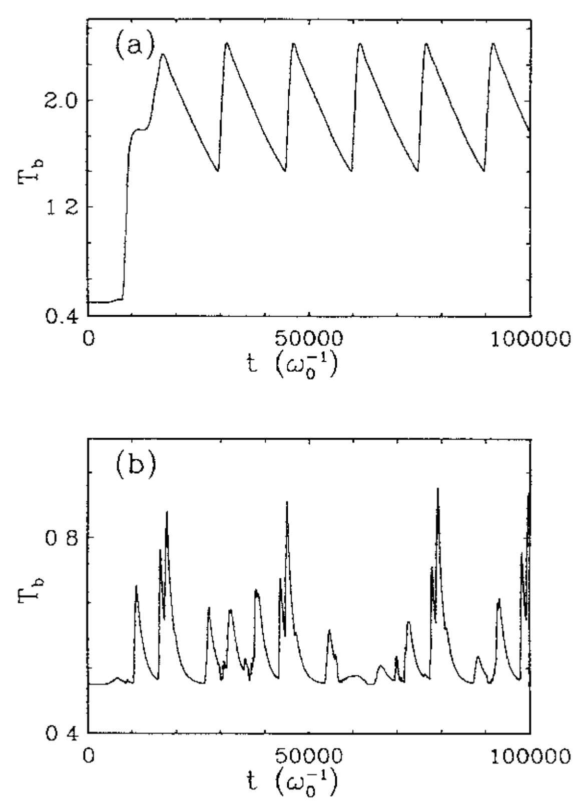

Fig. 8

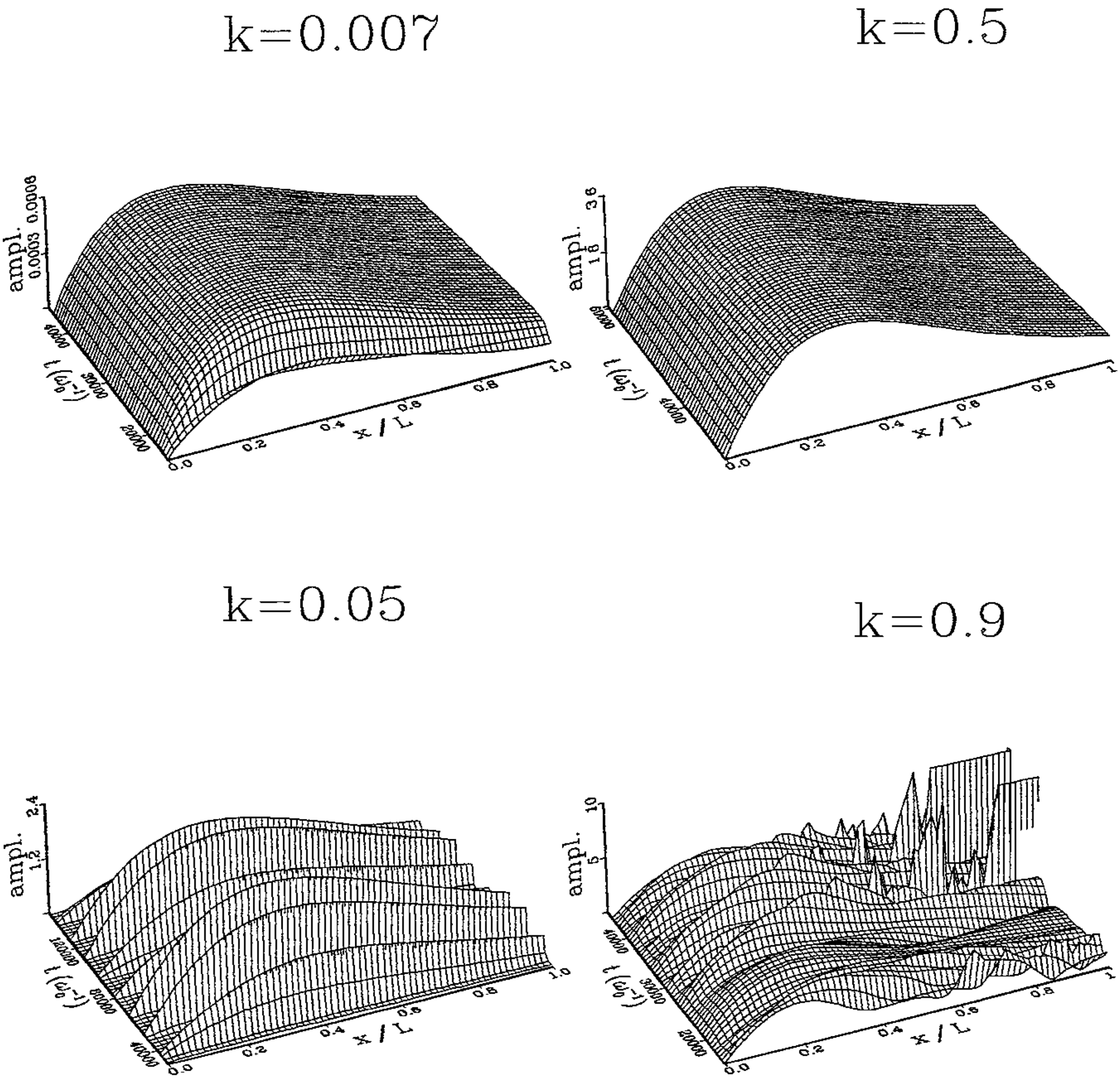

Fig. 9

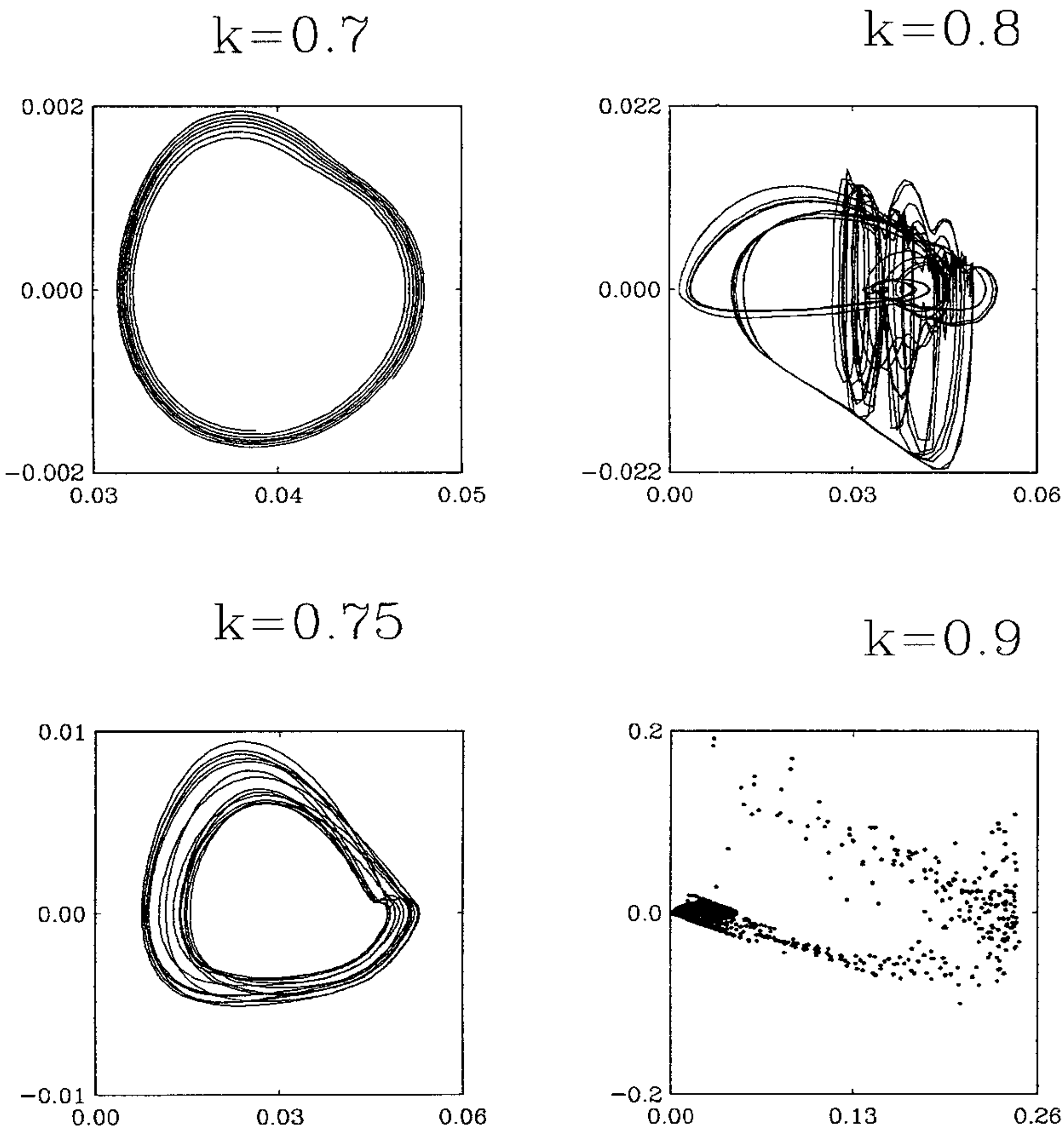
k=0.7
0.002
0.000
−0.002
0.03
0.04
0.05
k=0.8
0.022
0.000
−0.022
0.00
0.03
0.06
k=0.75
0.01
0.00
−0.01
0.00
0.03
0.06
k=0.9
0.2
0.0
−0.2
0.00
0.13
0.26

Fig. 10

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