Self-organization in a dissipative three-wave interaction

M. M. Škorić
Vinča Institute of Nuclear Sciences, P.O.B. 522, 11001 Belgrade, Yugoslavia

T. Sato
Theory and Computer Simulation Center, National Institute for Fusion Science, Toki-shi, 509-52, Japan

A. Maluckov
Graduate University for Advanced Studies, Hayama, Kanagawa 240-01, Japan

M. S. Jovanović
Department of Physics, University of Niš, P.O.B. 91, 18001 Niš, Yugoslavia

(Received 3 February 1999)

A nonlinear three-wave interaction in an open dissipative plasma model of a stimulated Raman backscattering is studied. An anomalous kinetic dissipation due to electron trapping and plasma wave breaking is accounted for in a hybrid kinetic-fluid scheme. We simulate a finite plasma with open boundaries and vary a transport parameter to examine a route to spatio-temporal complexity. An interplay between self-organization at micro (kinetic) and macro (fluid) scales is found through quasi-periodic and intermittent evolution of dynamical variables, dissipative structures and related entropy rates. A consistency with a general scenario of self-organization is claimed. [S1063-651X(99)17011-9]

PACS number(s): 52.40.Nk, 05.65.+b, 52.35.Mw, 52.65.−y

I. INTRODUCTION

In recent papers on complexity and self-organization in plasmas by Sato *et al.* a profound underlying structure in strongly nonlinear and complex plasma phenomena was revealed [1]. Self-organization is a generic process of a creation of order in a nonlinear far-from-equilibrium system open to an environment [2]. Free energy supply, nonlinear instability and structural bifurcation which result in dissipation, entropy production and its subsequent removal from a system are key governing points [1,2]. The above concept, as a working hypothesis, was successfully applied in studies of markedly diverse 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 found [1].

In this paper we examine an open convective dissipative model of a stimulated Raman backscattering. In earlier 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 spatiotemporal patterns, examining the partition of energy among coherent structures has found a growing complexity as the pumping increases. However, based on general advancements in studies of plasma complexity [1, 2] it appears plausible that due to turbulence related anomalous dissipation, self-organization to a state of reduced complexity should be realized. To emulate the effect of entropy balance we introduce a hybrid three-wave interaction model that includes a phenomenological kinetic dissipation via particle trapping and wave breaking.

II. 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 [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 wave numbers is satisfied, the pump parametrically excites the stimulated growth of the daughter waves from their thermal noise level.

Stimulated Raman scattering involves parametric coupling of an electromagnetic pump to an electron plasma wave and a scattered electromagnetic wave [8]. Various applications in laboratory: laser and radio-frequency wave driven plasmas, as well as in space and astrophysical plasmas were attempted [8,10,11]. We examine a nonlinear evolution of a stimulated Raman backscattering in an open dissipative plasma model. Generally taken, the invariants point to an onset of nonstationarity for conditions of imperfect phase matching. Studies of spatiotemporal complexity in a fluid model of stimulated Raman backscattering in a bounded weakly dissipative plasma were attempted by Škoric *et al.* [3]. A continual increase in complexity with a control parameter (e.g., pump strength) was predicted by this model, thus establishing its place in a growing family of paradigmatic physical phenomena that display an intermittent route to spatio-temporal chaos [6].

However, the effects of anomalous Raman dissipation and plasma heating followed by entropy expulsion, were omitted in this model [3]. It is a purpose of this study to introduce a plausible entropy inventory by a phenomenological modeling of anomalous kinetic dissipation related to Raman complexity. In long saturated regimes, we shall look for intermittent evolution, generic to an open system under a continual free energy supply [1].

Extensive studies of nonlinear stimulated Raman backscattering have been performed by analytics, fluid and particle simulations [3,8,7]. In a strongly driven case, Raman instability exponentiates until arrested by nonlinear and dissipative effects. The saturation comes, basically, through pump depletion and/or higher-order nonlinearities as well as kinetic dissipation related to electron trapping and plasma wave breaking [8,7]. While pump depletion is readily included in fluid modeling, the latter effects are inherently kinetic. However, after more than two decades of intensive particle simulation studies, nonlinear Raman scattering is understood to possess relatively clear, albeit anomalous overall features [8].

As a result of electron trapping and breaking of large plasma waves a hot tail-suprathermal electron population is generated. The corresponding velocity of hot (fast) electrons roughly equals the phase velocity of the electron plasma wave. As a general feature, two temperature (Maxwellian-like) electron distribution is recorded, for the thermal (bulk) and suprathermal (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 has enabled useful scaling relations and semi-empirical formulas, typically extracted from the averaged (time and shot) short-run data. Generally taken, a realistic long time saturation (e.g., $>10\,000$ plasma wave periods) does not appear to be assessable to even high performance particle simulation due to required computer time and limitations of the numerical scheme involving large number of particles [8,13].

It is this situation that has motivated us to address a problem of anomalous Raman in a long time evolution. We shall study a possible saturation to self-organizing plasma states using a general concept of complexity in plasmas in a system open to an environment [1]. 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 [12], planned for the future.

At this point we shall refer to more recent extensive studies of nonlinear Raman saturation by Rose *et al.* In distinction to a simple adiabatic nonlinearity (e.g., relativistic type) in our equation (6), these authors introduce strongly nonlinear Langmuir wave dynamics. Based on Zakharov's fluid model, processes like Langmuir decay, wave collapse and density modification are included in this description [9]. One- and two-dimensional (2D) simulations allowed comparison with realistic laser-plasma experimental conditions. In comparison, our weakly coupled three-wave interaction (3WI) model attempted to include basic kinetic effects in 1D Raman model. Although simple, kinetic dissipation was self-consistently coupled with Raman dynamics to study self-organized saturated states. An important fact appeared, that both of above models predict an intensity dependent spectral broadening and incoherence paradigm for Raman backscatter, as only recently was observed in experiments [9].

III. A THREE-WAVE COUPLED MODE MODEL

Stimulated Raman backscattering in a plasma is a paradigm of a three-wave parametric interaction whereby a strong electromagnetic wave (0-pump) decays into an electron plasma wave (2) and backscattered wave (1) downshifted in frequency. This coupled 3WI process obeys a resonant matching condition for wave frequencies and wave numbers, in the form

$$\omega_0=\omega_1+\omega_2, \quad \vec{\mathbf{k}}_0=\vec{\mathbf{k}}_1+\vec{\mathbf{k}}_2. \tag{1}$$

In the one-dimensional case which is of major importance the linear parametric Raman backscatter growth rate is given by

$$\gamma_0\approx 0.5\beta_0\sqrt{\alpha/(1-\alpha)}\,\omega_0, \tag{2}$$

α being the ratio between the electron plasma frequency and the frequency of the pump:

$$\alpha=\omega_{pe}/\omega_0=\sqrt{n_0/n_{cr}}. \tag{3}$$

and the quantity β_0 is a relative pump strength, the ratio between the electron quiver velocity in the pump and the speed of light. In a bounded, uniform, completely ionized plasma, the spatio-temporal evolution of the coupled waves' normalized, slowly-varying complex amplitudes $a_j(\xi,\tau)$ is governed by the following set of partial differential equations [3]:

$$\frac{\partial a_0}{\partial \tau}+V_0\frac{\partial a_0}{\partial \xi}=-a_1a_2, \tag{4}$$

$$\frac{\partial a_1}{\partial \tau}-V_1\frac{\partial a_1}{\partial \xi}=a_0a_2^*, \tag{5}$$

$$\frac{\partial a_2}{\partial \tau}+V_2\frac{\partial a_2}{\partial \xi}+\gamma a_2+i\sigma|a_2|^2a_2=\beta_0^2a_0a_1^*, \tag{6}$$

where time and space coordinates are measured in units ω_0^{-1} and L^{-1}, respectively,

$$\tau=\omega_0 t, \quad \xi=\frac{x}{L}. \tag{7}$$

Dimensionless group velocities of the waves are

$$V_0=\frac{c^2k_0}{\omega_0^2L}, \quad V_1=\frac{c^2k_1}{\omega_0\omega_1L}, \quad V_2=\frac{3k_2T}{m_e\omega_0\omega_{pe}L} \tag{8}$$

with a plasma wave damping rate given by γ. Ions are kept fixed to preserve the plasma quasineutrality. Damping of the light waves is neglected, while T designates the bulk electron temperature. An important feature of the system [Eqs. (4)–(6)] is the self-modal cubic term in the plasma wave equation. It appears as a nonlinear phase shift due to a detuning of a large amplitude plasma wave. A time-only (space-only) version of [Eqs. (4)–(6)] was studied in detail, and it was shown to exhibit bifurcation to a low-dimensional chaos under restricted conditions. The spatially extended model is of a more physical significance and have recently revealed by these authors, rich complexity related to low-dimensional as well as spatio-temporal chaos [3,5,7].

The system [(4)–(6)] was solved in space-time for standard initial and finite boundary conditions. In the loss-free steady state with zero phase shift, this system predicts the well known elliptic function solutions, together with three (Manley-Rowe) conserved integrals [3,4]. However, with a nonzero phase shift ($\sigma > 0$) in finite boundaries, these invariants are broken. Thus a violation of the steady-state assumption, points to a nonstationary Raman saturation. Indeed, subsequent evolution exhibits a quasiperiodic route to low-dimensional intermittency to finally result in a fully developed spatiotemporal chaos, in this fluid model [(4)–(6)]. 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 evolution 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 this way, effective damping $\gamma(t)$ and the electron temperature $T(t)$ in 3WI, appear as dynamical variables, in contrast with a standard model that assumes a constant plasma background. Therefore, we expect to study dissipative effects on longtime Raman saturation and kinetic self-organization in an open system.

IV. KINETIC-HYBRID SCHEME

We chose to simulate conditions relevant to anomalous Raman saturation in an open system, which means allowing an energy exchange between an interaction region and the plasma environment. To emulate basic kinetic effects missed by the original fluid 3WI model [(4)–(6)], we propose a phenomenological ''hybrid'' scheme which includes 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 [(4)–(6)]. As a consequence, we shall introduce the suppression of Raman instability by hot electrons through a linear Landau damping. We further assume that the effective damping (γ term) of plasma waves is due to both linear Landau damping on hot electrons and nonlinear term—due to bulk electron acceleration via trapping. Finally, we add a simple energy balance equation to model bulk heating via the redistribution of the absorbed energy between bulk (thermal) and hot (suprathermal) 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 hybridlike 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 in order to try closer fits by adjusting free transport parameter in our scheme. In that way we expect to be able to address a longtime Raman saturation in an open system, an important question that remains difficult to answer even by highest performance particle simulations [8].

We start by assuming the electron distribution function, for thermal (bulk) and hot component, to be approximated by bi-Maxwellian [7,8]:

$$F(x,t,v) = n_h(x,t) f_h(v) + n_b(x,t) f_b(v), \tag{9}$$

where n_h and $n_b (\gg n_h)$ stand for slowly varying hot and bulk electron densities, respectively, with each $f(v)$ normalized to unity. 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

$$j_h(x,t) = \int_{hot} vF(v)dv = n_h(x,t) \int_{-\infty}^{\infty} v f_h(v) dv + n_b(x,t) \int_{v_{ph}-v_{tr}}^{v_{ph}+v_{tr}} v f_b(v) dv, \tag{10}$$

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

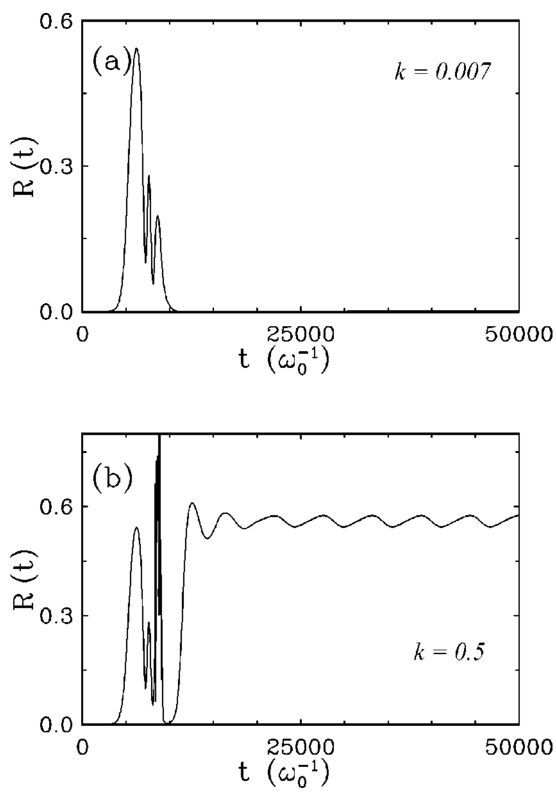

FIG. 1. Time evolution of the Raman reflectivity for transport parameter k corresponding to (a) closed model (inhibited transport, $k = 0.007$). (b) Open model ($k = 0.5$).

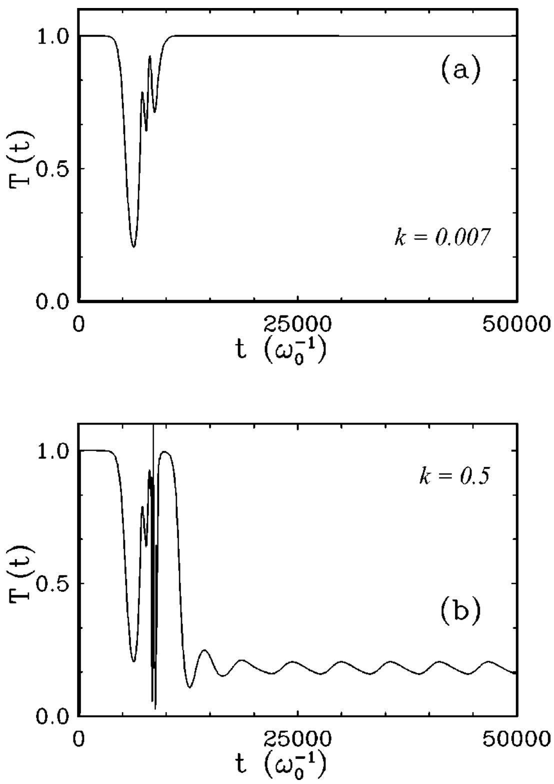

FIG. 2. Time evolution of the Raman transmittivity for transport parameter k corresponding to (a) closed model (inhibited transport, $k=0.007$) and (b) open model ($k=0.5$).

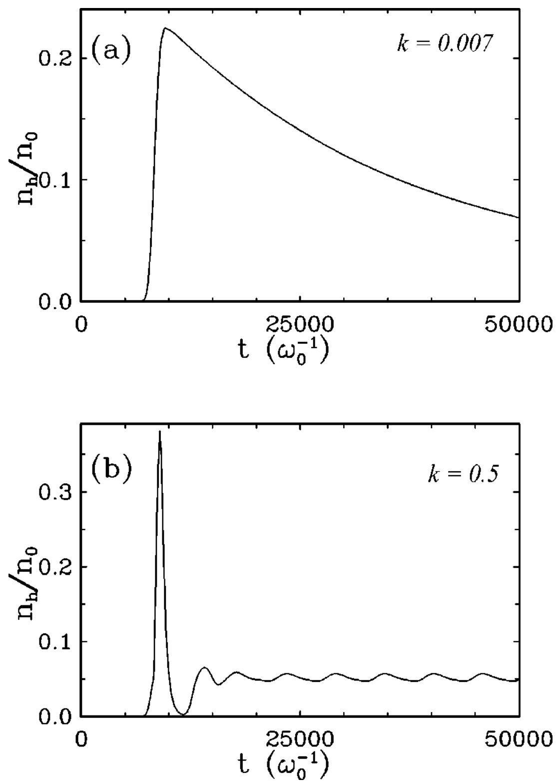

FIG. 3. Hot electron density variation in time related to Figs. 1 and 2: (a) $k=0.007$ and (b) $k=0.5$.

$$\frac{d}{dt}n_h(x,t) \equiv \frac{\partial}{\partial t}n_h(x,t) + \operatorname{div} j_h = 0 \qquad (11)$$

or, after performing the spatial average, defined as

$$\langle \cdots \rangle_L \sim \frac{1}{L}\int_0^L (\cdots)\,dx, \qquad (12)$$

where $n_h(t)$ is hot density averaged over the plasma length L, we obtain

$$\frac{d}{dt}n_h(x,t) + \frac{1}{L}j_h(x,t)|_0^L = 0. \qquad (13)$$

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

$$\frac{dn_h(t)}{dt} = \frac{n_b(L,t)}{L}\int_{v_{ph}-v_{tr}(L,t)}^{v_{ph}+v_{tr}(L,t)} v f_b dv - \kappa n_h(t). \qquad (14)$$

We note $v_{tr}(0,t)=0$ due to the boundary condition for a plasma wave. The loss term is due to electrons which escape through open plasma boundaries, with $\kappa = k v_h/L = k v_{ph}/L$, and $k=1$ and 2 for a free streaming and a Maxwellian flow, respectively. We now proceed to evaluate the effective damping rate in the plasma wave equation (6). 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 appearing regularly in the literature [4,8]. Further, we introduce the spatially integrated plasma wave energy density, through

$$W(t) = \frac{1}{L}\int_0^L \frac{1}{8\pi}|E(x,t)|^2 dx. \qquad (15)$$

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

$$2\gamma(t)W(t) = 2\gamma_{Landau}(t)W(t) + \frac{mn_b(L,t)}{2L}\int_{v_{ph}-v_{tr}(L,t)}^{v_{ph}+v_{tr}(L,t)} v^3 f_b(v)\,dv, \qquad (16)$$

where an integral term, gives a nonlinear term in a plasma wave damping, thus 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 denotes energy, ϕ_i denotes energy flux)

$$\frac{d}{dt}\sum_i w_i(x,t) = \frac{\partial}{\partial t}\sum_i w_i(x,t) + \operatorname{div}\sum_i \phi_i(x,t) = 0. \qquad (17)$$

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

$$\frac{d}{dt}\sum_i W_i(t) + \frac{1}{L}\sum_i s_i(x,t)|_0^L = 0. \qquad (18)$$

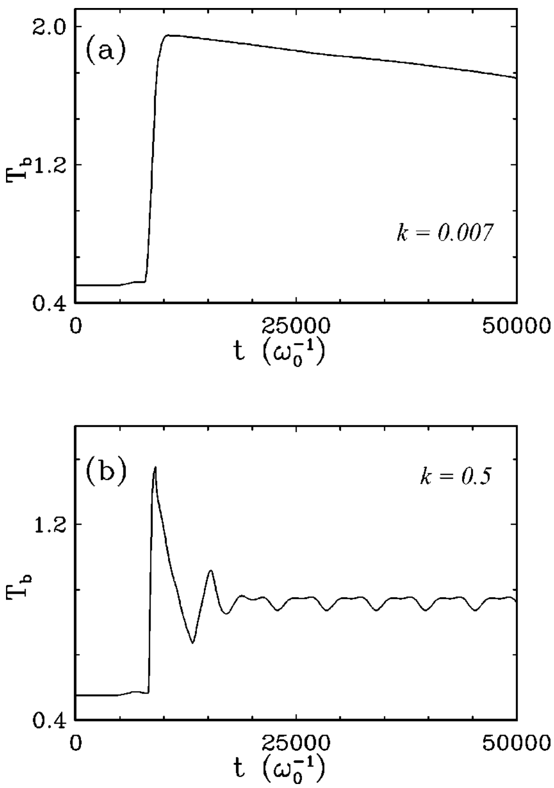

FIG. 4. Bulk temperature variation in time, related to Figs. 1 and 2: (a) $k=0.007$ and (b) $k=0.5$.

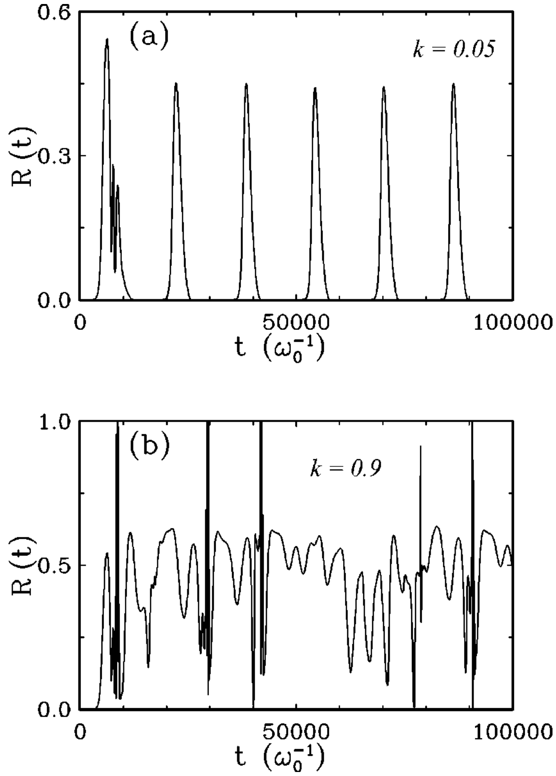

FIG. 5. Time evolution of the Raman reflectivity showing a complexity of the (a) quasiperiodic ($k=0.05$) and (b) intermittent type ($k=0.9$).

For our system, the plasma wave, thermal and hot component: $W_i(t) => W + E_{th} + E_h$ the electron energy densities are simply: $E_{th} = n_b T_b$ and $E_h = n_h T_h$; and the average energy flux, is given by $\Phi_{th} = \pm v_{th} E_{th}$ and $\Phi_h = \pm v_h E_h$. For the Maxwellian, the above energy flux is multiplied by a factor ~ 0.65. However, in real plasmas, an inhibited energy flux is modified by a parameter $k \sim (0-1)$; in a heuristic model of a highly complex electron energy transport [8]. The $\pm$ sign indicates the flux direction at the plasma boundary (at $x=0,L$). By using the above expressions, the equation for the thermal energy variation is given as

$$\frac{d}{dt}[n_b(t)T_b(t)] = 2\gamma W(t) - \frac{d}{dt}[n_h(t)T_h(t)] - \frac{k}{L}[\Phi_{th} + \Phi_h - \Phi_q]\Big|_0^L, \qquad (19)$$

where we have introduced Φ_q as the return flux of fresh ambient electrons through an open plasma boundary (vide infra). We note in passing a simplified form of Eq. (10) with respect to a lack of a finite relaxation time, that is normally required for a heat transfer via e.g. hot-bulk electron collisions.

V. OPEN BOUNDARY MODEL

We introduce a model with boundaries open to electromagnetic waves and plasma electrons. Accordingly, we allow a 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 quasineutrality. Accordingly, a long-time Raman saturation could 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: $J_{\mathrm{tot}} = J_{out} - J_{in}$, with $J_{out} = J_{th} + J_h$, for thermal and hot electron contributions. We further write: $J_{in} = n_q v_0$, where $n_q v_0$ stands for a current of ambient electrons streaming into a plasma layer. By requiring the total current at the boundary to be zero, one readily evaluates J_{in} in terms of the thermal and hot components. The energy flux carried by ambient electrons (with the temperature T_0) is simply $\Phi_q \sim J_{in} T_0$, making the calculation of the loss term in the thermal balance equation an easy task.

In further studies we shall refer to the above model as the open one, in contrast with 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 (Φ), coefficient restricted to low values. As for the Maxwellian with an open boundary we get the factor $\sim$ 0.65; one should expect a wide range of dynamical regimes between these two extreme transport cases.

VI. KINETIC SELF-ORGANIZATION

We briefly analyze Raman complexity obtained in our simulations. We chose parameters of the ''standard case'' studied in depth in a fluid 3WI model (vide supra) [3]. Initial plasma parameters are: the electron density is 0.1 of the criti-

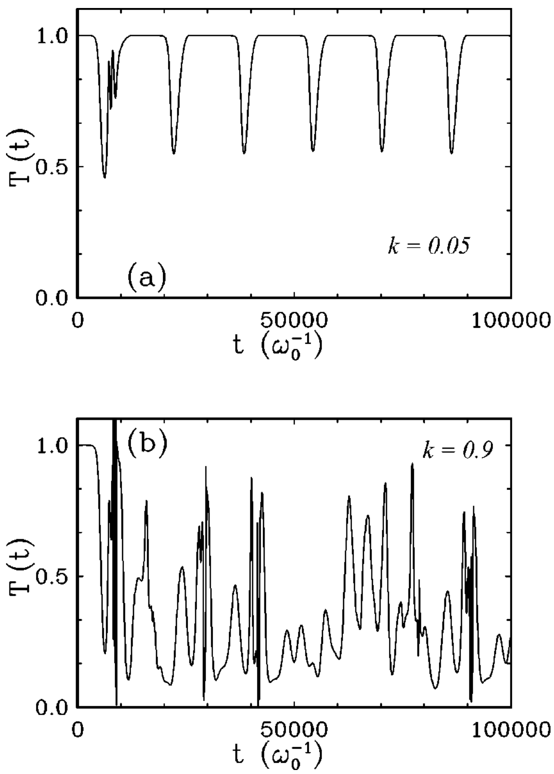

FIG. 6. Time evolution of the Raman transmittivity showing a complexity of the (a) quasi-periodic ($k=0.05$) and (b) intermittent type ($k=0.9$).

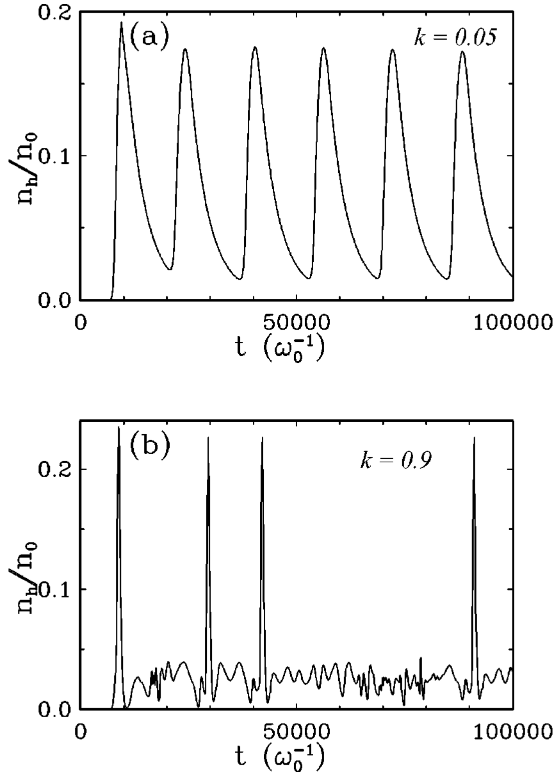

FIG. 7. Hot electron density variation in time related to Figs. 5 and 6: (a) $k=0.05$ and (b) $k=0.9$, exhibiting strong quasiperiodic (a) and intermittent (b) pulsations.

cal density, the electron temperature of 0.5 keV and the plasma length $L=100c/\omega_0$. 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 coefficients in time, as well as the evolution of hot electron density and bulk temperature. We fix the pump equal to 0.025. For two cases of an open ($k=0.5$) and nearly closed ($k=0.007$) system, after transient pulsations reflectivity saturates to a quasisteady state. As expected, the transmittivity follows the same scenario. However, while for the open system reflectivity saturates to a high-finite value, in a strongly confined-closed system reflectivity quickly drops to zero due to a complete Raman suppression (see Figs. 1 and 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 the latter case, the moderate hot electron population, which is locked to a finite-plasma wave as a source of hot electrons, saturates to a quasisteady state. In distinction, in the 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. In the open system, temperature saturates to a 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 the closed system, rapid and large temperature rise is observed, to reach its maximum by halting Raman instability, later to experience slow cooling through inhibited boundaries (Fig. 4).

Further, we carefully vary a control parameter k to study generic structural bifurcations along the route to complexity (see 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 quasiperiodic dynamical state, observed readily in a train of temporal pulses in the reflectivity and transmittivity. 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 sawtooth oscillations reminiscent of those observed in tokamak plasmas. By further exploring a parameter space for the open system with $k=0.9$ we find a transition to a quasiperiodic 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 ($T_h \sim 22$ keV) as a striking feature of this type of kinetic self-organization (Fig. 7). Bulk temperature follows an intermittent scenario, by exhibiting quasiperiodic (QP) fluctuations, somewhat above its initial value (Fig. 8). Finally, we show a temporal route to complexity by plotting a phase space attractor for the hot electrons (Fig. 9). 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.

VII. DISSIPATIVE STRUCTURES AND ENTROPY RATE

Self-organization in strongly nonlinear far-from-equilibrium systems leads to a creation of ordered states that

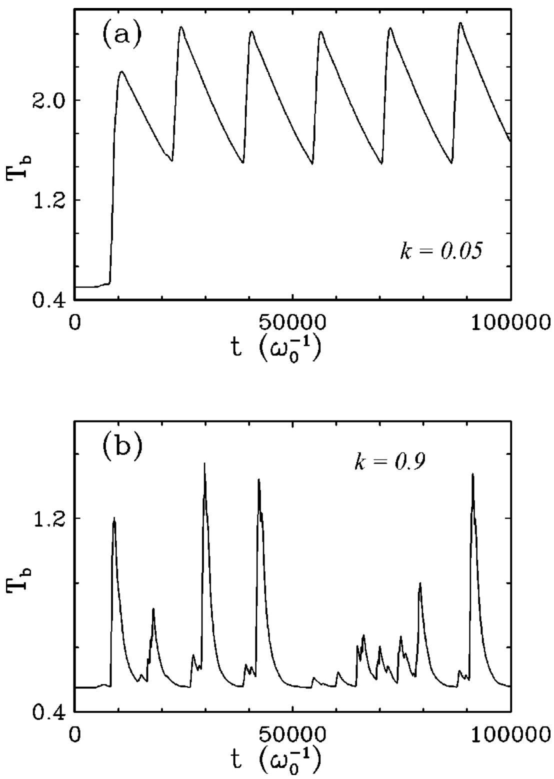

FIG. 8. Bulk temperature evolution in time, related to Figs. 5 and 6: (a) $k=0.05$ and (b) $k=0.9$.

reflect an interaction of a given system with its environment. These dynamical structures or patterns, named dissipative structures to stress the crucial role of dissipation in their creation, have become a central theme of the science of complexity [1,2]. On the other hand, there is a fundamental role of the entropy, in particular, the rate of entropy change in an open system. The rate of entropy production and its removal

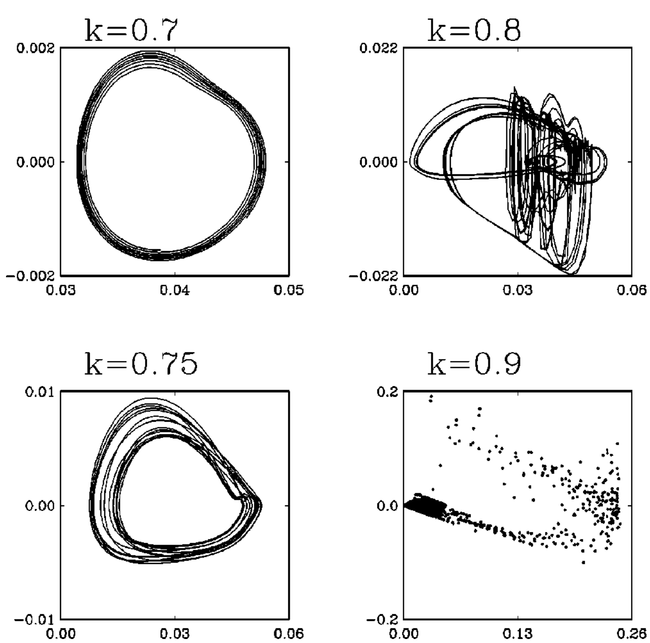

FIG. 9. Phase diagrams of the hot electron temporal evolution. Onset of complexity is connected with typical ''stretching and folding'' of periodic orbits.

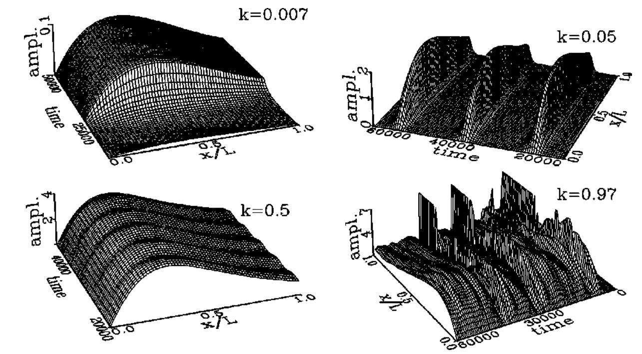

FIG. 10. Spatiotemporal profile of the electron plasma wave for varying k values. Different dissipative structures are seen on the route to complexity, from the steady-state via quasiperiodic to intermittent regimes.

basically governs self-organization features of a system. A large amount of effort has been spent in attempts to relate the entropy rate extrema to structural bifurcations and transitions between different ordered states [1, 2].

First, we focus at self-organized dissipative structures developed at macroscales. Indeed, in our model, basic wave and fluid density variables were assumed to vary slowly in space-time. Therefore, we expect that original spatiotemporal profiles, found in simulations, should correspond to large dissipative structures, self-organized at macroscale levels. As an illustration, we plot the plasma wave profile (Fig. 10), in particular, 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]. Spatiotemporal complexity of quasisteady and traveling wave patterns with regular and chaotic features is found in different states of self-organization.

However, a hybrid nature of our model will also allow us to recover kinetic properties of self-organization. By using an analytical dependance of the electron distribution on varying hot (bulk) temperature and density (7) we shall expose a genuine picture of kinetic self-organization at plasma microscales. To show the self-organization featuring micro-levels,

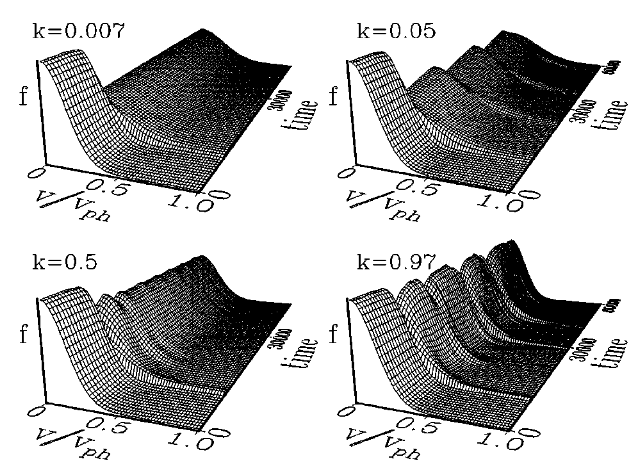

FIG. 11. Three-dimensional view of the electron velocity distribution in time for different saturated Raman regimes, as indicated by values of parameter k. Microkinetic scale self-organization of varying complexity is revealed in both thermal and suprathermal (hot) regions of the electron distribution.

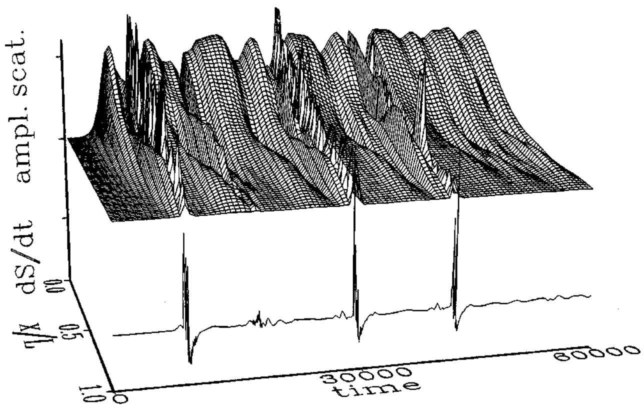

FIG. 12. Dissipative backscatter and plasma wave structures vs corresponding entropy changes in time. Positive entropy jump coincides with an onset of chaos, while a negative burst indicates a transition from a chaotic to a laminar phase.

we plot the electron velocity distribution function. In Fig. 11 we see a three-dimensional view of the electron velocity distribution in time for different saturated Raman regimes, as indicated by values of parameter k. Kinetic self-organization of varying complexity is revealed in thermal and suprathermal (hot) regions of the electron distribution. Furthermore, one can observe a complex connection and interplay between macro and micro levels of self-organization in a plasma.

Finally, in Fig. 12 we plot the entropy rate $dS(t)/dt$ in time together with a spatio-temporal profile of the scattered wave energy. We calculate the entropy S related to electron distributions as: $S(t)=S_b(t)+S_h(t)$, where

$$S_i(t)=-\int_0^L dx\int_{-\infty}^{\infty} dv\, f_i(x,v,t)\ln f_i(x,v,t), \quad (i=b,h). \tag{20}$$

For an intermittent regime, featuring an interchange between chaotic and laminar phases, we find a clear evidence of structural transitions corresponding to the maximum (positive) and minimum (negative) entropy rate. As a striking example of self-organization in an open system we find a rapid entropy increase which coincides with an onset of a chaotic phase. Subsequent anomalous dissipation and entropy growth is halted by a sudden entropy expulsion into the environment. Negative burst in entropy rate indicates a bifurcation from a chaotic, back to a laminar quasiperiodic phase. An intermittent nature of this regime is shown through a repetitive pattern of behavior. We note that complex dissipative wave structures are mapped onto a more simple entropy rate time series. Intervals of near zero entropy rate during a laminar phase, mean a net balance between the entropy production and its expulsion. This appears to be an example of a stationary nonequilibrium state possibly realized in a strongly nonlinear open system [2].

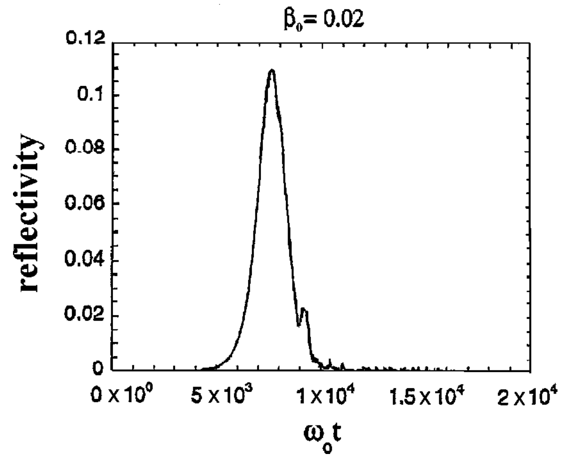

FIG. 13. Simulation data for the Raman reflectivity in time obtained by a $1\frac{1}{2}$ electromagnetic, relativistic, particle-in-cell code (after Miyamoto *et al.* [13]). Initial plasma parameters were the same as above, with a pump equal to 0.02.

VIII. SUMMARY

In summary, we believe that our findings appear to be first indication of a generic intermittent scenario in a kinetic self-organization of anomalous Raman instability. Although phenomenological rather than rigorous our dissipative 3WI open model has self-consistently accounted for the entropy production and removal, for both thermal and suprathermal electrons. In this way, rich transient Raman complexity gradually gets self-organized and attracted to definite saturated dynamical states, such as: steady-state, quasi-periodic and intermittent ones. At this point we may note that one is able to claim a consistency with the working hypothesis and general scenario of self-organization in plasmas [1]. As a further step, we expect an important justification for our hybrid-modeling of saturated Raman complexity by the novel open boundary particle simulation currently under development [12]. As an early illustration, we show in Fig. 13 recent particle-in-cell simulation data for a model of an isolated plasma slab in a vacuum [13]. For the same parameters particle simulations show an evident support of above Raman reflectivity patterns [Fig. 1(a)] obtained for a nearly closed $(k=0.007)$ system.

ACKNOWLEDGMENTS

We acknowledge the partial support granted to one of us (M. M. Š.) by the Ministry of Education, Science and Culture of Japan. The hospitality of the National Institute for Fusion Science is gratefully acknowledged. This work was supported in parts by the Ministry of Science and Technology of the Republic of Serbia, Contract No. 01E11.

[1] T. Sato and the Complexity Group, Phys. Plasmas **3**, 2135 (1996); **2**, 3609 (1995).

[2] G. Nicolis and I. Prigogine, *Exploring Complexity* (Freeman, New York, 1989).

[3] M. M. Škorić, M. S. Jovanović, and M. R. Rajković, Phys. Rev. E **53**, 4056 (1996); Europhys. Lett. **34**, 19 (1996).

[4] R. Z. Sagdeev and A. A. Galeev, *Nonlinear Plasma Theory* (Benjamin, New York, 1969).

[5] D. J. Kaup, A. Rieman, and A. Bers, Rev. Mod. Phys. **51**, 275 (1979).

[6] M. C. Cross and P. Hohenberg, Rev. Mod. Phys. **65**, 851 (1993).

[7] D. W. Forslund, J. M. Kindel, and E. L. Lindman, Phys. Fluids **18**, 1002 (1975).

[8] W. L. Kruer, *Physics of Laser Interactions* (Addison-Wesley, New York, 1988).

[9] H. Rose, Phys. Plasmas **5**, 3868 (1998); **5**, 3876 (1998); **6**, 1294 (1999).

[10] B. Coppi, R. D. Blanford, and M. J. Rees, MNRAS **262**, 603 (1993).

[11] S. J. Karttunen, T. J. Pattinkagas, R. P. Salomaa, and S. K. Sipila, Nucl. Fusion **31**, 1079 (1991).

[12] H. Takamaru, T. Sato, R. Horiuchi, K. Watanabe, and Complexity Group, J. Phys. Soc. Jpn. **66**, 3826 (1996).

[13] S. Miyamoto, K. Mima, M. M. Škorić, and M. S. Jovanović, J. Phys. Soc. Jpn. **67**, 1281 (1998); private communication.