Complexity, Dissipation, Order Out of Chaos and Chaos Out of Order

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We present and analyze some aspects of the physics of dissipative phenomena. Attention is called to its connection with the emerging theory of complexity, and its place in the realm of nonlinear physics. This nonlinearity has a fundamental role in determining complex behavior in open systems far away from equilibrium. In many cases it shall lead to the formation of self-organized synergetic behavior at the macroscopic level, in the form of the so called Prigogine's dissipative structures. Dissipation is then not a source of decay but has a constructive role, maybe including the emergence of life, natural evolution, and the astounding functioning of living systems. Two cases – dealt with within the framework of the rising Informational Statistical Thermodynamics – eventually relevant to the functioning of biosystems are presented. They illustrate the connection among the four items in the title of this paper.

I. Introduction

In 1970, in the issue of Wednesday October 6 of the daily newspaper Suddeutsche Zeitung, the Nobel Prize Werner Heisenberg presents an article titled "The End of Physics?"[1]. It was motivated as a response to the posture of some physicists, according to whom all that is of interest in the realm of the physics would be exhausted after all the problems posed in the area of elementary particles are solved. "For, it might be argued, all matter and all radiation consists of elementary particles and, hence, a complete knowledge of the laws governing their properties and behavior, in the shape, say, of a "world formula", would also be bound to establish the basic framework for all physical processes. So even if extended developments could still be appended in applied physics and technology, the questions of principle would all have been settled, and fundamental research in physics would have come to an end". Heisenberg - with his geniality and foresight – defends in the article an opposing position, answering that "in time to come it will often be difficult, perhaps, to decide whether an advance in knowledge represents a step forward in physics, information theory, or philosophy, whether physics is expanding into biology or whether biology is employing physical methods and approaches to an ever greater extent. It would thus be possible to speak of a closing off of physics only if we were arbitrarily prepared to define certain methods and conceptual patterns as physical ones and to assign other ways of putting the problem to other sciences. But this is hardly likely to happen; for the characteristic feature of the coming development will surely consist of the unification of science, the conquest of the boundaries that have grown up historically between the different individual disciplines". In a sense he predicts a return to the Aristotelian concept of a unifying natural philosophy.

Other renowned authors as Freeman Dyson[2], Wladimir Ginzburg[3], and Herbert Fröhlich[4] have also expressed, at near the same time as Heisenberg, similar ideas. In particular they call the attention to the differentiation between microphysics (or the mechanicist and reductionist point of view accompanied by deterministic laws) and macrophysics (the physics of large (macroscopic) systems, let them be physical, chemical,

biological, technological, etc., to which should apply statistical laws). The connection of both would be given with the introduction of *macro-concepts*[4], i.e. own characteristics of dynamical systems beyond the laws of microphysics, a topic, in a sense to be touched upon within the theme to be considered here.

Less than twenty years after Heisenberg's article, some authors consider that we are at the birth of "a new physics", whose expanding frontiers rnay be concentrated into three aspects, namely[5]

1. The very *small* (in large part the age old quest for the building blocks of matter and their interactions).
2. The very large (that is mainly astrophysics and its connections with cosmology and gravitation).
3. The very complex (here is the emerging Theory of Complexity and its eventual relevance in a global understanding of Nature, is the subject of our interest here and where the question of macro-concepts lies).

This last item, the subject of this special section of the Braz. J. Phys., rnay be considered in a sense an answer to Heisenberg's premonition of an extended natural philosophy that rnay even incorporate the social sciences. In fact, Theory of Complexity is acquiring popular disclosure, as can be registered with the publication of an article in Times Magazine with the suggestive (albeit somewhat sensationalist) title of "The new field of complexity rnay explain mysteries from the stock market to the emergence of... Life, the Universe, and Everything"[6].

It is difficult to name the "founding fathers" of the theory of Complexity. Since it involves the dynamics of systems, it rnay be noticed that unifying aspects of the question rnay go back to Ludwig von Bertalanffy who in the decade of the thirties gave origin to the Theory of Dynamical Systems[7]. His work was followed and extended by many authors, among them Robert Wiener, Claude Shannon, R. Backminster-Fueller, and others. In connection with the area of physico-chemistry, biology, and later on other disciplines, we rnay mention the work of the Nobel Prize Ilya Prigogine and the Brussels' School[8–21], and also the discipline of Synergetics initiated by Herman Haken[22,23]. A main propagandistic "prophet" of Theory of Complexity is the Nobel Prize Philip Anderson[24,25]. In his articles, Anderson sides with Heisenberg, in that he challenges the radical reductionist theory maintained by a majority of elementary particle physicists. His criticisms are not only on the philosophical position of the latter, but also on the attempt by them to gain political power in the scientific community and in the state councils. In the article "More is Different"[24] he argues that the reductionist hypothesis does not absolutely imply in a "constructionist" one: the dexterity to reduce everything to simple fundamental laws does not imply in the ability to rebuild the universe on the basis of them, the reductionist hypothesis breaks down when confronted with the double difficulty of scale and complexity. This article by Anderson is considered to be one of the first Manifestos concerning the emergent Theory of Complexity. Moreover, Anderson sustains the point of view that each level of description has its own "fundamental" (in some sense) laws, and its own ontology, and that the challenge is how to conceptualize this novelty. In this he is accompanied, among others, by Leo Kadanoff, who stated that "... [summarizing] the complexity of the world in a few simple laws [...] we have chosen to ignore the wonderful diversity and exquisite complication that really characterize our world [...] Physicists have begun to realize that complex systems might have their own laws, and that these laws might be as simple, as fundamental and as beautiful as many other laws of Nature"[26]. Also in this context, Prigogine and the Brussels' School have called the attention to the necessity of a reformulation of the scientific thought allowing to incorporate the question of organization and evolution at a holistic level of description of dynamical systems, and to look upon the constructive role of the irreversible processes: "The belief in the simplicity of the microscopic level now belongs to the past. Classical physics has emphasized stability and permanence. We now see that, at best, such qualification applies only to very limited aspects. Wherever we look, we discover evolutionary processes leading to diversification and increasing complexity".

So far we have been, in a sense, panegyrists of Complexity Theory, but we have not stated clearly what it consists on. As some author wrote, the definition of complexity is a complex matter, and the object of multiple discussions[27]. Complexity in a system is not to be confused with a system simply being complicated. Complication refers to a possible intricate characterization of the system, like, for example, the case of biological systems with entangled compositions of macromolecules involved in multiple and inter-related physical-chemical interactions. Biological systems are complicated, but as discussed below, they are also complex. The reason of its novelty does that a definition of complexity is not uniquely established, with different authors resorting to their "pet definition", as noticed by G. Parisi in his introductory presentation to the conference Measures of Complexity[28] (see also Ref. 25). We introduce here a characterization principle, quite simple and colloquial in nature, namely understanding complexity as a *behavior* of a system which shows large diversity and surprising aspects, given rise to an emergent structure of an unexpected character. Once again following Anderson[25] we cite his sentence that "emergent is a philosophical term going back to the 19th- century debates about evolution implying properties that do not preexist in a system or substrate. Life and consciousness, in this view, are emergent properties".

A system may be complicated, like the case of the dynamics in a crystal lattice, but to have a behavior of quite simple description, i.e. the normal modes of vibration in such example. On the other hand, a system may be quite simple, but it can show a very rich behavior of a quite unexpected character, e.g. the Lorentz model in atmospheric physics, the prototype of the modern theory of chaos[29]. Hence, in fact we should refer to a *complex behavior of a system* instead of a *complex system,* even though this last expression may be accepted as a short form. As noted, only recently – say in the last two decades – the systems with complex behavior have received an ample and systematic study; this is mainly a result of the construction of very rapid electronic computers, that allow to the scientists to model systems with which one cannot deal efficiently (even if possible) otherwise.

We go over next to the consideration of particular cases of complexity.

II. Dissipative structures

Complexity manifests itself in several types of situations in dynamical systems. Two are of particular relevance. One is the nowadays fashionable chaotic behavior in physical and other systems[26], where the idea that a system can be both deterministic yet unpredictable is still rather a novelty. As known, the reason can be traced to the system's extreme sensitivity (hypersensitivity) to the initial conditions. The other, and the one of interest here, is the case of open systems driven far away from equilibrium by intense external sources, where it is possible to find the emergence of ordered patterns on the macroscopic scale. These are the so called (by Prigogine), *dissipative structures*[8–21]. Dissipative because they occur in non-equilibrium open systems, i.e. in their dissipative regime, and structures because they involve a coherent behavior – in some sense to be explicited later on – at the macroscopic scale involving a huge number of individual components of the system (molecules, atoms, quasi-particles, etc.). They are self- organized because an organization – at the temporal or other kinds of levels - of these enormous number of components at a macroscopic scale is involved, and self because such organization is a result of the peculiar characteristics of the laws of evolution of the system and are not imposed by any external agent. As a consequence, it is said that it is one of the universal miracles of Nature that huge assemblages of particles subject only to the blind forces of Nature are nevertheless capable of organizing themselves into patterns of cooperative activity. Processes such as this, as already noted, have been brought to fame by the work of Ilya Prigogine and collaborators, who have developed for them a whole science of far-from-equilibrium thermodynamics for them. They have put into evidence the creative nature of dissipative processes in open systems as opposed to the old idea of decay by dissipation in isolated systems accounted for by the second law of thermodynamics.

Certainly biological systems are complex systems

by antonomasia, and among them the human brain is possibly the more complex system one can conceive. The theoretical approach to biological systems is extremely difficult, on one hand for they being quite complicate arrangements of interacting macromoleciiles involving an enormous amount of physical-chemical processes, and on the other hand for they not being quite amenable to experimental testing. Hence, clearly one should try an approach in steps of increasing difficulty. In a first step, it would be seemingly worth to test ideas, concepts and theories in more tractable systems admitting an accessible theoretical and experimental approach. One case may be that of semiconductors, which – for a clear technological interest – are the object of very extensive research, and other may be the case of simple models of biosystems[33–40], a couple of cases to be described later on in Sections III and IV.

Self-organization appears as a fundamental concept in biology, and so the Brussels' school has stated that "the spontaneous onset of self-organized states [is a phenomenon that] have completely changed our view of the physical sciences and their relation to the biosphere [...] A cell [...] is a highly structured entity with well defined temporal and spatial organization. The proper understanding of its behavior was beyond the reductionist methods of molecular biology [...] The concept of dissipative structures went in a opposite direction by showing that, under appropriate conditions, inert bulk matter is no longer simple and may show a great variety of complex behavior reminiscent of living states [...] the phenomenon of life seems "natural", an inevitable consequence of the ordinary physical-chemical laws which govern the entire universe [...] The bold and audacious hypothesis which assumes that life has been created as a result of the self-o'rganization of matter is known. At present time it seems [a] valid hypothesis which reconciles matter and life [and] we are entitled to hope that sometime in the future it can be proved unambiguously that self organized properties of reacting and flowing systems constitute the missing link in the evolution of molecule to man [...] We are encouraged in such an expectation by the existing theoretical models which show the feasibility of such endeavour"[17].

Thus, it appears that the point of view of the Brussels' school would tend to overcome the old controversy of reductionism vs. vitalism in the life sciences. In a certain sense we would have a scheme that covers both, requiring that besides the deterministic laws of physics along with its reductionist focus, one should incorporate laws that are characteristic to the macroscopic description of the system, namely the macroconcepts to which we previously referred to as suggested by Fröhlich[4].

Self-Organization in matter, as dissipative structures, can present itself under different aspects, namely, starting with disorganized states (stochastic thermal chaos), it may follow that at a "sufficient distance" from equilibrium (i.e. at a critica1 point depending on each case) organized patterns arise displaying:

i.) spatial order (morphogenesis),
ii.) temporal order (chemical, biological, and other types of "clocks"),
iii.) space and temporal order (chemical, and other types of waves),
iv.) transitions between homogeneous and stationary states (particular types of condensations),

and which are maintained by a flux of energy and eventually matter entering the system and being provided by externa1 sources.

The three usual illustrations often used in the literature on the subject are the cases of self-organization that refers to the fields of physics, chemistry and biology, namely, respectively, convective cells in Bènard's effect[41], chemical clocks[42], and slime mold aggregation[43]. These are only three of a quite large number of additional systems where macroscopic self-organization may occur. Let us recall that the emergence of order out of randomness and the formation of complex structures in non-equilibrium media came to the fore at the beginning of the second half of this century mainly in connection with problems in chemical kinetics and biology. But self-organization is a greatly ubiquitous and remarkably interesting subject that appears in a large class of systems, encompassing, among others,

a) hydrodynamic instabilities[41,44],
b) autocatalytic chemical and biological reactions[15,18,42].
c) cellular differentiation and morphogenesis[45–48],
d) neural networks and the brain's cognitive functions[49],
e) population dynamics and evolution[8,21,23,50]
f) planet atmosphere[51],
g) functioning of semiconductor devices[22],
h) nonequilibrium phase transitions[52], etc.

All these different systems present under appropriate conditions (namely, as already noted, when sufficiently far from equilibrium) a marked coherent behavior extending over a macroscopic scale. Clearly, these ordered states can only occur in *non-equilibriurn open systems* since the second law of thermodynamics precludes low entropy (i.e. ordered) structures. Furthermore, this macroscopic order may be visible in quite clear symmetries that arise out of thermal disorder (pictures are not presented here, but we refer the reader to those available in, for example, Refs. 8 to 21, 41 to 44, 46 to 48, and 51: these are "visual" manifestations of self-organization). It may be noticed that a rigorous definition of self-organization has not been given. In fact this is not easy, as it was already noted in connection with complexity in general (see Ref. 53). We have given an intuitive outlook, which we summarize *as:* self-organization is the establishment in a dissipative nonequilibrium open system of some kind of ordered structure (either stationary or with cyclical time variations) determined by the inner properties of the medium itself. This structure should be independent or weakly dependent on the characteristics of the source leading the system away from equilibrium, as well as on the initial state of the medium, and, in some cases, of the boundary conditions. It is thus a principle for self-organization to arise that the system loose any memory of the initial conditions, and that there be a direct link between the parameters of the structure and the properties of the dissipative medium. In brief, self-organization is a result of the development of instabilities in a disorganized (thermally chaotic) system with the stabilization of long-range coherent structures due to a balance between inner dissipative losses and inner processes, while receiving the energy and eventually mass provided by externa1 sources.

But one important point arises here. Such inner processes that are activated by the pumping of energy are to be of a nonlinear character (namely, implying in positive feedback and autocatalysis). This is a consequence of the fact that in the linear regime (sometimes referred to as the Onsager's regime) ordered structures are excluded due to the validity of Prigogine's theorem of minimum entropy production[15,16,54,55]. According to it there exists a tendency of the natural systems (in this linear regime) towards an atractor, which consists in a state of minimum entropy production and regression of fluctuations.

Thus, self-organization belongs to the realm of nonlinear physics. It is certainly a truism to say that the physics of nonlinear phenomena is receiving a great deal of attention nowadays (it is worth noticing that again Werner Heisenberg also foresought this development, see Ref. 56). Nonlinearity is difficult to define in an unambiguous way, aside, of course, by the character of the modellingequations. It has been noticed that, in particular, Schroedinger equation is linear, but has as a limit the Hamilton-Jacobi equation of Classical Mechanics which is nonlinear even for the free particle. The question is that in many cases, and here the word complexity comes in, nonlinearity is a way of description that deals with phenomena that admits large qualitative changes – sometimes of a "catastrophic character" – when modifications are imposed on the constraints applied on the system. Chaos, today a high fashion in physics after a long period of hibernation, is said to be considered a "symptom" of nonlinearity, so is also self-organization.

Nonlinear phenomena have been very important in technology, particularly in modern electrical engineering, and a typical case is the laser. Even in the case of the physics of condensed matter nonlinear phenomena are not new, suffice it to mention the theory of the plastic flow of dislocations, or the case that harmonic vibrations of the lattice cannot explain thermal expansion, which requires the introduction of nonlinear forces, *viz.* the anarmonic interactions.

Nonlinearity is very ubiquitous, and it is certainly in action in our daily life, and in all disciplines that deal with dynamical systems, e.g. in physics, chemistry, biology, engineering, ecology, economy, sociology, etc. But the renewed interest set forward by the physicists is of a basic character, in the direction to looking for the fundamental principles that are behind nonlinear phenomena. Rolf Landauer has stated [in the Conferente on Nonlinearity in Condensed Matter, Los Alamos National Laboratory, May 1968] that: "What was missing until about a decade ago, was not the sensibility to nonlinear phenomena, but only an appreciation for the remarkable diversity of behavior available in nonlinear systems: what is new is the desire to *celebrate* nonlinearity".

Notwithstanding these comments, it must be said that linear physics, which received ample attention for a long time, is certainly not exhausted. During decades, condensed matter physicists, to give an example, kept worrying about the implications of Quantum Mechanics – the major theory of our century – with a high degree of attention. Schroedinger, Heisenberg, Born, Dirac, and many others taught us how to deal with the complicated dynamical play of arrays of atoms. Nowadays, besides existing theoretical applications, there exists an live and growing interest in the nature of quantum theory of measurement and its consequences[57].

It is worth mentioning that very recently James Krumhansl has considered the question "Nonlinear Science: towards the next frontiers"[58]. In his words, nonlinear science has erupted in many directions over recent years, with many successes. Two main themes have been found in many different settings, like chaos and solitary wave phenomena [and we must add self-organization]. While these thems have been found initially in simple models useful for establishing mathematical methods and the behavior of exact limiting cases, their robust features give us assurance that they are generic. The next frontier is not so much in formalism, but in' how to achieve a realistic, eventually utilitarian, representation of actual physical, chemical or biological materials, that connects the experimentally significant behavior with its nonlinear properties. At the same time Krumhansl points to the danger that "exaggerated perhaps is that more and more nonlinear research is becoming either marginal or irrelevant, aided and abetted by the wide availability of larger computers, and the ease of formulating variations on a basic mathematical theme and doing one more case. Indeed, many of these incremental explorations yield fascinating special features. However, the important questions are: first, do they extend our general understanding; or, alternatively, do the special features really provide new, quantitative insight to some particular experimental observation ? It is not clear in many instances of published research today whether the answer to either is affirmative [...] Assuming that the objective is to have nonlinear dynamics describing reality, [it is proposed] the following check list for developing models: **(1)**Identify the phenomenon to be studied [...]; (2) Use physically realistic variables [.. .]; **(3)** Check frequently in the carrying out of the simulations whether it is better to reconsider the modeling of the science or to increase the detail (i.e. size) of simulation as the simulation goes forward."

Returning to the main point, we restate that nonlinearity in the evolution of processes is a fundamental characteristic for complex behavior to arise. This allows an improved characterization of complexity and, consequently, self-organization. In the linear regime of evolution is verified the *principie of superposition* (e.g. the lattice dynamics described by the superposition of normal modes), and no anomalous behavior is to be expected (as ensured by Prigogine's theorem of minimum entropy production). Complexity then can only be expected in conditions such that the superposition principle is not satisfied, and such is the case of nonlinear equations of evolution.

The so called Brussels' school has largely developed the thermodynamics theory of open systems, mainly for the study of auto-catalytic chemical reactions (see, e.g., Refs. 8 to 21). The thermodynamic (originally called universal) criterion for evolution and the criterion for (in)stability of systems arbitrarily away from equilibrium, contained in such theory, are capable to encompass a large variety of situations in open systems. Sev-

eral authors, mainly Prigogine and collaborators, have, on the basis of these results, advanced the idea that self-organization in open nonlinear systems may constitute a natural and compelling possibility of a mechanism for the emergence of life and for the puzzling problem of functional order in biological systems. Turing pioneered theoretical work on stationary spatial organization in a model chemical system[45], a predecessor of Prigogine's "Brusselator" (e.g. see Ref. 15) and Noyes' "Oregonator" (e.g. see Ref. 42). In these models critical points, at which the normal spatial homogeneous state becomes unstable are present. The nonlinear chemical reaction evolves beyond the critical point in such a way as to promote a stationary state in which the concentrations of the intermediate products vary sinusoidally in space. These authors suggest this phenomenon as a model for the physical-chemical basis of morphogenesis, and they draw analogies with biological examples of spatial chemical organization and prebiological evolution. Related to this point, Prigogine and co-workers stated that "if the system is able to evolve through successive instabilities, a mechanism must be developed whereby each new transition favors further evolution by increasing the nonlinearity and the distance from equilibrium."[21] Hence, formalisms and approaches to the subject may represent very useful tools for theoretical biology and sources for ideas and new concepts in the area, as shall be discussed later on. Certainly the extremely complicated heterogeneous spatial structure and functioning (temporal evolution) of the living organisms, already beginning with the elemental cell, set down quite difficult problems in Biology for the physicist and the chemist. Nevertheless, the fact that the scientific inquiring is at a very elementary and initial stage, and well away from an appropriate understanding of the processes of the organisms with life, it appears to be arising, as already commented, a starting point in the direction to shorten the gap that separates physics and biology.

In fluid dynamics nonlinearity comes primarily from convection terms involving the form $\vec{u}(\vec{r},t).\nabla$, where $\vec{u}$ is the field of drift velocity, and the instabilities appear when a certain control parameter – the Reynolds number (associated to the intensity of the externa1 source which is manifested through the value of the temperature gradient) – exceeds a critica1 value. In chemical reactions, nonlinearity is related to the concentration of reactants, and the critica1 condition depends on the chemical affinities, and in the case when inhomogenities are present, also on the diffusion coefficients. In physical devices, nonlinearity is expected in the distribution functions of the elementary components (molecules, atoms, electrons, quasi-particles, etc.), and the critical condition depends on the intensity of applied fields. As already noted, in all the cases when (and if) self-organization follows it is, a result of the fact that the pumped energy instead of being totally expended in useless thermal agitation may be partially redirected to the production of collective motion, and therefore to an increase of the degree of order because of the coherent character of the latter.

So far, we have given a overview and made several considerations over self-organized dissipative structures. Clearly, the next step is to attempt a more rigorous theoretical approach. In this direction we can enunciate two main questions that need to be addressed, namely,

1. Which is the microscopic origin of these transitions ?

2. How can we deal theoretically, and be able to provide a rigorous analysis of them ?

The description of macroscopic dissipative processes in matter has been tackled by means of different approaches. We have already noticed that phenomenological foundations are to be found in Generalized Irreversible Thermodynamics[15,16,55], and, of course, its improvements like Extended Irreversible Thermodynamics[59–63] and Rational Thermodynamics[64]. Powerful stochastic theories are also available[22]. Finally, in our view, a best approach for answering the questions above should be looked for in Nonequilibrium Statistical Mechanics, which, however, is not yet a fully developed discipline. It is our proposal that, in spite of yet unresolved basic conceptual problems, a first good approach on the microscopic level for the evidencing and description of the self-

organization can be obtained for the case of interacting many-body systems governed by Hamiltonian mechanics, resorting to mechano-statistical formalisms. One seemingly quite powerful and practical is the Nonequilibrium Statistical Operator Method (NSOM), which can be considered as implying in a far reaching generalization of Gibbs and Boltzmann ideas. Also, it seemingly appears as to be encompassed within the context of Jaynes' Predictive Statistical Mechanics[65]. The NSOM has been extensively reviewed by us[66,67], inclusive in articles in this Journal[68,69]. However, to be more precise, self-organized dissipative structures are to be encompassed within the framework of the so called Informational Statistical Thermodynamics (IST), which is a microscopic (mechano-statistical) approach to thermodynamics based on the NSOM (see Refs. 70 to 72, and also 68 and 69). Leaving aside the description of the method, which can be consulted in the cited references, we illustrate its application in two examples where the systems we consider display complex behavior and self-organization as shown in Sections III and IV.

III. Complex behavior in biopolymers

Quite interesting and illustrative examples of nonlinearity at work, producing what can be relevant biological effects, are *Fröhlich's effect*[73] and Davydov's *solitons*[74]. Frohlich's effect consists in that, under appropriate conditions, a phenomenon resembling a Bose condensation may occur in substances that possess polar vibrational modes. If energy is pumped into those modes and thence transferred to other degrees of freedom (a thermal bath), then a stationary state will be reached in which the energy content of the vibrational modes is larger than in thermal equilibrium. This excess of energy is found to be channeled into the rnodes lowest in frequency – similarly to the case of Bose condensation – provided the energy supply exceeds a critical value. Under these circumstances, a random supply of energy is thus not completely thermalized but partly used in maintaining a coherent behavior in the substance. On the other hand, A. S. Davydov showed that due to nonlinear interactions, of the same type as those responsible for Frohlich's effect, it is expected to arise a novel mechanism for the localization and transport of vibrational energy in proteins, namely the propagation of a solitary-like wave.

Davydov's theory has received plenty of attention, and a long list of results published up to the first half of 1992 are discussed in the excellent review of A. Scott[75]. As pointed out in that review, one question concerning Davydov's soliton is that of its stability in normal physiological conditions, that is, the ability of the excitation to transport energy (and so information) at long distances in the living organisms, in spite of the relaxation mechanisms that are expected to damp it out at very short (micrometer) distances.

We address these phenomena within the formalism of IST[33–37]. Consider a system where modes of polar vibration are excited by a continuous supply of metabolic energy. These polar modes are in interaction with a bath of acoustic-like vibrations through a nonlinear dynamics. The kinetic equations of evolution for the population of the vibrational modes are derived resorting to the NSOM. After a short transient time a steady state arises, where, after a certain critical threshold of the pumping intensity is achieved, there follows Frohlich condensation. In continuation, it is considered the propagation of oscillations in this polar system. The equation of evolution for their NSOM-averaged amplitude results from the Davydov's soliton type, but accompanied of thermal damping. The lifetime of the excitation in normal conditions is very short, but it can be shown that it increases enormously for the cases of propagation in Frohlich's condensate.

The systems' Hamiltonian is composed of the Hamiltonians of the free polar vibrations and the thermal bath. The former is assumed to have a frequency dispersion relation ω_q, and the latter Ω_q, with q running over the reciproca1 space Brillouin zone. The other contributions to the Hamiltonian are the one coupling the polar modes with an externa1 source, and the anharmonic interactions involving all possible three- quasi-particle (phonons associated to the two types of vibrations) collisions. Once in possession of the systems' Hamiltonian, the equation of evolution for the population of the polar modes, $\nu_q(t)$, is calculated resorting to

the nonlinear quantum generalized transport equations that the NSOM provides, but in the approximation we called second order approximation in relaxation theory (SOART for short)[76]. SOART is an instantaneous in time (memoryless) approximation, exact up to the second order in the interaction strengths. The final result takes the form

$$\frac{\partial}{\partial t}\nu_{\vec{q}}(t) = I_{\vec{q}} - \tau_{\vec{q}}^{-1}[\nu_{\vec{q}}(t) - \nu_{\vec{q}}^{0}] + \mathcal{J}_{\vec{q}}(t) \; . \qquad (1)$$

In this, $I_{\vec{q}}$ accounts for the creation of excitations as a result of the action of the externa1 pump. The second term, where ν^0 is the population in equilibrium at the temperature of the thermal bath, is a term of relaxation – at the rate τ^{-1} – to the thermal bath. The final term, $\mathcal{J}$, contains the nonlinear contribution that is to be responsible for Fröhlich's effect: The relevant terms in $\mathcal{J}$ are proportional to

$$\nu_{\vec{q}}(t)\nu_{\vec{q}'}(t)[1 - e^{\beta\hbar\Delta^{(-)}_{\vec{q},\vec{q}'}}] \quad \text{and} \quad \nu_{\vec{q}}(t)\nu_{\vec{q}'}(t)[e^{\beta\hbar\Delta^{(-)}_{\vec{q},\vec{q}'}} - 1] \qquad (2)$$

where $\beta = 1/k_B T$ and $\Delta^{(-)}_{\vec{q}\vec{q}'} = \omega_{\vec{q}} - \omega_{\vec{q}'}$.

Therefore, for $\omega_{\vec{q}} > \omega_{\vec{q}'}$ these terms lead to an increase in the population of the mode q at the expense of all the other modes higher in frequency, and consequently, those with the lowest frequencies are the most favored by the process.

In **Eq.** (1), q and q' run over the enormous number of values they take in the Brillouin zone, and so we have a complicated and quite large set of integro-differential equations coupling all those modes. We contour this difficulty resorting to a simplified model. Taking into account the above established fact that high frequency modes transfer energy to the low frequency ones, we introduce a crude model in which we consider the energy transferring modes as represented by a set of modes with a unique frequency ω_0 and contained in a region R_0 of the Brillouin zone, and another set of representative modes receiving such energy, having a unique frequency $\omega_1 (\omega_1 < \omega_0)$ and contained in a region R_1 of the Brillouin zone.

In that way we are left with only two coupled equations for these representative sets of modes. They are:

$$\begin{aligned} \frac{\mathrm{d}}{dt}\nu_0(t) &= I_0 - \tau_0^{-1}[\nu_0(t) - \nu_0^0] - g_1\eta e^{\beta\hbar\Delta}\nu_0(t) + \\ &+ g_1\eta\nu_1(t) - g_1\nu_1(t)\nu_0(t) \qquad (3a) \\ \frac{d}{dt}\nu_1(t) &= I_1 - \tau_1^{-1}[\nu_1(t) - \nu_1^0] - g_0\eta\nu_1(t) + \\ &+ g_0\eta e^{\beta\hbar\Delta}\nu_0(t) - g_0\nu_0(t)\nu_1(t) \; , \qquad (3b) \end{aligned}$$

where,

$$\begin{aligned} \Delta &= \omega_0 - \omega_1 \; , \qquad (4a) \\ \eta &= [\exp\{\beta\hbar\Delta\} - 1]^{-1} \; , \qquad (4b) \\ \nu^0_{0(1)} &= [\exp\{\beta\hbar\omega_{0(1)}\} - 1]^{-1} \; , \qquad (4c) \end{aligned}$$

and g_0 and g_1 are a measure of the intensity of the coupling between the two sets of modes, involving the strength of the interaction and the extension of the energy-momentum space available for the scattering events, determined by the conservation of energy and momentum.

Let us next consider the stationary state by setting $\dot{\nu}_0$ and $\dot{\nu}_1$, equal to zero (the upper dot stands for time derivative). Using Eq. **(3)** in this case we find that:

$$\begin{aligned} \bar{\nu}_0 &= (A_0 + C_0\bar{\nu}_1)/(B_0 + g_1\bar{\nu}_1) \qquad (5a) \\ \bar{\nu}_1 &= (A_1 + C_1\bar{\nu}_0)/(B_1 - g_0\bar{\nu}_0) \qquad (5b) \end{aligned}$$

where the bar over the populations stands for stationary-state values, and

$$\begin{aligned} A_0 &= I_0 + \tau_0^{-1}\nu_0^0; \quad A_1 = I_1 + \tau_1^{-1}\nu_1^0 \; ; \qquad (6a) \\ B_0 &= \tau_0^{-1} + g_1(1+\eta); \quad B_1 = \tau_1^{-1} + g_0\eta \; ; \qquad (6b) \\ C_0 &= g_1\eta; \qquad\qquad C_1 = g_1 + (1+\eta) \; . \qquad (6c) \end{aligned}$$

We look next for a numerical solution of the coupled pair of algebric equations (5). First, we multiply coefficients A, B, and C, *as* well *as* g_0 and g_1 by a scaling factor τ with dimensions of time to be determined later on. For illustrative purposes we take $g_0\tau \approx g_1\tau \approx 10^{-5}$; $\omega_0 \approx 10^{13}\mathrm{sec}^{-1}$; $\tau \approx 10\mathrm{ps}$; A $\approx 2 \times 10^{12}$ sec^{-1}; and identical intensities $I_0\tau = I_1\tau \equiv S$.

Inspection of Fig. 1 clearly shows the onset **of** Frohlich's effect at an intensity thereshold $S_c \cong 500$ (roughly given by the value of S where ν_1 steeply increases). The pumping modes, represented by ν_0, acquire a near constant value. Hence, it is undoubtedly

evidenced the condensation of excitations in the modes with the lowest frequency.

Moreover, it is worth mentioning that according to the NSOM, the phonon population $\nu_q(t)$ takes the form

$$\nu_q(t) = [\exp\{F_{\vec{q}}(t)\} - 1]^{-1} , \tag{7}$$

where $F_{\vec{q}}(t)$ is the NSOM Lagrange multiplier (intensive nonequilibrium thermodynamics variable in IST) conjugated to the basic variable $\nu_q(t)$. Making the choice

$$F_{\vec{q}}(t) = \beta(\hbar\omega_{\vec{q}} - \mu_{\vec{q}}) , \tag{8}$$

Eq. (7) takes ,aform reminiscent of a Bose-Einstein distribution with temperature T, but a different chemical potential $\mu_q(t)$ for each mode. Using Eqs. (7) and (8) we can write

$$\beta\mu_{\vec{q}} = \beta\hbar\omega_{\vec{q}} - \ln\left[1 + \frac{1}{\nu_{\vec{q}}}\right] . \tag{9}$$

In our model, according to the results of Fig. 1, with increasing ν_1 for the low frequency modes after the critica1 threshold has been achieved, μ_1 approaches $\hbar\omega_1$; this is clearly seen in Fig. 2. This leads then to a kind of near Bose-Einstein condensation, here not in equilibrium, but in nonequilibrium conditions.

Let us briefly consider the energetic implications of the result in the case of biosystems (which have typical values of the parameters as those already used). Considering an intensity S = 1000 (beyond the critical point), using $\tau_0 \cong \tau_1$ ≅ 10 picoseconds, and, we recall, ω_0 ≅ 10^{13} sec^{-1}; this requires a pumping power of roughly 6.4×10^{-9} watts per mode. Assuming that this power is provided by the hydrolysis of ATP, which produces 7.3 kcal/mol, in the event of an almost total absorption of this energy in the process, to sustain a stationary Frohlich condensate would require 2×10^{-13} moles of ATP per mole per second. Consider a near one-dimensional system (e.g. an a-helix protein): the Brillouin zone length is 10^7 cm^{-1}, and if we consider a sample, say, 10 cm long, the number of modes is $\sim 3 \times 10^7$. For a propagation of a signal in this condensate, a question to be considered below, taking, say, 10^{-5} sec for riding the distance of 10 cm (implying in a group velocity of roughly 10^6 cm/sec), for the process to be completed in the Frohlich condensate it would require $\sim 10^{-10}$ moles of ATP, a seemingly accessible value.

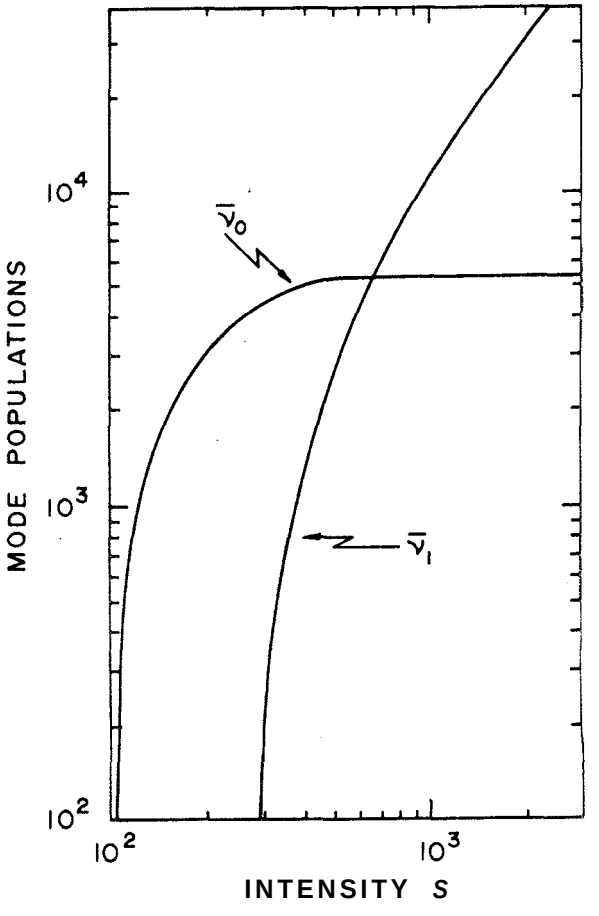

Figure 1: Population of the representative modes of high frequency, $\bar{\nu}_0$, and that of low frequency, $\bar{\nu}_1$, as a function of the source intensity (after Ref. 36).

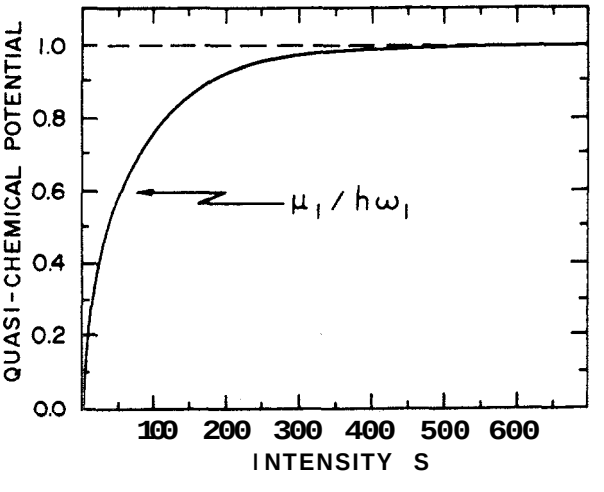

Figure 2: The quasi-chemical potential dependence on the source intensity for the representative modes of low frequency.

Another important consideration is the one related to the transient time that must elapse between the switch on of the pumping source and the emergence of the stationary-state Fröhlich condensate. Solution, in the given model, of the equations of evolution [Eq.(3)] allows us to estimate this time as being in the picosecond range, that is, Fröhlich's effect follows very rapidly after the vibrational modes begin to receive the energy from the external source.

Having dealt with the stationary-state of the model, let us consider next the dynamical aspects associated to the propagation of signals in these systems. For that propose, let us add in the description of the system in terms of the NSOM, the variables for the amplitude of vibrations, namely, $< a_q/t >$, that is, the average over the nonequilibrium ensemble of the dynamical quantity a_q. Resorting once again the NSOM-SOART, after some algebra we arrive to the equation of evolution for the amplitude, namely

$$\begin{aligned}\frac{\partial}{\partial t}\langle a_{\vec{q}}/t\rangle &= -i\omega_{\vec{q}}\langle a_{\vec{q}}/t\rangle - \Gamma_{\vec{q}}[\langle a_{\vec{q}}/t\rangle - \langle a_{\vec{q}}/t\rangle^*] + \\ &+ \sum_{\vec{q}_1\vec{q}_2}[R_{\vec{q}_1\vec{q}_2}\langle a_{\vec{q}_1}/t\rangle\langle a_{\vec{q}_2}/t\rangle\langle a_{\vec{q}_1+\vec{q}_2-\vec{q}}/t\rangle^* + \text{c.c}] \qquad (10)\end{aligned}$$

and, for the sake of simplicity, we omit to write down the expressions for the quantities Γ and R.

Consider now a one-dimensional chain in a continuum approach. Introducing the average field quantities

$$\psi(x,\text{t}) = \sum\langle a_{\vec{q}}/t\rangle e^{iqx} \qquad (11)$$

and taking for the frequency dispersion relation the approximated form

$$\omega_q = \omega_0 - \alpha q^2 \ , \qquad (12)$$

where ω_0 and α are constants, and after neglecting the terms that couple with the conjugated equations, we obtain that

$$\begin{aligned}i\hbar\frac{\partial}{\partial t}\psi(x,t) &= \left(\hbar\omega_0 + \hbar\alpha\frac{\partial^2}{\partial x^2}\right)\psi(x,t) - i\hbar\int dx'\mathcal{G}(x-x')\psi(x',t) + \\ &+ \int dx'\int dx"\mathcal{R}(x',x")\psi(x',t)\psi(x",t)\psi^*(x,t)\ . \qquad (13)\end{aligned}$$

In this equation, G and R are appropriate transforms of Γ and R in Eq.(10). Eq.(13) has the form of a Schroedinger equation with damping[77].

Introducing a local in space approximation, that is, neglecting space correlations, by writing

$$\mathcal{R}(x',x") = K\delta(x-x')\delta(x-x") \qquad (14a)$$

$$\mathcal{G}(x-\text{x'}) = \gamma\delta(x-x')\ , \qquad (14b)$$

Eq. 13 becomes

$$i\hbar\frac{\partial}{\partial t}\psi(x,t) = \left(\hbar\omega_0 + \hbar\alpha\frac{\partial^2}{\partial x^2}\right)\psi(x,t) - i\hbar\gamma\psi(x,t) + K|\psi(x,t)|^2\psi(x,t), \qquad (15)$$

which is of the form of the equation derived by Davydov in an alternative way, but, in the present case, clearly showing the damping effects associated with the term with coefficient γ. In conditions of equilibrium with a

thermal bath at the physiological temperature of 300 K, the damping constants can be evaluated in the case of the simplified model in terms of the two representative sets of modes previously described. In that case, we have that

$$\Gamma_0\tau \cong 0.054 + 30.6 g_1\tau + g_1\tau\nu_1^0 \cong 0.054, \quad (16a)$$

$$\Gamma_1\tau \cong 0.063 + 28.6 g_0\tau - g_0\tau\nu_0^0 \cong 0.063, \quad (16b)$$

for $g_0\tau = g_1\tau \cong 10^{-5}$. Since Γ_0 and Γ_1 can be obtained from the line widths of scattering bands[78], we can estimate the scaling time r. Since the lifetimes are of the order of a few tens of picoseconds, a pulse signal impinged on the system would be carried a few micrometers, since the group velocity is expected to be in the order of 10^5 to 10^6 cm/sec.

However the situation is "dramatically" modified if the excitation propagates in a nonequilibriurn background, namely the one provided by the stationary Frohlich condensate previously described. This is a result of the fact that the damping constants depend on the actual state of the system, being affected by the nonlinear anharmonic interactions, that are responsible, we stress, on one hand for Frohlich's effect, and on the other for Davydov's mechanism for soliton-like excitation propagation. Without going into details, in the case of the model we have been considering we can obtain the two characteristic damping constants, Γ_0 and Γ_1, in terms of the intensity of the pumping source, what is shown in Fig. 3.

Inspection of Fig. 3 clearly shows that while the lifetime of the high frequency modes decreases (that is, its inverse Γ_0 increases in the figure), after the critical point for the onset of the Frohlich's effect the lifetime of the low frequency modes in the Frohlich-Bose condensate increases enormously (that is, its inverse Γ_1 decreases to near zero). Consequently, we can expect a extremely rapid damping of the amplitudes $< a_q/t >$ for values of q in the region R_0 of the Brillouin zone, while those amplitudes for values of q in region R_1 (the modes low in frequency) are practically undamped. Consequently, those amplitudes with small lifetime decay rapidly, while those corresponding to modes in the Frohlich condensate (with Γ practically null) survive for long times. Hence, in the expression for the average field amplitude of Eq. (11), after a very short transient time (expected to be in the subpicosecond range), the summation in Eq. (11) can be restricted to the modes q in R_1 in reciproca1 space. Then in Eq. (15) the damping term disappears ($\gamma = 0$) and we obtain an equation formally identical to that for the undamped Davydov's soliton[74,75].

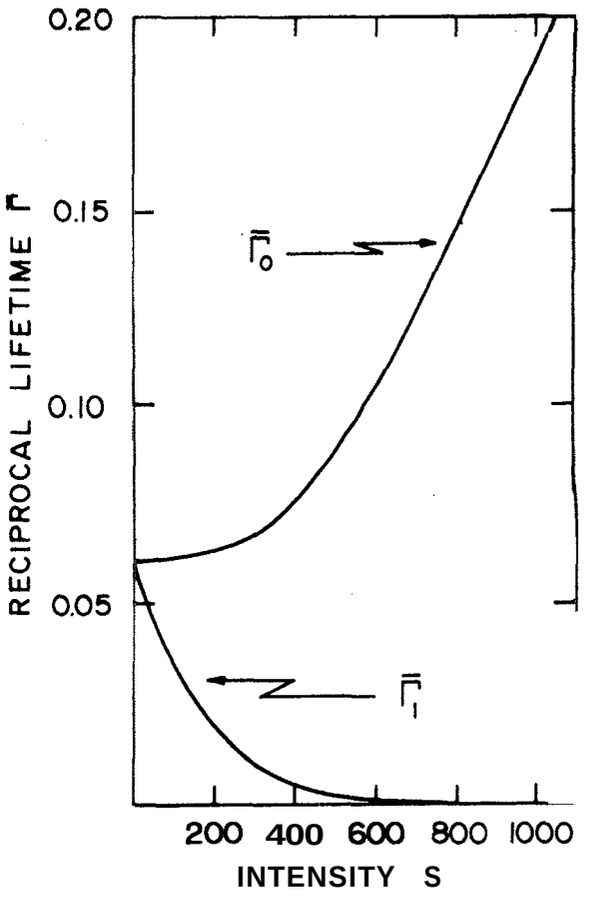

Figure 3: Reciproca1 lifetime, $\bar{\Gamma} = \Gamma\tau$ of the representative high frequency modes, $\bar{\Gamma}_0$, and that of the low frequency ones, $\bar{\Gamma}_1$ as a function of the source intensity (After Ref. 36).

Summarizing, we have considered a model for certain biological systems (e.g. the a-helix protein) of the type proposed by Frohlich and Davydov. Polar vibrational modes that are pumped by a source of energy, are in nonlinear anharmonic interaction with a thermal bath which remains at constant temperature and which is modelled as a system of acoustic-type vibrations. The vibrational polar modes are then an open system in (arbitrar~)nonequilibrium conditions. For the study of

its thermodynamic state we resorted to the seemingly powerful, concise and elegant NSOM, which, as noted, provides the foundations for Informational Statistical Thermodynamics, to which belongs such kind of problems.

We stress that two main results were described: on one hand, we have been able to demonstrate that such systems display a complex behavior, namely, that at a certain distance from equilibrium, namely, after a threshold value of the pumping source intensity has been achieved, there follows a steep increase in the population of the modes with low frequencies, in a way reminiscent of a Bose-Einstein condensation. This was predicted by Frohlich, and then we have called it Fröhlich's effect. There is a kind of self-organization in the system, governed by nonlinear effects in the equations of evolution, and thus, this phenomenon may be considered as the ernergence of a dissipative structure in Prigogine's sense. We also addressed the question of long-range propagations in the system we considered; this is an important open problem in bioenergetics. As noted, A. S. Davydov proposed that this is possibly accomplished through propagation of solitary waves in this nonlinear media. However, it was pointed out, and our calculations at the thermodynamic level showed, that in realistic physiological conditions it should occur a strong damping of the wave. But our calculations allowed us to show that this damping is dependent on the microscopic state of the system, and influenced by the nonlinearities responsible for both, Frohlich's effect and Davydov's soliton. As a consequence, after Frohlich condensation sets in, the lifetimes in the vibrations low in frequency (i.e. those modes in the Frohlich-Bose condensate), increase enormously. Therefore, a coherent excitation composed in terms of the low-lying in frequency excited states form a Davydov's **soliton-like** wave which travels umdamped in Frohlich *condensate.*

After the presentation of this example of complex behavior in sufficiently far-from-equilibrium nonlinear system, of eventually interesting biophysical applications, we briefly describe a possible case of a morphological transition, also of eventual biological interest.

IV. From self-organization to turbulent chaos

Spatial pattern formation is a subject of increasing interest in fields like chemical-physics, hydrodynamics and biology, e.g. the area of embryology. Recent extensive review articles are due to Meinhardt[47] and Cross and Hohenberg[48]. In these cases one is dealing with open systems in far-from-equilibrium conditions, and, as already discussed, susceptible to develop spontaneous symmetry-breaking and self-organization in dissipative structures. We are interested in this section in the case of morphological transitions of such type. In a pioneering paper, Turing[45] showed that the development of structure in biology (morphogenesis) may find a physical basis in the instability of certain reacting systems with respect to symmetry-breaking perturbations. These need to be open systems under the action externa1 sources pumping energy on them, for example, the case of photoexcitation through illumination with electromagnetic radiation of different wave lengths. Microwaves, in particular, are strongly absorbed in water, which represents a most important component of biological systems. Coupling of photo processes with electronic excitations may allow for the possible ernergence of dissipative spatial structures maintained by ambient illumination, and thus to have an important role in biomorphogenesis.

We address a question of this kind[38–40]. Let us consider a large array of atoms forming a long chain of macromolecules in, say, a biopolymer. The electronic states consists of localized bonding states in a fully or partially (p-type material) occupied narrow band, which we describe approximately by a parabolic band of free carriers with a very large effective mass. The higher-energy anti-bonding states consist in a non-occupied large band, also described by a parabolic band of itinerant electrons with small effective mass. The system is under illumination by radiation with a large spectrum of frequencies. As a result, in photon absorption processes, electrons are transferred from the bonding to the anti- bonding band states, thus creating electron-hole pairs. The photoinjected excess energy received by these carriers is dissipated in recombination processes and relaxation to the vibrational modes of the system.

Under continuous illumination, after a transient time has elapsed, a steady-state sets in, in which it is present a concentration n of photoinjected pairs. The system is taken to be in thermal contact with a reservoir at temperature T which is assumed to be kept constant by means of effective homeostatic processes, and we further assume that the carrier system is in near thermal equilibrium with it. Hence, in this way, the carrier system is brought to a stationary and homogenous state (for an example in semiconductor physics see Ref. 79). This is the so called thermodynamic branch of solutions, which, according to Prigogine's minimum entropy production theorem, is a stable one in the linear regime around equilibrium. We consider next the situation when the carrier system is driven far from equilibrium, and we perform linear stability analysis (see for example Ref. 15) encompassing inhomogenous situations. This is done considering the case of a space dependent fluctuation in the carrier density. We resort to the case of the NSOM in SOART to derive the corresponding equations of evolution. For the description of the macroscopic state of the system, and for the particular problem in hands, we choose as a basic set of macrovariables the carrier concentration and carrier energy (the first is fixed by the intensity of the source of radiation and the second by the concentration and the temperature T), and to introduce spatial inhomogenity to the problem, we include the non-diagonal elements of the single-particle distribution matrix, namely

$$n^{e}_{\vec{k}\vec{Q}}(t) = Tr\{c^{+}_{\vec{k}+\vec{Q}}c_{\vec{k}}\rho(t)\}, \tag{17a}$$

$$n^{h}_{\vec{k}\vec{Q}}(t) = Tr\{h_{-\vec{k}-\vec{Q}}h^{+}_{-\vec{k}}\rho(t)\}, \tag{17b}$$

where $c^{+}(c)$ and h^{+}(h) are creation (annihilation) operators of electrons (e) and of holes (h) respectively, and p is the auxiliary NSO corresponding to this case. The Q wavevector Fourier amplitude of the charge density, in units of the electronic charge, is given by

$$n(\vec{Q},t) = \sum_{\vec{k}}[n^{e}_{\vec{k}\vec{Q}}(t) + n^{h}_{\vec{k}\vec{Q}}(t)]. \tag{18}$$

The Hamiltonian of the system is composed of the energy operator for the carriers which will be treated in Landau's quasi-particle approach with Coulomb interaction dealt with in the random phase approximation, and the contributions due to the interactions of the carriers with the externa1 radiation and recombination fields of photons. The interaction of the carriers with the phonons is neglected, since it is only relevant to the exchanges of energy that have already led the electron system quasi-temperature to near coincide with that of the reservoir and, thus, the vibrationals degrees of freedom do not play any relevant role part in the analysis that interest us here.

We consider next the equations of evolution for the basic macrovariables, which are derived in SOART approximation in the NSOM. As noticed, the quasi-temperature of the carriers is fixed by that in the reservoir, and their concentration is determined by the stationary condition and reflects the balance between the number of carriers produced by illumination and the number that disappears in luminescent recombination. The equations of evolution for the variables of Eq. (17) are

$$i\hbar\frac{\partial}{\partial t}n^{e}_{\vec{k}\vec{Q}}(t) = -\Delta E^{e}_{\vec{k}\vec{Q}}n^{e}_{\vec{k}\vec{Q}}(t) - 2V(Q)\Delta f^{e}_{\vec{k}\vec{Q}}(t)n(\vec{Q},t) + iB^{e}_{\vec{k}\vec{Q}}(t)n^{h}_{\vec{k}\vec{Q}}(t) + iB^{h}_{\vec{k}\vec{Q}}(t)n^{e}_{\vec{k}\vec{Q}}(t) + \mathcal{N}^{e}_{\vec{k}\vec{Q}}(t), \tag{19a}$$

$$i\hbar\frac{\partial}{\partial t}n^{h}_{\vec{k}\vec{Q}}(t) = \Delta E^{h}_{\vec{k}\vec{Q}}(t) + 2V(Q)\Delta f^{h}_{\vec{k}\vec{Q}}(t)n(\vec{Q},t) + iB^{h}_{\vec{k}\vec{Q}}(t)n^{e}_{\vec{k}\vec{Q}}(t) - iB^{e}_{\vec{k}\vec{Q}}(t)n^{h}_{\vec{k}\vec{Q}}(t) + \mathcal{N}^{h}_{\vec{k}\vec{Q}}(t), \tag{19b}$$

$$\Delta E^{e(h)}_{\vec{k}\vec{Q}} = \epsilon^{e(h)}_{\vec{k}+\vec{Q}} - \epsilon^{e(h)}_{\vec{k}}, \tag{20a}$$

$$\Delta f^{e(h)}_{\vec{k}\vec{Q}} = f^{e(h)}_{\vec{k}+\vec{Q}}(t) - f^{e(h)}_{\vec{k}}(t), \tag{20b}$$

$$V(Q) = 4\pi e^2/\mathcal{V}\epsilon_0 Q^2, \qquad (20c)$$

with $\epsilon^{e(h)}$ being the electron (hole) band energy (to be taken in the effective mass approximation), $V(Q)$ is the Fourier Q-component of Coulomb interaction, ϵ_0 is the static dielectric constant, and V is the volume of the system. Furthermore, $f_k^{e(h)}$ are the carrier populations in band states, $\mathcal{N}^{(h)}$ are nonlinear (bilinear in fact) terms in the variables of Eq. (17) that are coupled through the Coulomb interaction and the interaction with the radiation fields (we omit to write down their cumbersome expressions, since they are not going to have relevance in what follows). Nonlinearities in the basic variables are also present in the distributions $f_k^{e(h)}$ and, through these, in the coefficients B which are given by

$$B_{\vec{k}\vec{Q}}^{e(h)} = A_L\mathcal{G}(\omega_L) + A_R(\epsilon_{\vec{k}}^x + E_G)f_{\vec{k}}^{e(h)} + \text{ same term with } \vec{k} \leftrightarrow \vec{k}+\vec{Q}, \qquad (21)$$

where

$$A_L = (2\pi^2\hbar e^2 E_G/\epsilon_\infty(\epsilon_{\vec{k}}^x + E_G)^2 m_x c)I_0, \qquad (22a)$$

$$A_R = e^2 E_G/\epsilon_\infty \hbar c^3 m_x\ . \qquad (22b)$$

We have introduced a source of radiation (lamp) characterized by a frequency spectrum

$$I(\omega) = I_0\mathcal{G}(\omega)\ , \qquad (23)$$

where I_0 is an intensity amplitude and $\mathcal{G}(\omega)$ a normalized spectral distribution function. Moreover, in Eq. (21), $\hbar\omega_L = E_G + \epsilon_{\vec{k}}^x$ as a result of energy conservation in the absorption process, and $\epsilon_{\vec{k}}^x = \hbar^2k^2/2m_x$, with $m_x^{-1} = m_e^{-1} + m_h^{-1}$ being the excitonic mass, ϵ_∞ is the high frequency dielectric constant.

A steady-state solution (the so called fix point or singular point) of Eq. (19) corresponds to $n_{kQ}^{e(h)} = 0$, i.e. the homogenous state, which, as noted, is stable in the linear regime around equilibrium (limit of weak illumination). To look for its possible instability in far-from-equilibrium conditions, we analyzed the eigenvalue spectrum of the set of linearized equations (19), that is, taking in them $\mathcal{N} = 0$ and for distributions f their values in the homogenous state (i.e. we perform linear stability analysis; see for example Ref. 15). In particular we consider the case of null eigenvalue corresponding to the onset of an instability against a static inhomogenity.

For this case of null eigenvalue, the linearized Eq. (19) has the solution

$$n_{\vec{k}\vec{Q}}^{n(h)} = 2V(Q)N_{\vec{k}\vec{Q}}^{n(h)}D_{\vec{k}\vec{Q}}^{-1}n(\vec{Q}), \qquad (24)$$

where

$$N_{\vec{k}\vec{Q}}^{e(h)} = -\Delta f_{\vec{k}\vec{Q}}^{e(h)}\Delta E_{\vec{k}\vec{Q}}^{e(h)} + i[\Delta f_{\vec{k}\vec{Q}}^{h} - \Delta f_{\vec{k}\vec{Q}}^{e}]B_{\vec{k}\vec{Q}}^{e(h)}, \qquad (25a)$$

$$D_{\vec{k}\vec{Q}} = -\left(\Delta E_{\vec{k}\vec{Q}}^{e(h)} - iB_{\vec{k}\vec{Q}}^{h}\right)\left(\Delta E_{\vec{k}\vec{Q}}^{h} + iB_{\vec{k}\vec{Q}}^{e}\right) + B_{\vec{k}\vec{Q}}^{e}B_{\vec{k}\vec{Q}}^{h}. \qquad (25b)$$

Adding up both expressions in Eq. (24) – namely the e– and h– contributions – we find that

$$n(\vec{Q})\left[1 - 2V(Q)\sum_{\vec{k}}(N_{\vec{k}\vec{Q}}^{e} + N_{\vec{k}\vec{Q}}^{h})D_{\vec{k}\vec{Q}}^{-1}\right] = 0\ , \qquad (26)$$

which besides $n(Q) = 0$, the thermodynamic branch of solutions (homogenous state), admits a nonvanishing value for $n(Q)$ (inhomogenous solution) if the expression within the square brackets is null. It is worth noticing that the expression contained between the square brackets is the wavevector-dependent static dielectric function of the nonequilibrium carrier system and, accordingly, we indicate it by $\epsilon(Q)$. Since it is a complex quantity, to set it equal to zero requires that both the real and the imaginary part be null. The imaginary part vanishes identically, as it should because it is the zero frequency value of the imaginary part of the dynamic dielectric function which is for all systems an odd function of the frequency[80]. We look then for the zero in the real part taking the limit of small Q, meaning $Q^2 \ll \bar{k}^2$, where the last term is the average of the carriers squared quasi-momentum. Furthermore, at room temperature and not too high densities of photoinjected carriers, the distribution function of the latter can be approximated by Maxwell-Boltzmann distributions depending on temperature T and concentrations n_e and n_h of electrons and holes respectively.

Let us now consider the quantities B of Eq. (21): they are composed of two parts, one resulting from illumination [the first on the r.h.s. of Eq. (21)] which we call B_L, and the other associated to recombination effects, which we call B_R. Let us consider two limiting cases that lead to simple and immediate results. First, take the case when B_L gives a much smaller contribution than B_R, for example illumination with a lamp with a very short spectral distribution (a laser would be the extreme case of monochromatic radiation). Then

$$R_e\epsilon(Q) \cong 1 + (1/\Lambda_{DH}Q)^2 \tag{27}$$

where Λ_{DH} is Debye-Huckel screening length

$$\Lambda_{DH}^{-2} = 4\pi(n_e + n_h)e^2/\epsilon_0 k_B T\ , \tag{28}$$

and clearly no zero of Eq. (27) is possible and the homogenous state is always stable.

On the other hand, if B_L predominates over B_R, as expected for the case of intense illumination with a large spectrum of frequencies and for small values of E_G and f_k [cf. Eq. (22)], we find that

$$Real\epsilon(\vec{Q}) = 1 + \frac{8\pi e^2}{\epsilon_0 Q^2}\beta\frac{m_h n_e - m_e n_h}{m_h - m_e} \tag{29}$$

with $\beta = 1/k_B T$. If $n_e = n_h =$ n, i.e. an intrinsic-type material with the presence of only photoinjected electron-hole pairs, we recover the result of Eq. (27). But, since $m_h > m_e$, a zero of Eq.(29) can be obtained if $n_h > n_e$, i.e. in the case of an extrinsic-type p-doped material. Hence, in this case, for given Q and $m_e n_h > m_h n_e$, a zero of equation (29) follows for

$$Q^2 = [8\pi e^2/\epsilon_0(m_h - m_e)k_B T](m_e n_h - m_h n_e)\ . \tag{30}$$

If we write $n_h = n_0 +$ n and $n_e =$ n, where n_0 is the extrinsic concentration of holes, the critica1 concentration, n*, of photoinjected carriers at which it follows the instability of the homogenous state against the formation of an inhomogenous state is given by

$$n^* = \frac{1 - A_0 Q^2}{r - 1} n_0\ , \tag{31}$$

where $A_0 = (r - 1)\Lambda_0^2$, $\Lambda_0^2 = \epsilon_0 k_B T/8\pi e^2 n_0$, and $r = m_h/m_e$.

It must be stressed that our treatment implies that n_0 is high enough so as to produce a fluid of itinerant holes in the bonding band, meaning that it is required a concentration of carriers enough to produce screening effects capable to allow for the presence of mobile holes. This seems to be the case in proteins[81], where the concentration n_0 is of the order of 10^{18} cm^{-3}.

Summarizing, for given n_0 (the density of holes in the p-type material) there exists a critica1 intensity I_0^* of the pumping source (which fixes the critica1 concentration n*, of Eq. (31), of photoinjected carriers) which determines a branching point of solutions (bifurcation point) of the equations for the density of carriers with the emergence of a steady state with spatial ordering. This result suggests then the possibility of a morphological transition from the homogenous spatial distribution of carriers to a patterned structure, consisting of a superposition of steady-state charge density waves of electrons and holes, clamped together through the effect of Coulomb interaction. Such superposition is the one consisting of all the Fourier amplitudes $n(Q)$ for the values of Q that for any $I_0 > I_0^*$ (I_0 being the critica1 intensity for the primary bifurcation to appear) are allowed by Eq. (30) and (31). Interna1 symmetries and boundary conditions impose limitations fixing permitted values for Q. First, if L is the length of the polymer chain then we should have $Q = l(2\pi/L)$, where $l = 1, 2, \ldots$, and second there is a limiting value of l, say l_M, such that $Q(l_M) = l_M(2\pi/L) \leq Q_B$, where Q_B is the half-extension of the Brillouin zone, therefore

$$(2\pi/L) \leq Q \leq l_M(2\pi/L), \tag{32a}$$

with $l_M =$ integer part of $[Q_B L/2\pi]$. However, there is an alternative cut-off condition arising out of the fact that, of course, the expression on the right of Eq. (31) must be positive, and so,

$$l_M = \text{integer part of } [L/2\pi\Lambda_0\sqrt{(r-1)}], \tag{32b}$$

and l_M is the smaller of both limiting values.

In continuation, once the instability of the homogenous state has been ascertained, let us analyze the

emerging dissipative structure. For that purpose we consider now a description of the system in IST-NSOM including as a basic variable the carrier density $n(Q)$, and in Eq. (19) we desconsider the coupling between the different Fourier amplitudes, i.e. we neglect N, and the limit of weak density amplitude is taken, meaning that $n(Q) \ll$ n for all Q. We consider the contributions, in lowest order, of the emerging density amplitudes to the distribution functions, which take the form

$$f_{\vec{k}}^{e(h)} \cong \bar{f}_{\vec{k}}^{e(h)} \left[1 + \frac{1}{2}|F(\vec{Q})|^2\right] , \qquad (33)$$

where $F(\vec{Q})$ is the NSOM Lagrange multiplier associated to the basic variable $n(Q)$, i.e.

$$F(\vec{Q}) = \delta\bar{S}/\delta n(\vec{Q}) . \qquad (34)$$

Here $\bar{S}$ is the IST-NSOM entropy in this case, and $\bar{f}$ is the distribution in the homogenous state. After some algebra (we omit here details of the calculations to be reported elsewhere[39,40]) we find that

$$|F(\vec{Q})|^2 = \frac{\epsilon^0(\vec{Q}; n^* + \Delta n)}{\mathcal{A}(\vec{Q}; n^* + \Delta n)} \cong \Lambda_0^{-2} n_0 \mathcal{A}(\vec{Q}; n^*) , \qquad (35)$$

where ϵ^0 is the dielectric function calculated in the homogenous state and n* + An is the concentration of photoinjected carriers with n* being the corresponding to the first bifurcation and An a smail increase beyond this value (i.e. it corresponds to an intensity I_0 slightly larger than I_0^*), and

$$\mathcal{A}(\vec{Q}; n^* + \Delta n) = \frac{8\pi e^2}{\epsilon_0 \mathcal{V}} \frac{m_e m_h}{m_h - m_e} \beta \sum (f_{\vec{k}}^h - f_{\vec{k}}^e)^2 . \qquad (36)$$

Since the concentration of the photoinjected carriers and the intensity of the radiating source are related by the balance condition in the stationary state, we can find that[39,40] in the immediate neighborhood of the primary bifurcation

$$|n(\vec{Q})|^2 \approx (\theta - 1)^\gamma , \qquad (37)$$

where

$$\theta = I_0/I_0^* \qquad (38a)$$

$$\gamma = 1/2 \qquad (38b)$$

Eq.(37) resembles the behavior of the order parameter in the case of phase transition theory in a Landau approach, with the critical exponent being one half. On the other hand, the IST-entropy can be calculated to obtain

$$\bar{S} - \bar{S}_0 \approx -|n(\vec{Q})|^2 , \qquad (39)$$

clearly showing that the informational entropy in the ordered state is smaller than the entropy $\bar{S}_0$ in the "disordered" homogenous state. Finally, an order parameter can be defined, namely

$$\Delta = 1 - \frac{\bar{S}}{\bar{S}_0} \approx |n(\vec{Q})|^2 \approx (\theta - 1)^\gamma . \qquad (40)$$

So far, we have considered the immediate neighborhood of the primary bifurcation. Let us go beyond that point. First. it should be noticed that the primary bifurcation, once given n_0, follows for a critical intensity I_0^* and gives rise to a single Fourier contribution with $Q^* = l_M(2\pi/L)$, and corresponds to a critical concentration of photoinjected carriers given by

$$n^*(l = l_M) n_0 \left[\frac{1}{r-1} - \left(\frac{2\pi\Lambda_0}{L}\right)^2 l_M^2\right] . \qquad (41)$$

Consider L $\sim$ 10 cm, r $\sim$ 10, $Q_B \sim 3.8 \times 10^6$ cm^{-1}, and $\Lambda_0 \sim 3.8 \times 10^{-7}$ cm ($n_0 \sim 10^{18}$ cm^{-3} and T $\sim 300K$), then $l_M \sim 1.37 \times 10^6$ and $n^*(l_M) \sim 8 \times 10^{11}$ cm^{-3}. With increasing intensities additional bifurcation points arise implying in the ernergence of additional Fourier contributions to the carrier charge density, ending up in the final possible value $l = 1$ [cf. Eq (31)]. Using the same parameters as above, we find that n*$(l = 1) \sim 4.4 \times 10^{17}$ cm^{-3}.

Consequently, with increasing intensity of the pumping source more and more waves of increasing wavelengths $(L/2\pi l)$ contribute to the formation of the charge density wave. Therefore, at a sufficiently intense value of the excitation it has arised an overextended level of organization such that it resembles a chaotic behavior, usually referred to as *durbulend* chaos. We have then, in this case of population inversion of electrons, the ernergence of a situation that appears to be akin to

Landau's proposal for turbulence in fluids[82]. Hence, it follows a particular route to chaos (resulting as a consequence of the discrete increase of wave lengths from $L/2\pi l_M$ to $L/2\pi$), to be labelled Landau-Prigogine's route to chaos, implying in going from thermal stochastic chaos (the thermodynamic branch corresponding to the homogenous state), to order (emergence of the ordered dissipative structure: the morphological transition), to further order, to an excess of order resembling deterministic chaos (large number of modes contributing to the carrier charge density wave). We can draw a linear stability diagram. For this we introduce the quantity

$$\gamma(l) = n^*(l)/n_0 = \mathrm{a} - bl^2 , \qquad (42)$$

where [cf. Eq.(31)]

$$a = (r-1)^{-1}; \quad b = (2\pi\Lambda_0/L)^2 , \qquad (43)$$

which is depicted in Fig. 4. For the permitted region of values of Q it is indicated the regions of instability of the different Fourier components in the carrier charge density wave.

Moreover, it can be noticed that defining the series of numbers

$$\mathcal{L}(l) = \frac{\gamma(l) - \gamma(l+1)}{\gamma(l+1) - \gamma(l+2)} = \frac{2l+1}{2l+3} \qquad (44)$$

we obtain a number independent of the characteristic parameters of the system, indicating a certain kind of universality. This quantity $\mathcal{L}(l)$ varies between the values 3/5 for $l = 1$ to near 1 for $l = l_M$, in a sequence shown in the stair-like diagram in Fig. 5.

In conclusion of this section we may say that, order and functioning in biosystems is a problem with a long history of interest attached to it and being a puzzling question in physical-chemistry. We have considered in this section one particular aspect of it, in the case of a quite simplified model of an open biophysical system. We have shown that in the case of a pdoped sample, as it seems to be the case of certain proteins, a bifurcation point follows at a certain threshold of intensity of the source of radiation, when the homogenous steady-state becomes unstable against the formation of a stationary charge density wave. This biological pattern formation may follows as a result of nonlinear kinetic effects that describe production and decay rates involving autocatalytic effects. We are in the presence of an example of the emerging theory of complexity, referred to in the first section, when nonlinear terms involving strong positive feedback processes lead to unexpected and, in a sense, counter-intuitive phenomena.

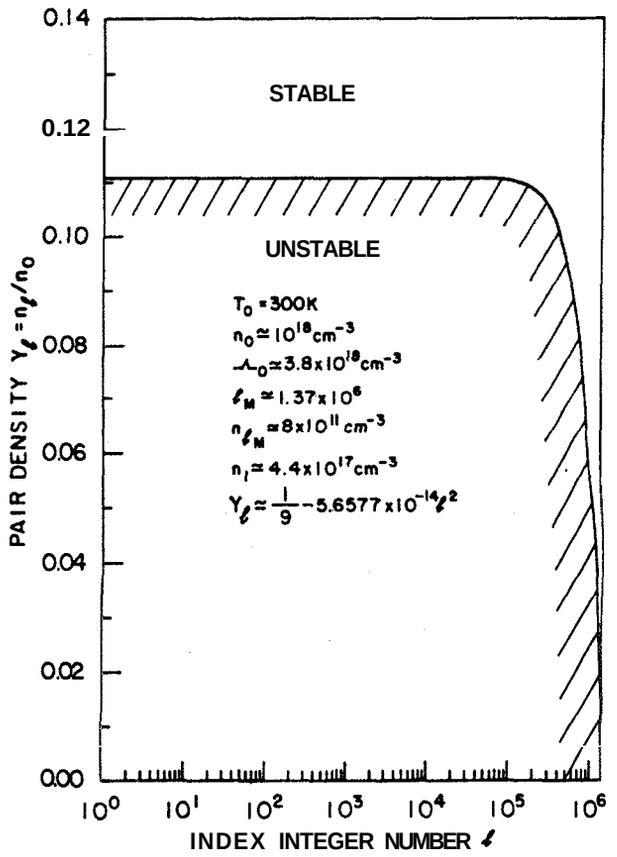

Figure 4: The marginal stability curve (after Ref. 39).

We have emphasized here the possible influence of electrons in certain type of biological systems. In this context, our results seem to be related to A. Szent- Gyorgyi's view that hole mobility in the extended ground states of protein molecules may lead to the building of higher structures and to control all differentiation, namely that electronic properties may be responsible for the activity and the subtletly of many biological functions[83]. We have seen that p-type doping was essential to the emergence of the dissipative structure. So, in this respect, it is worth to cite Szent-Gyorgyi[83]: "What nature does is to induce mobility

into the electrons of the protein by incorporating an electron-acceptor into the molecule. A closely analogous process is widely used in semiconductor industry in the construction of radio, television or computers. It is so called doping. It is the most basic process of that industry. Nature discovered it billions of years before man did."

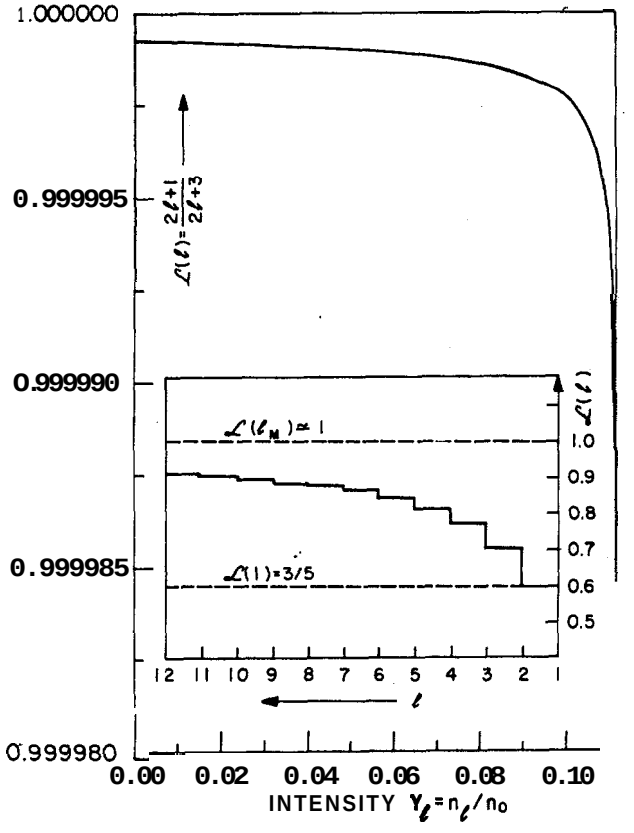

Figure 5: The caracteristic numbers defined in Eq. (44) as a function of the pair density. The lower inset illustrates the stair-like behavior of this series of characteristic numbers (after Ref. **39**).

As a final word, we stress that we have explicitly used photoexcitation of electrons from the bonding to the anti-bonding energy levels, but the final result is depending only on the existence of the resulting population inversion, and, therefore, the phenomenon may also be expected for any other type of excitation process capable of producing such population inversion.

V. Coneluding remarks

We have mainly devoted the preceding sections of this paper to considerations on the aspects of the' physics of dissipative phenomena. Attention was called to its connection with the emerging theory of complexity, and attached nonlinearity of the kinetic laws governing the behavior of natural systems. This nonlinearity plays a relevant role in the behavior of open systems in sufficiently far-from-equilibrium conditions, which may lead to the formation of self-organizing macroscopically ordered dissipative structures (after Prigogine's terminology). The thermodynamics of irreversible processes far from equilibrium have led to the discovery that the fluxes passing through certain physical-chemical systems and shifting them away from equilibrium can give rise to phenomena of spontaneous self-organization, symmetry breaking and a growing tendency towards complexity and diversity, with all the underlying possibilities that such behavior may provide in, besides physical-chemical, all dynamical systems, like biological and social as well[53]. Dissipation, contrary to what was early thought, is not a source of decay but, it must be emphasized, has a constructive role, maybe including the emergence of life, natural evolution, and the astounding functioning of living systems[8–21].

For that reason, it was stated that "...our vision of Nature is undergoing a radical change toward the multiple, the temporal and the complex. Curiously, the expected complexity that has been discovered in Nature has not led to a slowdown in the progress of science, but on the contrary, to the emergence of new conceptual structures that now appear as essential to our understanding of the physical world – the world that include us [...] Indeed, today we are beginning to go beyond [..] the world of quantity into the world of qualities and thus of becoming [...] we believe it is precisely this transition to a new description that makes this moment in the history of science so exciting. Perhaps it is not an exaggeration to say that it is a period [...] in which a new view of Nature was being born"[11].

The aspect of coherence in dissipative structures is amazing. The system behaves as a whole: it is structured as though each component were "informed" about the overall state of the system. The general mechanism capable of producing a symmetry break (a new structure) is connected with transport and/or

chemical reactions. A new concept of complex organization is required to connect the various levels of description and account for the relationships between the whole and the behavior of the parts[13]. It is interesting to note that structures in complex systems arising at bifurcation points (where fluctuation plays a fundamental role), seems to have been predicted by James Clark Maxwell, more than a century ago, who pointed that "Every existence above a certain rank has its singular points. At these points, influences whose physical magnitude is too small to be taken into account of by a finite being may produce results of the greatest importance"[84].

Also, in connection with the synergetic behavior of dissipative structures it is interesting to mention Volkenstein's assertion that "Darwin developed the principles of synergetics in the case of living nature a long time before its general formulation [...] For the first time in the history of natural sciences the mechanism for the formation of an ordered, directed process – the biological evolution – in a system with randomly properties was established"[85].

In the *previous* sections we have considered this question of self-organization. In them we noticed that the so called thermodynamic branch of solutions of the equations of evolution of an open macroscopic system – namely the one that develops continually from equilibrium with increasing values of the externa1 constraints – is stable, according to Prigogine's theorem of minimum entropy production, until eventually the system is shifted to a certain distance from equilibrium. At a critica] point, it occurs a branching point of solutions, and the thermodynamic branch becomes unstable against the formation of an ordered – in some sense– structure. At the branching point a particular fluctuation (the one associated with the degree of order to follow), which regresses while the thermodynamic branch is stable, now increases leading to the ordering of the system on the macroscopic scale. Consequently, chance and necessity have a delicate interplay in self-organization: near a bifurcation, fluctuations (a random element, viz. chance) would play such role, while between bifurcations the deterministic aspects of the equation (necessity) would become dominant. From a point of view of biological systems this appears to establish a sharp contrast between the arguments of Monod[86] and Prigogine[8–21]. For Monod, there is no theory of organization, with the living beings merely carrying out a program that has already been written and on whose origins it is not possible to formulate hypothesis that are subject to scientific theorization. In Prigogine's perspective, the living system does not appear as a rigidly conservative mechanism, but rather as a system that itself contains the *potentiality and the stimuli for evolving*, and indeed, in a certain sense, cannot help evolving to subsist. Maybe it can be said that Prigogine's approach conciliates the warring parties in the reductionist vs. vitalist controversy in biological sciences, providing a generalized broad scheme, as already commented in an earlier section.

In Section II, we mentioned the necessity to provide a theory for an as rigorous as possible description of these dissipative structures, including in the case of natural systems a microscopic background plus the connection with the relevant macroscopic aspect within the context of a dynamic system theory. We have called the attention to the fact of a possible framework provided by statistical mechanics, which can be formulated in terms of a scientific logic for inference as the one synthetized by Jeffreys[87] and Jaynes[65]. The nonequilibrium statistical operator method[66–69], as derived in the context of Jaynes' Predictive Statistical Mechanics, appears as an extremely powerful formulation to deal with Hamiltonian dynamical systems when arbitrarily away from equilibrium. As already mentioned, the NSOM provides a nonlinear quantum generalized transport theory of large scope[76]. This theory allows to derive the equations that rule the evolution of the macroscopic state of the system. The stability of the solutions (that characterize the macroscopic state of the system) of these equations can be analyzed by the usual mathematical methods (while a physical interpretation is found in the Glansdorff-Prigogine's thermodynamic criterion for (in)stability[16]) and eventual bifurcation points are determined.

When a bifurcation arises at a critica1 point of so-

lutions, the next step is its careful analysis in the neighborhood of the critical point, where the deterministic treatment (ruled by the equations of evolution) is to be complemented with an statistical study of fluctuations[88]. As already noticed, these fluctuations are relevant for the kinetic of the transition between structures through the critica1 point: the self-organized state arises as a result that nonlinear effects (positive feedback, autocatalysis) promote an amplification of the fluctuation associated to the new kind of order on the macroscopic scale, leading to the emergence of the ordered dissipative structure, which now becomes stabilized. Below the critical point the thermodynamic branch is stable and this fluctuation (the one to generate the new structure) simply regresses, that is, it "dies" without achieving the objective to give "life" to the new structure.

We have just referred to the possible instability of the thermodynamic branch (the thermal stochastic chaotic regime) against the emergence, in a bifurcating point of solutions, of a self-organized dissipative structure. However, the existence of chains of bifurcations cannot be excluded: the emerging structure at the first bifurcation out of the thermodynamic branch (primary bifurcation) can, when the system is driven further and further away from equilibrium, become unstable against the emergence of a new dissipative structure, and so on, in – in certain sense – a process of constant evolution (the system becomes "more and more organized"). It rnay follow a case of bifurcations leading to a state which is apparently disorganized, arising what can be considered a kind of deterministic chaos (or "turbulent" chaos) as a result of a surcharge (or "hyperinflation") of organization.

In Sections II and IV, we have given examples of the emergence of complex behavior associated to dissipative processes, dealt with in the framework of Informational Statistical Thermodynamics based on the NSOM.

In Section III, we have considered a simplified model of a biopolymer, and we analyzed the nonequilibrium stationary state of its polar vibrations. These polar modes are excited by means of a coupling with an external source of metabolic energy, and they are in anharmonic interaction with an elastic continuous media. Groups of polar modes are coupled in the equations of evolution through nonlinear terms. This nonlinearity becomes responsible for a new and unexpected phenomenon characterizing complex behavior in this system: after a certain level of intensity of the excitation is achieved, the polar modes with the lowest frequencies enormously increase their population in what is reminiscent of a Bose-Einstein condensation (the so called Frohlich's effect)[73]. Such phenomenon is regarded to be of relevance for the development of biological processes. The formation of this "Frohlich condensate" rnay be followed by the establishment of a metastable electret state and accompanying long range electrical forces that rnay influence basic properties of biological systems[89,90]. Moreover, as shown, it rnay bear upon the question of propagation of signals in biosystems. The point is that the solitary waves proposed by Davydov[74] as the mean of propagation of biological signals, which are strongly damped in normal physiological conditions, may, instead, display long range propagation without appreciable decay, when traveling in Frohlich condensate. This is a question of relevance in bioenergetics.

In Section IV, we considered a question related to morphological ordering. In the case of a simple model representing long chains of protein macromolecules p-type doped, our results seem to point to the possible existence of an instability of the homogenous state against the formation of spatial order in the electron density, once a population inversion of carriers has been established. It rnay be noticed that in the treatment of the problem we described, we kept fixed the positive background of ionic charges. It is quite plausible that the attractive interaction of the latter with the carriers will tend to allow the ions to follow the electronic charge density wave, thus producing an overall ordered pattern in the system (a so called conformational-like transition). As shown, after the first critica1 point (primary bifurcation) is surpassed, there follows a cascade of bifurcations (along with the increase of the intensity of the pumping source), corresponding to a multiplication in the wave lengths of the Fourier amplitudes that con-

tribute to the composition of the charge density wave. In this way, the system is led to a route going from thermal stochastic chaos, to order, to turbulent deterministic chaos. As noted this may be of pertinence in biomorphogenesis, and provides a theoretical calculation showing the eventual relevance of the charge carriers in the evolution and functioning of life, as suggested by A. Szent-Gyorgy[83].

As final words, we would like to, once again, emphasize the possible large relevance of dissipative processes in self-organization. A fundamental one is, of course, the question of life on Earth. Citing expressions of the Brussel's School, "Such phenomena [self-organization] have completely changed our view of the physical sciences and their relation to the biosphere. Bulk matter is no longer an inert object that can only change if acted upon. On the contrary, it can have its own will and versatility and ability for interna1 organization. Such findings have considerably narrowed the wide gap existing between matter and life. We now have enough elements in hand to allow us to hope for a distant day when matter can be made to become alive through the action of ordinary physico- chemical laws. Such a perspective is a revolution in science."

In conclusion, we have tried in this paper to give a brief overview on the fundamental aspects of physics, or more generally of the natural sciences, implied in the title, namely, complexity, dissipation, order out of chaos, and chaos out of order.

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