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On the complex self-organized systems created in laboratory

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Complexities are systems that emerge spontaneously i.e., through instability, when a local acting external cause drives locally an asymptotic stable medium at a critical distance from its initial thermodynamic equilibrium. In plasma diodes such bifurcation-like instability act as memory marks attributing to the system the ability to work as a multifunctional electronic device. Different kind of negative differential resistances are grounded on a new scenario of self-organization that involves direct conversion of thermal energy in electric field energy.

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1. Introduction

Self-organization is the basic concept of the science of complex systems whose foundation resides in principles as „order through fluctuations" expressed by Ilya Prigogine or „order from noise" enunciated by Heinz von Foerster. This means that self-organization is considered to be triggered by internal variation at microscopic scale that, in certain conditions, initiate a nonlinear process finished with the emergence of order out from disorder. This process not elucidates up yet is considered one of the most challenging problem of nonequilibrium physics [1]

The first experimental results considered to be illustrative for self-organization are the so called Bénard cells and the Belousov – Zhabotinski reaction. Later, many phenomenon as for example magnetization, are cited in the literature for evidencing the presence of self-organization.

Although the emergences of spatial and spatiotemporal patterns in plasma devices are phenomena known long time ago, their relevance for self-organization was firstly reveal only two decades ago [2].

Here we present experimental results proving that at the genuine origin of self-organization is a nonlinear process (instability) that, once initiated by a well known external cause, evolve naturally by a mechanism not explainable by the known laws of the physic. The final product is a complexity whose structure and behaviour are maintained by a functional double layer that work as a special kind of machine i.e., it performs labour extracting thermal energy from the environment by a mechanism exploiting collective effects of quantum processes [3,4].

2. Experimental results and discussion

Experimental results offering information concerning the mechanism by which an asymptotic stable medium locally driven at a certain critical distance from thermodynamic equilibrium evolves into a self-organized state, are obtained in experiments performed in plasma diodes [2-4]. These experiments investigated the conditions that precede the appearance of an instability whose results is the spontaneously self-assembling of a complexity that reveal all qualities of an intelligent material [3]. Thus, by possessing memory, the complexity is able to encode instructions offered by the environment that enable it to work, under suitable conditions, as a multifunctional circuit element. These instructions are related to the presence of certain distribution functions of the electrons located in the environment, in our case the plasma [4]. A plasma diode is schematically presented in Fig. 1. It consists from a plasma source that acts as a cathode, from which the plasma diffuses toward an anode (marked by A in Fig. 1). Both electrodes are placed in a vessel that contains gas at a low pressure. The diode is included in a circuit that contain an external dc power supply (PS in Fig. 1) and a load resistor (R in Fig. 1).

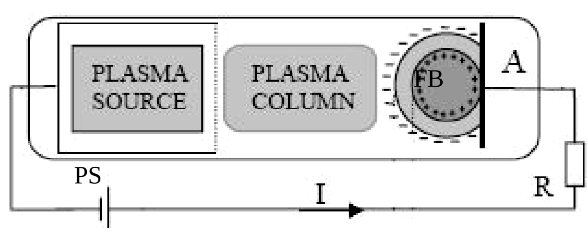

Fig. 1. Scheme of a plasma diode and its connection in a circuit containing a dc power supply PS (FB – fireball)

By gradually increasing and subsequently decreasing the voltage of PS, the typical static current-voltage characteristic shown in Fig 2 is obtained. Its shape prove that the current *I* transported through the plasma show variation that depends on the voltage *V* i.e., on the elementary processes produced by the electrons after their acceleration in the electric field created by A.

Knowing that the electric field created by A penetrated the plasma only a certain distance, that depends on the plasma parameters and the voltage of A, the electrons obtain energies that depends on the voltage of A. This voltage, marked by *V* in Fig 2, is controlled by the voltage delivered by PS but because of the presence of R, its value is different from that delivered by the PS. Thus, by gradually increasing the voltage of PS firstly appears a variation of *I* as that evidenced by the branch marked **a-b** in Fig 2. This branch, during of which *I* increase proportionally with *V*, reveal the presence of an Ohmic

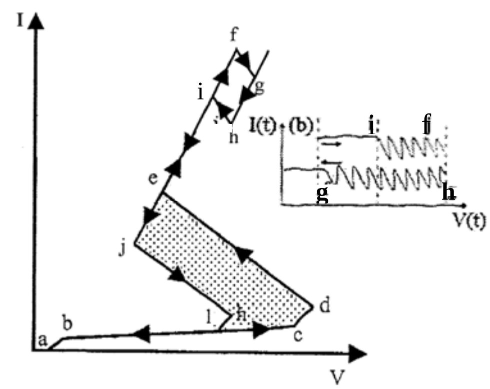

Fig. 2. Typical static current – voltage characteristic of a plasma diode.

behaviour of the gaseous conductor. Such behaviour is determined by inelastic collisions taking place between the electrons accelerated in the electric field created by A and the neutrals present in the plasma. In this phase of the plasma diode the work done by the external PS is used to produce disordered energy (heat, incoherent light etc). When the voltage of PS is increased so that *V* reach values for which excitations of neutrals appear in the plasma, the slope of the static *I(V)*-characteristic is changed (branch **b-c** in Fig. 2). This happens because of the accumulation of those electrons that lost their kinetic energy after atom excitations. So, in front of the anode a plasma sheath enriched in electrons is formed, located in the region where the excitation cross-section function begins to increase suddenly. Acting as a barrier for *I*, the evolution of the negative sheet concomitant with *V* changes the internal resistance of the plasma and simultaneously the slope of the static *I(V)*-characteristic. By continuing to increase the voltage of PS, *V* reaches a value for which the electrons accelerated in the electric field of A becomes able to produce ionizations of the atoms presented in the plasma. Since during ionizations free electric charges (electrons and positive ions) are produced, the current *I* collected by A begin to increase concomitant with *V* (branch **c-d** in Fig. 2**)**. By taking into account the energy dependence of the ionization cross-section function at a certain distance from A, namely that for which the ionization cross-section begins to increase suddenly, positive ions are accumulated. Since the electrons that produce and that result after ionizations are quickly collected by A, while the positive ions remain, because of their greater mass, for a longer time located in the region where they are produced, a positive net space charge in front of A is formed. This is located, in respect to the negative space charge, closer to the anode. So, a bipotential structure appears as two adjacent space charge structures with opposite sign, located in the regions where the excitation and ionization cross-section function suddenly increase. It sustains a local potential drop whose value increases concomitantly with *V* because the voltage increase determines new accumulation of electrons and positive ions. For "manufacturing" this bipotential structure, the PS performs labour by accelerating in the electric field of A the electrons extracted from the plasma. A part of the work done by the PS appears as energy located in the electric field of the bipotential structure. By continuing to increase the voltage of PS, *V* reaches a critical value that corresponds to the point marked by **d** in Fig. 2, for which the current *I* collected by A grows abruptly i.e., through an instability (branch **d-e** in Fig. 2). This takes place under the condition that the voltage of PS is maintained constant so that the abrupt grow of *I* is not determined by the increase of the electric field sustained by the PS. Since concomitant with this instability *V* decreases in the same way, this phenomenon signify the appearance of an internal acting positive feedback mechanism identified in the plasma diode as a self-enhancement of the production of positive ions [3]. Produced in the absence of any external driving force, this self-enhancement process is based on successive acceleration of groups of electrons extracted from a population whose thermal energy distribution function corresponds to a quasi-Maxwellian one. During this self-enhancement process, the thermal energy extracted from the plasma is directly converted in energy located in the electric field of the bipotential structure. Such a process is initiated with the "help" of the external PS that performs labour for accelerating consecutively groups of electrons whose thermal energy decreases concomitant with the increase of their number [3]. Because A collects the electrons produced and resulted after ionization at the positive side of the bipotential structure, the potential drop sustained by it increases during this instability. However, as proved by the experimental result presented in the figure 3, in the final phase of this evolution of the bipotential structure the potential at its positive side surpasses the potential of A. This signifies that in the final phase the bipotential structure evolves by a mechanism not controlled by the PS because of the fact that A ceases to accelerate electrons, since between the positive side of the bipotential structure and *A* exist an electric field that decelerates them. This is an experimental result whose importance was ignored up yet by the community of the plasma physicists although its consideration is, as we will show in the following, essential for demonstrating the presence of self-organization phenomena in a plasma diode.

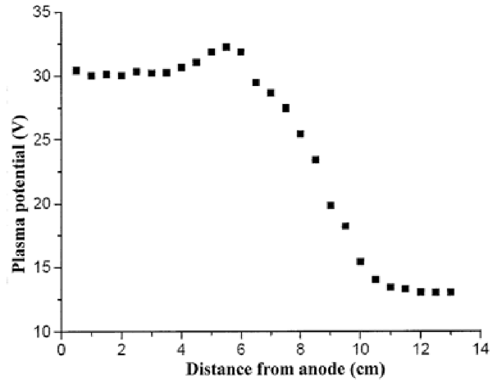

Fig. 3. Variation of the potential measured by an emissive probe after its axial displacement in front of the anode.

Thus, the presence of an electric field that decelerates the electrons, proves that, in the final phase of the evolution the bipotential structure, the PS ceases to produce work for accelerating toward A the electrons that appears after ionizations at its positive side. In other words, after an evolution initiated by local acceleration of electrons in the electric field of A, in the final phase of its evolution the bipotential structure is able to accelerate by itself the electrons, maintaining in this way at a constant value the amount of energy located in its own electric field. It is important the fact that this amount of electric field energy corresponds to a bipotential structure which potential at its positive side surpass the potential of A. By reaching this phase of evolution, the increase of the potential drop sustained by the bipotential structure is stopped. This takes place in the moment when a statistical equilibrium between the rate of accumulation of electrons and positive ions at the two side of the bipotential structure balance the rate of the lose of electrons and positive ions produced by recombination, diffusion and so on in the same region. During this state, that is reached after a expansion of the bipotential structure [2], the bipotential structure borders a complexity that appears as a coherent apparent stable and luminous gaseous body dubbed fireball. The fireball survives in this apparently stable state because the bipotential structure have assimilated (learned), during its emergence by self-organization, to perform all of the operations required to ensure its permanently produced self-assembling process. In this state the bipotential structure acts as a self-consistent “machinery” that performing a set of operation encoded in its space charge arrangement explains the survival of the fireball. This machinery works by a mechanism that involves emission of incoherent light i.e. by exploiting collective effects of quantum processes. By this mechanism, thermal energy extracted from the plasma is continuously converted in energy of the electric field located in the bipotential structure [3,4].

As proved by experiments, in spite of the presence of a decelerating electric field between the positive side of the bipotential structure and A, a part of electrons, namely that whose kinetic energy is greater than a certain critical value, reach the surface of A. This means that the self-consistent bipotential structure acts as an internal source of current that continuous to maintain the intensity of I at the values marked by **e** in Fig. 2. This state of the fireball is maintained also when V is decreased (branch **e-j** in Fig. 2). This signifies that the self-enhancement process of the production of positive ions, initiated in the moment when V reaches the critical value marked by **d** in Fig. 2, continuous also when V is decreased up to the value marked by **j** in Fig. 2.

Placed in plasma that reaches by diffusion the region where the bipotential structure emerges, the single source of energy able to sustain the self-consistent state of the bipotential structure is the thermal energy located in the plasma. This proves that the bipotential structure at the border of the fireball actually acts as machine that, by extracting thermal energy from the plasma produce work accelerating the electrons in its potential drop. By producing this work, the self-consistent bipotential structure is actually a functional double layer (FDL) able to convert directly thermal energy in electric field energy [3,4]. Located at the border of the fireball, FDL ensures its existence as a self-organized complexity as long as the plasma supplies with matter (positive ions and electros) and thermal energy its continuously produced self-assembling process. The evolution of the bipotential structure into a FDL that borders the fireball takes place naturally because the final phase of this evolution corresponds to a local minimum of the free energy.

As afore mentioned, after the emergence by self-organization the fireball is able to survive also when, by decreasing the voltage of the PS, V has values smaller than those required to initiate its emergence. This means that the fireball is characterized by a certain robustness that endowed it to “resist” as a self-organized complexity also when the condition that have initiated its emergence don’t exist. This is proved in Fig. 2 by the presence of the hysteresis phenomenon. The survival of the fireball as long as the intensity of I runs through the branch **e-j** in Fig. 2, proves that the FDL at the border of the fireball continuous to perform all operations ”learned” during its emergence by self-organization. This takes place under conditions that the cause that initiated its emergence disappear i.e., the voltage V is smaller as the critical value for which the fireball emerged. As general accepted, the presence of a hysteresis phenomenon is a hint that the complexity emerged by self-organization is endowed with a special kind of memory proper to all self-organized systems [5]. This memory physically based on direct conversion of thermal energy in electric field energy, enables the fireball to perform, under suitable conditions, all of the operations learned during its emergence by self-organization [2]. So, for example the plasma diode that includes in its circuit a complexity (the fireball) was encoded with a set (algorithm) of instructions that enable it to work, for example as different kind of negative differential resistances (NDRs). By sustaining for example oscillations, by a mechanism related to an S-shaped NDR [6] the current *I* flowing through the diode runs through all branches of the first hysteresis cycle shown in Fig 2. This means that during every period of the oscillation an amount of power corresponding to the aria of the first hysteresis cycle is injected in the oscillatory circuit. This power has its origin in the thermal energy converted in the electric field of the FDL from the border of the fireball during its emergence by self-organization [3,4]. Injected in the oscillatory circuit in the moment when the fireball de-aggregates (point **j** in Fig. 2) this power entertains the amplitude of the oscillations at a constant value. The de-aggregation of the fireball is related to the presence of R that, by supporting a proper potential drop that depends on *I*, diminishes the potential drop supported by the plasma diode at the critical value for which the fireball de-aggregates. So, the plasma diode acts as an S-shaped NDR which, by working as a machine that use thermal energy extracted from the plasma, is able to produce useful work [6].

When the voltage of PS is increased the fireball remains as a stable spatial ordered space charge configuration attached at A up to the moment when *V* reaches the value marked by **f** in Fig 2. In this moment, the fireball transits into a dynamic state during of which from its border FDLs detach periodically [7]. This is a more advanced state of self-organization of the fireball that involves spatiotemporal order. Since during this dynamic state two FDL simultaneously exist in the plasma diode, one in a moving phase and one in a forming phase, there are also two barriers for *I*. Consequently the current *I* flowing through the plasma diode suffers periodic limitations whose presence is evidenced in the dynamic characteristic presented in the window shown in Fig 2. Once started this dynamic state, the fireball continuous to exist in a steady state (ordered in behaviours) also when, by decreasing the voltage of PS, *V* decreases from the value marked by **g** to that marked by **h** in Fig. 2. This means that the plasma diode reveal the presence of a Z-shaped bistability that, in the static *I(V)* characteristic, appears as an N-shaped NDR. Consequently, in the dynamic state of the fireball the plasma diode works as a system that, based on a proper ‘code” of instructions, learned during its transition by self-organization, is able to sustain oscillations in a suitable connected oscillatory circuit. Both qualities, namely to work as an S and N respectively, shaped NDR reveal that the FDL at the border of the fireball performs labour. This labour involves operations “learned” during the aforementioned two phases of self-organization namely the spatial and the spatiotemporal one.

The experiments performed in the last time proved that, by increasing the pressure of the gas located in the plasma diode, the dimensions of the fireball decrease at values that reaches in the range of micrometers. Such phenomena are intensively investigated in the so-called microdischarges [6]. The importance of these investigations consists in the fact that it reveals the presence of a scenario of self-organization similar to that emphasized by usual plasma diodes. Thus, the experiments prove that essentially in the emergence of a self-organized complexity is a critical value of the ionization rate that, once reached, determines the development of an instability. This instability that work as an autocatalytic process [4] could be initiated/sustained in certain fluids or solids by a nonlinear chemical process. In living “material” such processes are related to the presence of enzymes [4].

3. Conclusions

By taking into account the size of the fireballs emerged in microdischarges, their investigation falls in the realm of the thermodynamics of the small systems [8]. This means that during self-organization the known laws of thermodynamics cease to work. This is evidently an important experimental result because the single strategy available to be used by nanotechnology for mastering advanced materials with defined physical, chemical or biological characteristics is the self-organization. Consequently, information concerning the genuine origin of the self-organization as that described in this paper potentially offer a new insight into a mechanism already described [4] that, defying the second law of thermodynamic, potentially explain phenomena important for modern technologies but also for elucidating enigmas of the nature.

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