Theoretical and Experimental Results on the Charge Transport in Plasma Structures Through Spontaneously Symmetry Breaking.

New Transport Mechanisms in Composite Materials

CAMELIA POPA[1,2], PETRICA VIZUREANU[3,*], IRINEL CASIAN BOTEZ[4], CRISTINA-MARIA STOICA[5], ANA NICUTA[6], CARMEN NEJNERU[3], LUMINITA BIBIRE[7], ADRIAN GHENADI[7]

[1] Gh. Asachi Tehnical University, Department of Physics, 56 Mangeron Bd.,700050, Iasi, Romania
[2] Al. I. Cuza University, Department of Physics, Carol I Bd., 700505, Iasi, Romania
[3] Gh. Asachi Tehnical University, Faculty of Materials Science and Engineering, 56 Mangeron Bd.,700050, Iasi, Romania
[4] Gh. Asachi Tehnical University, Faculty of Electronics and Telecommunication, 56 Mangeron Bd., 700050, Iasi, Romania
[5] Stefan Lupascu Institute of European Studies, 40 Ipsilanty Str.,700029, Iasi, Romania
[6] Gh . Asachi Technical University, Faculty of Civil Engineering and Building Services, 53 Mangeron Bd., 700050, Iasi, Romania
[7] University of Bacau, Department of Engineering, 157 Marasesti Str., 600115, 601146, Bacau, Romania

The dynamics of the plasma discharge through spontaneous symmetry breaking as double layer Langmuir, anodic patterns etc., is treated by means of the fractal description. Considering that the charge carrier movements take place on fractal curves, the electric charge transport is studied in an extended model of scale relativity. Using the motion equation for the complex speed field for the irrotational movement the generalized Schrödinger equation is obtained, and in the absence of dissipation a generalized Korteweg de Vries type equation is obtained. The process is also analyzed at the microscopic scale, when the electrical conductance increase is controlled by means of the soliton coherence. When the external field exceeds a critical value, the solitons which stocks the energy break down and simultaneously release the energy to the environment. The same mechanism can explain the charge transport in composite materials (e. d. nanostructures). Moreover, some correspondences between the theoretical model and the behaviour of the patterns generated by laser ablation are analyzed.

Keywords: fractal space-time, charge transport mechanism, nanostructures, composite materials

Turbulence is not only active on a wide range of length scales, but it is filled with localized coherent structures that make quantities such as energy, anisotropy and pressure highly intermittent. The plasma turbulence is usually characterized by assuming that the fluctuations are randomly distributed in space and time [1]. It was shown that the turbulences in a plasma discharge have the same origin as the periodical ones, but that in this case, stochastic causes decide about the moment when the unstable state of one or more double layers (DLs), coupled by current, starts its proper evolution process [2]. The experimental data evidence that the global evolution of the plasma discharge containing a system of DLs is the result of the mutual influence of two or more individual DLs coupled by the current flowing through them [3-6]. The chaotic regime observed as non-coherent variations of the current appears when the correlations between the proper dynamics of each of DLs do not exist and each of their dynamics starts at random, independently of each other. The observed behavior is similar to the chaotic dynamics of coupled non-linear oscillators [7]. Studying the evolution of an oscillating DL, the transition to chaos can be done by various ways:

- for small values of the discharge current in diffusion plasma, by the appearance of sub-harmonics with amplitudes higher than those of the basic frequency;
- for intermediary values of the discharge current, by the appearance of sub-harmonics and also by enhancing the frequency spectrum;
- for high values of the discharge current, by enhancing the frequency spectrum, leading to the generation of frequency bands with peaks close to the noise level.

Two general properties of turbulence in plasma discharge resulted:

a) non-linearity, a basic property of all numerical models of chaos;

b) intermittency, which causes the characteristics of turbulence change over a relatively short time or space scale, that necessitates the use of suitable statistical description in order to study the long term dynamical behavior.

On such a description is based the fractal formalism [8-10].

A fractal structure is a manifestation of the universality of self-organization processes in the plasma discharge, a result of a sequence of spontaneous symmetry breaking. The space-time itself may be a fractal. In such a context, taking into account the way by which the energy of the discharge plasma is obtained, we distinguish two ways in which self-organized structures can be generated [11-13].

The intermittent self-organization

If the discharge plasma receives energy gradually and continuously, its evolution will depend on the non-linearity of the system and on the information exchange between the system and the medium. The system evolves to a critical state due to the random fluctuations; intermittently ordered structures appear in the system and its energy varies

* email: peviz2002@yahoo.com

irregularly between the local maximum and minimum of the vicinity of the critical state. Experimentally, the critical state is obtained, for example, close to the ionization potential of the gas (for details see [3-6]);

Cascade self-organization

If the energy is pumped suddenly into the discharge plasma and then cut off from the external power source, its dynamics will be a relaxation towards a stable self-organized state. The condition is that the energy pumping time be shorter than the dynamic response time of the plasma. In these conditions, the plasma "sees" the energy pumping process as a sudden one.

The dynamics of the transition of a plasma discharge from "disorder" to "order" needs a new type of description: the fractal one, which includes both. So, this paper attempts to build a dynamics of the "multiparticle" systems on a fractal time-space. This will be applied to the study of the anodic patterns in plasma discharges, double layer Langmuir, etc., by means of the spontaneous symmetry breaking mechanism. Moreover, some considerations on the charge transport mechanism in nanostructures is considered.

Theoretical model

Scale relativity [14] is a new approach to understand quantum mechanics, and, moreover, physical domains involving scale laws, such as chaotic systems. It is based on a generalization of Einstein's principle of relativity to scale transformations. Namely, one redefines space-time resolutions as characterizing the state of scale of reference systems, in the same way as speed characterizes their state of motion. Then one requires that the laws of physics apply whatever the state of the reference system, of motion (principle of motion-relativity) and of scale (principle of SR). The principle of SR is mathematically achieved by the principle of scale-covariance, requiring that the equations of physics keep their simplest form under transformations of resolution.

According to scale relativity, a non-differentiable continuum is necessarily fractal and the trajectories in such a space (or space-time) own (at least) the following three properties:

- the test particle can follow an infinity of potential trajectories: this leads us to use a fluid-like description (fractal fluid);

- the geometry of each trajectory is fractal (of fractal dimension D_F - [15] or, in particular, of fractal dimension $D_F = 2$ as in Nottale's approach of the SR). Each elementary displacement is then described in terms of the sum $d\boldsymbol{X}=dx+d\zeta$, of a mean classical displacement $dx = \upsilon dt$ and of a fractal fluctuation $d\zeta$, whose behaviour satisfies the principle of SR (in its simplest Galilean version). It is such that: $\langle d\xi \rangle = 0$, $\langle d\xi^2 \rangle = 2D(dt)^{(2/D_F)}$ and $\langle d\xi^3 \rangle = (2D)^{3/2}(dt)^{(3/D_F)}$ where D defines the fractal/non-fractal transition, *i.e.* the transition from the explicit scale dependence to scale independence. The existence of this fluctuation implies introducing new second and third order terms in the differential equation of motion;

- time reversibility is broken at the infinitesimal level: this can be described in terms of a two-valuedness of the velocity vector, υ_+ the "forward" speed and υ_- the "backward" speed, for which we use a complex representation,

$$\boldsymbol{V} = (\boldsymbol{v}_+ + \boldsymbol{v}_-)/2 - i(\boldsymbol{v}_+ - \boldsymbol{v}_-)/2$$

These three effects can be combined to construct a complex time-derivative operator [16],

$$\frac{\delta}{dt} = \frac{\partial}{\partial t} + \boldsymbol{V}\cdot\nabla - iD(dt)^{(2/D_F)-1}\Delta + \frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3 \quad (1)$$

so that the first Newton's principle in its covariant form becomes $\boldsymbol{\delta V}/\mathrm{dt} = 0$, i.e..

$$\frac{\delta \boldsymbol{V}}{dt} = \frac{\partial \boldsymbol{V}}{\partial t} + \nabla\left(\frac{\boldsymbol{V}^2}{2}\right) - \boldsymbol{V}\times(\nabla\times\boldsymbol{V}) - iD(dt)^{(2/D_F)-1}\Delta\boldsymbol{V} + \frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3\boldsymbol{V} = 0 \quad (2)$$

with $\nabla^3 = \sum_{i=1}^{3}\partial^3/\partial x_i^3$

Therefore, the sum of the local time dependence, $\partial_t\boldsymbol{V}$, of the convective term, $\boldsymbol{V}\cdot\nabla\boldsymbol{V}$, of the dissipative one, $\Delta\boldsymbol{V}$, and of the dispersive one, $\nabla^3\boldsymbol{V}$ is null in any point of the fractal space-time. This result shows that transport process [17], in plasmas has hysteretic properties [18, 19]. The fractal fluid can be described by Kelvin-Voight or Maxwell rheological model with the aid of complex quantities, *i.e.* the complex speed field, the complex acceleration field etc. and complex structure coefficients, *i.e.* the imaginary viscosity coefficient, $\eta = iD(dt)^{(2/DF)-1}$ as it will be shown below.

We assume that the motion of the fractal fluid is irrotational, $\nabla \times \boldsymbol{V} = 0$, and then we can choose $\boldsymbol{V}$ of the form

.

$$\boldsymbol{V} = \nabla\phi = -2iD(dt)^{(2/D_F)-1}\nabla(\ln\psi). \quad (3)$$

In these conditions, Eq. (2) takes the form

$$\frac{\delta \boldsymbol{V}}{dt} = \frac{\partial \boldsymbol{V}}{\partial t} + \nabla\left(\frac{\boldsymbol{V}^2}{2}\right) - iD(dt)^{(2/D_F)-1}\Delta\boldsymbol{V} + \frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3\boldsymbol{V} = 0 \quad (4)$$

and ψ satisfies a generalized Schrödinger type equation

$$D^2(dt)^{(4/D_F)-2}\Delta\psi + iD(dt)^{(2/D_F)-1}\partial_t\psi + i\frac{\sqrt{2}}{3}D^{5/2}(dt)^{(5/D_F)-2}(\nabla^3\ln\psi)\psi = F(t) \quad (5)$$

Particularly, when the dispersion is absent, Eq. (4) becomes a generalized Navier-Stoke (GNS) type equation,

$$\frac{\delta \boldsymbol{V}}{dt} = \frac{\partial \boldsymbol{V}}{\partial t} + \nabla\left(\frac{\boldsymbol{V}^2}{2}\right) - iD(dt)^{(2/D_F)-1}\Delta\boldsymbol{V} = 0 \quad (6)$$

with imaginary viscosity coefficient, $\eta = iD(dt)^{(2/DF)-1}$. From here, using Eq. (3), the Schrödinger type equation results

$$D^2(dt)^{(4/D_F)-2}\Delta\psi + iD(dt)^{(2/D_F)-1}\partial_t\psi = 0. \quad (7)$$

Moreover, for $D = \eta/2m$, with η the reduced Planck's constant, m the rest mass of the test particle and for the fractal dimension, $D_F = 2$, *i.e.* the Nottale's approach [14], the previous equation is reduced to standard Schrödinger equation.

Correspondences with known theoretical results

In the particular case when the dissipation is absent, Eq.(4) becomes a generalized Korteweg de Vries (GKdV) type equation,

$$\frac{\partial \boldsymbol{V}}{\partial t}+\boldsymbol{V}\cdot\nabla\boldsymbol{V}+\frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3\boldsymbol{V}=0 \quad (8)$$

Let us choose the function $\psi=\sqrt{\rho}\exp(iS)$ with $\sqrt{\rho}$ the amplitude and S the phase. By substituting the complex velocity field (3), $\boldsymbol{V}=\boldsymbol{v}+i\boldsymbol{u}=2D(dt)^{(2/D_F)-1}\nabla S-iD(dt)^{(2/D_F)-1}\nabla\ln\rho$ in Eq. (8), and separating the real and imaginary parts, we obtain the equation system,

$$\begin{aligned}&\frac{\partial \boldsymbol{v}}{\partial t}+\nabla\left(\frac{\boldsymbol{v}^2}{2}-\frac{\boldsymbol{u}^2}{2}\right)+\frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3\boldsymbol{v}=0\\&\frac{\partial \boldsymbol{u}}{\partial t}+\nabla(\boldsymbol{v}\cdot\boldsymbol{u})+\frac{\sqrt{2}}{3}D^{3/2}(dt)^{(3/D_F)-1}\nabla^3\boldsymbol{u}=0\end{aligned} \quad (9.a,b)$$

In the differentiable case, *i.e.* at the macroscopic scale, $\boldsymbol{u}=0$ or, ρ=const., and for the one-dimensional case, with the dimensionless parameters,

$$\phi=(j/j_0)=q\rho v/j_0,\qquad \tau=\omega_0 t,\qquad \xi=k_0x,$$

and the normalizing conditions

$$(k_0j_0/6q\rho\omega_0)=\sqrt{2}D^{3/2}(dt)^{(3/D_F)-1}(k_0^3/3\omega_0)=1,$$

Eqs. (9a,b) take the form,

$$\partial_\tau\phi+6\phi\partial_\xi\phi+\partial_{\xi\xi\xi}\phi=0 \quad (10)$$

These equations have the solution,

$$\phi(\xi,\tau)=2a\left(\frac{E(s)}{K(s)}-1\right)+2a\cdot cn^2\left\{\frac{\sqrt{a}}{s}\left[\xi-2a\left(\frac{3E(s)}{K(s)}-\frac{1+s^2}{s^2}\right)\tau+\xi_0\right];s\right\} \quad (11)$$

where *cn* is the Jacobi's elliptic function of *s* modulus [20], K(s), E(s) are the elliptic complete integrals, and ξ_0 constant of integration. As a result, at the macroscopic scale, the electrical charge transport in plasmas is achieved by one-dimensional cnoidal oscillation modes of the charge current density.

This process is characterized by:

- the normalized wave length

$$\lambda=\frac{2sK(s)}{\sqrt{a}} \quad (12)$$

- the normalized phase speed

$$v_f=4a\left[3\frac{E(s)}{K(s)}-1-\frac{1}{s^2}\right] \quad (13)$$

- and the normalized group speed,

$$v_g=4a\left[3\frac{E(s)}{K(s)}-1-\frac{1}{s^2}+3\frac{E^2(s)+2(s-1)E(s)K(s)-(s-1)K^2(s)}{E(s)K(s)+K^2(s)-sK^2(s)}+\frac{2(s-1)K(s)}{s^2[E(s)+K(s)-sK(s)]}\right] \quad (14)$$

In such a conjecture, the following results:

i) by eliminating the parameter a from relations (12) and (13), one obtains the dispersion relation, $v_f\lambda^2=A(s)$, with $A(s)=16[3s^2E(s)K(s)-(1+s^2)K^2(s)]$.

By numerically evaluating the quantity $A(s)$, it results that only for $s=0\div 0.7$, $A(s)\approx$ const, and the dispersion equation takes then the form $v_f\lambda^2$ = const.

ii) the parameter s becomes a measure of the electric charge transfer in plasmas. Thus, for $s\to 0$, λ, v_f and v_g are small, while for , $s\to 1$, λ, v_f, and v_g are high.

iii) the one-dimensional cnoidal oscillation modes contain as subsequences:

a) for s=0 the one-dimensional harmonic waves:

b) for $s\to 0$ the one-dimensional waves packet;

c) for s = 1 the one-dimensional soliton;

d) for $s\to 1$ the one dimensional solitons packet.

The subsequences a, b describe the electric charge transport in a non-quasi-autonomous regime (for details see [18, 19], while the subsequences c, d describe the electric charge transport in a quasi-autonomous regime. Therefore, these two regimes (non-quasi-autonomous and quasi-autonomous) are separated by the 0.7 structure, a value in agreement with the experimental data [21].

The previous results show, through the normalized group speed (14), an increase of the charge transport in plasmas by means of quasi-autonomous structures. They can provide a possible explanation of the anomalous incre M.-A. ase of the electrical conductance that was experimentally observed in [18, 19].

Let us now study the previous phenomenon in the non-differential case, *i.e.* at the microscopic scale. This can be achieved by the substitutions $\phi=(v_f/4)f^2$ and $i\eta=(v_f/4)^{1/2}(\xi-v_f\tau)$ in (10). By an adequate choice of the integration constants, it becomes, $\partial_{\eta\eta}f=f^3-f$ *i.e.* a Ginzburg-Landau type equation [22]. The following results:

1) the η coordinate has dynamic significations and the variable f has probabilistic significance. The space-time becomes fractal [14];

2) according to [23] we can build a field theory with spontaneous symmetry breaking. The fractal kink solution,

$$f_k(\eta)=f(\eta-\eta_0)=\tanh\left[(\eta-\eta_0)/\sqrt{2}\right] \quad (15)$$

spontaneously breaks the "vacuum" (the minimum energy states of the system) symmetry by tunneling, and generates coherent structures. This mechanism is similar to the one of superconductivity [24]. In this case, anodic patterns, double layer Langmuir etc., are generated;

3) the normalized fractal potential takes a very simple expression which is directly proportional with the density of states of the fractal fluid,

.

$$Q=-(1/f)(d^2fd\eta^2)=(1-f^2). \quad (16)$$

When the density of states, f^2, becomes zero, the fractal potential takes a finite value, Q = 1. The fractal fluid is normal (it works in a non-quasi-autonomous regime) and there are no coherent structures in it. When f^2 becomes 1, the fractal potential is zero, *i.e.* the entire quantity of energy of the fractal fluid is transferred to its coherent structures. Then the fractal fluid becomes coherent (it works in a quasi-autonomous regime). Therefore one can assume that the energy from the fractal fluid can be stocked by transforming all the environment's entities into coherent structures and then 'freezing' them. The fractal fluid acts as an energy accumulator through the fractal potential Eq.(16). Particularly, Eq.(15) corresponds to the double layer potential distribution, while Eq.(16) gives the double layer field distribution;

4) by substituting (15) in (16) the fractal potential (16) becomes a soliton,

$$Q=\sec h^2\left[(\eta-\eta_0)/\sqrt{2}\right] \quad (17)$$

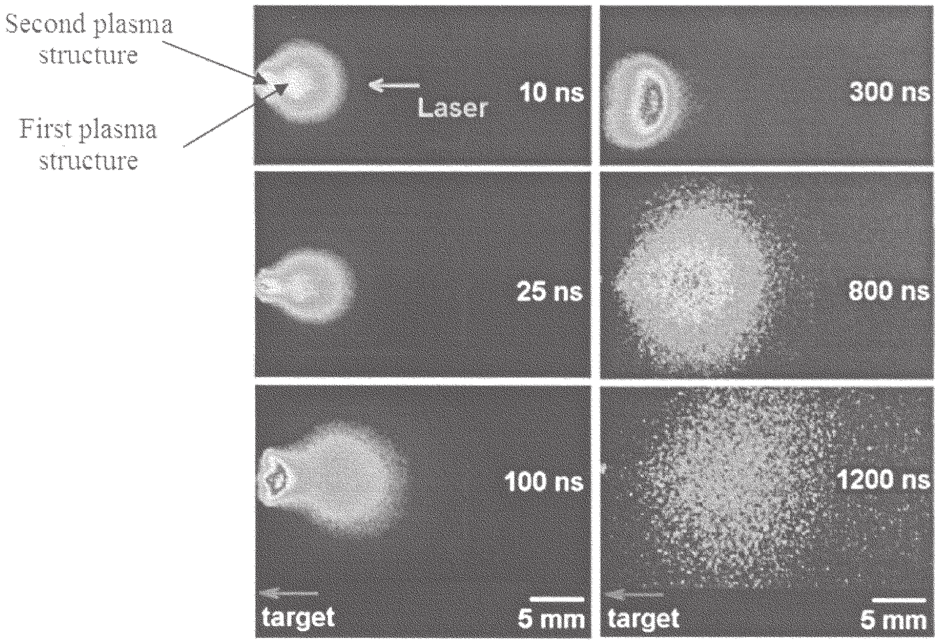

Fig. 1. The evolution of visible emission from the aluminium laser-plasma plume recorded using an ICCD PI MAX camera (gating time 20 ns). The laser beam energy was 40 mJ/ pulse and background pressure 10^{-6} Torr

In certain conditions of an external load (*e.g.* an external stress) the soliton breaks down (blows up) a free energy. As a result, the plasmas energy increases unexpectedly.

Correspondences with experimental results

Laser produced plasma (LPP) is a topic of growing interest in different fields such as material processing[25, 26], diagnostic techniques[27] and space applications. Pulsed laser deposition has been successfully employed for the deposition of thin films of classical and novel materials [25, 28]. The possibility of producing species in LPP with electronic states far from chemical equilibrium enlarges the potential of making novel materials that would be unattainable under thermal conditions.

For the experiments involving the interaction of intense laser pulses with matter, it is desirable to know directionality, velocity and other parameters of ejected plasma plume far from the target. The plume evolution includes two important parts: in the initial stage, i.e., during the laser energy deposition, the one-dimensional expansion takes place (large laser spot size compared with the skin depth); after some time, the plasma cloud becomes truly three-dimensional [29, 30, 31]. According with ref. [31, 32], both the elementary physical processes which require different scale times, and the patterns evolution [32] that requires different degrees of freedom (e.g., from 1, at the initial stages, to 3, at the final stages of the patterns induced by laser produced plasma), imply a non-differentiable space-time, i.e., fractals [33 - 40]. Moreover, the dynamic of the plasma transition from "disorder" to "order" needs also a fractal description. In some papers [31, 32], a mathematical model to describe some characteristics of the laser produced plasma expansion was established in the frame of scale relativity theory for an arbitrary topological dimension D_F. The numerical results and the analytical ones in the particular case $D_F = 2$ are compared with our experimental data [31, 32].

Experimentally the plasma was generated by laser ablation of an aluminum target using 532 nm radiation pulses from a Nd:YAG laser [32]. The laser pulse energy ranges from 10 to 80 mJ, in a pulse time-width of 10 ns, and it has been focused by a f = 25 cm lens at normal incidence on a aluminum target placed in a vacuum chamber (pressure $<10^{-6}$ Torr), to obtain the spot diameter at the impact point of 300 μm. The formation and dynamics of the plasma plume have been studied by means of an intensified charge-coupled device (ICCD) camera (PI MAX 576X384, gating time 20 ns) placed orthogonal to the plasma expansion direction. In figure 1 the ICCD images of the plasma plume at different times after the laser pulse are given. Successive pulses of energy 40 mJ were used. The images of these structures reveal a splitting process of the plasma blobs. Analyzing figure 1 we conclude the followings:

- in the range time 10-50 ns after the laser pulse, the visible emitting regions of plasma are almost stationary and they form two structures each having a maximum emissive region;
- by measuring the position of the maximum emissivity at different times, a linear dependence resulted. Then, the velocities of the two plasma formations have been calculated as being, $v_1=4.66 \times 10^4$ m/s , for the first plasma formation, and, $v_2=6.9 \times 10^3$ m/s for the second structure [31].

Theoretically, the velocity of first plasma structure can be roughly estimated by identifying it with the velocity of the vaporization front. Thus, by using the method from refs. [33 - 40], the energy conservation law gives, $v_1=F/\rho(\lambda_v+c \,.\, T_v)$, where F represents the laser fluency, ρ the target density, λ_V the vaporization heat, c the specific heat, and T_v the vaporization temperature. In our experiment (aluminum target), ρ = 2702 kg/m^3, λ_V = 293 kJ/mol, c = 0.9 J/(g . K) and T_v = 2792 K, and with $F=5.7 \times 10^{13}$ W/m^2, it results $\upsilon_1=7.1 \times 10^4$ m/s. The speed of the second plasma structure corresponds to the average speed of the shock wave that is induced and maintained by the energy absorbed from the laser beam. By using the method from refs. [33 - 40], and the energy conservation law, it results the expression, $\nu_2=[2\gamma(\gamma -1)F/\rho]^{1/3}$. For the same laser fluency and the adiabatic index γ =5/3 the previous relation gives $\upsilon_2=3.6 \times 10^3$ m/s. These results are in a reasonable agreement with our experimental data, having the same order of magnitude.

Conclusions

Considering that the charge carrier movements take place on fractal curves, the electric charge transport is studied in an extended model of scale relativity.

An equation of motion is deduced for the complex speed field, where the local complex acceleration, convection, dissipation and dispersion are reciprocally compensating. Using this equation, for the irrotational movement the generalized Schrödinger equation is obtained. The absence of the dispersion implies a generalized Navier-Stokes type equation, and from here, for the irrotational movement and fractal dimension $D_F = 2$, the usual Schrödinger equation resulted.

The absence of dissipation implies a generalized Korteweg de Vries type equation. In the one-dimensional macroscopic case, two flowing regimes (quasi-autonomous and non-quasi-autonomous) of the charge carriers are evidenced, the separation between them being made by the 0.7 structure that is experimentally observed. In such a conjecture, the increase of the electrical conductance in plasmas is connected with the increase of the group velocity at the passage from non-quasi-autonomous to quasi-autonomous regime.

At microscopic scale, the electrical conductance increase is controlled by means of the soliton coherence. When the external field exceeds a critical value, the soliton which stocks the energy breaks down and simultaneously releases the energy to the environment.

The same mechanism can explain the increase of the electrical conductance in composite materials (e. d. nanostructures), mainly in aluminium matrix composites.

Moreover, using the scale relativity theory model, some experimental results (e. d. the velocity of plasma structures generated by laser ablation) can be explained.

References

1. HORTON, W., Coherent Structures in Plasma Turbulence, Transport, Chaos and Plasma Physics 2: Advanced Science in Non-linear Dynamics, **9**, World Scientific, Singapore, 110, 1992

2. Proc., Fourth Symposium on Double Layers and Other Nonlinear Potential Structures in Plasmas: Innsbruck, Austria July 6-8, 1992, Ed. R. SCHRITTWIESER, W. , World Scientific Publishing, **I**, 87, 1993

3. ALEXANDROAEI, D., SANDULOVICIU, M., Phys Lett A, **122**, 1987, p.173

4. SANDULOVICIU, M., BORCIA, C., LEU, G., Phys Lett A, **208**, 1995, p.136

5. SANDULOVICIU, M., MELNIG, V., BORCIA, C., Phys Lett A, **229**, 1997, p.354

6. ALEXANDROAIE, D., SANDULOVICIU, M., Rom. J. Phys., **40**, 1995, p.841

7. CRISTESCU, C.P., STAN, C., ALEXANDROAIE, D., Phys. Rev. E, **70**, 2004, 016613

8. NICOLIS ,G., Introduction to nonlinear Science, Cambridge University Press, Cambridge, 1995

9. OLTEANU, M., PAUN, V.-P., TANASE, M., Rev. Chim. (Bucuresti), **56,** nr.1, 2005, p.97

10. NICOLIS, G., PRIGOGINE, I., Exploring Complexity- An Introduction, Freeman & Co., 1985

11. SATO, T., The Complexity Simulation Group. Complexity in plasma: from self organization to geodynamo. Phys Plasmas 1996; 3:2135-42

12. LOZNEANU, E., SANDULOVICIU, M., On the mechanism of patterns formation in gaseous conductors, XXV international conference on phenomenon of ionized gases, Nagoya, **3**. Nagoya, Japan, Toshio Goto Nagoya University, 2001, p. 165

13.SANDULOVICIU, M., Quantum processes at the origin of self-organization and chaos in current carrying gaseous conductors. In: Xxi international conference on phenomenon of ionized gases, Bochum, Germany. Proceedings, **III**, Invited Papers, 1993, p. 279

14. NOTTALE, L., Fractal Space-Time and Microphysics: Towards a Theory of Scale Relativity, World Scientific, Singapore, 1993

15. MADELBROT, B., The fractal geometry of nature, Freeman, San Francisco, 1982

16. MOON, F., Chaotic and Fractal Dynamics. An Introduction for Applied Scientists and Engineering, John Wiley & Sons Inc., 1992

17**.** PAUN V.-P., PAUN M.-A., TOMA A., CIUCU C., POPENTIU F., Mat. Plast. **45,** nr.1, 2008, p. 57

18. FERRY, D.K., GOODNICK, S.M., Transport in plasmas, Cambridge Univ. Press, 1997

19. IMRY, Y., Introduction to mesoscopic physics, Oxford Univ. Press, Oxford, 2002

20. BOWMAN, F., Introduction to elliptic function with applications, English University Press, London, 1955

21. CHATTI ,O., J.T. NICHOLLS, J.T., PROSKURYAKOV, Y.Y., LUMPKIN, N., FARRER, I., RITCHIE, D.A., Phys. Rev. Lett. **97,** 2006, 056601

22. JACKSON E.A., Perspectives of non-linear dynamics, Cambridge University Press, Cambridge, 1991

23. CHAICHIAN, M., NELIPA N,.F., Introduction to gauge field theoretic, Springer-Verlag, Berlin, 1984

24. POOLE, C.P., FARACH, H.A., GESWICH, R.J., Superconductivity, Academic Press, San Diego, New York, 1995

25. GEOGEAN, D. B., in Pulsed Laser Deposition of Thin Films, ed. D. B. Chrisey and G. K. Hubler (Wiley, New York, 1994) p. 132.

26. BECKER, M. F., BROCK, J. R., CAI,H., HENNEKE, D. E., W. KETO, J., LEE, J., NICHOLS, W. T., GLICKSMAN, H. D., Nanostruct. Mater. **10** (1998) 853

27. RADZIEMSKI, L. J., Spectrochim. Acta, Part B **57** (2002) 1109

28. AMEER-BEG, S., PERRIE, W., RATHBONE, S., WRIGHT, J., WEAVER, W., Appl. Surf. Sci. **127–129** (1998) 875.

29. GURLUI, S., AGOP, M., STRAT,M., STRAT,G., BACAITA, S., CEREPANIUC, A., Phys. Plasma **13** (2006) 063503.

30. AGOP, M., NICA,P., GURLUI,S., STRAT, G., STRAT, M., J. Opt. Adv. Mater., **10** (2008), 1526.

31. GURLUI, S., AGOP, M., NICA,P., ZISKIND, M., FOCSA, C., Phys. Rev. E **78** (2008) 062706.

32. NICA, P., VIZUREANU, P., AGOP, M., GURLUI, S., FOCSA,C., FORNA, N., IOANNOU, P. D., BORSOS, Z., Jpn. Journ. Appl. Phys. (accepted), 2009

33. IOANNOU, P. D., NICA, P., PAUN, V., VIZUREANU, P., AGOP, M., Physica Scripta, **78,** nr. 6, Article Number: 065101, 1 – 7, 2008

34. AGOP, M., NICA,P.E., IOANNOU,P. D., ANTICI,A.., PAUN, V. P., Eur. Phys. J. D., **49**, nr. 2, 2008, p.239

35. AGOP, M., RADU, C., BONTAS, T., El Naschie's E (infinity) space-time and scale relativity theory in the topological dimension D = 3, Chaos Solitons and Fractals, **38**, nr. 5, 2008, p. 1243

36. AGOP, M., PAUN, V., HARABAGIU, A., Chaos Solitons and Fractals, **37,** nr. 5, 2008, p. 1269

37. AGOP, M., RUSU,I., Chaos Solitons and Fractals **34**, 2007, p.172

38. AGOP, M., MURGULET,C., Chaos Solitons and Fractals **32**, 2007, p. 1231

39. GOTTLIEB, I., AGOP, M. , CIOBANU, G. , STROE, A.,Chaos Solitons and Fractals **30**, 2006, p. 380

40. AGOP, M. , ALEXANDROAIE, D.,CEREPANIUC, A., BACAITA, S., Chaos Solitons and Fractals **30**, 2006, p. 470

Manuscript received: 27.03.2009