Complex systems are a highly interdisciplinary research topic, which has been often tackled since 1980. The investigation methods rely on elements of theoretical physics (traditional mechanics, quantum mechanics, etc.) and on computer simulation. Such systems include interacting items (agents). Hence, the overall behavior of these systems cannot be predicted by the behavior of their individual elements and their superposition.

Among the most important properties of complex systems, one may distinguish emergence, self-organization, adaptability, etc.

The emergence of complex systems underlines the fact that the overall state of any such system is not identical with the sum of the individual states of its components.

The self-organization of complex systems means that when the value of an exterior constraint exceeds a certain threshold these systems evolve to stationary states by themselves and thus generate self-structures (patterns).

The adaptability of complex systems occurs when the state of these systems changes in response to an external stimulus. As they perpetually oscillate between equilibrium and non-equilibrium, complex systems are not rigid: any small induced change generates a series of fluctuations, thus exploring new stationary states.

Among these properties, complex systems have a strongly nonlinear behavior.

The purpose of this PhD thesis is the use of nonlinear dynamics elements to analyze the dynamics of a series of complex systems (multiphase fluids – Chapter I, drug-loaded polymer matrices – Chapter II, discharge plasmas – Chapter III, “liquid electroplating plasmas” – Chapter IV, ferromagnetic-ferroelectric nanocomposites – Chapter V). In practice, we suggest a theoretical unitary model based on the assumption that the movement paths of complex system agents are described by non-differentiable continuous curvatures. Thus, we considered that chaos is traditionally associated with spatial-temporal self-structures. Moreover, for large temporal scales in relation to the reversed dominant Lyapunov exponent, the deterministic paths are replaced by “collections” of potential paths, whereas the concept of defined positions is substituted by the concept of probability density. All these results are functional in the context of the Theory of Scale Relativity (TSR), according to which all physical phenomena are dependent on both spatial-temporal coordinates and spatial-temporal resolution scales. Non-differentiability then proves to be a fundamental and common characteristic of the dynamics of the complex systems analyzed here.

The original results of our theoretical research materialized in the publication of 12 scientific papers, of which 6 were published in ISI ranked journals (3 in international and 3 in national journals), 4 in CNCSIS B+ journals, a book published by a CNCSIS accredited publishing house and a paper read in an international conference.

In Chapter I, entitled "Dynamic States in Complex Fluids via Non-differentiability", we studied complex fluid dynamics considering that its entities move on fractal curvatures. We achieved the following results in dissipative movement approximation: i) the complex fluid streamlines are identified with the geodesics of a fractal space (if this is the case, autoconvection, autodissipation, autodispersion and autoacceleration reach an equilibrium in any point of the streamline), ii) we generalized fundamental theorems concerning standard to complex fluid dynamics, namely Helmholtz's theorem (the movements on fractal curvatures which are rotational at a given moment remain rotational at any later time, regardless of scale resolution) and Thomson's theorem (velocity vector circulation is preserved over time for movements on fractal curvatures which are independent of the resolution scale); iii) the one-dimensional dynamics of a complex dispersive fluid is achieved by cnoidal velocity field oscillation modes. This field is selfsimilar in relation to nonlinearity and is characterized by two states of flow: non-quasi-autonomous state (given by harmonic sequences and harmonic bunches) and quasi-autonomous state (given by soliton sequences and soliton bunches). The two states are separated by the value $s = 0.7$ of the nonlinearity degree. iv) since the cnoidal oscillation mode may be associated with a spatial-temporal network of nonlinear Toda oscillators, the abovementioned states of flow may be correlated with the two sequences of the network spectrum (optical and acoustic). Moreover, by the extension into the complex of the cnoidal oscillation mode, in which case the dynamics of the complex fluid entities are assimilated with vortex type objects, the full coherence condition of these structures involves internal forces responsible for inner compressive or repulsive stresses.

In Chapter II, called "Drug Delivery Mechanisms via Non-differentiability", we analyzed the dynamics of two types of drug-loaded polymer matrices: hydrogel loaded with an anti-inflammatory drug and nanoparticles loaded with an antitumor drug. Thus, for hydrogel, we determined a qualitative dependence between some of its "structural" parameters (distribution and diffusion parameters) and crosslinking time. Their variation with the crosslinking time is validated by experimental data. The big advantage of this approach, in which the complexity of the system is replaced by fractality, is that it provides an alternative to standard approaches based on the hypothesis of the continuity and non-differentiability of physical quantities, which makes it very difficult to consider all the phenomena involved.

In the second case, we were able to fit the experimental curvature described by the antitumor drug delivery from the nanoparticles with very good correlation coefficients (0.994), characteristic to Weibull's model and calculated by fractal approximation. The data we collected showed that the diffusion mechanism is complex, has a non-Fickian profile, and several degrees of freedom in the phase space. The parameters we calculated are correlated with the fractal dimension which is dependent on the diffusion order. Therefore, the mathematical model is viable.

The behavior of an incandescent diffusion plasma, studied in Chapter III, called "Chaotic Dynamics of Complex Structures of Spatial Charge via Non-differentiability. Experimental and Theoretical Approaches", is characterized by the formation, evolution and dynamics of multiple double nonconcentric layers. All of the above outlined a scenario of transition towards chaos through a cascade of subharmonic bifurcations.

A theoretical TSR-based model was developed in order to describe the formation, evolution, dynamics and transition towards chaos of multiple double nonconcentric layers. Thus, assuming that the plasma particles move on fractal curvatures, one may draw the following conclusions: i) plasma dynamics is described by fractal functions (which depend on both coordinates and scale resolution, in which case the velocity field becomes complex); ii) the complex velocity movement equation is of the Navier Stökes type, with imaginary viscosity coefficient; iii) for irrotational fluid movements, fractalization by stochasticization (i.e., the scalar complex potential of the velocity field has a statistical meaning) induces a generalized equation of the Schrödinger type. This enables us to apply "cloning" formalism based on which we analyzed the transition to chaos scenarios through cascades of subharmonic spatial-temporal bifurcations; iv) by using the Navier-Stökes movement equation applied to irrotational movements, we managed to separate complex velocity into two components (a real and an imaginary part) and to define the fractal hydrodynamic model. For a particular type of fractal potential, which requires adequate onset and limit conditions, the fractal hydrodynamic model enabled us to perform numerical simulations of multiple double nonconcentric layer dynamics, by means of the numerical solutions achieved. We found good agreement between the experimental data and the theoretical results.

In Chapter IV, entitled "Implications of Fractality on Electroplating Process Dynamics", the replacement of the complexity of the electroplating mechanism by fractality involved interdependencies between the process parameters. This is due to the fact that different nucleation mechanisms dominate at different time scales. Let us consider, for instance, instantaneous or progressive generalized nucleation. In such a context, the two mechanisms mentioned above were modeled by a Weibull relation for various time scales. Moreover, unusual electroplating behaviors, like for instance electrolytic "regression", may be accounted for based on the fractal hydrodynamic model, considering the spatial-temporal "interference" between the progressive and regressive bunches associated to a scalar velocity potential, for various onset velocity field values. The model was validated by studying the electroplating phenomenon in two lead acetate and copper sulfate solutions, respectively, of various molar concentrations and at various stresses.

In Chapter V, called "Nonlinear Effects in Complex Ferrite-Ferroelectric Systems. Analysis of Controlled Diffusion Properties", we showed that the microstructure and properties of ferromagnetic-ferroelectric nanocomposites consisting of hexagonal Z-like ferrites and ferroelectric combinations containing barium, strontium or titanium depend on diffusion dynamics on the edge of the nanogranules and may be reproduced by simulation.

The effective diffusion coefficient for each diffusate may be modeled using Hart's equation. The tensors of susceptibilities $\overline{\overline{\chi_e}}(E)$ and $\overline{\overline{\chi_m}}$, respectively, depend on the crystalline phase structure, on the nanogranule structure and on the diffusion layer, and were determined here by the energy variation method. By using the simulation method, we studied the diffusion properties dependent on the properties of diffusing substitution ions. The electromagnetic parameters may be controlled by varying the ratio between the mean thickness of the diffusion layer and the width of the granule border. ε_{eff} is a peak, whereas μ_{eff} is a minimum threshold characteristic of the specific $\bar{d}_{Cr}$ value, which is dependent on crystalline nanogranule structure and not on phase concentration.

We found good agreement with the literature data for punctual results concerning the effective electromagnetic parameters of the nanocomposites considered. The reported results are only punctual and they do not cover the whole range of considered parameter values. We estimated a relative error of about 2.8% for the amounts determined by the simulation method employed.

Practical methods such as element diffusion attenuation, sintering temperature decrease, etc. may be considered to increase electromagnetic parameter tunability.

Flaw influence over material parameters should be reduced by preventing asymmetrical combustion as much as possible. This may be achieved by including in the nanocomposite ceramics two constituent phases with similar sintering temperatures.

One should also bear in mind the existence of material resonances. This is important when choosing the operating frequency subfield of a specific application. Hexagonal ferrites have a strongly dielectric resonant peak above the 100 MHz frequency and up to a few GHz (depending on their structure), determined by dipole vibration. Piezoelectric vibration is also present in composites, within the MHz field. At the same time, hexagonal ferrites are weakly magnetized and consequently have several types of low resonance, such as magnetic range wall resonance and spin resonance. Their spectrum is very wide, stretching from the GHz to the THz areas.

Effective permittivity and permeability also present frequency dispersion as a phenomenon determined by the field-substance interaction and influenced by microstructure. Fortunately, frequency dispersion for ε_{eff} and μ_{ef}, respectively, does not exceed a few percentages in their relative variation, provided it is measured above the dielectric resonant peak of the materials considered and away from resonance.