Electrodynamic Aggregation of Nanodust as a Source of Long-Lived Filaments in Laboratory Electric Discharges and Space

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Abstract—**Formation of a skeleton composed of a fractal condensed matter was suggested to explain the unexpected longevity of filamentary structures observed in various laboratory electric discharges and space. We present the numerical modeling results on the electrodynamic aggregation of nanodust in the frame of a simple model which describes many-body system of magnetized thin rods (1-D magnetic dipoles), with electrical conductivity and electric charge, screened by an ambient medium. The model is shown to describe self-assembling of a coaxial tubular skeleton from initially linear filaments, composed of such blocks, between the biased electrodes, and self-assembling of a quasi-planar skeletal network from similar filaments, detached from electrodes and located within a plasma filament.**

Index Terms—**Carbon nanotube (CNT), electric current filament, fractal condensed matter, plasma, skeleton, 1-D magnetic dipole.**

I. INTRODUCTION

THE PHENOMENON of filaments, shown as a filament of plasma emissivity, exhibits common features in the laboratory electric discharges and space [1]–[3]. These include, in particular, the topology of networking of filaments and the unexpected longevity of such a structuring if compared to predictions of description at a microscopic level.

In space, the filaments are strongly associated with plasma phenomena since pioneering efforts by H. Alfvén and his collaborates and successors (see monographs [4], [5] and regular issues [6]–[8]). The concept of "plasma cable" [4] gave a chance for electrodynamics to provide the long-range bonds in cosmic space and, thus, extended the scope of electrodynamics to larger length scales it was thought before.

Here, we present the recent results of numerical modeling which originated from the hypothesis [1], [2] aimed at the explanation of the unexpected longevity of filamentary structures observed in various laboratory electric discharges and space. Major point of the approach is the formation of a skeleton composed of a fractal condensed matter. At the present stage of research, we test the capability of the electrodynamic aggregation of nanodust in the frame of a simple model which describes many-body system of magnetized thin rods (i.e., lengthy, 1-D magnetic dipoles), with electrical conductivity and electric charge, screened by an ambient medium.

II. PHENOMENON OF "UNIVERSAL SKELETAL STRUCTURES" (USS): MAJOR POINTS AND BRIEF HISTORY

The fine structure of networking of filaments was revealed by V. A. Rantsev-Kartinov [3], [9] in the database from his former experiments in the Z-pinch facility. The most intriguing point for the theory appeared to be the treelike nonaxisymmetric structure around the main body of the Z-pinch plasma column and, particularly, the presence of structures—thick strata and thin filaments—directed nearly transversely to the Z-pinch plasma column.

Interpretation of these data in the light of two phenomena, namely:

1) magnetic flux ropes in space (i.e., nearly force-free magnetic configuration, which are thought to be capable of self-sustaining [10]),
2) the success in confining the nearly force-free magnetic configuration in an electrically conducting chamber (experiments with spheromaks and reversed field pinches) [11],

has lead the author to a new magnetic configuration and new source of fractality. The assumption of a strong confinement of magnetic field in the flux tubes allowed the treatment of a long-lived filament in plasmas as an elastic thread. The latter can produce a compact strongly twisted loop that is directed transversely to the thread—as it can be immediately checked via twisting an ordinary thread. In plasmas, this corresponds to the formation of an almost-closed helical heterogeneous magnetoplasma configuration (it was called a heteromac [3], [9]). Such a branching-off process makes single filament a fractal dendritic structure (Fig. 1). In terms of conventional plasma physics, the heteromac may be a result of strongly nonlinear kink mode in an originally straight plasma column, which is subjected to twisting of the spatially distributed ("diffused") electric current passing through the column.

The heteromacs were suggested [12] to produce cellular and bubblelike clusters. In particular, this hypothesis was applied to interpreting the Aurora phenomena in terms of a high-current Z-pinch. The discovery [12] that objects from the Neolithic or Early Bronze Age carry patterns associated with high-current

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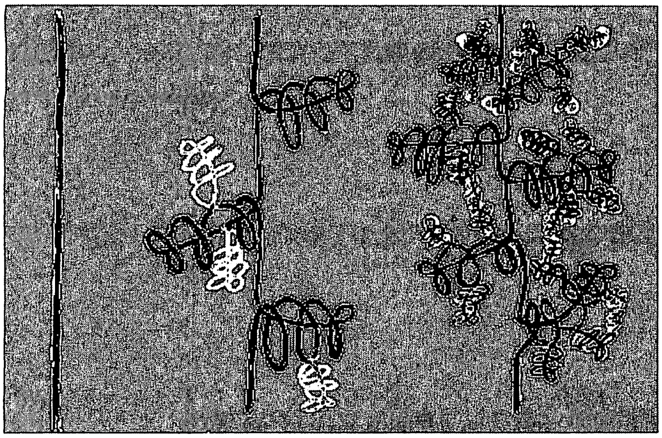


Fig. 1. Schematic drawing of successive branching of an originally 1-D filament (left drawing), which produces the heteromac(s) (center) and makes individual filament a fractal formation (right) [3].

Z-pinches provides a possible insight into the origin and meaning of these ancient symbols (primarily, petroglyphs). This conclusion is based on a direct comparison of the graphical and radiation data from high-current Z-pinches to these patterns.

The heteromac hypothesis, however, still leaves open the question about the origin of the longevity of observed filamentation. Here, a major difficulty is the unknown mechanisms in suppressing all the short-scale instabilities, which the plasma is rich with: the matter is that, in the successful MHD simulations of filament's dynamics, these instabilities are wisely ignored. For instance, the two-fluid description of plasma—with allowance for the Hall effect-produced "loosening" of the boundary between the plasma column and the ambient magnetic field—makes this boundary pretty unstable in contrast to the observations of long-lived filaments in the high-current electric discharges [3], [9]. The latter implies that successful MHD simulations may implicitly exploit the physics hidden at length scales which are smaller than those treated in the MHD codes.

A search for microscopic mechanisms of longevity of filaments was stimulated by the following two findings by V. A. Rantsev-Kartinov:

1) observations of transverse-to-electric current, few-centimeters long and ~1-mm-thick straight filaments [3] of an anomalously long lifetime [1], [2] in the plasma of gaseous electric discharge, namely a Z-pinch;
2) identification of opaque "dark" filaments [3] in the Z-pinch and astrophysical objects.

This led the author to hypotheses [1], [2], [9] for the following:

1) essentially quantum nature of the unexpected longevity of such filaments;
2) the presence, in the observed macroscopic filaments, of a tubular skeleton which is a fractal condensed matter composed of superlarge molecules [most probably, of wildly formed carbon nanotubes (CNTs)];
3) self-similarity of skeleton's structure (i.e., successive repeat of the same structure—in given case, a tubule—at various length scales, starting from nanoscale), which manifests itself as the "generations" of self-similar tubules, generally unlimited in size;
4) self-assembling of a skeleton during electric breakdown stage of discharge (or similar transient process) via electrodynamic coupling of nanoblocks, with dominant contribution of magnetic dipole attraction.

In the proof-of-concept studies, V. A. Rantsev-Kartinov revealed the following phenomena:

1) the presence of skeletal structures of certain distinctive topology (namely, tubular and cartwheellike structures, and their simple combinations) in the range of 10^{-5}–10^{23} cm in laboratory electric discharges of various type [13] (including the dust deposits in tokamak [14], [15]), severe weather phenomena [16]–[18], and space [17];
2) the trend toward self-similarity within above skeletal structures;
3) self-illumination of skeletal structures, in their critical points, in the range of 10^{-1}–10^{22} cm (e.g., the shining butt-end of a truncated filament) [17], [19];
4) some signs of skeletal structuring in the galaxy redshift surveys in the range of 10^{24}–10^{26} cm [16], [20].

The proof-of-concept studies enabled us to call these structures (namely, tubular and cartwheellike structures, and their simple combinations) a USS [21]. The topological identity (i.e., the similarity) of the above structures (particularly, of the cartwheel as a structure of essentially nonhydrodynamic nature) and the observed trend toward assembling of bigger structures from similar smaller ones (i.e., the self-similarity), which are identified in the range of 10^{-5}–10^{23} cm, enabled us to put all these skeletal structures under one roof and claim the probable presence, in these structures, of a skeleton composed of a fractal condensed matter of particular topology of the fractal [17]. Specifically, this matter may be self-assembled from nanotubular blocks in a way predicted in [1], [2], and [9] (formation of tubular macroblocks from tubular nanoblocks) and found in the skeletons in the submicrometer dust particles [14], [15]. Also, the following facts, namely:

1) the presence of skeletons of certain topology in the dust particles and films [14], [15], and hailstones [16]–[18],
2) fine resolution of nanotubular filaments in the dust deposits [14], [15],
3) the presence of carbon in these dust deposits [22],

suggested the presence of CNTs in the above skeletons.

The prediction [1], [2], [9] of the phenomenon of skeletons in a wide range of lengths, starting from nanoscale structures, was based on appealing to exceptional electrodynamic properties of their hypothetical building blocks—first of all, the ability of these blocks to facilitate the electric breakdown in laboratory discharges and to assemble the micro- and macroskeletons. The CNT [23] or similar nanostructures with participation of other chemical elements have been suggested [1], [2], [9] to be such blocks. Among the properties of CNTs, which that time were already identified in the literature and stimulated the choice [1], [2], we have to mention, first of all, anomalously high-strength, high enough conductivity of individual nanotubes in a wide range of major parameters (that promised making them an ideal 1-D quantum wires), ability of CNTs to form large macroscopic clusters and, finally, most economic consumption of the relevant available material to produce stable long-range quantum bonds. These properties allow, to our mind, the buildup of the Eiffel-Tower-like tracery structures with minimal mass for a given strength of the entire construction.

The self-assembling of skeletons was suggested to be based dominantly on magnetic phenomena [1], [2], [9], [17]. The indications on the ability of CNTs, and/or their assemblies, to trap and almost dissipationlessly hold the magnetic flux come from the following observations. Superconductorlike diamagnetism in the assemblies of CNTs at high enough temperatures was reported in [24] and [25]. The evidences were obtained for the self-assemblies of CNTs (which contain, in particular, the ring-shaped structures of few tens of micrometers in diameter) inside nonprocessed fragments of cathode deposits, at room temperatures, [24] and for the artificial assemblies, at 400 K [25]. However, observations of room-temperature superconductorlike diamagnetism in CNT assemblies are still limited to these two groups. The evidences and arguments for the room-temperature superconductivity in individual CNT, and in artificial and natural assemblies of CNTs, are summarized in [26].

We also have to mention the observations of unexpected ferromagnetism of a pure carbon, namely, rhombohedral C_{60}, with a Curie temperature near 500 K [27], and room-temperature ferromagnetic nanotubes controlled by electron or hole doping [28]. The recent survey of experimental evidences for, and theoretical models of, the unexpected magnetism of carbon foams and heterostructured nanotubes is given in [29]. The monograph [30] gives an overview of the magnetism of metal free carbon-based compounds and materials.

All the aforementioned evidences in favor of the USS phenomenon made it reasonable to extend the phenomenon further to cosmological length scales. Such an extension leads to hypothesis for a baryonic skeleton of the Universe (BSU), which has to be in thermal equilibrium with cosmic microwave background radiation [16], [19], [31]. First, mechanical strength of skeletal matter may resolve existing controversy between the following: 1) purely gravitational dynamics of galaxies' periphery and of galaxies in the clusters of galaxies and 2) empirical law "mass versus luminosity." This, in turn, may avoid the necessity to introduce a "dark matter." Second, anomalous blackness of self-similar skeletal matter (similar to that observed in the ultradisperse materials, like carbon black) gives BSU a chance to be compatible with very high isotropy of cosmic microwave background radiation, i.e., BSU is dark because it is very cold and very black [31].

The recent survey [32] of evidences for, and the models of, self-similar skeletal structures in fusion devices, severe weather phenomena and space, shows the current status of the USS project (for popular description, see [21]).

III. PROBABLE MECHANISMS OF ELECTRODYNAMIC AGGREGATION OF MAGNETIZED NANODUST

Despite the fact that the aforementioned experimental evidences for magnetism of carbon-based nanostructures need stronger tests and confirmations, they additionally stimulate explicit demonstration of the capability of magnetized nanotubular blocks to self-assemble the tubules of higher generations [1], [2] and sustain the integrity of the assembled skeleton.

A. Simple Model of a Skeletal Matter, Composed of 1-D Magnetic Dipoles

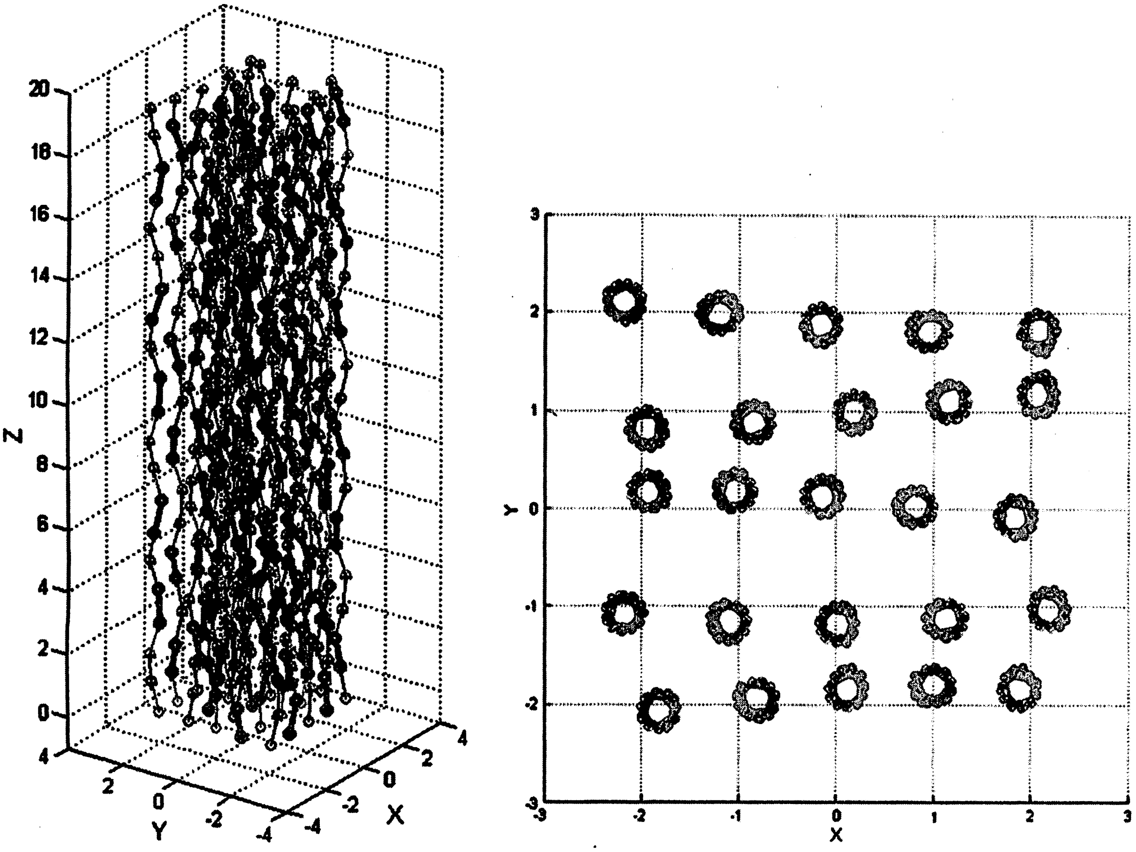
The study of skeletal matter formation was started with formulating a simple model of hypothetical skeletal matter [33]. The problem is treated within as simple framework as possible. We assume the elementary building block to possess the following electrodynamic properties:

1) one-dimensional static magnetic dipole moment (such a dipole may be represented as a couple of magnetic monopoles located on the tips of a long thin rod of the fixed length L, with magnetic charge of the monopole, in the units of electron charge e, being equal to $Z_M = \Phi/4\pi e$, where Φ is the magnetic flux that is trapped in the rod. Here, we consider discrete values of magnetic flux, with minimal value Φ_0);
2) two point masses m on the tips of the rod are connected with a massless rigid bond;
3) elasticity of the tips of the rod, which gives spherically symmetric repulsion of attracting monopoles at close distances (see [33, Fig. 1]);
4) static electric charge Ze, which is located in the center of the rod and may be exponentially screened by the ambient medium with a screening length r_D (e.g., positive electric charging may be caused by the field emission, at least thermal one; note that ejected electrons with nanotube may form a macromolecule and screen nanotube's positive charge);
5) longitudinal electrical conductivity.

These properties allow the modeling of many-body interaction of magnetic dipoles (i.e., of circular electric currents in the walls of 1-D dipole) and of longitudinal electric currents in the dipoles, as well as many-body cross interaction of circular and longitudinal electric currents.

The capability of the model formulated in [33] was demonstrated by tracing the dynamics of an ideal "manually assembled" tubular skeleton subjected to the impact of magnetic field from a pulsed distant electric current, for total number of the dipoles $N_{\text{dip}} = 294$ (see [33, Sec. 3]). The results show the capability of such a skeleton to sustain its integrity under the action of strong external forces. The deformation of initially straight skeleton by the bending force of magnetic field of external electric current produces almost a loop which—if closed at the subsequent stage, not described by the model [33] (strong collision of the edges of the skeleton would require more intricate model)—gives qualitative description of a part of possible scenario of formation of hollow toroidal structures, of $\sim$100 nm in size, observed in the experiments [34] on the laser pulse irradiation of carbonaceous target.

Similar modeling for larger number of dipoles $N_{\text{dip}} = 582$—for the same conditions and additional push of the initial skeleton transversely to its axis—showed similar behavior, namely, bending and stretching of skeleton under its conserved integrity [35].



(a) (b)

Fig. 2. (a) Three-dimensional and (b) top-on views of the initial position of a bunch of filaments composed of 1-D magnetic dipoles for the following set of parameters: Total number of blocks $N_{\rm dip} = 500$, number of blocks in filament = 20, number of filaments = 25, magnetic charge $Z_M = 2Z_{M0}$ (thick magenta blocks) and $Z_M = Z_{M0}$ (others), fraction of magnetically double-charged blocks $f_{2Z_{M0}} = 2/7$, electric charge $Z = Z_{M0}$, and screening length $r_D = 1$. Space coordinates are given in the units of dipole's length L.

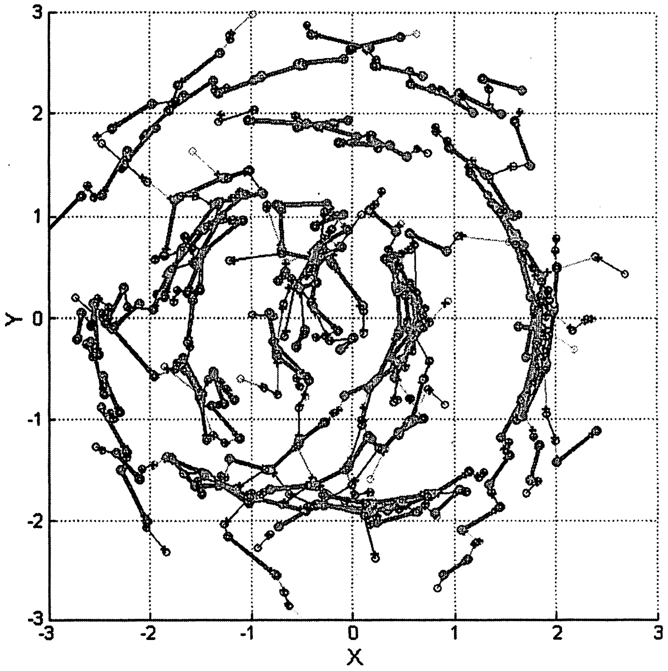


Fig. 3. Top-on view on a bunch of filaments in Fig. 2 at the quasi-stationary stage $(t \sim 8(mL^3)^{1/2}(Z_{M0}e)^{-1})$ for electric current force coefficient $F_{0JJ} \equiv (J_0L/cZ_{M0}e)^2 = 0.25$, brake coefficients for tip's collision, $(k_{\rm br})_{\rm dd} = 100$, and for brake in the ambient medium, $(k_{\rm br})_{\rm dm} = 3$ (all the forces are in the units $(Z_{M0}e/L)^2$, see [33]).

B. Self-Assembling of Tubular Skeletons From Electric Current Filaments Composed of Magnetized Thin Rods

The capability of nanoblocks to aggregate toward self-assembling of macroscopic skeletons with the help of nanoblocks' magnetism should be demonstrated on the example of electrodynamic self-assembling of a tubular structure of the second generation (in terms of the studies in [1], [2], and [9]) under conditions peculiar to electric breakdown.

Consider a bunch of filaments, which are composed of successively connected magnetic dipoles with the properties 1)–5). The filaments are connected to the biased electrodes [specifically, $z = 0$ and $z \approx 20$, cf., Fig. 2(a)], which carry a constant electric current J_0 through each of them, with a half of magnetic flux on the tip of each boundary block being trapped by the boundary surface. Thus, the ends of the filaments are magnetically bound to electrodes and may move freely along their surface. Such an ensemble may also describe, to certain extent, a part of much longer bunch of electric current filaments. The above system models the initial stage of skeleton formation, starting, however, from initial conditions which require separate substantiation to be done at the next step of approaching the overall dynamics of self-assembling.

We assume that essential feature of the filaments is the spatial inhomogeneity of magnetic charging along the filament, namely, the presence of uncompensated magnetic dipoles of

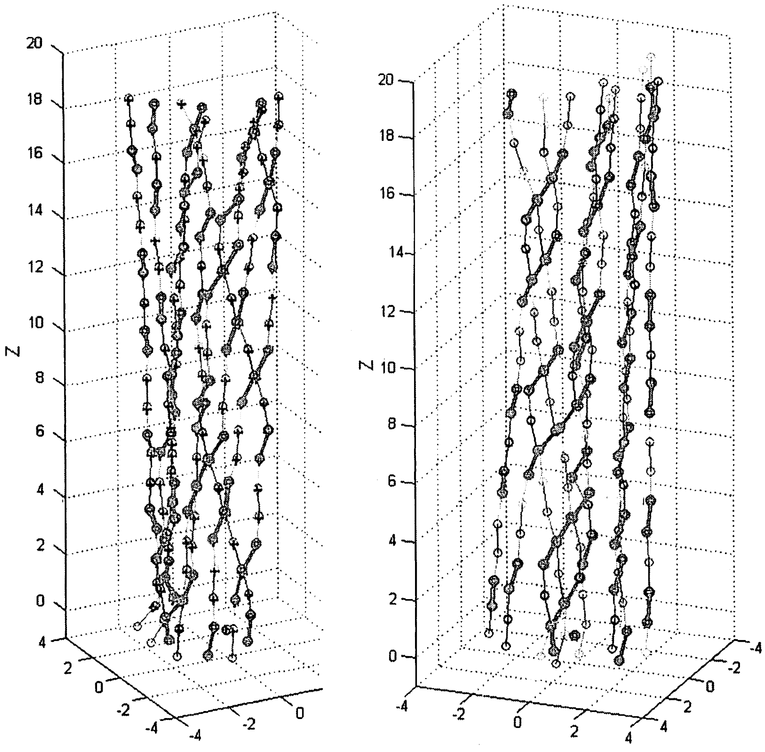


Fig. 4. Left: Part of the outer shell of coaxial tubular structure in Fig. 3, as shown from the left lower corner. Right: The opposite part of the outer shell of coaxial tubular structure.

$Z_M = 2Z_{M0}$, which is incorporated in the linear filaments with a constant fraction $f_{2Z_{M0}}$ with respect to background dipoles of $Z_M = Z_{M0}$. The evolution of such a system is governed mainly by the attraction of electric currents, electric repulsion of blocks at distances less than the screening length, and interaction of uncompensated magnetic dipoles with similar closest neighbors and with magnetic field of total electric current through the filaments. The latter interaction declines the uncompensated dipoles in azimuthal direction and, in a many-body system, makes the density of dipoles azimuthally symmetric. The equilibrium of the attraction, which is caused by ponderomotive force, and the nonscreened electric repulsion at close distances allowed the derivation of approximate analytic scaling law [36] for equilibrium spatial distribution of dipoles, which appeared to be in good agreement with numerical modeling results.

Numerical modeling of $\sim 10^3$ such dipoles demonstrates main features of self-assembling as follows: 1) self-reduction of spatial dimensionality of structuring, due to combined action of the ponderomotive attraction and the close Coulomb repulsion of filaments; 2) magnetic coupling of neighboring filaments within the formed cylindrical structure, due to a fraction of the dipoles with uncompensated magnetic flux in the filaments, and formation of tubular skeleton via such a magnetic "threading." The perfection of self-assembled skeleton depends on the fraction of the dipoles with uncompensated magnetic flux and the periodicity of their location within the initial filaments. The results for $f_{2Z_{M0}} = 1/3$ are presented in [36]. Here, we illustrate the possibility of tubular skeleton self-assembling for less favorable value of $f_{2Z_{M0}} = 2/7$ and respective quasi-periodic location of the double-charged magnetic dipoles. It is shown in Figs. 3 and 4 that these conditions retain the opportunity for magnetic threading of the neighboring filaments to give a network that is woven in the frames of a reduced 2-D freedom of filaments.

The numerical evidences for skeletal tubular structuring with imperfect structure of the wall suggest that the diversity and limited distinctness of available signs for tubularity of structuring, including the coaxial tubularity, in various data from laboratory and space may correspond to the diversity of initial conditions for the stage of evolution which is modeled in this paper.

C. Planar Skeletal Structuring of Magnetized Dust in a Plasma Filament in Laboratory and Space

Besides the above problem of evolution of a bunch of electric current filaments between biased electrodes, it is of interest to model the evolution of similar bunch of filaments detached from electrodes and subjected to the impact of plasma component, specifically, magnetic field of a plasma filament of electric current which may form together with dust filaments and live after decay of electric current in the dust filaments. Such a model is aimed at describing the self-assembling of skeletal structuring from a strongly magnetized dust under the condition of transient phenomena in laboratory electric discharges and space: detachment of dust filaments from mother electrode(s), destruction of quasi-stable dust-based filaments, etc.

Consider again a bunch of filaments (Fig. 5), which are composed of successively connected magnetic dipoles with the properties 1)–5), in external magnetic field produced by electric current filament of radius $R_{\rm pl}$ and total current $J_{\rm ext}$ with a uniform current density within the filament's circular cross

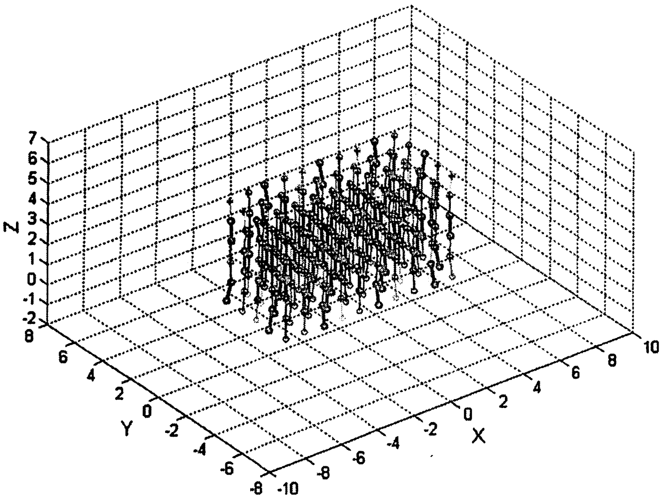


Fig. 5. Three-dimensional view of the initial position of a bunch of filaments composed of 1-D magnetic dipoles for the following set of parameters: Total number of blocks $N_{\rm dip} = 250$, number of blocks in filament = 5, number of filaments = 50, magnetic charge $Z_M = 2Z_{M0}$ (thick magenta blocks) and $Z_M = Z_{M0}$ (others), fraction of magnetically double-charged blocks $f_{2Z_{M0}} = 1/3$, electric charge $Z = Z_{M0}$, and screening length $r_D = 1$. Space coordinates are given in the units of dipole's length L.

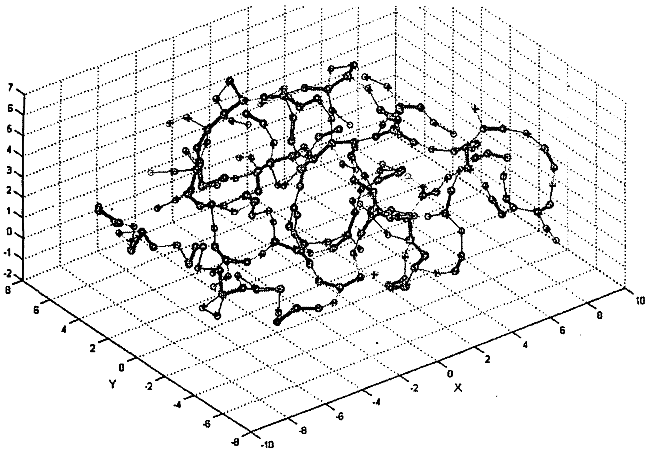


Fig. 6. Three-dimensional view on a bunch of filaments in Fig. 5 at the quasi-stationary stage $(t \sim 20(mL^3)^{1/2}(Z_{M0}e)^{-1})$ for brake coefficients for tip's collision, $(k_{\rm br})_{\rm dd} = 100$, and for brake in the ambient medium, $(k_{\rm br})_{\rm dm} = 3$ (cf. Fig. 3), and magnetic field of electric current filament of radius $R_{\rm pl} = 6\ L$ and total current coefficient $F_{J\rm ext} \equiv J_{\rm ext}L/cZ_{M0}e = 2.5$.

section. The plasma filament and initial dust filaments have the same direction. Similar to the case of the previous section, namely, the magnetic field of the current passing through the dust filaments, the magnetic field of plasma electric current tends to orient along the field's direction the dipoles with uncompensated magnetic flux and the edge dipoles. This results again in the reduction of spatial dimensionality of structuring, from initial quasi-homogeneous 3-D system to a quasi-planar one. The subsequent magnetic coupling of the filaments due to a fraction of the dipoles with uncompensated magnetic flux in the dust filaments leads to networking and formation of a quasi-planar skeletal structure. We illustrate this evolution with an example of total number of dipoles $N_{\rm dip} = 250$ to have the final structure transparent enough to the observer (Figs. 6 and 7).

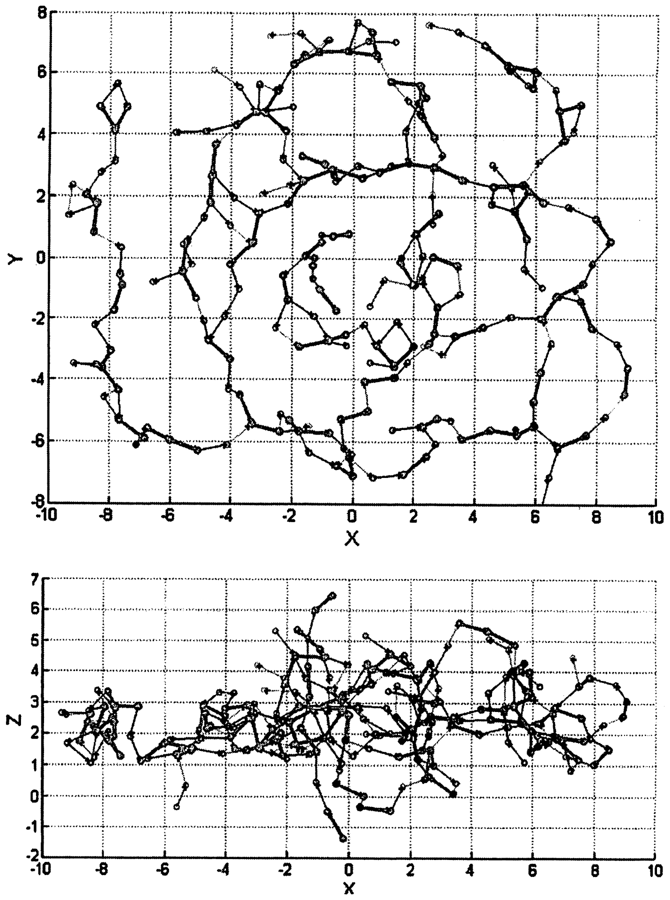


Fig. 7. Top-on (top) and side-on views (bottom) on a bunch of filaments in Fig. 6.

The resulted structuring suggests that the formulated problem, namely, evolution of currentless initially linear dust filaments (i.e., ones detached from the electrodes or any other source of electric current) in the magnetic field of an external filamentary electric current, may reproduce certain features of quasi-planar structuring identified in various observational data from laboratory electric discharges and space.

IV. CONCLUSION

The formation of a skeleton composed of a fractal condensed matter was suggested [1], [2] to explain the unexpected longevity of filamentary structures observed in various laboratory electric discharges and space, as well as in some numerical MHD simulations. Here, we presented the numerical modeling results on the electrodynamic aggregation of nanodust in the frame of a simple model [33] which describes many-body system of magnetized electrically conducting thin rods (1-D magnetic dipoles). The model [33] of magnetic aggregation of nanodust is capable of describing, for a large number of dipoles ($\sim 10^2$–10^3), the following:

1) self-assembling of a coaxial tubular structure in a bunch of initially linear filaments of electric current, which is composed of 1-D magnetic dipoles (Figs. 2–4);
2) self-assembling of a quasi-planar skeletal structure in a bunch of similar currentless filaments in the magnetic

field of an external filamentary electric current (Figs. 5 and 6);

3) stability of an ideal "manually assembled" skeletal matter [33];
4) the trend toward production of hollow toroidal structures by the external and internal forces [33], [35], [36].

At the present stage of numerical modeling, it is not possible to indicate the complete set of conditions that are necessary for self-assembling of a fractal condensed matter which has been predicted, in rough detail, in [1], [2], and [9] and verified in analyzing the vast amount of experimental data [13]–[18], [32]. Anyway, the above results give partial support to hypotheses [1], [2], [9].

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