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Self-similarity of plasma networking in a broad range of length scales: From laboratory to cosmic plasmas

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A newly developed method of high-resolution processing, called a method of multilevel dynamical contrasting, is applied to analyze numerous data from laboratory electric discharges and observations of cosmic plasmas in a broad spectroscopic range from rf to soft x-ray images. A high degree of self-similarity of plasma structuring is found in a very broad range of length scales, from individual filaments in laboratory discharges to the structures in the universe, which resemble electric currents networking in laboratory plasmas. The results presented illustrate recently suggested [Kukushkin and Rantsev-Kartinov, Laser Part. Beams **16**, 445 (1998)] generic features of networking in plasmas: (1) long-living (nonfluctuative) filamentation of electric current; (2) formation of a fractal structure made of single filament and complicated interaction of these ''fractal'' filaments; (3) formation of a percolating network that includes, in particular, formation of the ''stockings'' woven by the individual filaments. *© 1999 American Institute of Physics.* [S0034-6748(99)60801-2]

I. INTRODUCTION

Formation of structures in plasmas is a well recognized fact. The structuring is commonly associated with strong nonlinearities of various interactions of waves and particles and may be treated in terms of synergetics.[1] It appears that the structuring exhibit lifetimes largely exceeding those predicted by the linear magnetohydrodynamics (MHD) in a near-equilibrium range of states. The latter is true of the filaments of electric current as they often appear to sustain their integrity as long as the plasma itself exists and to dominate in plasma dynamics.[2,3] However, the role of filamentation in global plasma dynamics seems to be underestimated yet. Existing numeric hydrocodes for modeling most of the plasmas consider the plasma as a nonfilamentary medium. This could be a reason for the unsatisfactory situation around developing a reliable theoretical description for many important phenomena in plasmas (e.g., heat and particle transport in fusion plasmas). There were a number of attempts to treat the plasma as a set of topologically one-dimensional filaments (fibers) of electric current interacting with each other; however, this appeared to be still insufficient for overcoming existing difficulties in predicting global behavior of plasmas.

The present article proposes to demonstrate the existence of a key element in plasma structuring which, to our mind, has been overlooked, namely the ''nonfluctuative'' nature of the filaments of electric current. This implies that the filaments, besides their unexpectedly long lifetime, possess unexpectedly strong internal elasticity that leads to a long-living networking of electric currents in plasmas. The present demonstration is based on the results of a high-resolution processing, called a method of multilevel dynamical contrasting, of numerous data from laboratory electric discharges and observations of cosmic plasmas in a very broad range of length scales. Here we illustrate the applicability of the method[4] for processing the images in a broad spectroscopic range, from rf to soft x-ray images, and introduce a novel element of networking, namely formation of the ''stockings'' woven by the individual filaments.

II. A METHOD OF MULTILEVEL DYNAMICAL CONTRASTING

Formation of complicated three-dimensional (3D) structures in plasmas with substantial deviations from axial symmetry is a challenge to conventional approaches of reconstructing the macroscopic parameters of a continuous medium. Even in the case of applicability of the tomography methods which are based on processing a set of images taken from different positions, either of the optics collecting the plasma self-emission or of the sounding equipment, the heterogeneity of plasma structuring makes the originally *ill-suited* problem much more hard for choosing a reasonably unique solution. On the other hand, the heterogeneity caused by the plasma networking, unlike to irregular, stochastic heterogeneity, opens the possibility to reconstruct the networking, provided the latter manifests itself in a broad range of absolute values and spectral distributions of emitted radiation. It appears that the latter is the case for a very wide class of laboratory and cosmic plasmas. The hypothetical networking suggested by the analysis[5,6] of the database on large-scale filamentary magnetoplasma configurations implies that there is a hierarchy of electric current filaments and their networking. An extrapolation of phenomena[5,6] to the larger and smaller length scales leads to the conclusion that the fine resolution of available 2D images with respect to absolute values of the intensity could shed considerable light on the survivability (i.e., the lifetimes) of individual filaments, their interaction and networking. To this end, a method of multi-

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level dynamical contrasting has been developed which allows one to identify the 3D networking in plasmas.

The method is based on the following assumptions suggested by the results of compiling the database from various diagnostics[5,6] (visible light and x-ray imaging, laser interferometry and shadowgraphy).

(a1) The image allows the extraction of individual *filaments of enhanced emissivity* because the jump of observed intensity at the borders of the individual filaments exceeds, by a factor up to several units, the level of irregular fluctuations of the intensity around the border (i.e., the border is resolvable on the background of irregular fluctuations and other formations located on the same line of sight).

(a2) The variation of the observed intensity within a certain filament in its longitudinal direction, if interpreted in terms of the *perspective*, allows the reconstruction of the 3D (curvilinear) shape of the filaments (i.e., resolving the observed intensity in a longitudinal direction makes the filament's image a volumetric one).

(a3) The interpretation of superposed images of different filaments is feasible, allowing for the filament's refractive index (e.g., the filament of a denser plasma works as a *negative lens*).

Within the frames outlined the identification of structuring involves a compilation of the following procedures:

(p1) The processing involves, as a major element, the proper contrasting of the images. As far as the filamentation has its own hierarchy within a broad range of absolute values of the intensity, the contrasting should be essentially a *multilevel* one. Thus, one has to sustain a 2D step-wise transformation of the 2D distribution of the observed intensity within the image. The strategies of contrasting may resemble those used in the methods of fractal dimension analysis.

(p2) In order to prevent one from misinterpreting the structuring which may and often does occur for a fixed map of contrasting, a variation of the levels of contrasting is needed (we call this a *dynamical* contrasting). Dynamical contrasting implies that only those structures are actually present in plasma which survive while the multilevel contrasting varies. Unfortunately, sometimes the complexity of dynamical contrasting makes it very difficult to illustrate conclusions which came from watching an animated cartoon: presentation of only a few pictures, or even a single one, leaves the reader an opportunity to believe in the author's sound mind.

(p3) Finally, extraction of structuring requires respective extraction of certain levels of observed intensity, e.g., within a band at a certain level of intensity. Such a processing (we call this a *stripping* of the image) makes the identification of structuring much easier and more reliable.

There is also one more circumstance that makes the identification of structuring more reliable. This is a strong deviation from local thermodynamic equilibrium (LTE) in the sense that the plasma appears to be a fine, short-scale ''mixture'' of the states covering a broad range of effective temperatures, ionization states, etc. (This is true, e.g., of the most of inertially confined plasmas.) Under these conditions the structuring may be often seen simultaneously from processing the images taken in essentially different spectral ranges of emitted radiation. The matter is that the images taken (e.g., in visible light and soft x rays) disclose quite the same patterns of structuring at length scales much larger than those of the above-mentioned mixing. This does not imply that the absolute values of intensities observed in different frequency ranges must have the same order of magnitude. Nevertheless, with increasing the sensitivity of diagnostics one could resolve the structuring in various frequency ranges.

A detailed illustration of the successive stages of stripping the original visible-light image of the Z-pinch may be found in Ref. 7, Sec. II.

III. THE HIERARCHY OF PLASMA NETWORKING

An application of the method outlined in Sec. II enabled us to formulate generic features of electric-current carrying plasmas.[4] Here we give a short scope of the hierarchy of plasma networking that includes the following levels of self-organization in plasmas.

A. Filamentation of electric current

The lowest level pertains to the well-known fact of the filamentation of electric currents.[2,3] However, the nonfluctuative nature and the respective, unexpectedly large lifetime of the filaments—as compared to predictions of conventional theories of plasma kinetics and magnetohydrodynamics—have not been recognized in full. For instance, as far as the filaments are formed at the very birth of the plasma, there is no need to treat filamentation as a self-organization of the originally nonfilamentary plasma. However, one may treat conventional, nonstructured plasmas as a limiting case of the microscopically filamented plasmas.

The interpretation of the filament(s) of emissivity is a complicated task. However, in what follows we will associate the term ''filament'' with a fiber of electric current which is known to be subject to a pinching by its self-magnetic field and, thus, can simultaneously be a filament of particle density and/or temperature. Fortunately, major conclusions about plasma structuring appear to be rather insensitive to rigorous mathematical definition(s) of the filament. Indeed, the data suggest that each individual filament is formed by at least a couple of the mutually wound subfilaments (see Fig. 1, upper) to make the filament stable and elastic both in transverse and longitudinal directions. Note that the interchanging of subfilaments within the filament makes them identical and substantially increases the stability of the filament.

The thinnest filaments resolved in laboratory plasmas produce damage of the micrometer size scale at the surface of the electrodes. It was found[3] that with increasing electric current the projection of the interior of the electron beam filament shows a circle with a spot in the center. This is compatible with the transverse projection of the two wound subfilaments (see Fig. 1, upper).

It appears that the strongest filaments may retain their integrity during the entire period of electric discharge. For instance, this is clearly seen from tracing the dynamics of filaments in Z-pinch discharges from the very early stage of

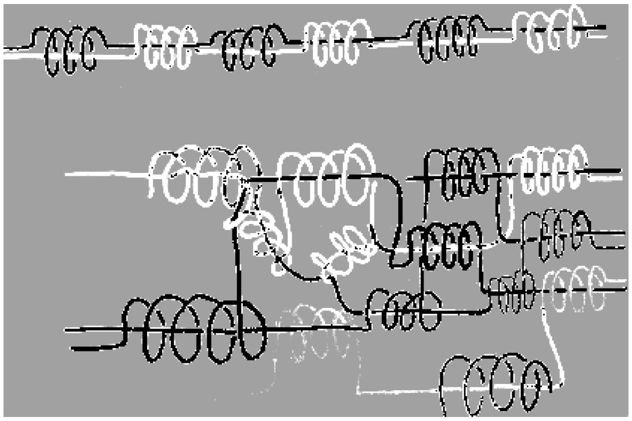

FIG. 1. A schematic drawing of the internal structure of the typical individual filament (upper) and of typical networking of filaments (lower).

the implosion up to compression of filaments at the stagnation stage.[4]

B. Fractality of individual filament

The next level of structuring relies on a fractality of individual filaments. The filament tends to make its internal electric currents (i.e., its subfilaments) magnetic-field aligned and, regardless of internal structure of subfilaments, possesses magnetic torsion which is acquired at the filament's birth and evolves in time. The accumulation, above some threshold, of the energy of the filament's local torsion releases in forming a compact, twisted loop which branches off the filament's main line, roughly in the perpendicular direction (Fig. 2, center). This forms an almost closed helical heterogeneous magnetoplasma configuration (we called this configuration a *heteromac*[4]). Such a branching off makes the single filament a fractal, *treelike* structure (Fig. 2, right). Significantly, the observed branching suggests that the elasticity of the filament is, to a large extent, similar to that of the ordinary elastic thread with relatively free end points because the thread, if twisted enough, produces the same structure.

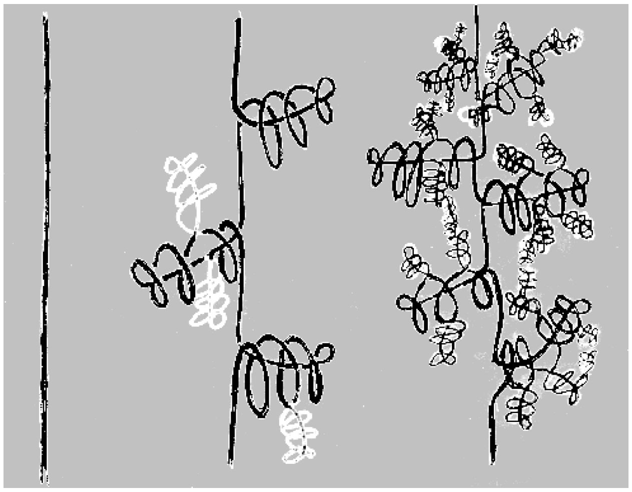

FIG. 2. A schematic drawing of successive branching of an originally one-dimensional filament (left drawing), which produces the heteromac(s) (center) and makes individual filament a fractal formation (right).

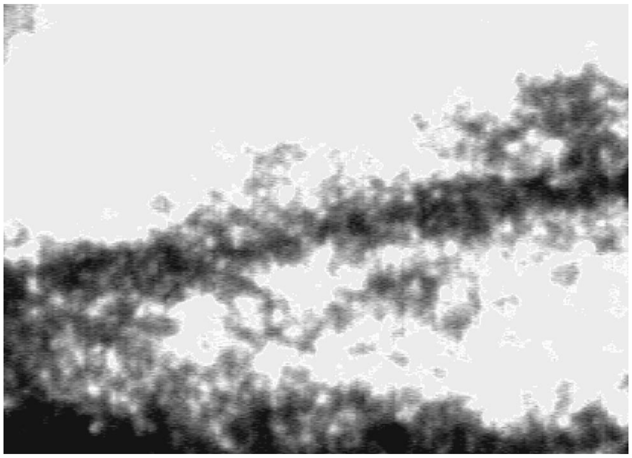

FIG. 3. The image of individual filament extracted from visible light image of Z-pinch discharge (2.2×1.6 cm, Z-pinch axis is directed horizontally).

Figure 3 shows an individual filament resolved in visible light at the initial stage of Z-pinch discharge (here and below, for Z-pinch experimental conditions see Ref. 7, Sec. II). Figure 4 shows formation of distinct heteromacs on the individual filament. The filament (and its internal structure, of much larger length scale) and in another frequency range can be found in Fig. 17 in Ref. 4 which gives a processed image of the ultraviolet picture of the Sun[8] (that figure was to illustrate the existence of a hypothetical *dark filaments* in cosmic space as it has been suggested by extending the approach,[4] formulated originally for laboratory plasma, up to maximal identified length scale in the universe, thus extending the pioneering approach by Alfvén;[9] see Sec. 6 in Ref. 4). Moving from the Sun to larger length scales, one may find the signs of a distinct filament in a processed image of the radio source[10] (Fig. 5). The matter is that the stellar objects appear to be incorporated into a unified network and, thus, either belong to a local thick filament or are entered by the thin filaments (also see Fig. 20 in Ref. 4 and Figs. 6 and 7). Significantly, very often the sequence of stars indicates that their mother (dark) filament is quite similar to the layout of hot spots at individual electric current filament in laboratory plasmas.[4]

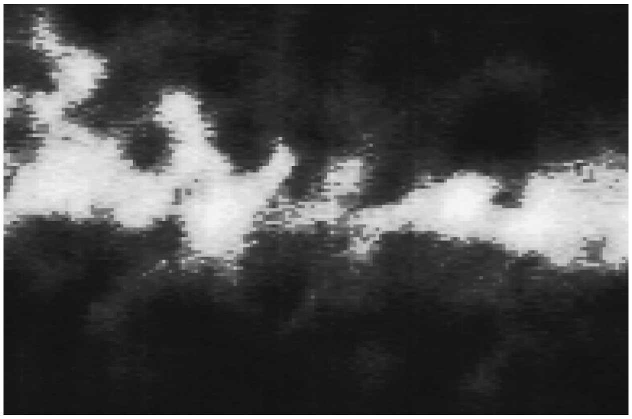

FIG. 4. Formation of distinct heteromacs on the individual filament (0.8 ×0.6 cm, Z-pinch axis is directed horizontally).

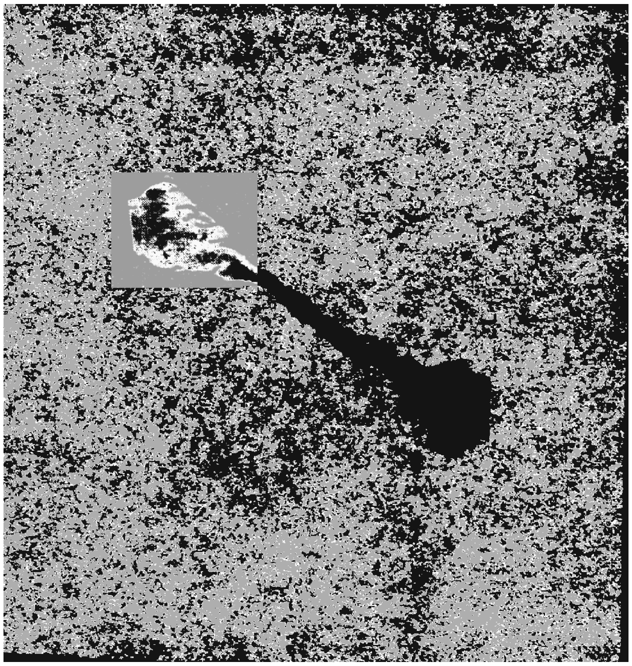

FIG. 5. A distinct filament which enters the lower part of the dumb-bell of the radio source 2354+471 (wavelength $\lambda = 20$ cm, original picture from Ref. 10).

C. Networking of filaments

Interaction of individual long-living filaments (both fractal and non-fractal) leads to a networking of electric currents in plasmas. Significantly, in laboratory plasmas the networking starts from the very beginning of discharge and very often leads to formation of the stocking(s) which is/are *regularly* woven by the individual filaments (see Fig. 1 in Ref. 7). Such a structuring takes place in a broad range of length scales and electric current values. In particular, the interchanging of subfilaments merely looks like an internal networking of subfilaments. Numerous exciting examples of networking may be found in cosmic space. For instance, the arms of spiral galaxies usually look like a branch of a tree (i.e., like thick filaments) with the stars being the ''fruits'' illuminating the fine structuring of the arms. Unlike the purely gravitational picture, there may be seen the sequences of stars directed roughly perpendicular to the galaxy's arm (i.e., the heteromacs). Figure 6 shows a processed image of the spiral galaxy M100 (the original is taken from the Hubble Space Telescope gallery)[11]. At the periphery of the galaxy the image is inverted to show the integrity of networking inside and outside the core. Also a number of unexpectedly long ''needles'' may be seen. Figure 7 shows a networking involving the galaxy M33 which looks like a stratum formed by the heteromacs branching off a distinct thick filament (note that the heteromac is obviously a stiffer formation than its mother filament and should, therefore, possess larger energy density and stronger emissivity).

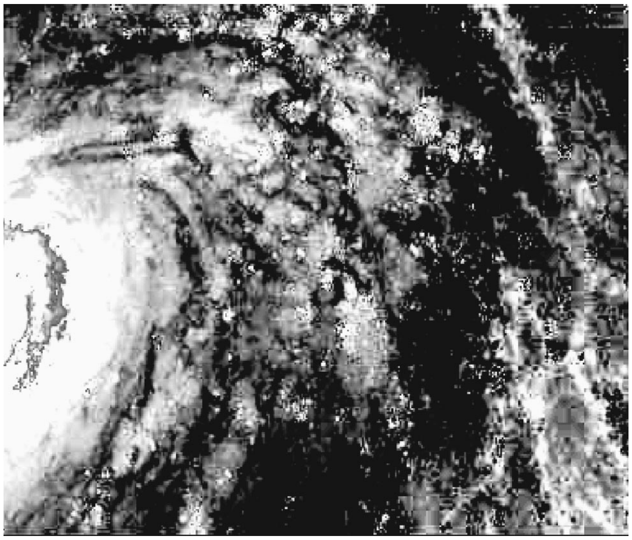

FIG. 6. The arms of spiral galaxy M100 (Hubble Space Telescope gallery, Ref. 11) contain the sequences of stars directed roughly perpendicular to galaxy's arm and thus resemble heteromacs branched off the arm. At galaxy's periphery (right hand side of picture) the image is inverted to show the integrity of networking inside and outside the core.

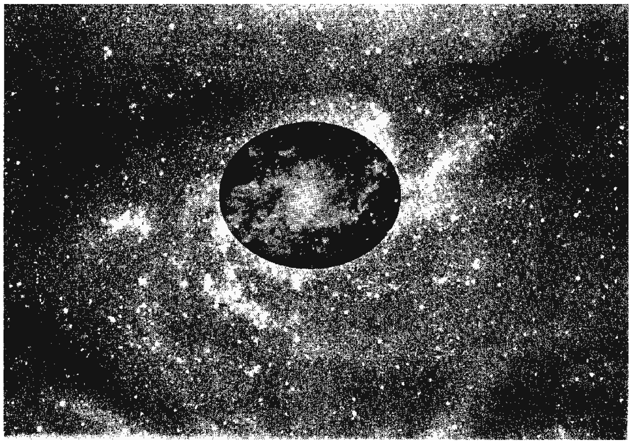

FIG. 7. A networking, which involves the galaxy M33, suggests the galaxy to be a stratum formed by the heteromac(s) branched off a giant cosmic filament (or a filamentary network). The ''necking'' of this filament is seen just below the core of the galaxy (see Sec. III in Ref. 7).

D. Fractality of the entire plasma

The fractality of individual filaments and their networking leads to a fractality of the entire plasma in which the filaments have enough self potential energy and enough freedom. This implies the self-similarity of the building blocks of the network at essentially different length scales. For instance, the entire plasma formation may have the form of few filaments only or even of a single one (the well-formed Z-pinch at stagnation stage often resembles a single filament). And conversely, the individual filament has a complicated internal structure which tends to take the form of a fractal force-free configuration. This is why the heterogeneous structuring of the filament may be seen in a broad spectroscopic range of emitted radiation, regardless of the lower cutoff length scale for the thinnest filament (a *protofilament*, which we associate with at least a couple of the mutually wound streamers).

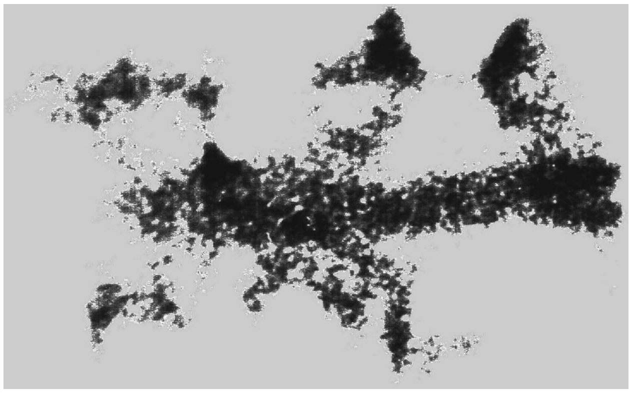

FIG. 8. The cancer-like formation in a ‘‘stripped’’ image of a small part (7.5 cm diam circular layer) of the 60 cm long Z-pinch (Z-pinch axis is directed horizontally).

E. Percolatory networking and plasma synergism

Finally, the long-range bonds provided by the filaments make the network of electric currents in the plasma a *percolating network*. Such a network is characterized by the correlation length tending to infinity with saturation of the local bonds between the neighboring building blocks of the system (the latter corresponds to achieving a threshold, the percolation threshold). The strongest filaments (i.e., ones possessing highest electrical conductivity) form a backbone component of the entire network (this works like a *central* nerve system of the plasma body), whereas the weaker filaments form a local order within the entire network (this works like a *peripheral* nerve system). Significantly, the percolation in plasmas is based mostly on the long-living structures rather than the fluctuative, purely chaotic formations so that the interpretation of structuring in plasmas in terms of the turbulence in the fluid-like plasmas should allow for the anomalous survivability of filaments. Thus, the self-organization goes far beyond the fractality as itself. The above sequence of processes—from forming the proto-filaments to networking of filaments to give the filament-made stocking(s)—may be considered as a self-organization cascade in a wide range of length scales. The resulting synergism may be illustrated by the fact that sometimes plasma formations resemble biological structures (see Fig. 8 taken from the same Z-pinch experiments[7]).

ACKNOWLEDGMENTS

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