FILAMENTATION AND NETWORKING OF ELECTRIC CURRENTS IN DENSE Z-PINCH PLASMAS

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Abstract

The results of high-resolution processing using the multilevel dynamical contrasting method of earlier experiments on linear Z-pinches are presented which illustrate formation of a dynamical percolating network woven by long-living filaments of electric current. A qualitative approach is outlined which treats long-living filaments as a classical plasma formation governed by the long-range quantum bonds provided, at the microscopical level, by nanotubes of elements of optimal valence. The self-similarity of structuring in laboratory and cosmic plasmas is shown, and examples are found of nanotube-like and/or fullerene-like structures of cosmic length scales.

1. INTRODUCTION

Recently [1] the self-similarity of plasma structuring, in a very broad range of length scales and macroscopic densities of electric current, has been revealed in analyzing laboratory and cosmic plasmas, with the help of the multilevel dynamical contrasting method [1]. This covered about thirty orders of magnitude, from micrometer thickness of individual filaments in laboratory discharges to about 10^{27} centimeter size of the structures in the universe, which resemble the plasma formations in magneto-inertially driven systems (gaseous [1], wire and wire-array Z-pinches [2], and plasma foci [3]). The broadness of the length scale range and the unique survivability of the filaments (very often some of the filaments sustain their integrity during almost the entire period of the discharge; in gaseous Z-pinches, from electrical breakdown up to the Z-pinch neck's disruption [1]) suggest that the microscopic mechanism of the filamentation could have a universal nature. The unexpectedly high elasticity and enhanced conductivity of filaments suggest that only the quantum bonds can provide such a survivability rather than classical magnetoplasma mechanisms. The dissociation of conventional molecules at the ambient plasma temperatures in the range above 1 eV should prevent sustaining the long-range quantum bonds. Therefore, the identification of strong long-range bonds in high-current gaseous discharges [1,3] suggests that there should be a sort of fiber-like molecule of enhanced stability.

The latter is the case for the carbon nanotubes that have been discovered [4] and intensely investigated in recent years (see, e.g., the survey paper [5]). The following properties of the nanotubes are essential: (i) unique mechanical stability and cohesion; (ii) high efficiency of cold autoemission of electrons and thermoelectric emission; (iii) the ability of assembling large, macroscopic clusters; (iv) high enough conductivity of individual nanotubes in a wide range of major parameters that make some of them ideal 1-D quantum wires; (v) most economic consumption of the relevant available material to produce stable long-range quantum bonds. There are a number of sources for forming the nanotubes under laboratory conditions: namely, (a) vacuum pumping system (organic or silicon oil are normally used in the diffusion pumps); (b) vacuum chamber internal surfaces (in well-formed plasmas, as a rule, one may find carbon: namely, graphite-containing walls and limiters in most "successful" tokamaks and other magnetic-confinement facilities); (c) the loads (e.g., better operation of the organics-containing condensed-matter liners in dense Z-pinches). The production of the nanotubes in relevant quantities seems to be a key element of the pre-breakdown stage of those electric discharges which produce long-living filaments and, consequently, well-formed plasmas. A qualitative model of electrical breakdown, which is based on the production and assembling of the nanotubes to give observable long-living filaments of electric current, and its relationship to the streamer mechanism of the static-voltage electrical breakdown are presented in [6].

2. NETWORKING PICTURE: FROM PROTOFILAMENTS TO COSMIC SCALE AGGREGATES

The thinnest filament is the 1-D formation in which the nanotubes are successively connected by the effective current of plasma electrons. The instability of this formation makes it reasonable to associate the term protofilament with the configuration which can self-sustain its structure. The latter is true of a couple of the mutually wound subfilaments. It follows from the qualitative picture [6] that (i) the mutual winding of self-sustained electric currents (due to the tendency of the system to build up a force free magnetic configuration) starts at nanometer length scales and is supported by the quantum and classical electric currents, respectively, on and around individual nanotubes; (ii) this self-organization process sustains the observed fractality (i.e. the self-similarity of structuring at various length scales) throughout the entire range of length scales via sustaining the plasma-solid structuring of the system [individual nanotube + its microplasma]. The latter system plays the role of the basic microscopic building block of the resulting percolating network.

2.1. Dendritic structures, the "needles", and the "stockings"

The analyses [1] enables us to suggest that the anomalously high, on ordinary plasma scales, elasticity and, sometimes, even the stiffness/rigidity of the observed filaments, stem from the presence of the microsolid component of high electrical conductivity. The latter component allows electric current to concentrate at a level sufficient for the magnetic forces to glue the microsolid component to produce an elastic formation. With increasing electric current through the filament and respective growth of the azimuthal component, kinks appear which gradually produce highly localized twisted loops. Such a loop forms an almost closed, heterogeneous magnetoplasma configuration (so called heteromac [1]). Formation of heteromacs makes an individual filament a dendritic structure (Figs 1 and 2; the optics collected the light through a circular diagnostic window, in a perpendicular direction to the facility's major axis, from a layer of 7.5 cm diameter and 5 cm depth, located on the major axis of the facility; for other experimental conditions see [1]). This leads to fractality of individual filaments. The sticking of microsolid blocks together in the heteromac results in the formation of a needle-like structure directed, as a rule, perpendicular to the major direction of the electric current (Fig. 3) (see also Figs 5(a), 6, 10, and 11(a) in [1]). The plasmas which manage to form long-living filaments of electric current are able to make long-living networks of these filaments. Microscopically the networking can manifest itself in establishing microsolid links in direction perpendicular to the current, with the help of available nanotubes. This process starts immediately after breakdown and may produce complicated nested cages, if the available deposit or other sources of nanotubes are sufficient. The resulting magnetic structure around the cage has the form of a "stocking" woven by the plasma component of the respective filaments (Fig. 4). Such a structure was called a "magnetic stocking" [7] and was suggested to be the basis for explaining a number of phenomena observed in tokamak plasmas like, e.g., the transport barriers at low-number rational magnetic flux surfaces.

The networking picture allowed us [1] to suggest a transparent qualitative picture for the following phenomena: (1) formation of electric current precursors on the axis, in advance of the major current sheath's convergence; (2) fine structure of the Z-pinch's main body and halo; (3) picture of development and saturation of the magnetically-driven Rayleigh-Taylor instability, allowing for the current sheath's filamentation; (4) the necking of filamentary Z-pinch; (5) fine structure of hot spots. These results allow one to identify the mechanisms responsible for depleting the energy density in the neck.

2.2. Rigid-body structures in space

The self-similarity [1] of networking in a very broad range of length scales, if compiled with the qualitative approach [6] to the microscopic picture of filamentation, suggests the existence of nanotube-like and/or fullerene-like structures of macroscopic size. This implies that the quantum bonds which produce rigid-body formations like nanotubes and fullerenes may produce rigid bodies of much larger length scale with the same topology of the links between major building blocks. This opens unprecedented opportunities to investigate structuring at atomic and molecular length scales by analyzing formations that are much easier to observe. Alternatively, the presence of rigid-body formations of macroscopic size in laboratory electrical discharges and cosmic plasmas may be regarded as evidence for the quantum nature of long-living filamentation. Laboratory plasmas are prolific with various patterns of resolvable long-living rigid-body structures (see Sec. 2.1). However, the most exciting examples come from the cosmic length scale database available from the NASA Hubble Space Telescope Gallery [8]. First, the data suggest that stars or other similar radiation sources merely illuminate locally the structures which seem to penetrate the entire universe (cf. magnetoplasma universe concept [1], Sec. 6). Here, the best example is what the astronomers called "powerful laser beamed from chaotic star" [8]. The "doomed" star observed in our galaxy in ultraviolet radiation and called Eta Carinae reveals a fairly regular form of the nebula's outer shell. A typical fragment shown in Fig. 5 suggests that the hypothetical laser beams could merely be filaments of microsolid origin (note the presence of single heteromacs on these filaments and the dendritic structure of the "beams"). Second, the results suggest that endohedral fullerenes [9] of several-wall and single-wall structure and similar nanotubes may be the "microscopic generators" of the structuring of most planetary nebulae. The petal-like structure of the image of planetary nebula IC 3568 (Fig. 6) signals the presence of strong rigid-like bonds between central mass and the "quantized" outer shell. Figure 7 shows what the astronomers called "the final blaze of glory of Sun-like star" [8], with the tubule-like structure being interpreted as a shell of ejected glowing gas. The microsolid component-based approach suggests this to be a macrotube illuminated and distorted by the encapsulated star. The same could be true of similar macrotubes of non-single-wall structure available in [8].

3. CONCLUSIONS

The whole picture of well-formed plasmas results from the complicated interplay of the conventional, fluid component and the microsolid component. The addition of the microsolid component's dynamics to existing theoretical formalisms and computational schemes might significantly extend their capabilities. The strong coupling of the physics of well-formed plasmas to solid state physics that is suggested by the results of the present paper, on the one hand, doesn't contradict the well-known successes of the existing approaches and formalisms (e.g., the long-living filaments may be responsible for the suppression of numerous instabilities predicted by the theory) and, on the other hand, opens new opportunities for resolving existing difficulties (e.g., in describing the nonlocal transport phenomena).

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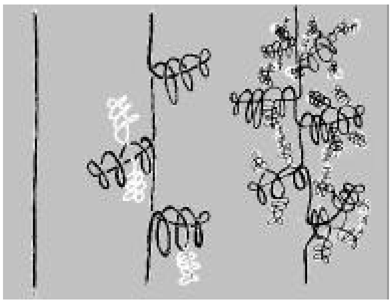

Fig. 1

FIGURE CAPTIONS

Fig. 1. A drawing of the branching which produces the heteromac(s) and makes an individual filament a fractal formation.

Fig. 2. Typical experimental picture (taken in visible light, 15 ns exposure) of individual strong filaments in the Z-pinch (positive, frame width ≈2 cm). A heteromac is seen which branches off the individual filament in the right-hand side of the figure.

Fig. 3. The needle in the lower window, where the contrast of the original image (similar to Fig. 2; negative, frame height ≈ 7.5 cm) has been enhanced, is perpendicular to the major current.

Fig. 4. A stripped image of the dense Z-pinch (visible light image, similar to Fig. 3) which exhibits formation of the stocking woven by the plasma component of long-living filaments.

Fig. 5. The beam-like structures produced by the "doomed" star Eta Carinae [8], which possess internal structuring, similar to that of the microsolid-based filaments, and acquire dendritic form.

Fig. 6. The processed image of planetary nebulae IC 3568 suggests the presence of strong rigid-like bonds between central mass and "quantized" outer shell.

Fig. 7. The tubule-like structure of what the astronomers called "the final blaze of glory of Sun-like stars" [8]. The microsolid component-based approach suggests this to be a macrotube illuminated and distorted by the encapsulated star.

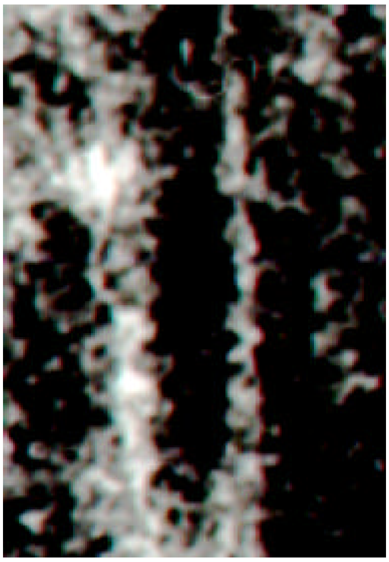

Fig. 2

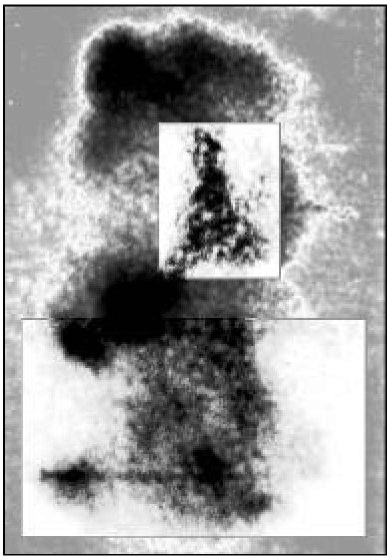

Fig. 3

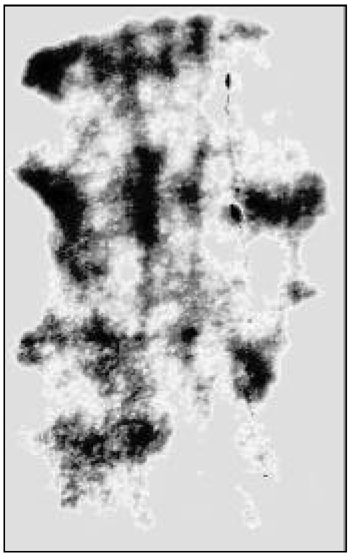

Fig. 4

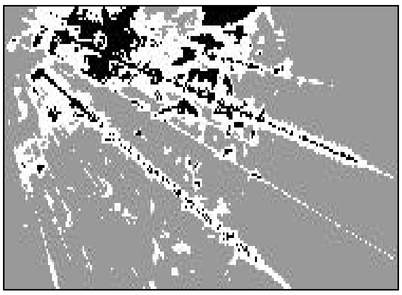

Fig. 5

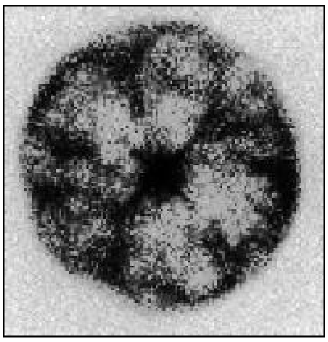

Fig. 6

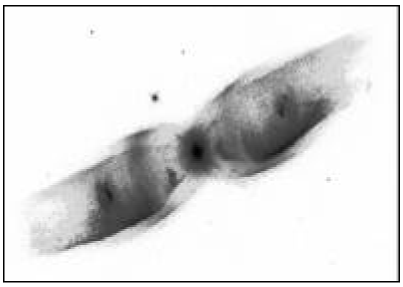

Fig. 7