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# A Hybrid of Aerogel and Plasma Models of Ball Lightning: an Inductive Storage Wildly Formed by a Nanotube-Assembled Skeleton

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1. Introduction. An analysis of the probable role of nanodust in severe weather phenomena [1(A,B)] encourages us, in extension of [1(C,D)], to come back to the ball lightning (BL), another atmospheric phenomenon whose longevity is anomalous from viewpoint of plasma chemistry kinetics. A fusion of the following two hypotheses, namely:

(1) for the probable role of nanotubular dust in the observed anomalous longevity of filamentary structures in electric discharges [1(E)] (see [1(F)] for a survey of proof-of-concept studies of that hypothesis, and [1(A)], for a summary), and

(2) for the origin of BLs, especially of those of *high energy store*, treated as a rare atmospheric analog of much more investigated phenomenon - the filaments of electric current in high-current laboratory discharges,

enabled us to suggest a unified treatment of both phenomena that requested, though, substantial modification of the existing approaches to each of them. Regarding the BL, this resulted [1(C,D)] in the following alterations of the concept [2,3] of the presence, in BL, of a rigid skeleton of aerogel type.

(i) A (ball-shaped) skeleton is electrodynamically assembled from solid nanoblocks *in advance* of plasma formation (contrary to formation of nanoblocks at the stage of plasma decay/cooling by the plasma coagulation/clustering and further assembling of a fractal from such blocks [2,3]). Thus, we suggest to interpret post-discharge observations [2,4] of fractal aggregates fastened to the walls of the vacuum chamber as being caused by the nucleation/deposition of the vapor at a skeleton formed yet at the electric breakdown stage of discharge.

(ii) A search for nanoblocks which may *facilitate* electric breakdown (e.g., via anomalous emission of electrons by these blocks, both via thermal and electric field-emission mechanisms), assemble *macroscopic* skeleton, and trap and hold, with *low dissipation*, the magnetic field and high-frequency (HF) EM field, suggested a new candidate - nanotubular structures (most probably, carbon nanotube (CNT)).

(iii) A substantial store of *magnetic* (and electromagnetic) energy in BL is possible (~ > 1 MJ), which is finally responsible for luminosity of BL during anomalous long time (contrary to luminosity due to hot-spot *chemical* combustion of skeleton [3]), and for elasticity of BL.

Such an approach delivers key role to anomalous magnetic properties of nanoblocks and of their assemblies. Evidences for such properties in CNT assemblies were reported recently (see refs. [17,18] in [1(A)]). Evidences [5] for skeletal structures composed of nanotubular blocks, in the dust deposits in tokamak, also support this approach.

2. BL as an inductive storage.

The above approach [1(C,D)] to BL gives the following hybrid of «aerogel» model [2,3] and «plasma» models of BL (for the comparison of these models see survey [3(A)]).

In the plasma models, BL is considered to be a product of electric discharge which gives the spheromak magnetic configuration. This assumption is well supported by the experimental data on spheromak production and confinement in a magnetic flux conserver, and by the success of theoretical prediction [6] of evolution towards force-free magnetic configuration. The strong point of plasma models of BL is that this approach relies on the well-known advantages of spheromak configuration for confining the plasma. The weak point of any plasma model is that the lifetime, $(\tau_E)_{pl}$ , of plasma thermal energy is too short – at least, because of radiative losses. Indeed, available experimental data on $\tau_E$ in laboratory plasmas suggest that, for energy store of 10 kJ (which is typical value both for the laboratory spheromaks, without auxiliary heating, and for BLs ), the value $(\tau_E)_{pl}$ ~ 1-10 ms is much smaller than typical BL's energy lifetime, $(\tau_E)_{BL}$ ~ 10 s. It looks like the spheromak magnetic configuration may actually result from a localized electric discharge in the atmosphere (e.g. from lightning stroke) but the plasma itself is not able to confine the stored magnetic field for long. Therefore, one has to append the plasma model with a highly conducting matter capable of confining the residual magnetic field.. Such a matter has to cope with the heritage of the initial, «plasma» stage of BL, which, for BL of diameter $D_{BL}$ and of stored magnetic energy $E_{MF}$, may be estimated as follows:

$$I_p(MA) \sim \sqrt{\left[\frac{E_{MF}}{10\,kJ}\right]\left[\frac{10\,cm}{D_{BL}}\right]},\; B_p(T) \sim B_t(T) \sim 3\sqrt{\left[\frac{E_{MF}}{10\,kJ}\right]\left[\frac{10\,cm}{D_{BL}}\right]^3} \qquad (1)$$

where $I_p$ is the total electric current, $B_p$ and $B_t$ are the space-averaged poloidal and toroidal magnetic fields, respectively, and $p_{MF}(M\,Pa) \sim 10\,(E_{MF}/10\,kJ)\,(D_{BL}/10\,cm)^{-3}$ is magnetic pressure which for typical BL is as high as ~100 atmospheres.

Let us assume that a BL's skeleton is formed according to items (i) and (ii) of Sec. 1. Note that survivability of skeleton at plasma stage may be possible due to «wild cable» mechanism [1(G)]: an intense luminosity at this stage comes from plasma which is intermittently isolated from the *cold* skeleton by the Miller's force of HF EM field. The total mass of CNT skeletal matter, $M_{CNT}$, which may carry the current of Eq. (1), may be estimated in terms of the typical diameter of CNT, $d_{CNT}$ ; the average number of walls in the CNT, $N_W$ ; and the value of electric current through *individual* CNT, $I_{CNT}$:

$$M_{CNT}(g) \sim 0.1\sqrt{\left[\frac{E_{MF}}{10\,kJ}\right]\left[\frac{D_{BL}}{10\,cm}\right]}\left[\frac{10\mu A}{\mathrm{I_{CNT}}}\right]\left[\frac{\mathrm{d_{CNT}}}{nm}\right]\mathrm{N_W}\,. \qquad (2)$$

Note that the current density of $10^7$-$10^9$ A/cm$^2$ through individual CNT is possible, with $I_{CNT}$ being as high as ~10-1000 μA (see, e.g., [7]).

Assuming that the BL's energy lifetime $(\tau_E)_{BL}$ is determined by the dissipation of magnetic field through Joule heating of CNT skeletal matter, one may estimate the upper value of the resistivity, $\rho_{CNT}$, of this matter:

$$\rho_{CNT}(\Omega\,cm) \le 10^{-8}\left[\frac{D_{BL}}{10\,cm}\right]^2\left[\frac{10\,s}{\tau_{BL}}\right] \qquad (3)$$

(note that evidences and arguments for the room-temperature superconductivity in individual CNT, and in artificial and natural assemblies of CNTs, are summarized in [8]).

Such a hybrid of «aerogel» and «plasma» models of BL is aimed at eliminating the weak points of these approaches via appealing to the properties of CNT's which, however, require much stronger confirmation.

3. Evidences for similarity of fine structuring. The verification of the above approach may include a comparison of the fine structuring found [1(E,F)] in the long-lived skeletal structures in the high current laboratory discharges (including, the fractality of skeletons assembled from tubular and cartwheel-like structures), with that of (i) aerogels and (ii) ball-shaped luminous objects, not necessarily BL's (!), produced by the powerful lightning. Such a comparison (Figs. 1, 2) give a support to the approach of Secs. 1,2.

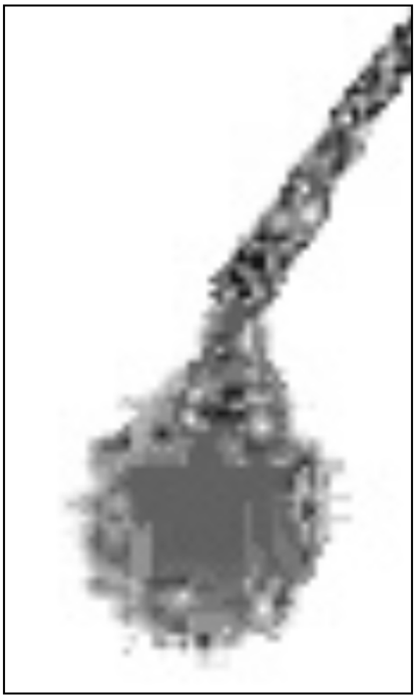

Fig. 1. A fragment of the image of the end point of the powerful lightning which took the form of a ball-shaped structure of the estimated diameter of several meters (the original image is taken from the web-site of Long Island Lighting Co.). The processing of the image with the method of multilevel dynamical contrasting [1(H)]) reveals, on the right-hand side of the ball, the elliptic image of the cartwheel-like structure with the cartwheel's axis directed perpendicular to electric current in the lightning. It looks like the ball may contain a tubular structure (seen as a thick black band) whose axis is directed transversely to lightning's direction.

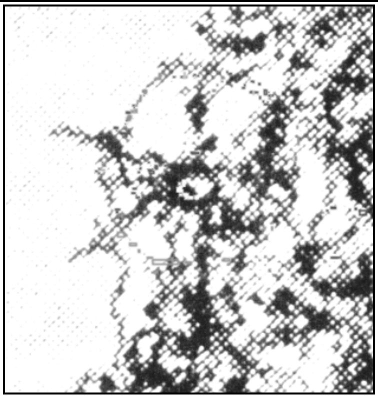

Fig. 2. A fragment of scanning electron microscope image of the aerogel thread [9] obtained in the experiments on laser irradiation (of intensity ~ $10^7$ W/cm$^2$ ) of metallic target in external electric field (image width is ~ 8.5 μm). Such an aerogel is found [9] to be composed of ~10 nm thick filaments. A cartwheel-like structure in the center of the image is located on the left border of the thread's image, where it is easier to identify such a structure. Typical location of cartwheels at thread's surface (namely, perpendicularly to thread's axis) is similar to that of cartwheels found [1(F)] in Z-pinch plasma column.

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