NATURE OF ARTIFICIAL AND NATURAL BALL LIGHTNING

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Introduction

Investigations connected with artificial and natural ball lightnings (ABL and BL) are of interest with respect to a technology of production of high energy objects which can be applied, for example, in transportation of energy for long distances and plasma assisted combustion. Simultaneously created plasma and gas discharge devices for generation of these objects are of self-consistent interest since they could be used in solution of applied problems.

On a basis of experiments [1-3] we consider a model of ball lightning (BL) with a cover made of a melted material and filled by an evaporated gas. It is a natural generalization of a theory [4] elaborated in [5] where BL was considered as an object appearing at a linear lightning impact to the earth with a solid or melted cover filled by a powder material of reduced oxides (for example Si appearing at SiO_2 reaction with organic materials, C, H).

Undertaken experiments [1,2] have shown an appearance of fireballs in discharge conditions in specially designed tubes filled by different organic or inorganic materials, for example basalt which contains Si. (Usually in the scientific literature by fireballs are understood luminescent objects of artificial or experimental modeling but by ball lightning is understood the natural phenomenon.) These objects lived portions of a second being of several mm in a diameter. Their life finished with an explosion or decay. The microscopic analysis of the objects residuals showed that their inside structure consisted of pores and cavities as if the vaporizing processes took place inside them. New experiments [3] undertaking with capillary plasma generators have confirmed many features of fireballs – ABL. This circumstance lead us to a new analysis of works with explosions of experimentally created ABL. Known experiments on creation of empty metallic spheres at explosions of titanium foils in a liquid [6], and explosions of luminescent spheres in experiments with discharges created by Tesla coils [7] indicate an important role of vapor inside of created luminescent objects.

This role is considered in the present paper and included into a new model of BL presented below. As it was shown in [4] cluster theories of [8-9] cannot explain high energy content of BL [10], and their development cannot explain its origination at the linear lightning stroke into the Earth and metallic objects well established in observations [8].

I. Experiments with ABL

I.I. In this section we discuss experiments on creation of artificial ball lightning (ABL) developed in works [1,2] and in [3]. They are devoted to application, generally speaking, of the capillary plasma generator and its modification [2].

A first group of experiments on creation of artificial ball lightning (ABL) were carried out in specially designed tubes [1,2]. The analysis of video recordings of these devices work (it will be clear below) [1,2], the remains of objects and their traces on targets, has allowed to draw a conclusion on presence in them of the oxide, dusty or air-gel covers. Analysis of remains has shown a creation of new, denser core, having the smaller size and continuously generating a cover in the course of existence. The core could be both a tangle of fibers, hollow, porous and firm, but the average density of its substance was always considerably smaller than the density of the initially used material.

On the basis of a small number of cases when it was possible to connect an ability to blow up with the structural remains; the assumption has been made, that namely the firm core and the processes with it effectively leads to the explosion. Objects without a firm core at hitting of an obstacle increase somewhat brightness of the realized luminescence. On the other hand, the objects which do not have fibers on a firm surface in the structural remains do not float in air.

For clarification of roles of a firm core and an air-gel cover in the formation of the specified properties of the fireball we have made the following experiment. In the polymeric tube in length of 160 mm and with diameter of 15.8×10 mm the electric discharge was realized in the 20 mm gap between end faces of the steel electrodes screwed up in the tube with a carving 10.5×1 mm. The tube with the electrodes was located in an aperture of the steel cap tool with a carving 16×1 mm and length of 140 mm, consisting of two halves, which were pulled together by 8 bolts M14, see Fig.1.

For protection of the tube wall from the breakthrough and release of the discharge products in the middle of the tool cap, between the end faces of the electrodes there was made an aperture of 3-3.5 mm in diameter near the tube and of 14 mm in its outer part. The capacity store of 3.9 mF could be charged to 5 kV and be discharged through a throttle by an inductance of 20 μH. Current and radiation sensors allowed to define the moment of the discharge products exit concerning the moment of the discharge current termination. In Fig.2 one can see a plasma stream going out from the hole of this device when alumina or other metallic powder was located inside it.

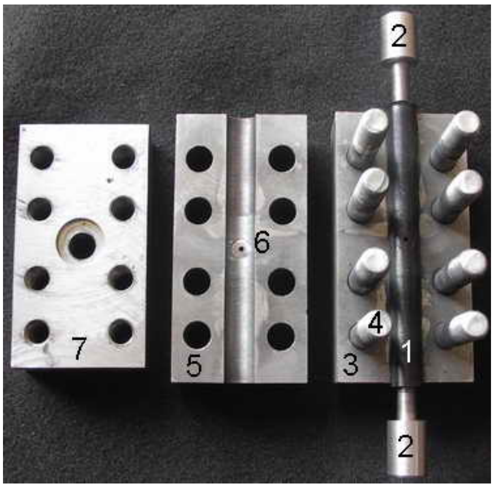


Fig.1.Discharge device. 1- polymeric tube. 2-electrodes. 3-back side of the steel cap. 4- fixing bolts. 5 – front side of the internal steel cap. 6 - internal aperture. 7 – reinforcing cover with an outside aperture [1].

For creation of objects on the basis of air-gel (type 1) 0.5 g of basalt threads was distributed over the discharge chamber, and the store was charged up to 1.8 kV.

For creation of objects with a firm core (type 2) the basalt threads were crushed in a mortar and pressed in the anode, the store was charged to 2 kV.

In the third case (type 3) 1g of the basalt threads and 0.5 g of polymeric fibers were grinded to powder in the mortar and filled the chamber, and on an axis the steel needle in length of 19 mm and 0.6 mm in diameter was inserted. The store was charged to 2 kV.

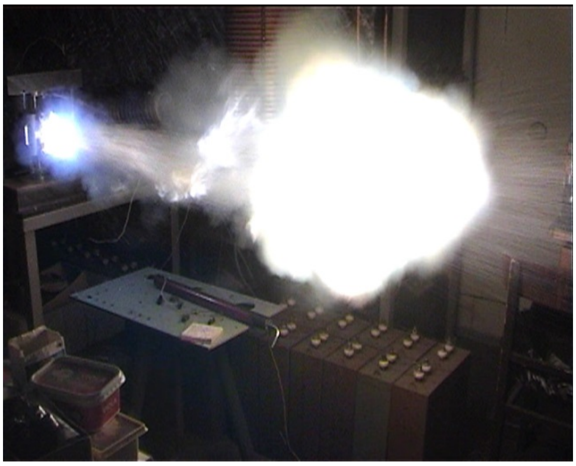


Fig.2.typical appearance of ta plasma flow from the hole in the tube at location of alumina and other metallic powders [1].

The video recording was made by means of the video camera SONY HDR-HC9 in the mode DV of 200 fields per second 720×576 p. In all cases after the discharge realization firstly appeared the supersonic plasma stream, it formed a spherical plasmoid in the stagnation zone. The luminescent formations flying from the discharger after the plasma stream had the low speed, which did not exceed 25 m/s.

Objects of the first type at diameter smaller than 1 cm had a lifetime of ~ 0.35 s. Their brightness and velocity decreased quicker in the beginning and end of the lifetime than in the middle. The trajectory of their movement could contain turns and accelerations. Their structural remain was a tangle of black fibers.

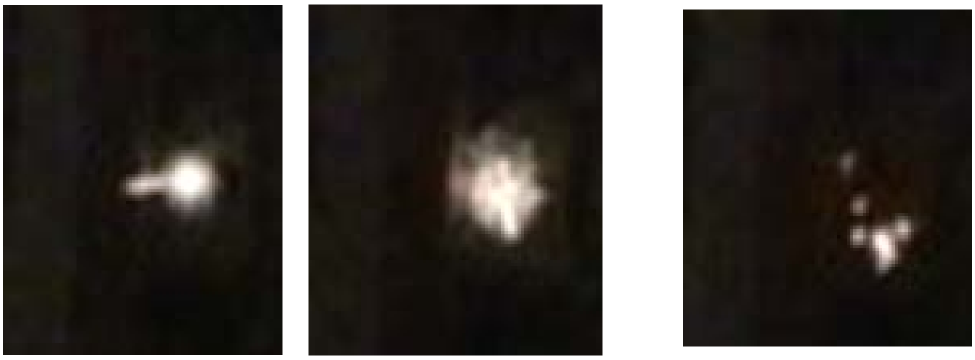
Objects of the second type did not reduce brightness. At the diameter of the object nearby 1 cm, it starts to avalanche- like increase up to the explosion moment approximately during 10-20 ms; nhe diameter of the object considerably increases.

In Fig.3 one can see a sequence of this object movement frames with the explosion at the 130-th millisecond of its life time.

The part of the substance remains in the discharge chamber. In Fig. 4 a,b one cane electronic microscopy images of a piece of this substance which has stuck in the front of the outlet hole. Fig.4a and Fig.4b show that the cover has appeared during the discharge pulse; it consists of cavities created during the boiling of basalt.

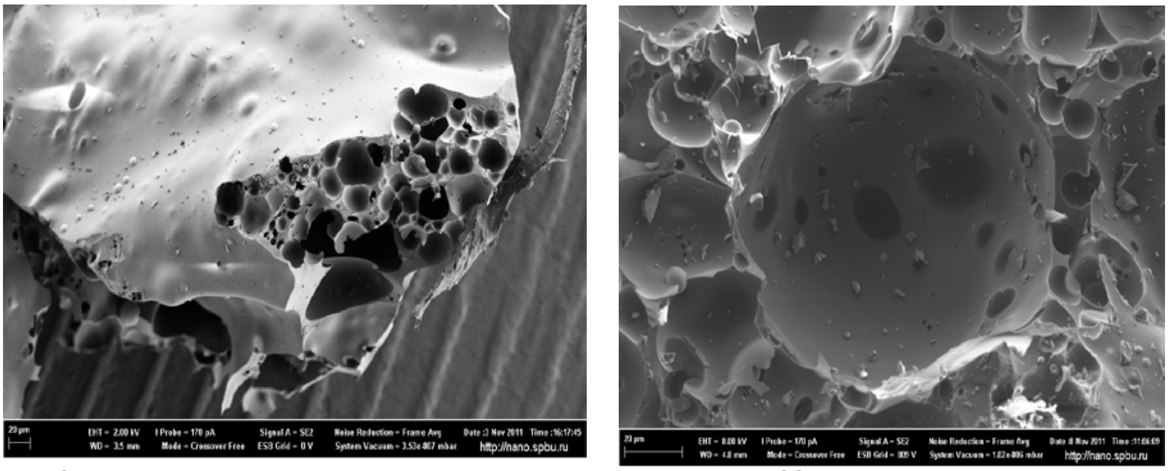
These images of cavities say about processes of boiling inside the structure with creation of vapor with risen pressure, which lead to the explosion of the ball

The behavior of the objects of the third type essentially differed from the described above. One of them had a bright luminescence at the start from the discharge device, approximately through 10 ms after the discharge, it moved with a speed about of 25 m/s. During the first 60 ms its speed was stabilized at a value of about 5 m/s, and the luminescence has decreased to poorly noticeable in the video recording. During the subsequent 150 ms the object, moving over a horizontal trajectory without change of the speed and brightness, has turned to the right for 90 degrees and has passed along a case. After that its luminescence began to amplify, it has sharply stopped and has slightly jumped aside, having thrown out sparks, hanged for 100 ms, and then began to fall vertically with gradual attenuation of the luminescence. Full time of its existence before the luminescence went out was about 0.6 s.



3.a) 3. b) 3.c)

Fig.3 a)-c) Sequence of the object explosion events [1].

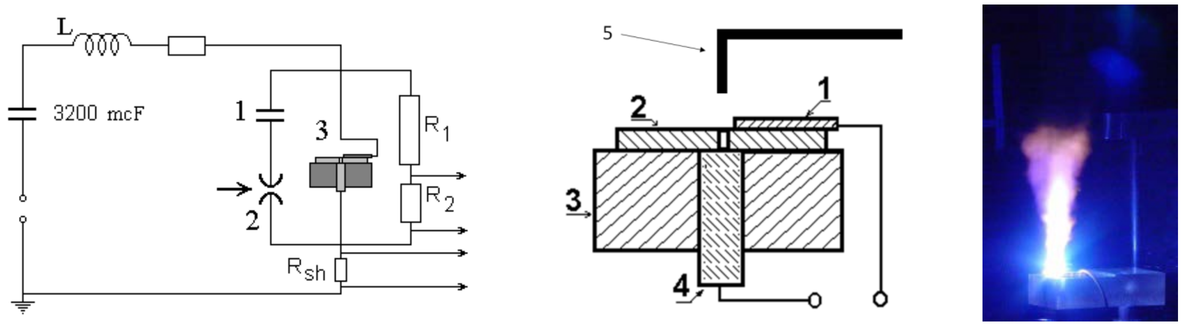


4.a) 4.b)

Fig.4 a), b) - images of the surface substance (scale 20 μ m) [1] .

II. Here we describe a group of experiments [3] which are development of successful experiments on production of ABL on a basis of organic polymeric materials [11]. These experiments were carried out using a capillary plasma generator. A schematic diagram of the plasma generator is presented in Fig.5a. It represents a circuit which includes a capacity (1), a commutator (2) and the discharge device (3), which is composed of planar electrodes separated by a dielectric capillary, see Fig. 5b. Above an output hole (a capillary), from which the plasma jet is ejected into air, a metal wire is located. It is used to form the ABL at interaction of the plasma with the wire metal. The maximal current value was 100 - 150 A. The total storage capacity was C = 3200 μF. For realization of a discharge we used a capillary in the plexiglass (PMMA) with a diameter of 1-2 mm and a length of 3-4 mm. The lower electrode (4) in Fig.5b is made of tungsten alloy with copper, the upper electrode is of copper, the remaining elements of the construction of the plasma generator are made of the plexiglass.

A video recording was carried out in a continuous mode with a help of the video camera with a frame duration of 33 ms. A typical length of the plasma jet from the capillary was 10−12 cm. Energy stored in the generator was estimated as $W_n = \frac{C\cdot U^2}{2}$, where C = 7 mF –is the capacity of the storage, U = 300 V is the voltage at the generator, so W_n = 315 J. The energy going to the jet is usually 50-60% of the energy inputted to the generator, i.e. $W_j \approx 170$ J. A typical appearance of the discharge plasma is given in Fig.4c. A typical discharge time was 10-12 ms, and the maximal time was about 15 ms.

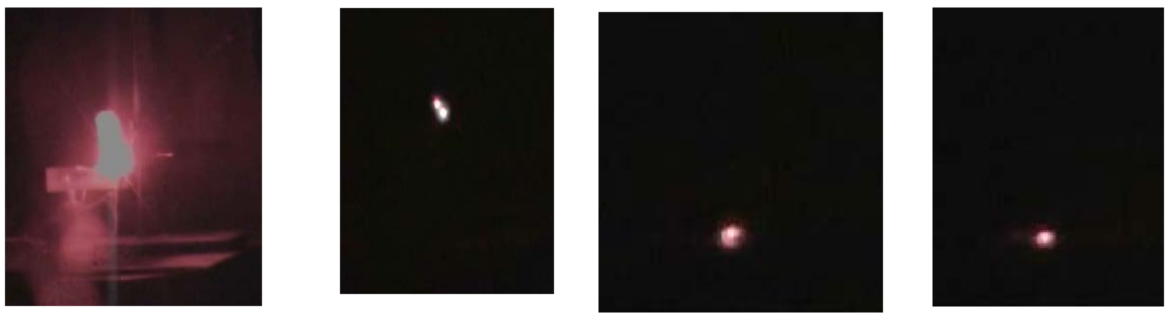


a) b) c)

Fig. 5. Capillary plasma generator. a)1 – initiating capacity, 2-commutator, 3 –capillary, R_1, R_2 – resistances of a voltage divider. b) 1,4-electrodes, 2-dielectric plate, 3-plasma generator's base, 5-metallic wire. c) Capillary discharge at organic glass base [3].

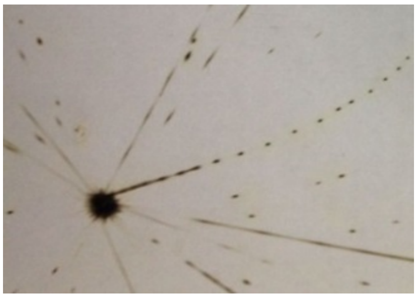
Experiments have been done on the interaction of the plasma jet with a wire of the alloy consisting of about 70% Sn, 20% Pb and 10% organic additives. The lower part of the wire (of a length ~ 0.3-0.5 mm) was heated and melted; and luminous objects flew along with the plasma jet. Frames of these objects are shown in Fig.6 a-c. Fig. 6a corresponds to the discharge, in which ABL have appeared, first frame. In Fig. 6b one can see appearance of two ABLs in the second frame. In the following frames only one object (from initial two) taken at the frames 21 st and 31 st is represented. Later, it has disappeared. The lifetime of such objects was about 1-1.5 s. The apparent diameter of the object was up to 5 mm.

In order to investigate a structure of the luminous spheres, around the experimental setup was spread a sheet of white paper, and ABL, flying out of the plasma jet, fell on the paper leaving traces, see. Fig.7. In the case of Fig.7a a trace in a form of a star has remained on the paper. It allowed to make an assumption, that the explosion of the ABL of alloy and destruction of its material took place at a contact with the paper. It could be realized at a break of the ABL surface at falling with ejection of a vapor from its core. In the case of Figure 3b marks resembled ordinary spots remaining at the fall of a liquid drop; the object did not explode. It "jumped" over the paper, leaving traces of a series of 20 and more. Traces of these objects did not exceed 2 mm in a diameter, and their average value was 0.5-0.8 mm. The size of the "stars" in Fig.6a reached 5-6 mm.



a) *b)* *c)* *d)*

Fig.6. Appearance of ABL. a)-the discharge, b) 2-nd frame, c)-21st frame, d)-31st frame [3].


a

b

Fig.7. Appearances of ABL traces [3].

There were also done experiments in which the ABLs fell into a cuvette with water. In Fig.8.one can see an appearance of these balls. Some of them sank in it. Some of them appeared on the water surface. The average radius of these floating spheres was 1 mm. When one tried to get the sphere out of the cuvette, it was destroyed. Inside of the cover one found a metal ball of ~ 600 µm in a diameter.

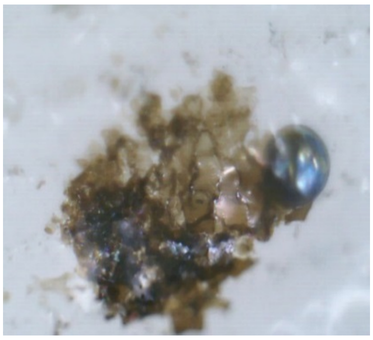
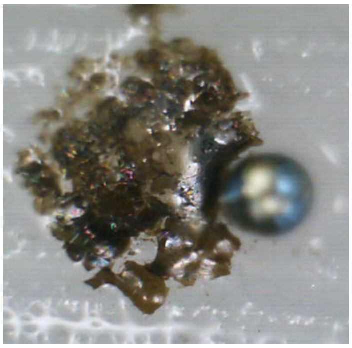
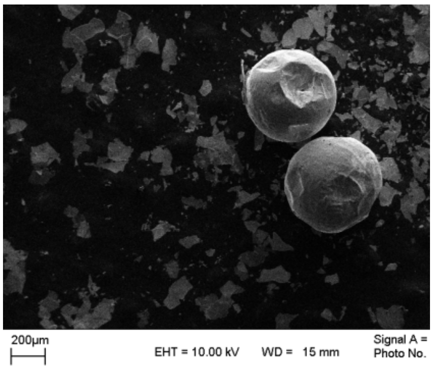
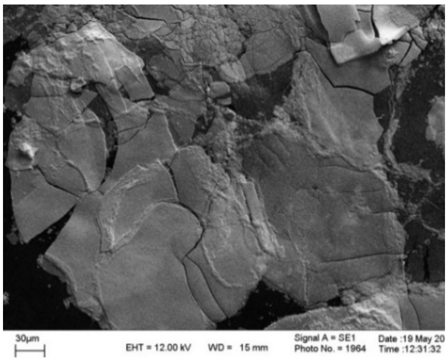



Fig.8.Typical sizes of the ball composition: diameter of the cover d = 1 mm, diameter of the ball 0.2-0.6 mm [3].



a)



b)

Fig.9 Photos of the sphere. An internal ball a), a cover b) [3].

Fig.9a shows a SEM photograph of two balls got from two "hollow" spheres, and Fig. 8b shows a cover of the "hollow" sphere. From these photos one can find that the ball's diameter was about 600-640 µm and a thickness of the cover was about 8-12 µm. There was also held a mass spectrometric analysis of the material of the balls and covers. The composition of the sphere was O: Sn: Pb = 14.95: 67.59: 17.34%. The composition of the cover included light metals. However, an amount of oxygen is higher in the cover. This speaks about possible oxidation processes at the formation of the cover.

An appearance of the metallic ball in the "hollow" sphere when it falls into the water indicates the condensation of a vapor inside the metallic sphere at its cooling. This confirms the conclusion of [5,11] on the possibility of the objects formation filled with a metallic steam at the interaction of the plasma with metallic objects.

Character of death of the obtained ABL suggests different modes of energy input into the metal: a formation of the structure with a cover and the vapor inside it and with solid core.

The lifetime of ABL with respect to luminescence obtained with a help of the heat equation with thermal radiation of the metallic ball gives values close to the experimentally observed.

Determined diameter of the metallic ball inside the cover allows to estimate energy going to vaporization at creation of ABL. This estimation can be considered as ABL energy since the heat of evaporation is greater than the heat of combustion of metallic components in O_2 and the heat of fusion.

The corresponding formulae has a form $E_{es} = 4/3\pi r^3 (\eta_{Pb}\rho_{Pb}H_{Pb} + \eta_{Sn}\rho_{Sn}H_{Sn})$. Energy density equals to $W_{es} = E_{es}/(4/3\pi r^3)$. Here η_{Pb}=0.676, η_{Sn}=0.173 are portions of Pb and Sn (see above); densities of Pb and Sn are ρ_{Pb}=1.132·10^4 kg/m^3, ρ_{Sn}=7.31·10^3 kg/m^3; and evaporation heats of Pb and Sn are H_{Pb}=8.6·10^5 J/kg, H_{Sn}=2.53·10^6 J/kg, respectively.

Formulas give E_{es}≈1.15 J and W_{es}=9.7·10^9 J/m^3. These values agree with estimates for high energy of BL given in [4,10].

2. To natural BL

Multitude of BL observations [8,17] showed that many observers detected thin BL cases and also their destruction at explosion. Impact of the linear lightning to different materials – organic and inorganic and their mixtures (for example- soil) lead to creation of long-lived luminescent objects. So an idea of BL creation at linear lightning impact to materials [4,5] is reasonable.

From this point of view BL can be created even at the linear lightning impact to ice in clouds: in this case some weak lightning discharge can create bubbles filled by the water vapor and covered with electric charge producing a plasma and its luminescence. The same result can be achieved at the linear lightning impact to wood, pieces of metal, plastics, surfaces of airplanes and so on.

As it was shown in a number of experiments that a cover creation can take place in the state near the triple point when quasi-liquid films are formed. Such a state can be easily created at impact of the linear lightning or a high power discharge to a material with local rising of temperature and pressure in it. In the process of the relaxation, such a material passes through a triple point and has a capability to create a film of the cover.

BL carries a non-compensated electric charge due to charging in special conditions, for example, by the linear lightning originated in clouds. This circumstance seriously changes the situation. At BL consideration one has to include the Coulomb and the polarization influences [11.18] on the balance of pressure inside and outside of BL. In the following section we consider Si-based BL with silicon or water vapor inside it. Here we consider a sphere filled by vapors of the melted material and covered by some case – a cover made of the oxide of the melted material.

Pressure balance in natural BL

Energy of BL. The most important question is the BL energy. We will consider two model variants of the structure of BL- vapor of SiO_2 or H_2O in a shell of SiO_2 To answer this question, we first determine the pressure of the atomized gas inside the BL acting on its surface. Then, knowing the pressure and the enthalpy of vaporization, or the energy density per atomization of one water molecule, we determine the specific energy of such a BL.

Let us apply obtained above information and consider BL as the unipolarly charged sphere, which has an excess of charges of one sign. As it follows from [4,10] towards BL surface acts a pressure caused by the polarization of the cover [14] compressing it to the center, pressure of the Coulomb rejection of the same named charges inside the case of BL, external pressure of an atmosphere and the pressure of the gases inside the case. Then f_{pol} is the polarization force – the shrinking pressure [4,10] when a dipole layer is created on a dielectric case:

$$f_{pol} = \frac{\sigma a(2R+a)}{\varepsilon_0 (R+a)} Q, \qquad (1)$$

here *a* is the case thickness, σ -is a charge of the surface unit, *Q*-is a charge of the sphere. For Si and H_2O *σ* proves to be of the same value about σ = 1.6 C/m^2. ε_0 is the dielectric constant, *R* is the radius of the sphere.

A force of the Coulomb charges rejection f_C acting the case is defined by the following equation [4]:

$$f_C = \frac{1}{4\pi\varepsilon_0} \frac{Q^2}{(R+a)^2}.$$

$f_{atm} = 4\pi(R+a)^2 p_0$ - a force of atmospheric pressure, $p_0 = 1.03\cdot 10^5 Pa$ - atmospheric pressure.

$f_{surf} = 8\pi\alpha(R+a)$ - a force of a surface tension. α -coefficient of the surface tension

$w = P_a = N_a kT$ - a pressure inside the sphere, a pressure inside the sphere - P_a, density of atoms inside the sphere- N_a, T –gas temperature inside the sphere. k –is the Boltzmann constant.

So the equation of the forces balance has a form

$$f_{surf} + f_{atm} + f_{pol} - f_C - w \cdot 4\pi (R+a)^2 = 0 \qquad (2)$$

A Bl mass can be determined from the equation:

$$M = m_a \cdot N_a \cdot V = \frac{4}{3}\pi R^3 \cdot m_a \cdot N_a ,$$

where m_a is a mass of the atomic particle of a gas.

The energy density of BL can be determined on the basis of the relation

$$E = m_a \cdot \frac{w}{kT} \cdot \lambda,$$

where λ - is the enthalpy of vapor or a density of the water atomized gas , J/m³. At the main material SiO_2, $\lambda \approx 9.55 \cdot 10^6$ J/kg, and at the main material H_2O $\lambda \approx 5.1 \cdot 10^7$ J/kg .

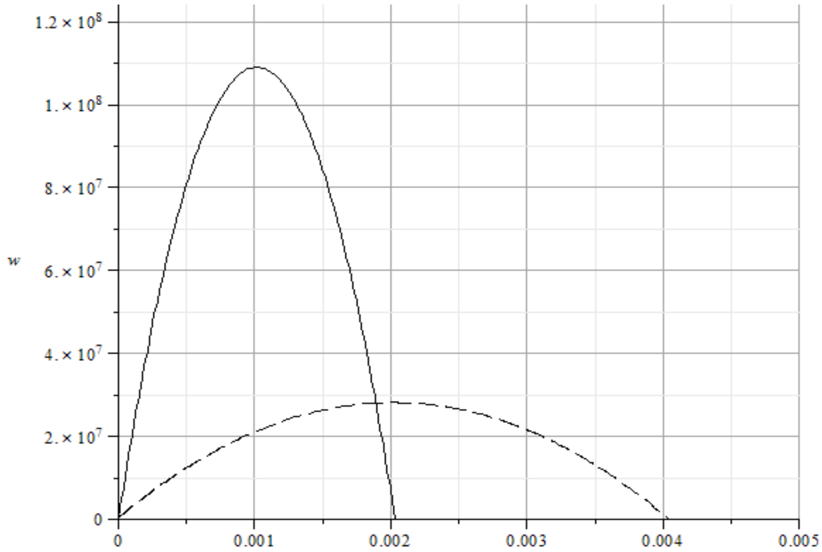


Fig.10. Dependence *w (Q)*, J/m³, at —— R=5 cm, ---- R=10 cm, σ =1.5 Cu/m², a=1 mm

The shell consists of a modified melt of SiO_2 and its alloy with soil components. We assume here that the gas temperature inside the shell is of the order of 2000 K, typical for the boiling point of SiO_2 .

Table1 1.

σ, $\frac{C}{m^2}$	a, mm	R, cm	*W*, J/m³	Q, C	N_a, m^{-3} SiO2, H2O	M, kg SiO2	M,kg H2O	E,J/m³ SiO2	E,J/m³ H2O
1.5	1	5	$9.60 \cdot 10^7$	0.001	$3.46\ 10^{27}$	0.19	0.06	$3.19\ 10^9$	$5.10\ 10^9$
1.5	1	10	$2.45 \cdot 10^7$	0.002	$8.91\ 10^{26}$	0.37	0.11	$8.16\ 10^8$	$1.31\ 10^9$
1.5	1	50	$1.00 \cdot 10^6$	0.01	$3.64\ 10^{25}$	1.83	0.55	$3.32\ 10^7$	$5.30\ 10^7$
4.5	1	5	$8.59 \cdot 10^8$	0.003	$3.11\ 10^{28}$	1.67	0.5	$2.86\ 10^{10}$	$4.57\ 10^{10}$
4.5	1	10	$2.22 \cdot 10^8$	0.006	$8.02\ 10^{27}$	3.33	1.0	$7.38\ 10^9$	$1.18\ 10^{10}$
4.5	1	50	$9.06 \cdot 10^6$	0.029	$3.29\ 10^{26}$	16.6	5.0	$3.01\ 10^8$	$4.82\ 10^8$
4.5	10	5	$5.28 \cdot 10^{10}$	0.03	$1.93\ 10^{30}$	166	50	$1.76\ 10^{12}$	$2.82\ 10^{12}$
4.5	10	10	$1.72 \cdot 10^{10}$	0.06	$6.24\ 10^{29}$	333	100	$5.73\ 10^{11}$	$9.18\ 10^{11}$
4.5	10	50	$8.52 \cdot 10^8$	0.29	$3.12\ 10^{28}$	1650	493	$2.83\ 10^{10}$	$4.52\ 10^{10}$

In Fig.10 one can see typical values of ***w***, J/m³, via BL charge *Q*, Cu. From the figure one can see that the pressure *w(Q)* varies in wide limits with respect to a value of Q . It has a maximum at which can be realized the highest values of BL ***w*** and energy respectively at given width of the cover and density of polarized charges on it.

Being movable by the electric field of the Earth, BL can approach the windowpane and "penetrate" the room through a crack or a hole. In addition, it is capable, having spent part of its energy, to heat the glass to the melting temperature and form an opening in it. But this "material" BL is unable to pass through the glass, leaving no trace at all.

In Table 1 one can see BL parameters at different values of σ, a, *R*, *Q* calculated by formulas presented above at maximal value of *w(Q)* .

BL radiation

The cause of the generation of BL radiation in the optical and radio ranges can be a plasma created by the electric field of the charge, the motion of electric charges in the plasmoids forming its core, or processes that cause the plasma to pulsate near its shell [4,18]. The radiation of a BL can be of two types: equilibrium, when the shell of BL is filled with a gas. In this case, the heat is transferred to the shell by particles of vapor inside the shell; and none-equilibrium, when under the action of BL large charge near the surface, plasma appears as a result of ionization processes in a strong electric field. While the parameters of none-equilibrium radiation require special analysis, the parameters of the equilibrium radiation can be estimated as follows. We assume that the heating of the shell by the vapor is compensated by a thermal radiation from the surface of the shell, then if we assume that during the boiling all the molecules are decomposed into atoms then we can use the following equation of a real gas by (approximating heat capacity)

$$\frac{3}{2}N_a k_B \cdot \frac{4}{3}\pi R^3 \frac{dT}{dt} = -\sigma_{SB} \cdot T^4 4\pi R^2, \qquad (3)$$

k - Boltzmann constant, σ_{SB} - constant of Stefan-Boltzmann.

A solution of this equation for determining of the cooling time to the temperature T_1, if the initial gas temperature is much greater than the final gas temperature $T >> T_1$, has the form:

$$t_x = \frac{N_a \cdot k_B R}{6 \cdot \sigma_{SB} \cdot T_1^3}. \qquad (4)$$

If we substitute the following values of the average parameters of the BL from Table 1: $N_a=8\cdot10^{27}$ m^{-3}, *R*= 0.1 m, T1=500 K, we get $t_x \approx 260$ s. This value is comparable with the observed lifetime of ball lightning. However, in real conditions at high temperatures the heat capacity may not increase with temperature as in (3) and the time of thermal irradiation will be smaller. When eyewitnesses observe the light of the BL is mainly constant in time, which can be related both to the possibility of observing bright objects by a person, when the threshold of sensitivity of the eye is exceeded, and with the possibility of heating the BL shell by the none-equilibrium plasma on its surface.

BL discharge time

Let us estimate the discharge time of BL in the form of the unipolarly charged sphere as a result of collisions with ions of the opposite sign. We write the equation describing the balance of the charge *Q* of a ball of radius *R* when ions with a concentration of N_i, electron charge e, and drift velocity w_{dr} [4,18]

$$\frac{dQ}{dt} = -4\pi R^2 \cdot e \cdot N_i w_{dr} = -4\pi R^2 \cdot e \cdot N_i b_i E = -4\pi R^2 \cdot e \cdot N_i b_i \frac{Q}{4\pi \cdot R^2 \varepsilon_0} = -e \cdot N_i b_i Q / \varepsilon_0, \qquad (5)$$

b_i -is ions mobility, it is connected with a drift velocity by known equation $w_{dr} = -b_i E$. TA solution of (B6) gives an estimate of the typical time of BL discharging $\tau_{dis} = \varepsilon_0 / (b_i e \cdot N_i)$. Accounting the ion concentration in the normal air $N_i \approx 10^3$ cm^{-3} [9], and $b_i \approx 2.8\cdot10^{-4}$ $m^2/(V\cdot s)$ [9], one gets BL discharging time $\tau_{dis} \approx 1.9 \cdot 10^2$ s. It means that BL can soar in the air comparably long until it loses the charge. At that this time also corresponds to BL observation time.

BL at high electric charge

The connection between the charge on the sphere, its radius r_s and the electric field strength is given by the expression $Q = 4\pi\varepsilon_0 \cdot r_s^2 E$. A value of the charge at which the air breakdown occurs under normal conditions is $Q_{br} = 3.3 \cdot 10^{-4} r_s^2$ Cu, r_s is in meters. From Table 1 follows that near BL with high energy, the magnitude of the electric field strength will be larger than the breakdown field in air at atmospheric pressure. It would seem that such values close this BL model, because of breakdown to the Earth. However, studies with corona discharge [12] show that, at high fields around the charged electrode, fields of the order of 10^8 V/m are created, which are comparable with fields near the BL surface, and the plasma begins to pulsate (Trichel pulsations), and there is no breakdown to the Earth. This result is understandable. We will show this.

To do this, we use the expressions for the Debye radius r_d, at which the charge shielding takes place [13]:

$$r_d = \left(\varepsilon_0 \cdot k_B T_e / (e^2 \cdot N_e)\right)^{1/2}, \quad (6)$$

and the frequency of the plasma vibrations

$$\nu_p = \left(e \cdot N_e / (\varepsilon_0 \cdot m_e)\right)^{1/2} / (2 \cdot \pi). \quad (7)$$

At high electric fields in air an ionization of molecules by electrons is balanced by electron-ion recombination [13], therefore

$$\nu_i N_e = \alpha_{rec} N_e^2, \quad (8)$$

where ν_i is the ionization frequency, α_{rec}-coefficient of electron-ion recombination, N_e -the electron concentration.

At that a dependence of the ionization frequency via an electric field is [14] $\nu_i = \nu_{br} \cdot (E / E_{br})^{\beta}$, (9)

ν_{br} - is the ionization frequency at the breakdown electric field, β is the exponent of the electric field rising (in air at the atmospheric pressure E_{br}=3·10^6 V/m, β=5.34 [14]. At these parameters and the breakdown electric field [15] the electron temperature is T_e~3 эВ and N_e~10^{14} cm^{-3}. So one can get a value of the Debye radius at the breakdown r_{dbr}~ 1.3 ·10^{-4} cm. At that the plasma frequency is ν_{pbr}~9·10^{10} s^{-1}.

Using (6)-(9), and supposing that T_e and α_{rec} vary slower than E, one can get the following formulas for (8) and (9).

$$r_d \approx r_{dbr} \cdot (E / E_{br})^{-\beta/2},$$

this value drops with rise of the field near the ball. But the plasma frequency rises

$$\nu_p = \nu_{pbr} \cdot (E / E_{br})^{\beta/2}.$$

It is known from the electrostatics that the electric field near the ball varies with respect to distance from it R as

$$E = E_s \left(r_s / R\right)^2,$$

here E_s is the electric field near the surface of the sphere. From this one gets the distance

$r_{br} = r_s \cdot \left(E_s / E_{br}\right)^{0.5}$, at which conditions for breakdown are violated and the ionization stops.

For example at E_s / E_{br}=10, $r_{br} = r_s \cdot 10^{0.5}$ and r_d ~ 3.3 ·10^{-7} cm, ν_p ~ 3.6·10^{13} s^{-1}; but at E_s / E_{br}=100, $r_{br} = r_s \cdot 10$ and r_d ~ 6 ·10^{-9} cm, ν_p ~ 2.0·10^{16} s^{-1}. At all the distances smaller than r_{br} (closer to the surface) the screening of the ball and the high frequency plasma vibrations take.

Therefore, the breakdown near BL with high charges or high electric fields fields will not be realized, and the plasma oscillations will occur. We see that the field of a strong electric charge of BL can be the cause of the appearance of a pulsed or corona discharge on its surface and the formation of ozone and nitrogen dioxide [15].

When the charged core is closed by some conductor, BL can be discharged through this conductor and cause people and objects to be struck by electric shock.

BL levitation -soaring

The uncompensated electric charge of BL can cause its motion under the action of electric fields near the Earth. Like any material body, the BL is dragged by air during the movement and experiences the effect of the wind. However, if the strength of the electric field acting on it from the Earth's side is greater than the wind strength, the BL will move against the wind. If the BL with a charge *Q* and mass *M* is in an indifferent equilibrium in the air (levitates or soars), then the estimate of the minimum value of the electric field strength of the Earth (or Earth + cloud) E_{lev} when levitating the BL has the form obtained from the condition of the balance of forces acting on the BL:

$$M\,g + \frac{1}{16\pi\varepsilon_0}\frac{Q^2}{x^2} = E_{lev}Q\,. \qquad (10)$$

A question of the magnitude of the ground electric field is far from obvious. The fact is that there is an electrode effect associated with the emanation of αradon from the soil, which, depending on the conditions of air movement and the presence of surface aerosol, can vary greatly and lead to stabilization of the unstable solution of the equation (10) [18]. If the BL is under a cloud having a unipolar charge of 1 C, the electric field is estimated at $E_{lev}\approx$9 kV/m, and at 5 C $E_{lev}\approx$45 kV/m. So the effect of the initial conditions is important. In addition, the following characteristics can influence BL motion: Stokes force, the wind, decrease of the recombination of charges. From (10) we can obtain an expression relating the height of the BL motion above the Earth's surface with a mass, a charge of BL, and a local electric field

For example, at E_{lev}=2000 V/m, *M*= 0.2 kg и *Q*= 10^{-3}C *x*= 237 m, and at *M*= 0.06 kg and *Q*= 10^{-3}C *x*= 35 m. At E_{lev} =10^4 V/m, *M*= 0.001 kg and *Q*= 10^{-5} Cu *x*= 1.6 m. The most noticeable with respect to this mechanism is a possibility of levitation in conditions of a strong local electric field and a relatively large charge.

Conclusion

We have considered discharge experiments with exploding fireballs and explained their explosions by the influence of pressure of vapors acting the cover inside them.

The BL model with accounting of vapor action inside BL and the sublimation energy has been presented. Its energy proved to be much higher than those of combusting BL. This model allows more realistically consider high energy BL observations. It explains high BL energy density, high electric charge, long time with respect to equilibrium radiation and discharging, its levitation and some other BL features.

Concerning experimental modeling, our investigations indicate that though in a number of experiments were obtained objects filled by the vapor atoms, it is necessary to realize a unipolarly charged BL. Our experiments showed that it is impossible to realize it in conditions of glow, pulsed and arc discharges because of the plasma quasi-neutrality. Most probably for obtaining of BL one has to use corona and Tesla coils. However, many experiments with capillary discharges can help us formulate how to create stable spheres with charged shell.

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