Sources and components of ball lightning theory

A I Nikitin¹, V L Bychkov², T F Nikitina¹, A M Velichko¹, and V I Abakumov²

¹Talrose Institute for Energy Problems of Chemical Physics, Russian Academy of Sciences, Moscow, Russia.
²Lomonosov State University, Moscow, Russia

E-mail: anikitin@chph.ras.ru

Abstract. The article describes the cases when ball lightning (BL) exhibited an extremely high specific energy store (up to $10^{10}$ J/m³), a presence of uncompensated electric charge (up to $10^{-3}$ C) and an ability to generate high frequency pulses (up to 10 MW). It is shown that the realization of a combination of these properties of BL is possible if to consider it as a heterogeneous system consisting of a unipolarly charged core and a dielectric shell. In the electric field of the core charge, arises a force owing to the polarization of the shell that opposes the Coulomb repulsion force of the charges. BL models constructed according to the indicated principle are described: the electrodynamic model and the chemical-thermal model, which treats BL as a hollow sphere filled with steam. The requirement to take into account the main three properties of BL makes it possible to reduce the number of models of this natural phenomenon. Detailed cases of observations of high-energy lightning are analyzed.

1. Introduction

Scientific investigation of BL problem has started in 1838 by publication of F. Arago’s article [1]. Unfortunately, this investigation still did not led to understanding of physical nature of this natural phenomenon. A reason of this, apparently, is ignoring of key properties of BL and attempts to build its models on the base of some myths. These “myths” are: 1) an aspiration to build a model of BL in a form of homogeneous system stabilized only by internal forces and atmospheric pressure; 2) the statement that the average density of BL is close to air density; 3) the assumption of BL electric neutrality; 4) an attempt to explain BL luminescence only by thermal radiation of hot bodies [2–4]. It is time to define new basic properties of a BL which can form a basis of its theory creation.

In our opinion, ignoring of three major properties of BL – high energy storage, a presence of non-compensated charge and its ability to generate a large power radio emission – was a principal cause of failures of creation of BL theory. We consider the listed properties as key ones and we define on their basis the three base principles of its model developing – a heterogeneous structure, presence of charge carriers and ability of self-organizing of substance of BL core.

2. Cases of ball lightning energy measurement

The most mysterious property of BL is its ability to accumulate a big amount of energy in the limited volume. As the first documentary case of high energy BL observation one may consider the publication in the newspaper ”The Daily Mail (London)” on November, 5th, 1936 of a letter to the editor named “A thunderstorm mystery” [5]. “Sir, during a thunderstorm I saw a large, red hot ball come down from the sky. It struck our house, cut the telephone wires, burnt the window frame, and
then buried itself in a tub of water which was underneath. The water boiled for some minutes afterwards, but when it was cool enough for me to search I could not find nothing in it”. Dorstone, Hereford. W. Morris. The description of a case, published in the newspaper, became known to scientific community. This was during a discussion at the Institution of Electrical Engineers in London on January, 7th, 1937, following the presentation of a review paper by Professor B.J. Goodlet, entitled “Lightning” [6]. During the discussion Professor Goodlet estimated the energy content of the ball. He estimated that Mr. Morris’s description of the heating of the water suggested a temperature rise to 60°C. Thus, if the initial temperature was 20°C, $\Delta \theta = 40^{\circ}$ C. Four English gallons of water have a mass $m_1 = 18$ kg. The specific heat capacity of water $c = 4200$ J·kg$^{-1}$·K$^{-1}$, therefore $\Delta Q = m_1c\Delta \theta = 3.1$ MJ. After that he carried out other calculation based on the assumption, that all the water has heated up to 100°C, and a mass $m_2 = 1.8$ kg was evaporated. The latent heat of evaporation of water $L = 2.26$ MJ/kg, hence, $\Delta Q = m_1c\Delta \theta + m_2L = 10$ MJ. If to accept diameter of the ball equal to 10 cm, and energy equal to 3.1 MJ, the energy density of the ball can be estimated as $0.6 \times 10^{10}$ J/m$^3$. For the second variant the density of energy of ball lightning will appear equal to $\rho_E = 1.9 \times 10^{10}$ J/m$^3$.

The “natural experiment”, described by Mr. Morris, was not single. In August, 1962 in Ukraine near the city Perechin BL with the size of tennis ball fell in a trough with water for cattle. The water was almost completely boiled away from the trough, the cooked frogs laid at the bottom. The size of the trough was 0.3×2.5 m, depth of water layer was 15 cm [7, pp 106]. Accepting that mass of water in the trough was $m_1 = 112.5$ kg, mass of the evaporated water was $m_2 = 100$ kg, and water heating occurred from 10°C to 100°C, we find, that energy, transferred to water by BL, was equal to 269 MJ. The volume of a tennis ball 6 cm in diameter is equal to 113 cm$^3$, from here the energy density of the “Ukrainian” BL was $\rho_U = 2.38 \times 10^{12}$ J/m$^3$. This density is approximately in 100 times larger than energy density of the “English” BL. The error in definition by the observer of the size of the ball could become the reason of it. If its diameter was equal to 28 cm, the value of energy density would be nearly $2.4 \times 10^{10}$ J/m$^3$.

Next important event occurred in July, 1972 in Hungary [8]. At midday in presence of numerous factory workers a brightly shining ball the size of soccer ball fell in a pit with 120 liters of water. All the water has evaporated. For heating of 120 liters of water by 80°C and its evaporation the energy 311 MJ is necessary. Accepting the diameter of the ball equal to 25 cm, we find the energy density of the “Hungarian” BL $\rho_H = 3.8 \times 10^{10}$ J/m$^3$. Thus, it is necessary to regard the cases, when the energy of BL has been measured with the help of “water calorimeter”, as the reliable facts. Below we describe two new cases of estimation of BL energy.

Here is a story of engineer N.F. Ignatov, the participant of event that has occurred in July, 1964 at the river Ucha near the stop Mamontovka in the Pushkin district of the Moscow Region. The storyteller was then 20 years old [9]. “At that time I was the student of technical school of communication. At 4 o’clock in the morning I was fishing at the river Uaba. The sun has not risen yet, the weather was clear, there was no rain this morning and overnight. In the place of fishing the width of the river was 20-30 meters. I had a simple reed fishing-rod with an ordinary line and hook. Before the event I have caught 5-6 roaches which I held in the 10 l Gi pail. The pail was half-filled with water. I felt that a fish had eaten a worm from a hook. I took out a line with an empty hook from water and when I was carrying a hook, hanging on the line, above the water’s edge (the hook was about 1 meter above the ground), a shining ball with diameter about of 5 centimeters suddenly “clung” to it. I did not notice from where the ball had arrived. The weight of a sinker with the hook when the ball had stuck to it did not increase. I don’t remember the color of the ball, it was shining slightly brighter than a luminescent lamp, and its light did not blind eyes. The ball contour was accurate. I was confused and slowly lowered the hook with the ball, hanging on it, into the pail with the caught fish. At once the water began to hiss and gurgle, as it happens, when the heated stone is thrown into it. Water was boiling for some more minutes. Fishes were cooked so as it had been boiled too long: it had been skinned, scaled and gutted. At boiling a dense steam rose from water. The hook, tied to the line, had disappeared. The line remained untouched, it became only slightly shorter. In fear from uncertainty of what had occurred, I upset the remains of the water with fish on the ground and came to a hostel with the empty
pail. When I told my companions about the incident, they did not believe me: they decided that I had caught nothing and I was justifying myself for it. So I had to go and show them the boiled fish on the ground.”

Let’s estimate energy which was brought by BL in the pail with the caught fish. The capacity of a standard pail, made of Gi, we will accept equal to 10 liters. There was in it \( m_w = 5 \) kg of water and \( m_f = 0.9 \) kg of roaches (6 fishes with an average weight 150 g). The initial temperature of water we will accept equal to 20°C. Let the specific heat capacity of the fish is equal to specific heat capacity of water \( c_w = 4.2 \) kJ/kg·K·C. The energy, spent for water heating by \( \Delta \theta = 80^\circ \) C before boiling, is \( Q_w = c_w (m_w + m_f) \Delta \theta = 1.98 \) MJ. It is necessary to add to this result the heat \( Q_p \) spent for heating of the pail with mass \( m_p = 1 \) kg by \( \Delta \theta = 80^\circ \) C. A specific heat capacity of steel is \( c_s = 0.46 \) kJ/kg·K, therefore \( Q_p = c_s m_p \Delta \theta = 36.8 \) kJ. As a result we obtain that energy of the “Moscow” BL appeared equal to \( Q_M = Q_w + Q_p = 2 \) MJ. It is the lower estimate of energy. The eyewitness spoke about a production of steam at water boiling, on what, naturally, the part of energy of BL was spent. But, because data about quantity of the evaporated water is not available, we can tell nothing about amount of this additional energy. The volume of a ball of diameter 5 cm is equal to 65 cm³, from here we find, that the energy density in the ball lightning was not less than \( \rho_M = 3·10^{10} \) J/m³. As we see, this figure is well coordinated with the values of energy density of “English” (\( \rho_E = 1.9·10^{10} \) J/m³) and “Hungarian” (\( \rho_H = 3.8·10^{10} \) J/m³) BL. Apparently, the fishing hook has disappeared because of action on it of the high-frequency electromagnetic field, radiated by BL. The observers repeatedly informed about disappearance of metal subjects (rings, bracelets, etc.) after their meeting with BL [7, 8, 10, 11]. It is probably that water heating also occurred because of action of this electromagnetic radiation on it.

On May 27th 2013 at 15 o’clock of local time BL destroyed a house in the outskirts of village Mogsokhon of Kizhinginsky district of Buryatia [12]. According to stories of eyewitnesses of the event, “A usual rain began, but suddenly a thunder struck with such a force that passers-by and the cattle, being at this time in the street, crouched with horror and fled their several ways. A minute later after that the bright shining ball descended from the sky and forced its way into the house of the Bayan Sandanov’s family through a roof. Then there was a deafening explosion inside the house. A housewife, the spouse of Bayan, cleaning the kitchen after dinner, was in the house during the explosion. Found under pieces of a fallen wall she was seriously bruised and lost partially her hearing. The suffered woman was hospitalized. After the explosion the house was in a critical condition: doors and windows were smashed and thrown away at a large distance, the wall part fell, and the roof was partially destroyed (see Fig. 1). Because of BL explosion in many neighbor houses electric appliances were destroyed”.

Let’s try to estimate the energy of BL, which exploded in the house. We carry out estimation on a basis of definition of trinitrotoluene mass, which explosion leads to consequences similar to that, which occurred in the village Mogsokhon. According to a demolition guide [13, pp 125], for destruction of a flat package of logs a weight \( C \) (in grams) of a contact charge (directly located on the object to be undermined) is defined by a formula:

\[
C = kF,
\]

where \( F \) is an area of cross-section of a package (cm²), and a factor \( k \) is defined by a kind and a condition of wood. For a dry pine or a spruce \( k = 1 \). Let us accept the height of the wall, which fell out of the house, equal to \( H = 3 \) m. This wall is constructed out of 13 logs, from here we find a thickness of a log \( d = 23 \) cm and the cross-section of package \( F = H d = 6900 \) cm². From the formula (1) at \( k = 1 \) we find \( C = 6.9 \) kg of trotyl. A heat of trotyl explosion is equal to \( 4 \) MJ/kg [14, pp 250], so the energy, containing in 6.9 kg trotyl, is equal to 28 MJ. If blasting is carried out by a charge which is at a distance \( r \) (m) from a wooden wall, the weight of the charge \( C \) (kg) can be found from a formula [13, pp 127]:

\[
C = 30kdr^2.
\]

Here \( d \) (m) is a thickness of a log. If the charge is in the centre of a room of size \( 4 \times 4 \) m², then at \( r = 2.2 \) m and \( d = 0.23 \) m we find \( C = 33 \) kg trinitrotoluene, that is equivalent to energy of 132 MJ.
In the description of the event nothing is said about a size of BL. If to accept it equal to a diameter of “average” BL $D = 30$ cm, then the energy density of the “Buryat” BL $\rho_B$ will be from $2.1 \cdot 10^9$ J/m$^3$ to $9.3 \cdot 10^9$ J/m$^3$. These figures are of the same order, as values of energy density of highly energetic BL, about which it was spoken above. All that allows to say that BL is dangerous natural phenomenon. This conclusion is not coordinated with opinion of some researchers, who speak about insignificant danger of BL. For example, Stenhoff [5, pp 94] considers it as a non-dangerous object and all destructions, ascribed to it, explains by action of usual linear lightning.

Figure 1. The house wall thrown out by the explosion

3. Cases of pulse emitting of ball lightning energy

In [7] a case of golden bracelet evaporation by BL is described: “There was a thunder-storm. A woman was sleeping in a house, which doors and windows were reliably locked inside. She was woken by a sound of a lightning stroke similar to a shot. Coming to a window, she with a surprise has found a small hole in it with a size of fifty-kopeck piece (5 cm). And suddenly she had noticed that the golden bracelet has disappeared from her hand. On a wrist there was only a dark strip. (The analysis has shown that it was a gold oxide). Very careful searches gave nothing. Only a round fragment of glass with melted edges was found on a floor. It precisely coincided with the hole in window glass. A dog, killed by lightning, was found in a kennel near the house”. Let us estimate an energy spent by BL on evaporation of the bracelet. We will accept a mass of the bracelet $m_{br}$ equal to 50 g. The energy $Q_1$ of the bracelet heating from the room temperature $T_0 = 20^\circ$ C to the temperature of gold melting $T_m = 1063.4^\circ$ C is equal to $Q_1 = C_{Au} \cdot m_{br} \cdot (T_m - T_0) = 6.78 \cdot 10^3$ J. (Here $C_{Au} = 0.13$ J / (g∙К) is specific thermal capacity of gold). Energy $Q_2$ of the bracelet melting is $Q_2 = m_{br} \cdot l_{Au} = 3.2 \cdot 10^3$ J. ($l_{Au} = 63.97$ J/g is the latent heat of gold fusion). For increasing of the melt temperature to the boiling point $T_b = 2887^\circ$ C the energy $Q_3$ is necessary, $Q_3 = C_{Au} \cdot m_{br} \cdot (T_b - T_m) = 11.8 \cdot 10^3$ J. Specific heat of gold evaporation is $L_{Au} = 1.68 \cdot 10^3$ J/g, from here the bracelet evaporation energy is $Q_4 = m_{br} \cdot L_{Au} = 84 \cdot 10^3$ J. Total energy of the bracelet evaporation is $Q = Q_1 + Q_2 + Q_3 + Q_4 = 10^4$ J, and for evaporation of one gram of gold the energy $2.11 \cdot 10^3$ J is necessary. If to accept the time of evaporation of the bracelet equal to $10^{-2}$ s, then a power of the energy source should be no less than $P = 10$ MW.
On July 10, 2006 in Jūrmala city in Lithuania when a resident of Yelgava city Oleg Andrejev went from the sea to the coast, “a yellow-orange bright ball about of a tennis ball in size has flown” nearby him and “a strong roar has appeared. Oleg has fallen face downwards the sand. He did not lose consciousness, but he was very sluggish, its consciousness became disseminated. When Oleg was turned, his face has appeared covered with black soot. People, bathing at this time in the gulf, had felt appreciable current blow … The golden chain on Oleg’s neck had been evaporated, having left the appreciable burn round his neck in the form of a dotted line. There were traces of action of the lightning on his stomach and his heels” [11, pp 234] (see Fig. 2). If the mass of the chain was 17 g, the energy of its evaporation was nearby 36 kJ, and the power (at the explosion duration $10^{-2}$ s) was 3.6 MW.

In [15] a case of “theft” of ring metal subjects by BL is described: “In a barn on hay two – a man and a woman were sitting. Suddenly a body, more large than an apple, directed to a whiteness, in zigzag fashion. It had swum to them for a distance of one meter. Its body was sparkling, and the woman’s hairs (their length was 20-30 cm) had risen on end (as a fan), and the man’s hairs begun to move under a peak-cap … The ball had left the barn through a crack in a roof … Recovered, the observers had found, that the woman’s rings on fingers had disappeared, and the man’s chain of a penknife, a metal tip of a pen and metal rims on the boots, fixing edges of apertures for laces,” also had disappeared. If a reason of the specified subjects disappearance was their evaporation by BL energy, then for evaporation of a golden ring with mass 14 g the energy 30 kJ is necessary, and for the all gone subjects – it is several times more (nearby 100 kJ). Notice that the BL had spent for performing of the specified action only a part of its energy.

On August 12 1978 at 23 o'clock 20 minutes in Khabarovsk near Hasanovsky street during a pouring rain the spectators went out of the cinema “Zarja”, had heard a sharp whistle, reminding a work of jet engine. The whistle was accompanied by crash. It became light, as in the afternoon. Then over a cinema building BL of about 1.5 m diameter had appeared. A color of BL was orange, from it sparks were strewed. The BL had started to descend, had gone down to the earth surface through branches of trees, for an instant it had flashed over the earth and again had risen upwards. A strong explosion was heard, it became dark and silent. BL was observed during about one minute. On a distance up to 100 m electric wiring had been put out of action. Despite the torrential rain and wet soil, the soil’s site of 1.5 m diameter and depth of 20-25 cm had been charred, and a slag had been formed in it. The volume of the zone, filled with the slag, was nearby 0.4 m$^3$. The slag consisted not of solid crust, but of many pieces of irregular form with the average size of 5-6 cm. Some pieces were alloyed to each other. In total it had been found about a thousand of such pieces. The initial ground represented a sandy loam on the basis of quartz sand [16].

Authors of [16] had made experiments for definition of a method of power action on the soil, which result was a formation of the slag similar to the slag appeared at BL explosion. They found that similar results of action on the soil had been obtained at its heating by high-frequency radiation at frequency 13.56 MHz and power 60 kW. Authors had estimated the energy released at explosion of BL. BL action had led to heating to fusion temperature ($T_m = 1700^\circ$ C) $m_g = 440$ kg of the ground in a volume of the cylinder of diameter 1.5 m and height of 0.22 m and had evaporated $m_w = 175$ kg of
water from this volume. Having accepted a specific thermal capacity of the ground equal to $C_g = 0.84 \text{ kJ/(kg·K)}$, we find the energy, spent for its heating from the initial temperature $T_0 = 20^\circ \text{C}$ to the temperature of fusion: $E_g = C_g \cdot m_g \cdot (T_m - T_0) = 6.2 \times 10^8 \text{ J}$. For heating $m_w = 175 \text{ kg}$ of water from $20^\circ \text{C}$ to $100^\circ \text{C}$ energy $E_{hw} = C_w \cdot m_w \cdot (100^\circ - 20^\circ) = 0.59 \times 10^8 \text{ J}$ had been spent. ($C_w = 4.2 \text{ kJ/kg·K}$ is specific thermal capacity of water). Specific heat of water evaporation is $L_w = 2.26 \times 10^6 \text{ J/kg}$ [17 (35)]. For evaporation of $175 \text{ kg}$ of water an energy $E_{vw} = 3.95 \times 10^8 \text{ J}$ is needed. Thus, at a flash of BL with the diameter of 1.5 m the energy $E_t = E_g + E_{hw} + E_{vw} = 10.7 \times 10^8 \text{ J}$ had been released. The BL volume was $V_{bl} = 1.77 \text{ m}^3$, from here a density of its energy is $\rho_E = \frac{E_t}{V_{bl}} = 6 \times 10^8 \text{ J/m}^3$. If to accept a duration of flash of BL over the earth equal to 0.1 s, then the power of electromagnetic radiation will be $P = 10^{10} \text{ W}$. This very day in other area of Khabarovsk a ball lightning has flown in a tank with $m_{w2} = 7 \text{ t}$ of water and has heated it up to boiling [18 (36)]. Proceeding from it, its energy was $E_{bl2} = C_w \cdot m_{w2} \cdot (100^\circ - 20^\circ) = 2.35 \times 10^9 \text{ J}$.

The cases described above allow to draw a conclusion on BL ability to generate high-frequency radiation. The energy of the radiation pulse in some cases exceeds $10^5 \text{ J}$ that is 1-10 % of the average sized (10-20 cm) BL energy. Some representation about of wave lengths range of BL electromagnetic radiation can give a case of its observation by spouses Popele on January 6 2011 near Budapest in Hungary [19, pp 300]. Spouses managed to photograph BL laying on snow (see Fig. 3).

![Figure 3. Photo of BL on snow.](image)

The diameter of BL was nearby 50 cm. At the left and to the right of BL between it and the snow air luminescence has been observed. It is not excluded, that it had been caused by a corona discharge. The most surprising in described event was that the spouses, investigating after disappearance of the BL the place where it was laying before, had not found any traces of snow thawing. The reason of this can be that BL radiation lays in a range of radio-waves not absorbed by snow. For check of this idea we have placed a polyethylene box with snow into a microwave stove. At action on snow during 30 seconds of radio emission with the power of 850 W it remained untouched. This means, that the range of BL radiation wave lengths can be in the region 1-13 cm (the radiation wave length at which microwave stoves work, is equal to 12.25 cm) [19, pp 300].

4. Cases of manifestation of ball lightning electric charge action

In the previous section we told how BL having come at the distance of one meter to a woman’s head, had forced like a “fan” to rise her hairs. In [20] a similar case, told by E.N. Kudrjavtseva, is described: “In the summer of 1947 I was on tours with an ensemble in the Chernovtsy city in the Moldavian Soviet Socialist Republic. After rehearsal at 2-3 o’clock p.m., I came to a colleague to the house where she was temporarily living. It was a small one-storey house. We sat by a window opposite each other and were knitting. The window leaf was opened. The thunder storm in the street gathered, lightnings sparkled somewhere away, but here still there was calm. Suddenly I have looked at the girlfriend and have seen that her hairs have risen upwards (on end). She was looking at me with the eyes expanded from a fright because with me, as it has appeared, there was the same. We then
have told it to each other, and everyone on oneself did not feel anything unusual. Here we have seen that over us a ball of the diameter of 8-14 centimeters was floated. It was matte as a matte bulb, it was shining with brightness of the full moon. It moved very slowly. The room was small: the furnace was opposite the window, and in the room’s centre a bulb (40 W) was hanging on a long cord. When the ball was flowing near the lamp, the incandescent hair was lighted to reddish color though the switch was switched off (we have checked this). When the ball has flown away from the lamp, the incandescent thread has gone out also. Then the ball has flown near the oven, cautiously bypassing all corners and not touching it, has turned along the wall and again began to come nearer to us. We were sitting, not moving, not talking. When the ball has flown away from us the first time, our hairs have fallen down. Now at its approach they have risen again on end. The ball has floated over our heads and has taken off for a window leaf. Soon after that the thunder storm has burst, the rain poured, as from a bucket, but all has quickly ended”. If to accept a distance between a floor and a room ceiling equal to 2.3 m and to consider, that BL moved horizontally at a level of a window leaf height (nearby 2 m), it has passed at a distance of 1 m from the girls’ heads.

At popular lectures about electricity action an effective experiment is often shown. The girl with the dismissed hairs stands on an isolating support and she is suggested to touch a pole of the electrostatic generator by a conducting core. A wire, lying on a floor, is attached to the other pole. At increasing of a voltage up to 300 kV the girl’s hairs rise in the form of a fan. Let us estimate, at what value of an electric field intensity near to the girl’s head there is a force, capable to rise her hairs. Let us replace the girl’s figure with an ellipsoid of revolution with a size of big axis \(2a = 1.6 \text{ m}\) and a size of a small axis \(2b = 0.3 \text{ m}\). An electric potential on the big axis at a distance \(x\) from the centre of the conducting ellipsoid is defined by a formula [21]:

\[
\varphi = \frac{q}{4\pi\varepsilon_0(a^2-b^2)^{1/2}} Arth\left(\frac{a^2-b^2}{x^2+a^2}\right)^{1/2},
\]

and its capacity is:

\[
C = \left[4\pi\varepsilon_0(a^2-b^2)^{1/2}\right] /\ Arch\ (a/b).
\]

Here \(q\) is the charge of the ellipsoid, and \(\varepsilon_0 = 8.85\cdot10^{-12} \text{ F/m}\) is the electric constant. Electric field intensity \(E\) on the ellipsoid surface (at \(x = a\)), directed along the big axis of the ellipsoid, is:

\[
E = -d\varphi/dx = \frac{q}{[4\pi\varepsilon_0\sqrt{2}(a^2+b^2)]}.
\]

At \(a = 0.8 \text{ m}\) and \(b = 0.15 \text{ m}\) the capacity \(C = 4\pi\varepsilon_0\cdot0.333 \text{ F}\). At the ellipsoid potential \(U = 3\cdot10^5 \text{ V}\) its charge is \(q = C/U = 4\pi\varepsilon_0\cdot1.0\cdot10^4\text{°C}\). From the formula (5) we find the intensity of electric field at the “top” of the ellipsoid \(E = 10^5 \text{ V/m}\). Thus, for hairs raising the electric field intensity on the surface of the girl’s head should be no less than 1 kV/cm. This conclusion was checked up experimentally. For this purpose in the center of the electric condenser formed by two horizontal metal disks with diameters of 105 and 160 mm, displaced from each other at 50 mm, a piece of a cotton thread of 0.3 mm diameter and 45 mm length was placed. The thread was attached by one end to the bottom electrode. At voltage 10 kV the thread took a vertical position. Thus, for its raising electric field \(E_{up} = 10 \text{ kV/5 cm} = 2 \text{ kV/cm}\) is needed [22].

Now, knowing the value \(E_{up}\), we define a charge \(Q\) of BL for two described above cases. In both cases BL with the radius \(R_{bl} = 4 \text{ cm}\) has created the electric field intensity \(E_{up} = (1-2)\cdot10^5 \text{ V/m}\) at the distance \(R = 1 \text{ m}\). BL was indoors, therefore with good approximation it is possible to consider that the configuration of its electric field was close to a configuration of the spherical condenser field. For such a condenser the electric field intensity depends on the distance \(R\) to the charge centre as \(E = Q/(4\pi\varepsilon_0R^2)\) [23]. Assuming \(E = E_{up} = (1-2)\cdot10^5 \text{ V/m}\) and \(R = 1 \text{ m}\), we find \(Q = 4\pi\varepsilon_0R^2E_{up} = 10^5 - 2\cdot10^5 \text{ C}\). For such a charge the electric field intensity on the surface of BL (at \(R_{bl} = 410^{-2} \text{ m}\)) is equal to \(E_{bl} = 6.210^7 \text{ V/m} – 1.2\cdot10^8 \text{ V/m}\). It is by 20-40 times greater than the field intensity of air breakdown \(E_{bd} = 3\cdot10^6 \text{ V/m}\). Despite this, in both cases there was not information about a discharge presence between
BL and nearby subjects even when it was passing at a short distance from walls and metal subjects like a damper or furnace rings.

The reason of confinement of large charge of BL is, apparently, a presence of a good insulator in area between the charge carrier and its surface [22]. However, at shorting of this insulator with any conductor the current of BL discharge can cause fusion of a conductor or an arc discharge [5, 24, 20]. If the discharge current passes through a body of a person, it can lead to mutilations and even to death [24, 10, 20, 19, 25]. Let's define a risk to which the girls, observing BL with charge $Q = 2 \cdot 10^{-5}$ C were exposed. The electric capacity of a ball of radius $R_{bl} = 4 \cdot 10^{-2}$ m is equal to $C_{bl} = 4 \pi \varepsilon_0 R_{bl} = 4 \cdot 10^{-12}$ F. Accepting a resistance of the person’s skin $R_s$ equal to 1 kOhm, we find a characteristic time of pulsed discharge of the ball $t_{bl} = R_s \cdot C_{bl} = 4 \cdot 10^{-9}$ s. The maximum current of discharge $I_{max} = Q/t_{bl} = 5$ kA. A depth of a current penetration into a conductor (a thickness of a skin-layer) is $\delta = 50.33 (\rho \cdot \tau)^{1/2}$ cm. (Here $\rho$ is a specific resistance of a conductor, Ohm-mm$^2$/m, and $\tau$ is a pulse duration). For copper $\rho_{Cu} = 1.75 \cdot 10^{-2}$ Ohm-mm$^2$/m and at $\tau = 4 \cdot 10^{-9}$ s a thickness of the skin-layer is $\delta_{Cu} = 4 \cdot 10^{-4}$ cm. Assuming that the specific resistance of a person’s skin is greater than the specific resistance of copper by $10^3$ times, we find the thickness of the skin-layer at BL discharge $\delta_{bl} = 1.3 \cdot 10^{-2}$ cm. Discharge duration of typical linear lightning is about 100 $\mu$s. For the pulse of such duration a depth of a current penetration in the person’s body is $\delta = 2$ cm [26]. It is known, that danger of death is produced by passage of the current of 40-60 mA through a heart or the respiratory centre of brain [19, pp 230]. It is possible to expect, that a current of BL discharge, most likely, will pass through a skin of the victim, not coming in the vital centers inside a body. With this respect a BL blow is less dangerous, than a blow of a linear lightning [5].

An insulator between BL core and its cover is non-ideal. Therefore it is quite possible that in the over-breakdown electric field near BL surface a corona discharge, fed by a current of its charge leaking, can arise. Formation of ozone and nitrogen dioxide is probable in this discharge. Presence of these gases in the BL trace was experimentally proved by M.T. Dmitriev. He managed to observe BL on the bank of the river Onega in 1965. It looked as a bright white-blue ball of 6-8 cm diameter, surrounded by two covers: an internal dark-violet cover with a thickness of 1-2 cm and a bright-blue external cover with a thickness of 2 cm. It is quite probable, that the luminescence of these covers was caused by the corona discharge. Dmitriev had gathered air from the BL trace inside some evacuated flasks. “The analysis of the gathered gas has shown presence of ozone and nitrogen dioxide in quantities, appreciably exceeding their normal concentration in air. The concentrations of other gases, which are usually present in air, did not change” [25, 27].

5. Principles of approaching to explanation of ball lightning high energy content

So, BL ability to possess energy with density of (1-3)-1010 J/m$^3$ is the experimentally proved fact, which requires an explanation. Furthermore, a solution of the problem of large energy amount accumulation inside the limited volume can play a key role in solving of the BL problem as a whole. Almost two centuries of searches for solution of BL mystery show that ignoring of this property and attempts to develop a theory of an object with the energy density, which is three orders of magnitude smaller than that, which was measured, lead investigations of this problem into the deadlock [4]. Attempts to reduce this problem to existence of some mysterious reservoir of energy feeding BL through invisible channels proved to be fruitless [28, 29, 30]. Proposals to consider that BL energy is stored inside a radioactive nuclei or it has the source in merge reaction of deuterium nuclei are also far from reality [2, 31, 32]. In our opinion, one can consider as the most realistic only models, which assume a kinetic energy of BL substance as the basic reservoir of its energy [3]. However, in this case a serious problem of creating of forces, confining a system of moving particles inside a restricted region of space, arises.

In the model of BL, developed by the authors of this article [3, 4, 9, 11, 26, 33, 34], along with a possibility of accumulation of huge amount of energy, as its basic property, presence of non-compensated electric charge in it is considered. The requirement of presence of the positive charge automatically arises at development of the dynamic electric condenser model – a basic element of BL
core [26, 33]. At first sight, presence of non-compensated charge only complicates a problem of the forces search keeping together a compact energy rich system – BL. However, this is not so. Really, let us consider a hollow sphere with an internal radius \( R \) and with a cover with a thickness \( a \). Let us place inside the sphere a considerable quantity of charged particles with the total charge \( Q \). We consider that the cover does not let the charges to pass through it. If all charged elements are distributed on an internal surface of a cover in regular intervals, they will stretch it with a force [4, 9, 26, 33]:

\[
F_Q = \frac{Q^2}{8\pi\varepsilon_0 R^2}.
\]

Here \( \varepsilon_0 \) is an electric constant, \( \varepsilon_0 = 8.85 \times 10^{-12} \) F/m.

If the charges are moving inside the cover, instead of “sitting” motionlessly on the wall, then to the force \( F_Q \) of “Coulomb” pressure on the wall a force of “magnetic” pressure of currents \( F_m \) will be added. This force is approximately equal to \( F_Q \), so the resultant force \( F_{em} \), stretching the cover, becomes equal to:

\[
F_{em} = \frac{kQ^2}{8\pi\varepsilon_0 R^2}.
\]

Here \( k \approx 2 \). Now let us discuss, what will occur with the cover if to place the electric charge \( Q \) inside the sphere. We will consider that the cover consists of a dielectric, for example, water molecules, and charge \( Q \) is placed in the sphere center. In the electric field \( E = Q/(4\pi\varepsilon_0 R^2) \), produced by this charge, there will be a polarization of water molecules: on the cover’s outer side positive ends of dipoles, and on internal – negative ends will be located. The distance between water molecules in an ice crystal is equal to \( 3 \times 10^{-10} \) m and on the area of \( 1 \) m\(^2\) \( 10^{19} \) molecules will be located. If to accept a charge of the end of a molecule equal to the electron charge \( e = 1.6 \times 10^{-19} \) C, then the density of charges on a cover surface is equal to \( \sigma = 1.6 \) C/m\(^2\). The chain of the polarized molecules of water, which length is equal to a thickness of a cover \( a \), represents an electric dipole with the moment \( d = ea \).

Let us assume that the charge \( Q \) is positive. Then the inner surface of the cover will be dotted with negatively charged ends of molecules. These charges are attracted to the central charge \( Q \) with a force

\[
F_+ = \frac{4\pi R^2 \sigma Q}{4\pi\varepsilon_0 R^2}.
\]

Here \( 4\pi R^2 \sigma \) is the total charge of the dipoles’ ends on the inner surface of the cover. The positively charged ends of the dipoles are located on the outer surface of the cover. The number of these ends is equal to the number of the dipoles on the inner surface of the cover. The outer surface of the cover is repelled from the charge \( Q \) with a force

\[
F_- = \frac{4\pi R^2 \sigma Q}{4\pi\varepsilon_0 (R + a)^2}.
\]

The resulting force, shrinking the cover, is

\[
F_{sh} = F_+ - F_- = \frac{Q\sigma a (2R + a)}{\varepsilon_0 (R + a)^2}.
\]

We can see that the shrinking force \( F_{sh} = A(R,a) Q \) is proportional to the first degree of a charge, and the force \( F_{em} = B(R) Q^2 \), stretching the cover, is proportional to a charge square. Therefore in the range of small values of a charge (from \( Q = 0 \) to \( Q = Q_{max} \)) conditions, when the shrinking force \( F_{sh} \) will be more than the stretching force \( F_{em} \), can always be created.

In Fig. 4 plots of forces \( F_{em} \) and \( F_{sh} \) dependence on the charge \( Q \), acting on a sphere cover with internal diameter \( 2R = 10 \) cm and thickness of the wall \( a = 1 \) cm, are shown. It is possible to see that up to \( Q = 1.53 \times 10^{-2} \) C the force of the cover compression exceeds the force of its stretching. At the values of the charge, smaller than limit, the equilibrium condition of system can be supported due to an additional pressure upon an internal surface of the cover, created by the charge carriers, possessing kinetic energy.
Let the cover is stretched by a centrifugal force of objects with a total mass \(M\), which glide with a velocity \(V\) on the inner surface of the cover. In this case a force \(F_k\), stretching the cover due to particles movement is:

\[
F_k = \frac{MV^2}{R} = \frac{2E_k}{R},
\]

where \(E_k\) is the total kinetic energy of the particles.

![Figure 4. Lg Fsh (dotted line) and lg Fem (solid line) versus lg Q at R = 5 cm and a = 1 cm. Forces Fsh and Fem are in Newtons, charge Q is in Coulombs.](image)

One can find that the same expression for \(F_k\) is obtained if particles with a total kinetic energy \(E_k\) move chaotically. According to Fig. 4, for \(R = 5 \times 10^{-2} \text{ m}\) and \(a = 10^{-2} \text{ m}\) at \(Q = 10^{-2} \text{ C}\), \(F_k = F_{\text{Fem}} - F_{\text{Fsh}} = 2.97 \times 10^8 \text{ N}\). A volume of a sphere with internal radius 5 cm and wall thickness 1 cm is equal to \(V = 0.9 \times 10^{-3} \text{ m}^3\). According to formula (11), \(E_k = (F_kR)/2\). Thus, at \(Q = 10^{-2} \text{ C}\) kinetic energy \(E_k = 7.42 \times 10^6 \text{ J}\) and energy density \(\rho_W = 8.25 \times 10^9 \text{ J/m}^3\). As we see, the density of kinetic energy of particles at \(Q = 10^{-2} \text{ C}\) comes nearer to the value of energy density of highly energetic BL \((\rho = 10^{10} \text{ J/m}^3)\).

Above we already paid attention to that even for BL, possessing a charge \(Q = 2 \times 10^{-5} \text{ C}\), an electric field intensity near its surface appears to be above the breakdown value \(E_{\text{br}} = 3 \times 10^6 \text{ V/m}\) by 40 times. It is especially fair for the considered BL with the charge of \(Q = 10^{-5} \text{ C}\), for which the field strength is \(E = 2.5 \times 10^{10} \text{ V/m}\) and potential \(U = Q \cdot R = 1500 \text{ MV at } R = 6 \times 10^{-2} \text{ m}\). The engineers, testing high-voltage devices know that already at potentials \(2 - 5 \text{ MV} \) between the electrodes, displaced at some tens of meters, a spark discharge can pass [35]. The huge internal resistance of the generator of a current – the charged core of BL – can be a reason of such discharge absence between BL and subjects surrounding it. It is known, that a way, which the spark discharge should pass, is laid by a leader – a thin channel with a rather high temperature 3000-6000 K [36]. For heat maintenance (and, means, for high conductivity) of the leader during time of its “germination” \((10^{-4} - 10^{-3} \text{ s})\) it is necessary that through the channel the current, extracting a power not less than 130 W for centimeter of its length, was flowing. At smaller powers the channel cools down, its conductivity decreases, and advancement of the leader stops. According to estimations, for typical cases of a spark development in air at atmospheric pressure the current flowing through the leader channel cannot be smaller than 1 A [35, 36 (52, 53)]. However, for BL because of low conductivity of an interval between the charged core and its cover the current is limited by values of \(10^{-3} - 10^{-2} \text{ A}\). This cannot become an obstacle for maintenance of corona discharge on its surface, but, suppresses the possibility of spark channel formation [22]. It is fair for the “healthy” BL, which is in an equilibrium condition. At isolation infringement between a core and a cover BL charge can be discharged on surrounding subjects through the spark channel. Such cases, really, were observed [5, 24, 10, 25].
6. Details of heterogeneous models of ball lightning

In the previous sections we defined general requirements for BL structure. We came to conclusion that conditions of accumulation of large density of kinetic energy can be created in the two-component system, consisting of the charged core and the dielectric cover. Now it is the time to discuss in more detail a structure of the BL core and to discuss how the definite model can explain observable properties of BL. We will present here two approaches to creating of BL core model. According to the classification, used in [3], we name these models by “Model N” and “Model B”.

1. Model N.

In this model it is supposed that the space inside the BL cover is filled with certain “plasmoids”, possessing a non-compensated electric charge. The plasmoid is meant as a system of moving charges, kept together by own electric and magnetic fields [37]. However, it was proved that stabilization of the plasmoid only by internal forces is, basically, impossible. Any external force, for example, a force of gravitation, is necessary for this purpose [38]. In our case a role of this external force is played by the force of the cover compression. According to the formula (11) for BL with internal radius of the cover $R = 5 \cdot 10^{-3}$ m at charge value $Q = 10^3$ C the force, compressing the cover, is $F_k = 2.97 \cdot 10^9$ N, and a pressure inside the cover is $P_m = F_k/(4\pi R^2) = 9.5 \cdot 10^9$ Pa. That is almost by $10^9$ times greater than a force of the atmospheric pressure.

As a prototype of our plasmoid “the hydromagnetic plasma condenser”, invented in the fifties of 20th century, serves [39]. This condenser represents a disk of plasma, placed in a strong magnetic field. In this field positive and negative charges are separated: electrons move in an orbit of small radius around a magnetic field direction, and positive ions move in an orbit of the big radius.

Movement of charges influences not only the external magnetic field, but also the electric field between regions of separated charges. Basically, for existence of similar system of moving charges presence of an external magnetic field is not obligatory. Really, let us imagine a certain ring of electrons, moving in a closed orbit of radius $r$ in magnetic field $H$, which is created by the positive ions, rotating in an orbit of big radius $R$. These electrons are kept in the orbit, making drift movement in mutually perpendicular fields $H$ and $E$, where $E$ is an intensity of electric field between the internal electronic ring and the external ionic ring. Ions are kept in the orbit thanks to their attraction to the electronic ring (due to action of the field $E$ on them). Such a configuration is named in [26] “the dynamic electric condenser”, and the concept – the “electrodynamic model of BL” [33 (49)].

Equating a centripetal force $F_c = eE$ to centrifugal force $F_c = (m_p v_p)^2/2R$, we find an orbital velocity of an ion $v_p = (eER/m_p)^{1/2}$. Here $m_p$ is a mass of proton (of the most light positive ion), $m_p = 1.67 \cdot 10^{-24}$ kg; $e = 1.6 \cdot 10^{-19}$ C is a proton charge. We consider not relativistic case, therefore an intensity of electric field at $R = 10^{-6}$ m should not exceed $E = 10^{14}$ V/m, and at $R = 10^{-2}$ m must be $E < 10^{10}$ V/m. Rotation frequency of proton is $f_p = v_p/(2\pi R) = (eE/(4\pi m_p R))^{1/2}$. If the total charge of all protons is equal to $Q_p$, a current $I_p$, created by their movement, is $I_p = Q_p f_p = (Q_p^2 eE/(4\pi m_p R))^{1/2}$. This current generates a magnetic field intensity in the center of the proton orbit $H_p = I_p / 2R = (Q_p^2 eE/16\pi m_p R^3)$. As rough approach let us accept that electric field $E$, created by an electronic ring with the charge $Q_e$, is equal to a field of a point charge. (More exact expression can be found in [26, 33]). In this case

$$E = Q_e/(4\pi\varepsilon_0 R^2), \ \text{V/m}.$$  \hspace{1cm} (12)

(Here $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m is the electric constant). For such $E$

$$H_p = (Q_p^2 eE/(64\pi m_p \varepsilon_0 R^3))^{1/2}.$$  \hspace{1cm} (13)

Movement of electrons in mutually perpendicular electric $E$ and magnetic $H$ fields occurs in a cycloid [40]). For the way of electron was closed, it is necessary that the magnetic field was strong enough and the condition $H_p \geq (e\varepsilon_0 / \mu_0)^{1/2} E$ was satisfied [41]. Here $\mu_0 = 1.25 \cdot 10^{-6}$ V-s/A-m is the magnetic constant. In this case we find from (12) and (13) the relation between values of total charges of protons $Q_p$ and electrons $Q_e$:

$$Q_e^2 \geq (4\pi m_p Q_p R^2)/e\mu_0 = 0.1R Q_e.$$  \hspace{1cm} (14)
The analysis shows, that at \( Q_e = 10^6 \text{ C} \) the inequality (14) is carried out at \( R > 10^{-4} \text{ m} \), and at \( Q_e = 10^3 \text{ C} \), for its performance it is necessary, that there was \( R > 10^2 \text{ m} \). It means that in this area of values \( Q_e \) and \( R \) the total charge of protons exceeds the total charge of electrons, so the plasmoid (the dynamic electric condenser) is positively charged. For a movement of the charged particles without being braked due to collisions with air molecules, a high vacuum should exist inside the cover. Simultaneously the vacuum plays a role of an electric insulator between the dynamic condenser and the BL cover. The radius of the proton orbit aspires to increase. The expansion of the orbit can be constrained by mutual impacts of dynamic condensers (if there are many condensers inside the cover) or by their impacts with the cover wall. Due to losing of the core charge the cover becomes positively charged, this promotes process of “plasmoids” reflection from its wall.

In the considered above example we spoke about properties of BL of an average size with the diameter \( 2(R + a) = 2(5 \text{ cm} + 1 \text{ cm}) = 12 \text{ cm} \). Now let us discuss how its characteristics will vary at reduction of a size of its elements. Kinetic energy of the proton, hold in an orbit by field \( E \), created by the electronic ring (see formula (12)), is \( W_p = m_p v_p^2/2 = eQ_e/(8\pi\varepsilon R) \), and the total kinetic energy \( W_p \) of protons \( (N_p = Qpe) \) is:

\[
W_p = W_p N_p = Q_e Q_e e/(8\pi\varepsilon R) = 4.5 \cdot 10^9 Q_e Q_e / R. \tag{15}
\]

Considering a relation between values of total charges of protons and electrons (14), the formula (15) can be written in a form:

\[
W_p = \frac{m_p}{16\pi\varepsilon_0 e^2\mu_0} Q_e^{3/2} / R^{1/2} = 1.45 \cdot 10^9 Q_e^{3/2} / R^{1/2} \text{ J}. \tag{16}
\]

Accepting the plasmoid volume equal to \( V_e = 4\pi R^3/3 \), we find an average density of kinetic energy of protons: \( \rho_e = W_p/V_e = 0.35 \cdot 10^9 (Q_e^{3/2}/R^{1/2}) \text{ (J/m}^3). \). We see that at decrease of the plasmoid radius \( R \) the density of total kinetic energy grows. The limit to decreasing of the size \( R \) puts the requirement that the number of electrons in the system was not less than 100 \((Q_e \geq 1.6 \cdot 10^{-17} \text{ C})\). Besides, a cover of dielectric, capable to constrain an expansion of a core of the tiny ball lightning must exist. Let us estimate the minimum size of BL with a total charge of electrons \( Q_e = 1.6 \cdot 10^{-17} \text{ C} \).

Let in the formulas (7), (10) and (11) \( k = 2 \), \( E_k = W_p \). At small \( R \) the balance equation of forces, acting the shell of the plasmoid, can be written as:

\[
\frac{2W_p}{R} + \frac{Q^2}{4\pi\varepsilon_0 R^2} - \frac{Q\sigma a(2R + a)}{\varepsilon_0 (R + a)^2} = 0. \tag{17}
\]

Because \( R >> a \) let’s disregard terms with \( a^2 \). In the result we have:

\[
\frac{2W_p}{R} + \frac{Q^2}{4\pi\varepsilon_0 R^2} = \frac{4Q\sigma a}{\varepsilon_0 (R + 2a)}. \tag{18}
\]

Solving this equation with respect to \( a \), we find:

\[
a = \frac{RX}{1 - 2X}, \text{ where } X = \frac{\varepsilon_0}{4\sigma Q} \left(\frac{2W_p}{R} + \frac{Q^2}{4\pi\varepsilon_0 R^2}\right). \tag{19}
\]

Accepting the charge \( Q \) equal to the total charge of protons \( Q_p \), \( \sigma = 1.6 \text{ C/m}^2 \) and using expressions (14) and (16), we obtain:

\[
Q \approx Q_p = (0.1RQ_e)^{1/2} = 0.316 R^{1/2} Q_e^{1/2} \text{ and } X = \frac{12.696 \cdot 10^{-3} Q_e + 3.937 \cdot 10^{-3} Q^{1/2}}{R^{3/2}}. \tag{20}
\]

According to (19) the condition \( X < 1/2 \) should be satisfied. At small \( R \) and \( Q_e \) the first term in the expression (20) is much smaller than the second, therefore it is possible to write \( R^3 \geq (7.87 \cdot 10^{-3})^3Q_e \). From here we find the minimum internal radius of the BL cover with a charge \( Q_e \): \( R \geq 3.96 \cdot 10^{-2} Q_e^{1/3} \). At \( Q_e = 1.6 \cdot 10^{-17} \text{ C} \) radius \( R \geq 100 \text{ nanometers}. \) Estimations by the formula (19) show that the thickness \( a \) of a cover of tiny BL with the total charge of electrons \( Q_e = 1.6 \cdot 10^{-17} \text{ C} \) at increase \( R \) from
75 to 150 nanometers decreases from 493 nanometers to 28 nanometers and its diameter \(2(R + a)\) becomes about 360 nanometers. Apparently, it is the minimum size which BL can have. Let the cover consists of water and its thickness is equal to 28 nanometers. The size of water molecule is \(r_c = 1.5 \times 10^{-10} \text{ m}\), hence, a cover can consist of \(n_t = a/r_c = 190\) layers of molecules. Kinetic energy of ions in such BL (see the formula (16)) is \(W_p = 1.45 \times 10^5 Q \frac{3}{2} R^{3/2} = 2.4 \times 10^{-11} \text{ J} = 1.5 \times 10^9 \text{ eV}\). Having divided \(W_p\) on volume of BL with the cover, \(V_{bs} = 4 \pi (R+a)^3/3 = 2.36 \times 10^{-20} \text{ m}^3\), we find the energy density \(\rho_{wa} = 10^7 \text{ J/m}^3\). This value is much smaller, than the limiting energy density of BL. At growth of the total charge \(Q\), and at increase of BL size the density of protons kinetic energy, counting on total volume of BL \(V_{bs}\) can considerably exceed the above found figure. For example, for BL with internal radius of the cover \(R = 1 \text{ mm}\) and the charge \(Q = 10^{-6} \text{ C}\) its diameter will be \(2(R+a) = 2.64 \text{ mm}\), kinetic energy of protons \(W_p\) will reach 46 J, and the energy density – \(\rho_{wa} = 5 \times 10^9 \text{ J/m}^3\). A quantity of these small BL can appear inside a big container with a dielectric wall. If a total volume of such ball is equal to 1 liter (it is a typical volume of “macroscopic” BL), than their total energy will be nearby 5 MJ. If the cover of this container – a “composite” BL – appears to be transparent, then these small BL can be seen with naked eyes [20].

One of basic properties of BL is its ability to soar freely in air it marked in [5, 24, 10, 20, 25, 42]. Let us check, whether a considered model of BL in the form of hollow sphere with internal radius \(R = 5 \text{ cm}\) and a cover thickness \(a = 1 \text{ cm}\) is capable to such action. We will assume that the cover consists of the substance, which density is close to density of liquid water \(\rho_w = 10^3 \text{ kg/m}^3\). Volume of the cover of our BL is \(V_{sh} = 4\pi[(R+a)^3 – R^3]/3 = 3.81 \times 10^{-4} \text{ m}^3\), and its mass \(m_{sh} = \rho_w V_{sh} = 0.38 \text{ kg}\). Weight of the cover is \(P_{sh} = m_{sh} g = 3.74 \text{ N}\). Let an area inside the cover is filled with carriers of the positive charge, which total value is \(Q = 10^{-11} \text{ C}\). We will assume that charge carriers are protons. In this case their quantity in the cover is \(N_p = Q/e = 6.25 \times 10^{-15} - 6.25 \times 10^{-16}\), and a total weight \(M_p = m_p N_p = 10^{-8} \text{ kg}\). Near the ground surface an electric field always presents. At fine weather its intensity is nearby \(E_{gw} = 100-150 \text{ V/m}\), and during thunder storms it can be greater than \(E_{gw}\) by 100-1000 times [43]. For creation of an elevating force, equal to the weight \(P_{sh} = 3.74 \text{ N}\) of BL with charge \(Q = 10^{-2} \text{ C}\), an electric field with intensity \(E = P_{sh}/Q = 3.74 \times 10^2 \text{ V/m}\) is required. Because of leaking of BL charge into a space around it, a cloud of charges appears. Repelling of BL from this cloud can provide it soaring over conductors [5, 24, 7, 10, 20, 25, 42, 44]) and existence of groups of BL [46]. Elements of BL core represent magnetic dipoles. Because of chaotic movement of these elements inside a cover of BL, it has no macroscopic magnetic moment [34]. However, in an external magnetic field there can be a partial ordering of the moments of separate dipoles. Likely this can explain a case of lifting of horseshoe-shaped magnets by BL in air [7].

As the generator of electromagnetic radiation of BL electric charges (electrons and protons), moving on the closed orbits, apparently, serve. At performance of condition \(H_p \geq (\omega/\mu_0) N/E\) a velocity of electrons appears to be close to the light velocity. Such electrons become a source of a synchrotron radiation which frequency appears \(n\) times greater than the frequency of their orbital movement \(f_e = c/(2\pi r)\) (\(r\) – is a radius of an electronic orbit). A harmonic number \(n_{\text{max}}\) on which a maximum of radiation intensity falls, is [47]:

\[
n_{\text{max}} = \frac{(3/2)(1 – \beta^2)^{3/2}}{\alpha}
\]

(21)

Here \(\beta = \omega/c\) – is a ratio of electron velocity to the light velocity. A power of synchrotron radiation is inversely proportional to product of squares of radius of the electron orbit \(r\) and a parameter \(\alpha=1-\beta\) [47]. Calculations show, that if there is a “mechanism” of protons kinetic energy transfer to electrons, then a full energy of BL should “be highlighted” by electrons during \(10^{-3} \times 10^{-2}\) s [33]. However, this conclusion concerns only a case of light radiation by a single electron or by an electron bunch. If electrons are located along an orbit absolutely in regular intervals, they will not radiate light [40]. In our system with large number of electrons they will aspire to be distributed in an orbit in regular intervals. The wave length, on which a maximum of radiation intensity falls, depends on electrons velocity and can be different. Therefore a color of BL can be any. At infringement of uniformity of
electrons arrangement along an orbit, BL can radiate energy in a form of a short pulse. Apparently, the specified mechanism of BL radiation is realized not only in optical range, but also in the radio range.

The most probable reason of BL formation is a discharge of linear lightning (or, strictly speaking, any channel of enough strong current). Usually a voltage between a storm cloud and the earth is \( U = 10^9 \text{ V} \). A discharge of average lightning transfers a charge \( Q_l = 5 \text{ C} \) to the earth, from here its energy is \( W_l = U Q_l = 5 \times 10^9 \text{ J} \). At the energy density \( \rho_{bl} = 10^{10} \text{ J/m}^3 \) BL with a volume \( V_{bl} = 10^{-3} \text{ m}^3 \) possesses energy \( 10^3 \text{ J} \), that is 0.2 % of the linear lightning energy. According to the “scenario”, described in [3, 33, 34, 48], BL is generated near a bend of the linear lightning channel at passage of several return strokes through it. It is considered that thanks to action of the first return stroke in a space near to the bent channel the vacuum cavity is formed and there air ionization takes place. At passage through the channel of a current of the next discharge, a pulse of magnetic field with duration of forward front nearby 10 \( \mu \text{s} \) and with duration of a falling down part nearby 50 \( \mu \text{s} \) is generated. In a phase of increase of the magnetic field eddy electric field is generated. Under the influence of this field a separation of charges takes place: electrons are injected inside a vacuum cavity, and positive ions (protons) remain near its walls. During reduction of intensity of the magnetic field the direction of the eddy electric field vector changes to reverse. As a result of action of electric and magnetic fields, the acceleration of protons takes place, and a part of electrons, moving along magnetic field lines leaves the area near the channel of the lightning. As a result a positively charged system of moving charges (the dynamic electric condenser) is formed: an electronic ring, round which protons rotate. In electric field of non-compensated charge from water drops a cover can be formed. The single double ring of moving charges is thermodynamically unstable: according to the law of growth of entropy it is favorable for it to divide into elements of small size, which will fill in regular intervals a space inside the cover. The minimum size of these elements can be about 1 mm [11, 33, 34].

2. Model B.

Another “material” model of BL is the “chemical-thermal” model [11, 49, 50, 51, 52]. According to it, BL is a unipolarly charged object with a shell and a nucleus. The core can consist of atomized particles of water vapor or atoms of matter that appear when a linear lightning strikes a variety of materials, such as \( \text{SiO}_2 \), \( \text{Al}_2\text{O}_3 \), etc., or the soil, in the presence of water in the soil or without it. For simplicity of analysis, we assume that the energy of linear lightning in this case is sufficient to transfer the material to which it was exposed, into atoms of an ideal gas. Such an approach makes it possible to consider the possibility of the formation of high-energy BL, although it leaves the question open about the properties of BL in the composition of which are nucleus of vapor and droplets of the formed matter.

Electrons carried by linear lightning, when struck in materials at atmospheric pressure, quickly adhere to neutral molecules, forming negative ions. Therefore, the core material contains these ions, which determines the electrical properties of BL. In this case, the shell is a thin film of a melt or solidified substance. The charge is transmitted to BL from a linear lightning, and the stability of BL with respect to destruction, as in [9, 19, 26], and is provided by the polarization force that arises from the Coulomb influence of a unipolar charge. Inside such BL there is a mixture of a gas and negative ions of the atomized substance.

In contrast to Model N, in this model there are components inside the shell that are associated with the random motion of particles inside the shell. In this case, the energy of such BL is determined mainly by the energy of evaporation evolved at the destruction of the object, to a lesser extent – when the substance of BL burns and the average energy of the particles inside the nucleus at a given temperature and pressure. The release of energy during combustion is insignificant with respect to evaporation. The calculation of combustion processes of BL material in the air requires a more complicated model, but does not make a significant contribution to the energy density of BL [49].

Energy of BL. The most important question in this approach is the question of the BL energy. In order to find an answer to this question, we first determine a gas pressure inside BL, acting its surface. Then, knowing the pressure and enthalpy of vaporization, that is, the energy density per atom of the
substance or molecule of water, we will determine the specific energy of such ball lightning. We consider two possible cases of BL formation.

First, the composition of the shell and the gas inside BL differs little (experiments on the evaporation of basalt and steel [50-52] indicated this possibility). In this case, the existence of a shell is determined by the nonequilibrium processes in the plasma that occur when a linear lightning strikes the ground, when nonequilibrium processes of shell formation lead to a change in its physical properties, without affecting the chemical. For estimates in this case, silicon is considered, whose content in the earth’s crust reaches 50%. The gas consists of SiO2 silicon, and the shell consists of a modified melt of SiO2 and its alloy with soil components. For estimates, we assume that the temperature of a gas inside the shell is close to 2000 K and is equal to typical boiling point of SiO2.

Second: the core of BL consists of water vapor, and the shell – of SiO2. For estimates, we also assume that the temperature of the gas inside the shell is of the order of 2000 K, i.e. of the order of the boiling point of SiO2.

Let us write an equation of balance of forces acting the shell of such BL:

$$ F_{\text{surf}} + F_a + F_{sh} - F_{el} - w 4\pi (R + a) = 0, \quad (22) $$

where $F_a = 4\pi (R + a)^2 P_a$ – is a force of atmospheric pressure, $P_a = 1.03 \times 10^5$ Pa is the atmospheric pressure, $R$ is BL radius and $a$ is a thickness of BL shell.

$$ F_{sh} = \frac{\sigma a (2R + a)}{\varepsilon_0 (R + a)} Q $$

is a force of a polarization interaction of charges [11(27)], $\sigma$ is a surface density of charges on a shell (see above), $Q$ is BL charge, $\varepsilon_0 = 8.85 \times 10^{-12}$ F/m is the electric constant.

$$ F_{el} = \frac{Q^2}{4\pi \varepsilon_0 (R + a)^2} \quad \text{is Coulomb interaction of charges of the same sign force, which influences the shell [11].} $$

$$ F_{\text{surf}} = 8\pi a (R + a) $$

is the force of surface tension, $a$ is a coefficient of surface tension of the shell, $w$ – is the pressure inside BL (for simplified consideration, we do not take in account the own volume of the shell) – determines the internal energy of BL, which goes to collisions of gas particles with the BL shell and leads to its stretching. We believe that the processes of atomization of matter, Coulomb repulsion and polarization compression of the shell lead to the establishment of pressure inside BL. In its turn, the atmospheric pressure and surface tension practically do not contribute. From (22) follows the equation for its determination

$$ w = \frac{F_{\text{surf}} + F_a + F_{sh} - F_{el}}{4\pi (R + a)^2} \approx \frac{F_{sh} - F_{el}}{4\pi (R + a)^2}. \quad (23) $$

A concentration of particles $N_a$ inside ball lightning can be determined on a basis of the equation

$$ w = P = N_a k T, \quad (24) $$

here $k = 1.38 \times 10^{-23}$ J/K is Boltzmann constant, $T$ – the temperature of particles inside BL.

BL mass is determined as:

$$ M = m_a N_a V = \frac{4}{3} \pi R^3 m_a N_a, \quad (25) $$

here $m_a$ is a mass of a gas particle. BL energy density can be determined by an equation

$$ E = \frac{w}{kT} \left( m_a \lambda + \frac{3}{2} kT \right). \quad (26) $$

$\lambda$ is an enthalpy of a vapor – gas formation (energy of sublimation), or an energy density of water atoms recombination, (J/kg). At the main material SiO2 $\lambda \approx 9.55 \times 10^6$ J/kg [17 (35)], and at the main material H2O $\lambda \approx 5.1 \times 10^7$ J/kg (it is determined by data on water molecule bonds breaking [53]). In all the cases we have considered $m_a \lambda \gg \frac{3}{2} kT$, which is natural, because the sublimation energy is of
the order of the dissociation energy, and that, in turn, is much larger than the thermal energy of the gas particles.

On a graph of Fig. 5 one can see typical dependences of pressure \( w \) (J/m\(^3\), its dimension coincides with Pa) over the charge \( Q \) of BL. The strength of BL shell polarization compression is proportional to the charge \( Q \), and the Coulomb force resulting in the rupture of the shell is proportional to \( Q^2 \), they act in different directions, so there is a charge value at which these interactions are compared. With a larger value of BL charge, its main energy goes to stretching of the shell, and the internal energy that can be released and do a work falls. From Fig. 5 one can see that the pressure \( w(Q) \) varies widely depending on the value of \( Q \) and has a maximum at given values of the shell thickness and the density of the polarization charges located on it.

![Graph showing typical dependences of pressure \( w \) over the charge \( Q \).]

**Figure 5.** Typical values of \( w \) (J/m\(^3\)) with respect to BL charge \( Q \). Solid line \( R = 5 \) cm, dashed line \( R = 10 \) cm, \( \sigma = 1.5 \) C/m\(^2\), \( a = 1 \) mm.

Table 1 a)-b) presents parameters of BL for various values of \((\sigma, a, R, Q)\) calculated by formulas (22) - (26) at the maximum value of \( w(Q) \) which we are interested in, since we analyze an existence possibility of high-energy BL. The data in Table 1 show that the BL energy density varies widely, mainly depends on the shell material, which determines the surface density of the charge, the charge inside BL, a thickness of the shell, and a radius of the BL. The energy density depends little on a type of material inside the shell. Within the framework of this model, BL can have energy comparable with the observed.

| N | \( \sigma \), C/m\(^2\) | \( a \), mm | \( R \), cm | \( w \), J/m\(^3\) | \( Q \), C |
|---|---|---|---|---|---|
| 1 | 1.5 | 1 | 5 | \( 9.60 \times 10^7 \) | 0.001 |
| 2 | 1.5 | 1 | 10 | \( 2.45 \times 10^7 \) | 0.002 |
| 3 | 1.5 | 1 | 50 | \( 1.00 \times 10^6 \) | 0.01 |
| 4 | 4.5 | 1 | 5 | \( 8.59 \times 10^6 \) | 0.003 |
| 5 | 4.5 | 1 | 10 | \( 2.22 \times 10^8 \) | 0.006 |
| 6 | 4.5 | 1 | 50 | \( 9.06 \times 10^9 \) | 0.029 |
| 7 | 4.5 | 10 | 5 | \( 5.28 \times 10^{10} \) | 0.03 |
| 8 | 4.5 | 10 | 10 | \( 1.72 \times 10^{10} \) | 0.06 |
| 9 | 4.5 | 10 | 50 | \( 8.52 \times 10^8 \) | 0.29 |
Table 1 b). Parameters for determination of BL energy density.

| N  | $n$, m$^{-3}$ SiO$_2$, H$_2$O | $M$, kg SiO$_2$, M, kg H$_2$O | $E$, J/m$^3$, SiO$_2$ | $E$, J/m$^3$, H$_2$O |
|----|-------------------------------|--------------------------------|------------------------|------------------------|
| 1  | $3.46 \cdot 10^{27}$          | 0.19                           | 0.06                   | $3.19 \cdot 10^{9}$    | $5.10 \cdot 10^{9}$ |
| 2  | $8.91 \cdot 10^{26}$          | 0.37                           | 0.11                   | $8.16 \cdot 10^{8}$    | $1.31 \cdot 10^{9}$ |
| 3  | $3.64 \cdot 10^{25}$          | 1.83                           | 0.55                   | $3.32 \cdot 10^{7}$    | $5.30 \cdot 10^{7}$ |
| 4  | $3.11 \cdot 10^{28}$          | 1.67                           | 0.5                    | $2.86 \cdot 10^{10}$   | $4.57 \cdot 10^{10}$ |
| 5  | $8.02 \cdot 10^{27}$          | 3.33                           | 1.0                    | $7.38 \cdot 10^{9}$    | $1.18 \cdot 10^{10}$ |
| 6  | $3.29 \cdot 10^{26}$          | 16.6                           | 5.0                    | $3.01 \cdot 10^{8}$    | $4.82 \cdot 10^{8}$ |
| 7  | $1.93 \cdot 10^{30}$          | 166                            | 50                     | $1.76 \cdot 10^{12}$   | $2.82 \cdot 10^{12}$ |
| 8  | $6.24 \cdot 10^{29}$          | 333                            | 100                    | $5.73 \cdot 10^{11}$   | $9.18 \cdot 10^{11}$ |
| 9  | $3.12 \cdot 10^{28}$          | 1650                           | 493                    | $2.83 \cdot 10^{10}$   | $4.52 \cdot 10^{10}$ |

Radiation of BL. A question of BL radiation reason in this model does not have an unambiguous answer, since BL has complex internal and surface structure.

The cause of BL radiation generation in the optical and radio ranges can be a plasma created by an electric field of a charge, a high core temperature, the movement of electrical charges in the plasmoids that form its core, or processes that cause the plasma pulsations near its shell. Some of these issues were discussed in [19, 22].

The radiation of BL can be of two types. It can be equilibrium then the BL shell is illuminated, filled with hot vapor. In this case, the heat is transferred to the shell by particles of vapor inside the shell.

The radiation of BL can be also a nonequilibrium one. Then under the action of BL large charge, a plasma appears in the strong electric field near BL surface as a result of ionization processes. The lifetime of the nonequilibrium radiation is determined by a plasma lifetime at its surface, i.e. the time of the charge decreases. Parameters of the nonequilibrium radiation require a special analysis with development of this model, which is beyond the scope of this article.

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 thermal radiation from the surface of the shell, then we can use the following expression for the specific heat of a real gas [54]

$$
\frac{3}{2} N k B \frac{4}{3} \pi R^4 \frac{dT}{dt} = -\sigma_{SB} T^4 4\pi R^2,
$$

(27)

where $k_B$ is the Boltzmann constant, and $\sigma_{SB}$ is the Stefan-Boltzmann constant. The 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 a form:

$$
t_c = \frac{N k_B R}{6\sigma_{SB} T_1^3}.
$$

(28)
For example, let us substitute the following values of BL average parameters from Table 1 into (28): $N = 8 \times 10^{27} \text{m}^{-3}$, $R = 0.1 \text{m}$, $T_1 = 500 \text{K}$, we get $t_i \approx 260 \text{s}$. This value is comparable to the observable time of BL.

In works [55, 56] in erosive discharges on the basis of polymeric materials, luminous spherical objects up to 2 cm in diameter were obtained, which emitted glow for 1-2 seconds. At the same time, it seemed that the intensity of their radiation did not change during their lifetime, and then these objects instantly extinguished. Analysis of the video shooting showed that during 0.04 seconds there was a smooth fading, which was not recorded by an eye of the observer. Therefore, a constant intensity of the luminescence noted by BL observers is most likely an optical effect due to the fact that the eye does not distinguish the decrease in the intensity of the glow when BL is cooled from 2000 K to ~ 800 K. Subsequent cooling of BL, and a corresponding decrease in the luminescence intensity occurs rapidly. During this time of extinction, the eye does not have time to adapt itself to a low intensity of the luminescence, since the physiological adaptation time of the eye when observing bright objects is ~ 10 s [57].

According to (28), the emission time of BL radiation increases with the radius of the ball, so the increase in the lifetime of BL with an increase in its radius, observed by observers [58], is easily explained. The color of BL in this model is determined by a material of which its shell consists. Being movable by the electric field of the earth, ball lightning can approach a window glass and “penetrate” into the room through a crack or a crakcle [20]. In addition, it is capable, having spent part of its energy, to heat the glass to a melting temperature and form a hole in it [59]. But this “material” BL is unable to pass through a glass leaving no traces at all.

We described some of the features of this model. At present, the problem of BL transformation from a tape into a ball, and also folding a tape into a sphere, remains an open question in the framework of this model, the question of the magnetic properties of such BL is open, etc. However, there are reasons to suppose that these questions will find answers within the framework of classical mechanics and electrodynamics.

7. Conclusion

We have chosen here three “the link main things” of BL problem: high energy storage, presence of non-compensated electric charge and dynamic character of its arrangement. We came to conclusion, that these properties can be combined in the system, consisting of three elements: unipolar charge, a dielectric cover and charge carriers, which simultaneously serve as accumulators of BL energy. This conclusion, along with conclusion about “material” nature of BL, which we made on the basis of analysis of its interaction with glasses [60 (4)], allows to one, creating a theory of BL, to narrow a number of its models, having excluded from them these which cannot explain high energy storage of BL and its ability to possess non-compensated electric charge.

8. Acknowledgement

We thank Dr. V.I. Kulikov for useful discussion of the results of ball lightning explosion.

References

[1] Arago F 1838 Sur le Tonnerre. Annuaire au Roi par le Bureau des Longitudes. Notices Scientifiques pp 221
[2] Nikitin AI 2006 Will be a success of ball lightning problem solution in 21st century? Khimicheskaya Fizika. 25(3) pp 18-37. (in Russian)
[3] Nikitin AI 2004 The principles of developing the ball lightning theory. J. Russian Laser Research 25(2) pp 169-191
[4] Nikitin AI 2012 A new approach for solving of ball lightning problem – change of the paradigm Vestnik RAEN 2 pp 19-30. (in Russian)
[5] Stenhoff M 1999 Ball Lightning. An Unsolved Problem in Atmospheric Physics. New York: Kluwer/Plenum
[6] Goodlet BL 1937 Lightning *IEE J. London* 81 pp 1
[7] Imyanitov I, Tikhiy D 1980 *Beyond a Boundary of Science Laws* Moscow: Atomizdat, (in Russian)
[8] Egely G 1993 Analysis of Hungarian ball lightning observations *In: Progress in ball lightning research* Ed. AG Keul. Proc. VIZOTUM. Salzburg, Austria
[9] Nikitin AI, Bychkov VL, Nikitina TF, Velichko AM 2014 High-energy ball lightning observations *IEEE Transactions on Plasma Science* 42(12) pp 3906-3911
[10] Brand W 1923 *Der Kugelblitz* Hamburg: H. Grand
[11] Bychkov VL, Nikitin AI, Dijkhuis GC 2010 Ball lightning investigations *In: The Atmosphere and Ionosphere. Dynamics, Processes and Monitoring*. Eds. VL Bychkov, GV Golubkov, AI Nikitin. Dordrecht: Springer pp 201-373
[12] Dugarov BTs An accident in Mogsokhon [http://arigus-tv.ru/news/item/50247/ (in Russian)]
[13] A Management on Blasting Works Moscow: Military Publishing House of the USSR Ministry of Defence, 1963. (in Russian)
[14] *The Big Soviet Encyclopaedia* 1956 Ed. BL Vvedensky 43. Moscow: BSE, (in Russian)
[15] Likhoshyorstnykh GU 1994 Anomalous cases of meetings with ball lightning *In: Ball Lightning in Laboratory* Eds. RF Avramenko, VL Bychkov, AI Klimov, OA Sinkevich. Moscow: Khimia pp 218-223. (in Russian)
[16] Dmitriev MT, Bakhtin BI, Martynov VI 1981 Investigation of thermal factor of ball lightning *J. Tekhn. Fiz.* 51(12) pp 2567-2572 (in Russian)
[17] *Physical Values. Reference book*. Eds. IS Grigoriev, EZ Meylikhov. Moscow: Energoatomizdat, 1991 (in Russian)
[18] Batygin A, Mosin I 1989 Visit of “fiery” lady *Newspaper “Pravda”* N. 220. August, 8 (in Russian)
[19] Bychkov VL, Nikitin AI 2014 Ball lightning: A new step in understanding *In: The Atmosphere and Ionosphere. Elementary Processes, Monitoring, and Ball Lightning*. Eds. VL Bychkov, GV Golubkov, AI Nikitin Cham: Springer pp 201-367
[20] Grigoriev AI *Ball Lightning* Yaroslavl: YarGU Publisher, 2006 (in Russian)
[21] Landau LD, Lifshits EM 1959 *Electrodynamics of Condensed Media*. Moscow: Publishing of Phys.-Math. Literature (in Russian)
[22] Nikitin AI, Nikitina TF, Velichko AV 2013 Radio emission of corona discharge and ball lightning *Electrichestvo* 9 pp 12-22 (in Russian)
[23] Kalashnikov SG 1985 *Electricity* Moscow: Nauka (in Russian)
[24] Stakhanov IP 1996 *About Physical Nature of Ball Lightning* Moscow: Nauchny Mir (in Russian)
[25] Singer S 1971 *The Nature of Ball Lightning* New York: Plenum
[26] Nikitin AI 1998 Electrical capacitor as the element of the power core of ball lightning *Electr. Technol. Russia* 4 pp 70-85
[27] Dmitriev MT 1967 A nature of ball lightning *Priroda* 6 pp 98-106 (in Russian)
[28] Ohtsuki YH, Ofuruton H 1991 Plasma fireballs formed by microwave interference in air *Nature* 350(6314) pp 139-141
[29] Kapitsa PL 1987 About the nature of ball lightning *In: Experiment, Theory, Practice* Moscow: Nauka pp 55-61 (in Russian).
[30] Handel PH 1975 Maser theory of ball lightning *Bull. Am. Phys. Soc. Series ii*. 20(1) pp 26
[31] Altschuler MD, Houste LL, Hildner E 1970 Is ball lightning a nuclear phenomenon? *Nature* 228 pp 545-547
[32] Vlasov AN 2009 Is ball lightning an induction discharge in a vortical ring? *Nauka i Zhizn* 7 pp 28-34 (in Russian)
[33] Nikitin AI 2006 The electrodynamic model of ball lightning *Khimicheskaya Fizika* 25(3) pp 38-62 (in Russian)
[34] Nikitin AI, Velichko AM, Nikitina TF 2008 Principles of search of conditions of creating of ordered plasma structures *Proc. RAS. Energetics* 2 pp 115-132 (in Russian)
[35] Bazelian EM, Raizer Yu P 1997 *Spark Discharge* Moscow: MFTI Publishing (in Russian)
[36] Bazelian EM, Raizer Yu P 2001 *Physics of Lightning and Protection from Lightning* Moscow: FIZMATLIT (in Russian)
[37] Bostik WH 1956 Experimental study of ionized matter projected across a magnetic field *Phys. Rev.* 104(2) pp 292-299
[38] Shafranov VD 1957 About stable magneto-hydrodynamic configurations *J. Exp. Theor. Phys.* 33(3(9)) pp 710-722 (in Russian)
[39] Anderson O, Baker WR, Bratenahl A, Furth HP, Kunkel WB 1959 Hydromagnetic capacitor *J. Appl. Phys.* 30(2) pp 188-196
[40] Artzimovich LA, Lukianov SYu 1978 *Motion of Charged Particles in Electric and Magnetic Fields* Moscow: Nauka (in Russian)
[41] Landau LD, Lifshits EM 1961 *Theory of Field* Moscow: Nauka (in Russian)
[42] Barry JD 1980 *Ball Lightning and Bead Lightning* New York and London: Plenum Press
[43] Uman MA 1969 *Lightning* New York: McGraw-Hill
[44] Nikitin AI, Nikitina TF, Velichko AM 2010 Corona discharge and levitation of ball lightning *Electrichestvo* 3 pp 16-22 (in Russian)
[45] Nikitin AI, Leipunsky IO, Nikitina TF 2010 A role of eddy currents in creating of lifting force by an autonomous emitter of radio waves *Prikладная Физика* 2 pp 15-22 (in Russian)
[46] Nikitin AI, Velichko AM, Nikitina TF, Stepanov AI, Stepanov IG 2016 Observation and analysis of ball lightning group flights *Proc. 5th International Conf. “Atmosphere, Ionosphere, Safety” (AIS - 2016)* Kaliningrad pp 274-278
[47] Ternov IM, Mikhailin VV, Khalilov VR 1980 *Synchrotron Radiation and its Applications* Moscow: MGU Publisher (in Russian)
[48] Nikitin AI 2000 Creation of ball lightning at developing of linear lightning *Electrichestvo* 3 pp 16-23 (in Russian)
[49] Bychkov V 2010 Artificial and natural fireballs as combustion objects *IEEE Transactions on Plasma Science* 38(12) pp 3289 – 3290
[50] Emelin SE, Semenov VS, Bychkov VL et.al. 1997 Some objects formed in the interaction of electrical discharges with metals and polymers *Tech. Phys* 42(3) pp 269-277
[51] Emelin S, Bychkov V, Astafiev A, Kovshik A, Pirozersky A 2012 Plasma combustion nature of artificial ball lightning *IEEE Transactions on Plasma Science* 40(12) pp 3162-3165
[52] Bychkov VL, Chernikov VA, Osokin AA, Stepanov AI, Stepanov IG 2015 Modeling of artificial ball lightning with a help of capillary discharge *IEEE Transactions on Plasma Science* 43(12) pp 4043-4047
[53] Radzig AA, Smirnov BM 1980 *Reference book on atomic and molecular physics* Moscow: Atomizdat publishers (in Russian)
[54] Smirnov BM 1987 *Introduction to plasma physics* Moscow: Nauka publishers. (in Russian)
[55] Bychkov VL, Bychkov AV, Timofeev IB 2004 Experimental production of long-lived luminous organic polymeric objects *Technical Physics* 49(1) pp 128-133
[56] Bychkov VL, Bychkov AV, Timofeev IB 2006 Experimental modeling of long-lived luminous formations in air on a basis of polymeric organic materials *Khimicheskaya Fizika* 25(4) pp 89-96 (in Russian)
[57] Amirov AKh, Bychkov VL 1994 ANOVA of Several Parameters of the SKB Data Bank on Ball Lightning *Physica Scripta* 50 pp 93-96
[58] Amirov AKh, Bychkov VL, Bobkov SE 1998 On the dependence lifetime- diameter for ball lightnings *Physica Scripta* 58 pp 56-60
[59] Kolosovskii OA 1981 Observation of ball lightning track on the window glass *Zh. Tekh. Fiz.* 51 pp 856-858 (in Russian)
[60] Bychkov VL, Nikitin AI, Ivanenko IP, Nikitina TF, Velichko AM, Noisikov IA 2016 Ball lightning passage through a glass without breaking it *J. of Atmospheric and Solar-Terrestrial Physics* 150 pp 69-76