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On the possibility of making natural ball lightning using a new pulse discharge type in the laboratory

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Contents

Abstract. **A new type of electrical discharge was discovered in Gatchina, which produces long-lived luminous formations with the same unique physical properties as natural ball lightning. This paper reviews the research work on the Gatchina discharge that has been done by a number of independent groups and which has provided important insights into the nature of both the discharge and ball lightning formation processes. However, the luminous formations that appeared in the experiments by these groups have a shorter lifetime than objects created by the authors of the proposed method and fail to exhibit some of the specific properties of ball lightning. In this paper, the basic parameters and operation regimes of a facility for creating such formations are discussed; their optimization will eliminate these drawbacks. The review discusses the properties of both the discharge and the luminous objects formed in it, which were observed by the present authors and which other groups failed to reproduce. A model of natural ball lightning is proposed, in the framework of which the peculiar properties of the Gatchina discharge and of the long-lived luminous formations observed in it are explained. The experimental facility developed exhibits a number of features that allow the near-100%-effective production of long-lived luminous formations, thus enabling their physical characteristics to be studied, in principle, on a systematic basis.**

Keywords: Gatchina discharge, long-lived glowing formations, plasma sheet, macroscopic charge separation, barrier discharge, creeping discharge, ball lightning

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1. Introduction

In 2000, a new type of electrical discharge was discovered in Gatchina (Russia), which is realized above the surface of water in the air half-space [1, 2]. Scientists from Russia, Japan, Germany, the USA, Ukraine, and other countries participated actively in the Gatchina discharge investigations [3–38], since the long-lifetime luminous objects produced in the discharges bear striking resemblance to natural ball lightning. For instance, Friday [36] believes that the interest of many researchers exhibited in this discharge is due to the charm of the observed phenomenon and the exceptional simplicity of the experiment.

In Refs [1, 2], we demonstrated for the first time the capabilities of this discharge, in which the lifetime of the luminous object ranged up to 1 s without external energy input. More recently, we presented in Ref. [13] frames from a video showing that a decaying luminous object retained its diameter from the 160th to the 600th ms. The subsequent frames of the video were not presented in Ref. [13], but one could see from these frames that the glow decreased, with retention of the diameter, and terminated only in the 760th ms.

Figure 1. Long-lived luminous object produced in a dark room.

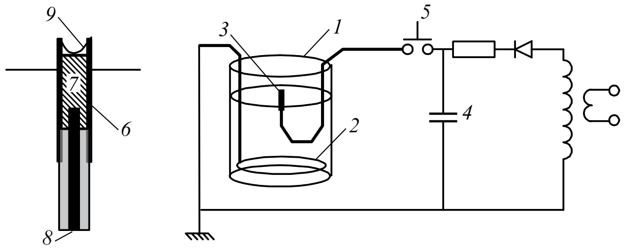

Figure 2. Setup for obtaining long-lived luminous objects. *1* — polyethylene vessel, 2 — ring electrode, *3* — central electrode, *4* — capacitor bank of capacitance 0.6 mF, *5* — spark gap, *6* — quartz tube, *7* — carbon or metal electrode, *8* — copper busbar, *9* — water droplet or substance introduced into discharge.

Figure 1 shows a photograph of a typical long-lived luminous object. This object, about 14 cm in diameter, rises above the water vessel on whose surface it was formed. The picture was taken in a dark room. To switch a discharge, it was necessary to illuminate a small area on the table with the spark gap on it. The window curtain was slightly moved aside to let the light enter the room through a small opening in it. The light illuminated not only the switch site but also the luminous object.

This illuminated spot acquired a white color, which changed to yellow. Red and dark red coloration was observed from the parts not illuminated by the light. The intrinsic object glow is rather faint, but it is clearly seen on the wave crests as red and scarlet red. The waves on the water surface were produced by after-discharge electrode swinging. The detailed color description will help us understand at a later time how the color of natural ball lightning changes and how it is possible to change the resultant object color without varying any parameters of the object-producing facility.

An analysis of the work dedicated to the study of this discharge shows that objects obtained by practically all research groups are inferior in quality to that depicted in Fig. 1. In particular, their lifetime ranges from 250 to 400 ms (up to 500 ms in some studies), and by this time they disintegrate completely, their glow terminates, and their diameter increases two- to three-fold. The sharp increase in diameter is testimony to a fast disintegration of the resultant structure, whose properties define the glow period and other parameters of the resultant objects.

It is likely that the description of our experiments was not minute enough, which hinders reproducing our results. This is the main reason for writing the present paper. For all the simplicity of the experiment, in the production of long-term luminous objects there are several parameters which have a critical effect on their properties, including the very possibility of their existence. Here, we consider the most important parameters of the facility and electrical discharge modes, adherence to which will make it possible to produce objects that glow for about 1 s and possess extraordinary combinations of properties inherent in natural ball lightning.

2. Facility description

The luminous object is created above a water surface in the air half-space. The discharge production facility is schematized in Fig. 2. Discharges are initiated in a polyethylene vessel 18 cm in diameter, with two electrodes in it.

The discharge is ignited by the central graphite electrode 6 mm in diameter, which protrudes above the water surface by 2–3 mm (item *7*). A quartz tube insulates the electrode side surface from the water. A ring electrode of opposite polarity (the anode) is in the water at a depth of no less then 15 cm and is grounded. Upon connecting the cathode to the discharge gap of a capacitor bank with a capacitance of 0.6 mF charged to 5.0–6.0 kV, a plasma sheet forms on the water surface, which is clearly seen in Fig. 1 borrowed from Ref. [7]. This plasma sheet transforms into a luminous surface, which separates from the water to form a ball-shaped luminous object as a result of the surface deformation. Under certain conditions, a luminous jet run out of the electrode additionally forms, which connects the cathode and the object under formation. This is achieved, for instance, by adding (by placing at the cathode; item *7* in Fig. 2) substances into the discharge that increase the kinetic energy of the object being formed. In this case, the luminous surface rises faster, expands vertically, and looks like a plasma jet. Depending on the fineness of the fraction introduced, it is 'digested' differently by the discharge. We tested the addition of silver graphite to the discharge: a small portion of its particles of larger size (tenths of a millimeter) escaped from the volume of the luminous object prior to its decay.

Also placed on the cathode were colloidal graphite and distilled water. These substances, when introduced in amounts below 20 mg, remained in the luminous objects up to their decay. The capacity of the luminous objects to hold additional substances in their volume was noted by Friday [36], who observed a sharp near-spherical boundary between the plasmoid and the environment. He studied the plasmoids using an Orbitrap mass spectrometer to identify the ions existing in the plasmoid. The use of isotopic labeling yielded quantitative evidence of the unique capacity of the plasmoid to prevent its contents from mixing with atmospheric air. Also elucidated was the origin of the molecules, radicals, and ions synthesized in the discharge [36]. We revert to this work below.

The jet may be formed due to a long discharge commutation time. In this case, the mechanism of jet formation changes: for instance, the electrode melts and the discharge goes into the arc mode. The discharge may also be implemented with hardly any jet.

In the 80–100th ms, the spark gap disconnects (residual voltage is under 3 kV, usually 2.5 kV) and a luminous surface with a jet (or without a jet) breaks away from the electrode to assume the shape of a ball. One may single out two discharge stages. The first is a plasma sheet, the luminous surface, and the jet, which retain a galvanic connection to the electrode. The second discharge stage sees the formation of an autonomous long-lived object, which exists for several hundred milliseconds without external energy input.

3. Observed effects

3.1 Synthesis of chemical substances in a discharge

The Gatchina discharge was originated as a continuation of research on erosion discharges [1]. The objects produced in erosion discharges possessed several anomalous properties. For instance, they could burn through a metal foil but could not set fire to an ordinary piece of paper, leaving hardly any trace on it [39, 40]. An interesting property of the erosion discharges was their capacity to produce filamentary and web-like objects. In our experiments, fluff-like thin fibers would float across the laboratory for several dozen seconds after discharge termination [10]. This took place when 5–10 mg of colloidal graphite was deposited on the electrode. In Ref. [40], the material for the fibers in erosion discharges came from a volatile plasmatron coating. The fibers were captured in a cell with liquid nitrogen, and then they spontaneously curled into balls. Nanofibers assembled in bundles and webs were observed in Refs [41, 42]. These papers are interesting in that the fibers comprised not only hydrogen and deuterium atoms, which is close to the present paper, but also metal atoms evaporated by laser pulses, these objects being produced in the quantum vortices of superfluid helium (formation of a nanowire). A nanowire web may find practical use. The fibers and bundles in Refs [40–42] and, for instance, in Figs 3 and 4 (in what follows, these pictures will be necessary in the discussion of the charge of the luminous objects) in our experiments ranged up to several centimeters in length. The production of similar structures is an indication of the possible existence of a common formation mechanism for these objects.

In Refs [40, 41] and for the discharge in Figs 3 and 4, the observation of fibers and fiber bundles is possible in the case of their low-temperature 'chilling'. This is a necessary operation for preserving these structures. In Ref. [40], it was possible to preserve them in liquid nitrogen, and in Ref. [41] in liquid helium. In our discharge (see Figs 3 and 4), web-like objects were not produced (colloidal graphite was not added to the discharge), and the fibers were not preserved. It is likely that they oxidize into gaseous products in the disintegration of the luminous objects.

It is also possible to obtain objects (like those in Fig. 1) without applying any substances to the electrode. To facilitate commutation, 10–20 mg of distilled water is usually deposited onto the electrode. The erosion of graphite electrode during the discharge is quite small and does not exceed 0.1 mg. Hence, it follows that the chemical compounds required to produce an envelope, which separates the luminous object from atmospheric air, should be synthesized in the course of discharge. Our viewpoint was confirmed by Refs [34–36], which showed that chemical compounds were synthesized in the course of discharge and their amount turned out to be very large. Simultaneously solved was the issue of participation of the water from the polyethylene vessel (item *1* in Fig. 2) in this process. According to mass-spectrometric measurements, with the use of D_2O instead of H_2O, the hydrogen-to-deuterium ratio in NH_3 showed that the last molecules were

Figure 3. Appearance of the envelope after removal of a part of the charge from the luminous object.

Figure 4. Loss of the envelope elasticity after a greater part of the charge as compared with Fig. 3 was removed from the luminous object.

actively produced in the plasmoid, i.e., that NH_3 was synthesized from the nitrogen and hydrogen contained in the air. This is not the sole example from Ref. [35] which permits concluding that atmospheric air contains enough 'building material' for envelope formation. Some of the compounds are produced with the participation of the water from the vessel. We list a small part of the observed singly charged positive ions: C_6H_9, C_3H_8NO, C_3H_8OH, $C_5H_9O_2$, $C_5H_{10}NO$, $C_7H_{18}N$, $C_{12}H_{25}O_3$, $H(H_2O)_2$, $H(H_2O)_3$, $NO(H_2O)$, NO, $(D_2O)_2D$, and $NO(D_2O)$; and also negative ions: NO_2, NO_3, HN_2O_5, and HN_2O_6.

The possibility that new compounds may also be synthesized became known to us from the following experiment. A water vessel (*1* in Fig. 2) was placed in a polycarbonate cylinder 20 cm in diameter and approximately 21 l in volume. An atmosphere of argon, carbon dioxide, nitrogen, air, and air with the addition of propane was prepared in the cylinder. A discharge into the atmosphere of the ordinary air turned out to lead to the most interesting result. After several discharges, the air in the cylinder would become red–brown–orange due to the production of a large amount of nitrogen dioxide (NO_2) with its characteristic pungent smell.

An interesting feature was associated with the addition of distilled water onto the electrode. Given in Ref. [10] are data on the rate of ascent of the luminous object in relation to the amount of water added. Without the addition of water, the rate was about 0.7 m s^{-1}. One can visually see that the object hangs in the air on passing by the sensor, which is used to measure the rate. On adding about 10 mg of distilled water, the rate of the object increased to ≈ 1.5 m s^{-1}, and on adding about 18 mg, the rate was ≈ 2.5 m s^{-1}.

The average diameter of the luminous object is equal to 14 cm. The air enclosed in it weighs about 2×10^3 mg. Variation of the weight of the added distilled water from 18 mg (1% of the weight of the luminous object) to zero entails a several-fold variation in the rate of the object. Its temperature was estimated at 330 K [4] proceeding from the dynamics of the object motion as a volume of warm humid air. At the point in time when the temperature was measured in Ref. [4], the dependence of the rate of the luminous object on the amount of added substance was not yet known, and therefore the temperature value calls for correction.

The water surface in the polyethylene vessel should be clean. For instance, if a mineral oil droplet is dripped onto the water surface (the layer of oil on the surface will be highly uniform, approximately one micrometer in thickness), the object will not be produced in the discharge. The discharge, usually noiseless, is attended in this case by a sound resembling that of tearing paper; the mineral oil 'curdles'.

Many researchers believe that the processes occurring on the water surface are central to the production of the objects. However, when the commutation time is shortened, the high residual voltage across the capacitors gives rise to a second luminous object at the spark gap bar. It will separate from the bar and continue to exist autonomously. Figure 5 displays a photograph which serves to illustrate the production of two objects in one discharge.

The effect illustrated in Fig. 5 suggests that the facility (see Fig. 2) produces a special case of discharge whose dynamics permit producing long-lived luminous objects also without the presence of water. In Ref. [7], we drew attention to this fact and noted that water fulfills mostly the function of a variable resistor. The authors of Ref. [9] obtained objects practically the same as ours without the use of water, which confirms the assumption made in Ref. [7]. However, their reproducibility was quite low in comparison with the practically 100% reproducibility of the Gatchina discharge.

3.2 Macroscopic charge separation

Macroscopic charge separation, which occurs in the course of a discharge time, gives rise to an uncompensated electric charge in long-lived luminous objects. This follows from the experiments carried out in Refs [7, 8, 10–12]. We emphasize that the anode was grounded in these experiments, since the luminous objects did not possess an uncompensated electric charge when the central electrode (cathode) was grounded. The cathode was grounded, for instance, in Refs [25–31], and the charge was absent. As also noted in Ref. [19], the anode should be grounded in order to obtain an uncompensated charge.

Figure 6 shows a plot obtained using a Langmuir probe in Ref. [7]. The experiment was performed as follows. The Langmuir probe was placed at a height of 25–45 cm above the central electrode. The minimal sensor position height was selected proceeding from the desirable luminous-object rise time to the sensor, 100 ms, measured from the instant of discharge termination (commutation closing). The object moves with a speed of about 1 m s^{-1} and runs up to the sensor in the 86th ms (in our case), completely passing by the sensor in the 153rd ms. The Langmuir probe nicely records the peak values of the current (of negative charge collection by the probe) in the passage of the front and rear wall positions of the object. A good explanation for this plot is provided by Fig. 7, which is given in Ref. [3]. In this figure, it

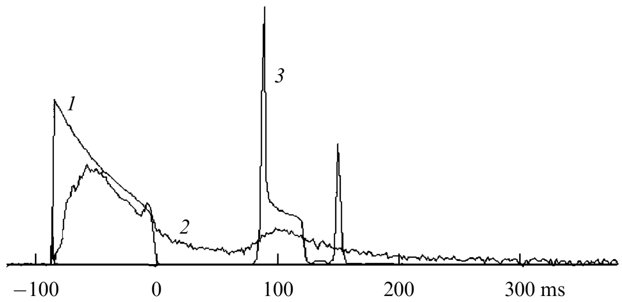

Figure 6. Curve *1* — voltage across the spark gap (5.5 kV). Curve *2* — luminosity of the glowing object in arbitrary units. Curve *3* — probe current, which corresponds to the collection of negatively charged particles. The time is measured from the instant of discharge termination. Use was made of an unbiased probe 0.45 mm in diameter. The current peaks correspond to the front (5 μA) and rear walls of the luminous object.

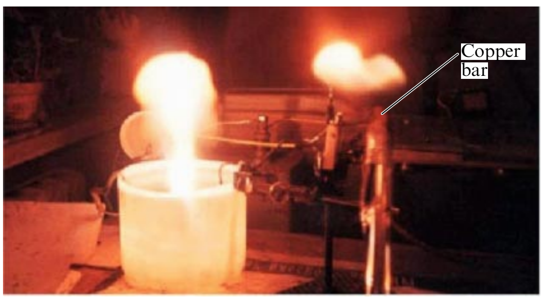

Figure 5. Two luminous objects emerging above the water vessel and the spark gap bar.

Figure 7. Visualized envelope of the luminous object. Inside of the envelope are luminous (top) and nonluminous (bottom) domains.

was possible to visualize an envelope which prevents the object's internal filling from mixing with the ambient air. By comparing Figs 6 and 7, it can be seen that the charge current appears when the front object wall passes by the probe (5 μA), continues in the passage of the luminous filling, interrupts in the passage of nonluminous space, and exhibits a second peak in the passage of the rear object wall.

The current peak at the rear wall is half as large, since part of the charges was removed by the Langmuir probe and another part of the charges leaked when the Langmuir probe was passing between the object's walls for 77 ms.

Increasing the input resistance of the Langmuir probe lowers the charge loss. But the luminous object interacts with conductors (the Langmuir probe is a small metal ball) irrespective of whether they are grounded or not. This effect distorts the resultant data. In Section 3.3, we will give examples of such an interaction.

To weaken the influence of this effect on the measurements, we performed them using a double probe and a dipole antenna, which were galvanically insulated from the recording instrumentation. The dipole antenna was essentially the same double probe with an interelectrode distance of 3 mm, but the electrodes were insulated (glass-coated). The dipole antenna can hardly interact with the luminous object, and so the data obtained using this antenna turned out to be the most interesting [7].

We cite an example of this experiment. The dipole antenna was installed in such a way that the object passed by the antenna without hitting it. Figure 8 shows the passage of the luminous object (A) past the dipole antenna ends (*1* and *2*). In the experiment, the object, approximately 8 cm in diameter, went along the x-axis past the dipole antenna. At the moment it passed by the antenna, the distance of the object wall from the antenna was about 2 cm. In the diagram of Fig. 8, d denotes the shortest distance of the object center from the dipole antenna.

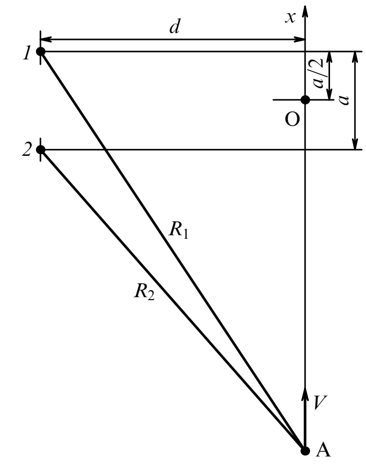

Figure 8. Diagram showing the passage of the luminous object (A) past the dipole antenna ends (*1* and *2*).

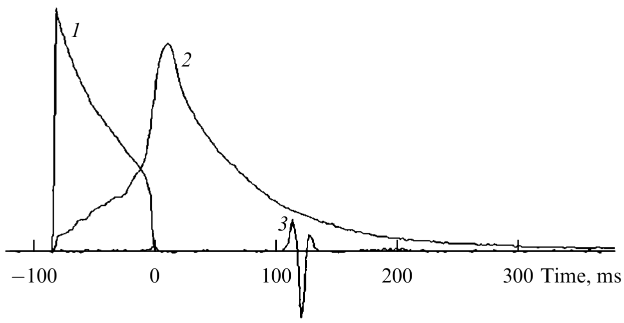

Figure 9. Experiment on the passage of the luminous object past the dipole antenna. Curve *1* — voltage across the discharge gap. Curve *2* — luminosity of the glowing object in arbitrary units. Curve *3* — dipole antenna signal.

Let us obtain the expression for the potential difference $\varphi_1 - \varphi_2$ across the dipole antenna ends and the observable signal $\Phi(x) = \mathrm{d}(\varphi_1 - \varphi_2)/\mathrm{d}t$:

$$R_1^2 = d^2 + \left(x + \frac{a}{2}\right)^2, \qquad R_2^2 = d^2 + \left(x - \frac{a}{2}\right)^2,$$

$$\varphi_1 - \varphi_2 = Q\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$$

$$= Q\left(\frac{1}{(d^2+x^2+ax+a^2/4)^{1/2}} - \frac{1}{(d^2+x^2-ax+a^2/4)^{1/2}}\right).$$

If $a \ll d$, then one can ignore the term $a^2/4$ in the radicand and take $Q/(d^2+x^2)^{1/2}$ out of the parenthesis, thus arriving at

$$\varphi_1 - \varphi_2 = -aQ\,\frac{x}{(d^2+x^2)^{3/2}},$$

$$\Phi(x) = \frac{\mathrm{d}(\varphi_1-\varphi_2)}{\mathrm{d}t} = \frac{\mathrm{d}(\varphi_1-\varphi_2)}{\mathrm{d}x}\,\frac{\mathrm{d}x}{\mathrm{d}t}$$

$$= -aVQ\left[\frac{1}{(x^2+d^2)^{3/2}} - \frac{3x^2}{(x^2+d^2)^{5/2}}\right],$$

or

$$\Phi(x) = A\,\frac{d^2-2x^2}{(x^2+d^2)^{5/2}},$$

where $A = -aVQ$ and $V = \mathrm{d}x/\mathrm{d}t$ is the velocity of charge motion.

The observed signal in the experimental plot (Fig. 9) is in satisfactory agreement with the expected signal $\Phi(x)$ given by the formula obtained above. In view of the model and calibration measurements, the uncompensated negative electric charge of the luminous object is, in this case, greater than 10^{-7} C ($2-4\times10^{-7}$ C). The objects produced in Refs [1, 2] possessed an uncompensated negative charge on the order of several microcoulombs at the instant of production [15], which leaked quite rapidly; 110 ms after the commutation closing, the charge lowered to $\approx 4\times10^{-7}$ C [7, 10], and 100 ms later the charge that ended up in the Faraday cylinder amounted to only $\approx 10^{-8}$ C [12]. The charge values cited above pertain to different luminous objects and are reflective only of the actual instance of charge leakage.

3.3 Interaction with conducting materials and dielectrics

Interesting evidence of the existence of an envelope and charge for the resultant objects was provided by photographs of the first discharges, when 'subtle' experimental details were insufficiently taken into account.

In particular, the electric fields of the wires were disregarded. One can see in Figs 10–12 that the object has a defect on its left side from the instant of time of its formation. We note that a wire from the anode passes on its left and the insulation of a short wire segment has only two layers, while the insulation is three-layered everywhere else.

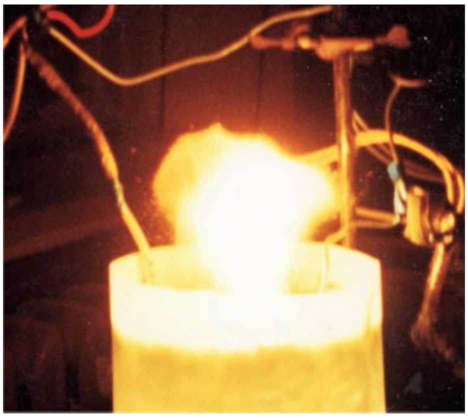

Figure 10. Interaction between the nascent luminous object and the wire segment with an insulation defect.

Figure 11. Development of the interaction between the luminous object envelope and the wire segment with an insulation defect.

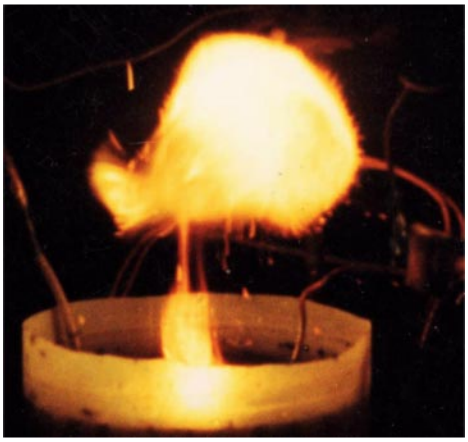

Figure 12. Separation of a part of the parent luminous object envelope in the course of its interaction with the wire segment having an insulation defect. Final stage of the process.

Yellow filaments stretch from the object to this wire segment, towards an enhanced electric field gradient. These filaments grow in time (Fig. 11) to turn into some formation (Fig. 12), which separates from the parent luminous object. On detaching from the object, this compact formation became a screen, which prevented our object from a contact with the positively charged wire. The photographs suggested that the nascent luminous formation had a material envelope and an uncompensated charge, which was later borne out.

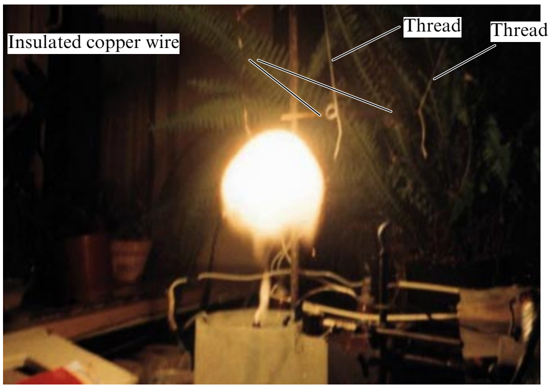

Figure 13. Experiment on the interaction of the rising luminous object with the metal wire located above its center.

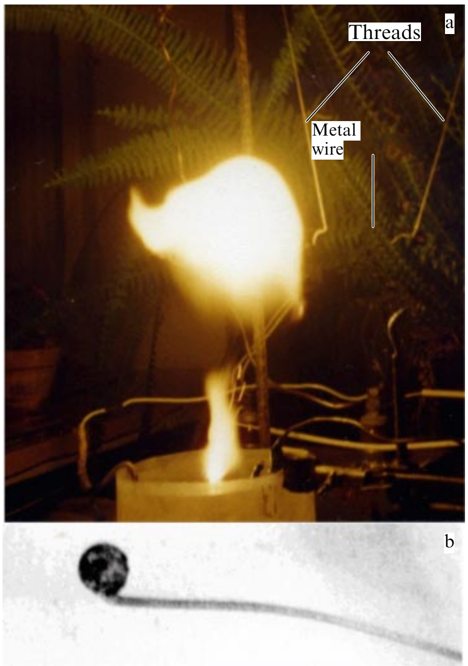

Figure 14. (a) Experiment on the interaction with a nichrome metal wire 0.1 mm in diameter. (b) The interaction resulted in the formation of a ball 0.5 mm in diameter. Temper colors are seen on a wire length of 2–3 mm sidewise the ball.

The interaction of luminous objects with conducting materials and dielectrics is exemplified in Figs 13–16. In these experiments, thin dielectric threads came down from a glass tube (a dielectric). Suspended by these (viscose and cotton) threads in the path of the object's motion were copper wires of various diameters, nichrome wires 0.1 mm in diameter and 10-to-300 mm in length, and a wire bent into a ring 60 mm in diameter. In Fig. 13, the luminous formation rises towards the insulation-coated copper wire. In Fig. 14, the insulation-free nichrome wire was located aside the rising object. At the instant of taking the photograph there was a small gap between the wire and the object (see Fig. 14). One can see in this photograph that the surface of the luminous formation stretches (is attracted) towards the wire. On the opposite side of the object, the surface also experienced deformation, supposedly because the object was displaced towards the wire. Figure 14b displays a photograph of the

Figure 15. Above the nascent luminous object is a nichrome wire ring suspended using thin threads. One can see a brush discharge towards the metal ring.

Figure 16. Nichrome wire ring suspended by thin threads is in the nascent luminous object. The metal ring melts at one site. The threads do not change their properties.

result of this attraction to the wire. The nichrome wire partially melted, and the melt metal formed a 0.5-mm diameter ball by the forces of surface tension. An energy of about 1 J went to melt the metal. Both short and long nichrome wires (0.1 mm in diameter) partially melted. The copper wire of small diameter partially melts. The copper wire of diameter 0.25 mm located as in Fig. 14 does not melt but is covered with temper colors on a length of 250–300 mm.

The clearly pronounced interaction between the charge of the luminous object and the charge induced on conductors may be illustrated as follows. A nichrome wire ring with a diameter of 60 mm and a larger area than in Fig. 14, where the induced charge will be higher, was placed in the travel path of the object. In this case, a brush discharge was initiated between the object and the ring conductor (see Fig. 15).

The nichrome wire ring in Fig. 16 is inside the nascent luminous object. At one site, the ring ruptured with the formation of balls ~ 0.3 and ~ 0.4 mm in diameter at the ends of the wire. This experiment is also interesting in that the dielectric threads and the separate prominent fibers, which the threads are made of, were inside the object for more than 0.5 s and did not change their properties (the fiber melting temperature is below 250 °C). Shabanov et al. [13] described experiments involving the placement of low-melt dielectric threads in the luminous objects, which confirm the fact that their temperature is below 200 °C.

4. Optimization of facility parameters

Different research groups assume that various factors affect the formation of luminous objects: the cathode material, or the capacitor charging voltage, or the amount of energy input into the discharge, or the composition and conductivity of water, etc. In the absence of a model of luminous object production, the variation of any element, parameter, or facility operation mode is implemented by an exhaustive method. The facility parameters and elements are numerous, so this search may take a long time.

In what follows we show that the main characteristic of an object which exhibits the specific properties inherent in ball lightning, is the presence of a significant uncompensated electric charge [7, 8, 10–12]. To obtain an object with an uncompensated charge, the facility elements should possess specific physical parameters and the optimal discharge modes should be adhered to. To retain the charge from spreading and recombination, an envelope must insulate it from the atmosphere. The envelope is close to a perfect sphere. A visualized envelope is presented in Fig. 7. The envelope is not usually seen due to its strong glow. It may be visualized by applying filters, and it is clearly seen against the background of the darker lower part of the luminous object.

There are several reasons that macroscopic charge separation and, accordingly, the formation of a charged object can be hindered: an unfortunate choice of capacitor charging voltage, commutation time, cathode material and diameter, polarity, grounding point, and water conductivity. The choice of the most important parameters is considered below in Sections 4.1–4.4.

4.1 Choice of capacitor battery charging voltage

The authors of Ref. [22] were among the first to take an interest in this discharge. They filmed a video and made spectroscopic discharge measurements in the phases of a plasma sheet, a jet, and a luminous ball formed. The duration of its glow without energy input did not exceed 200 ms.

One of the main reasons why the duration of object glow was short in that study was the insufficiently high charging voltage (4.5 kV) of the capacitor battery. In experiment [23], performed with the participation of one of the authors of Ref. [22], the capacitor charging voltage was raised to 6.0 kV and luminous object lifetime lengthened to 0.5 s.

Several physical processes exhibit threshold behavior. For a low capacitor charging voltage, below U_1, an electric arc ignites between the electrode and water. With increasing capacitor charging voltage ($> U_1$ up to U_2), there is a discharge with the features of an incomplete barrier discharge (a plasma sheet), which spreads from the electrode over the water surface. The processes occurring in the plasma sheet are favorable to the formation of a structure which exists autonomously for a long time. An analysis of the spectra recorded in Ref. [22] allows the conclusion that the initial nonequilibrium radiation with a large luminescent component degrades rapidly to a spectrum with a larger fraction of thermal energy, i.e., to the blackbody spectrum.

This is related to the discharge transfer to the arc mode. The farther the resultant structure is from the thermodynamic equilibrium (the larger the luminescent radiation fraction), the longer its lifetime.

On a further increase in the initial voltage across capacitor ($> U_2$), new threshold physical processes come into play, which impair the structure of the object up to its complete disintegration. The charging voltages chosen in Refs [22, 23] lie precisely around these threshold values. The series of investigations in Refs [22, 23] was continued in Ref. [24]. The voltage chosen in the last paper turned out to be closer to the optimal value and was equal to 5 kV. The authors demonstrated for the first time detailed photographs of discharge in the plasma sheet and jet phases. They proposed to mark out three phases of discharge process in the formation of the luminous object. The first involves a discharge on the water surface (a creeping discharge), the second phase sees the production of a jet (like the 'palpi of an octopus'), and the final phase covers the autonomous existence of the object. The authors of Ref. [24] believe that the second phase (the jet) plays the central role in the object formation mechanism. They suppose that this phase sees the delivery of high-energy atoms and ions to the plasma volume of the luminous object under formation, which, in the authors' opinion, provide its autonomous existence. Our observations do not confirm this. One can see in the photographs given in Ref. [24] that the lifetime of the luminous object, including the commutation time, does not exceed 300 ms. On the face of it, this is a surprising fact, because the charging voltage was chosen close to optimal. But the facility was slightly modified (a low-melt copper electrode was used), which shortened the lifetime of the luminous object.

4.2 Discharge duration

The commutation time (discharge duration) depends primarily on the charging voltage of the capacitors, their capacitance, and the cathode material. By way of example, in Ref. [22] it was shown that the discharge should be terminated at a relatively high residual capacitor voltage ($U_1 \approx 2.5-3$ kV) to prevent the barrier-to-arc discharge transfer. The commutation time has an upper bound, as well as a lower one. For the facility schematized in Fig. 2, the lower bound on the commutation time is about 50 ms, at which problems arise with arc quenching. In this case, the residual capacitor voltage is high, and at the spark gap bar a second luminous object appears, which separates from the bar to exist autonomously. Figure 5 shows a photograph with two long-lived luminous objects formed in one discharge.

Shown in Figs 6 and 17 are plots with close-to-optimal commutation times, typical current and discharge voltage curves. Figure 17 is also interesting as a demonstration of the durability of the object. The luminous object may break down under strong action, but when the impact is comparable to the strength of the resultant structure, the object continues to exist after undergoing this action. In this experiment, the luminous object rose to the level of an 11-mm long nichrome wire 0.08 mm in diameter, which was secured by its end to a dielectric, partially melted it, and continued to rise without disintegration. For 15 ms, the glow increased by 10% to form a 'plateau', after which it returned to the expected luminosity curve. A melted ball 0.2 mm in diameter was formed on the wire. An energy of about 0.03 J went to melt the wire. When use was made of a wire of greater length or of larger diameter, an energy of about 1 J was spent to melt (to heat) the wire.

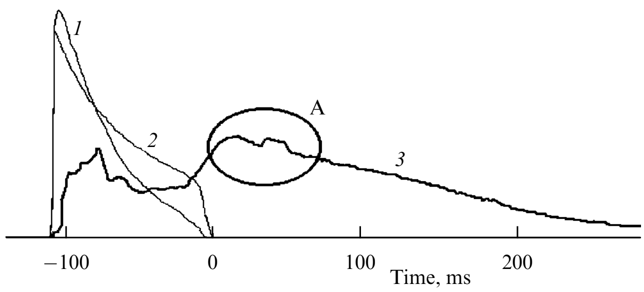

Figure 17. Experiment on the interaction of a rising luminous object with a thin wire 0.08 mm in diameter. As a result of the interaction, the wire end melted to form a ball 0.2 mm in diameter: *1* — current through the spark gap (52 A), *2* — voltage across the spark gap (5.5 kV), and *3* — object luminosity in arbitrary units. In domain A there is a plateau with enhanced luminosity at the instant the wire interacts with the luminous object.

This interaction had the result that the object decomposed and the glow terminated. Let us define more precisely the method for recording the glow in our experiments. The spatial domain from which the glow was detected may be seen in Fig. 10 of Ref. [10]. A photodetector recorded the glow beginning at a height of 15 cm and up to 50 cm above the water surface. When the object rose higher than 50 cm above the water level, the glow was no longer recorded.

Longer-than-optimal commutation times are responsible for the appearance of undesirable processes. First, a discharge voltage falling below the threshold one (U_1) gives rise to an arc discharge. Second, a long commutation time causes the electrode to melt. Electrode melting fosters the production of positive ions, which suppress the macroscopic charge separation.

In Ref. [13], we considered the effect of commutation time on the temperature of a long-lived luminous object. It was shown that lengthening the commutation time entails a sharp increase in the temperature, which amounts to several thousand degrees. This conclusion is based on the data obtained by Fantz et al. [28, 29]. In these studies, the plasma on the water surface existed up to 70 ms, and the commutation terminated at 150 ms. From the 70th to the 150th ms, the ball was separated from the water but was still connected to the central electrode by a plasma channel. At work during this period are processes that increase the temperature of the object, and increasing the temperature shortens the duration of its glow [13]. Furthermore, the discharge may transfer to an arc mode, whereby the charges recombine. When the commutation time is shortened to 80–100 ms, the glow time should become longer, which applies to Ref. [23] as well.

Generally, in the phenomenon under consideration, which exhibits features of an incomplete barrier (creeping) discharge, the discharge gap is not broken down, and a high-current phase is therefore absent, which entails a high uniformity of the plasma sheet. The current of the incomplete creeping discharge is restricted by the distributed capacitance of the dielectric substrate and is expressed as $I = U(\partial C/\partial t) + C(\partial U/\partial t)$, where U is the voltage across the electrodes, and C is the capacitance of the gap made up of the sheet plasma and the electrode separated from the plasma by the dielectric. When the dielectric surface is filled with the plasma, the current of the incomplete creeping discharge is determined only by the second term (the displacement current). The displacement current continues to heat the plasma and the temperature can reach $(2-3) \times 10^3$ K [43].

4.3 Cathode material and diameter

It is desirable that the electrode be made up of a material with a high melting temperature. We tested iron electrodes and obtained good results: the luminous object existed for more than 1 s. The luminous formations produced from a graphite electrode live up to 1 s, but the graphite electrode withstood several hundred 'shots' without replacement, while the iron one had to be replaced every 5–6 'shots'. The experiments were always duplicated, the data file records of the voltage, current, discharge duration, and object luminosity curves being hardly different in shape and time when use was made of graphite electrodes. Subsequent experiments were therefore carried out with graphite electrodes.

The choice of a copper electrode with a low melting temperature, which was made in Refs [22, 24, 27], turned out unfortunate. The lifetime of the objects in Ref. [27] was about 300 ms. Detailed spectroscopic measurements were made. Our comment on Ref. [22] applies to Ref. [27] almost completely. The facility in Ref. [27] was significantly modified, and already in Ref. [28] the glow lasted for about 450 ms. Upon optimizing several discharge parameters in Ref. [29], it was possible to lengthen the lifetime of the luminous objects to 500 ms. We believe that replacement of the copper electrode by a tungsten one was one of the main reasons for the improvement in the result.

The electrode diameter plays a significant role. We tested iron electrodes 1–1.5 mm in diameter. The electrode tip melted and was ejected with the formation of a ball. The glow duration of the objects obtained with iron electrodes 2.3–2.7 mm in diameter turned out to be the longest. Electrodes 5–8 mm in diameter yielded poorer results. Graphite electrodes 10 mm in diameter turned out to be less efficient than those that were 6 mm in diameter. Smaller diameters were not tested, since melted graphite points of diameter 0.5–1 mm appeared even on the 6-mm diameter electrodes (the melting temperature of graphite is about 4000 °C).

4.4 Polarity, grounding circuit, and other parameters

We opted to change the polarity of the central electrode. When a positive electric potential was applied to the central electrode, all parameters became significantly worse, which was also noted in Ref. [38].

The lifetime of the luminous objects obtained in Refs [1–8, 10–13] ranged up to 1 s. We emphasize that the positive electrode was grounded in these studies. When the positive electrode was grounded in Refs [7, 10, 12], the presence of a rather high negative uncompensated electric charge in the resultant objects was noted in the Sections concerned with the measurement of the electric charge. In Refs [27–29], the cathode was grounded. In this case, there was no uncompensated charge and the discharge glow time was getting significantly shorter. The nascent luminous object increased in diameter rapidly, which was an indication of a rapid decomposition of the resultant structure.

Varying, within reasonable limits, the surface area and conductivity of the water, as well as the intrinsic inductance of the circuit components, has no appreciable effect on the glow time. The water surface must be large enough for the realization of an incomplete barrier discharge. A vessel 18–20 cm in diameter is sufficient for our facility. The results obtained with a vessel 10 cm in diameter were poorer. Varying the immersion depth of the positive electrode from 15 to 20 cm had hardly any effect on the object's lifetime. The electrical resistance of the water between the anode and the cathode immersed in the water was equal to 1.2 kΩ. Raising the water conductivity and adding salts of hydrochloric and nitric acids entail a shortening of the glow time. Applying plasma switches, as well as introducing additional inductors and resistors into the measuring circuit, may significantly alter the discharge quality [44]. The circuit elements were connected with copper wires of the shortest possible length and a cross section of at least 5 mm^2.

An increase in the capacity of capacitors should be correlated with the energy input into the discharge. As shown above, after the dielectric surface is filled with plasma, the current of an incomplete creeping discharge is defined only by the second term (the displacement current), which continues to heat the plasma. At this point in time, the discharge commutation must be terminated. However, the commutation time should be sufficient for the production of molecules and radicals required for envelope formation.

The envelope is produced in a strong nonuniform electric field, in which dipole molecules and radicals move towards the field source, namely, towards the water surface. The rising luminous object has an uncompensated charge and retains a dense dipole envelope. It would be natural to suggest that the envelope became less dense on removing a part of the charge. As is clear in Fig. 3, the envelope does become more friable on removing a part of the charge. Observed are filaments and their bundles, which form a part of the object envelope, as discussed in Section 3.1. When a greater charge is removed from the luminous object, the envelope, apart from becoming friable, also loses its elastic properties (see Fig. 4).

It is noteworthy that the quartz tube (item *6* in Fig. 2) by the electrode (cathode) is above the graphite rod level for purely technological reasons. This structure is convenient for adding different substances to the discharge, as well as for imparting a closer-to-perpendicular trajectory to the motion of the luminous object.

5. Observable properties of natural ball lightning

There are several monographs and reviews describing numerous observations of natural ball lightning (see, for instance, Refs [45–57]). The number of ball lightning observations collected in only two databanks of I P Stakhanov and A I Grigor'ev [47, 50] amounts to about 10,000.

The data of these banks make it possible to draw a rather conclusive portrait of ball lightning. The main properties of ball lightning averaged over these two databanks represent the most frequently observed (typical) ball lightning.

Ball lightning is usually spherical in shape, but other shapes are also encountered (pear-shaped, ellipsoidal, annular, etc.). The probability that the observed ball lightning is ball-shaped reaches about 90%. Observed ball lightning ranges from 5 to 50 cm in diameter ($\approx 85\%$), the brightness is comparable to an incandescent lamp with a power of 10 to 200 W ($\approx 83\%$), and the color is white, red, orange, or yellow ($\approx 84\%$). Ball lightning travels horizontally ($\approx 75\%$) and smoothly ($\approx 83\%$) with a velocity of 0.1 to 10 m s^{-1} ($\approx 88\%$). The probability that the duration of observation falls in the range of 5 to 100 s is $\approx 77\%$, and in the range of 20–50 s is $\approx 22\%$.

Therefore, typical natural ball lightning looks like a luminous ball 5–50 cm in diameter which moves steadily at a speed of 0.1 to 10 m s^{-1} and infrequently changes its parameters (variations of brightness were observed in 3% of the events, of shape in 6.5%, of color in 2.5%, and of size in about 5% of the events). An analysis of the observed data additionally reveals several unusual, specific properties of natural ball lightning recognized by the majority of researchers. In particular:

(1) ball lightning, as a rule, interacts with conductors and not with dielectrics;

(2) ball lightning has a low temperature and at the same time shines: of 500 witnesses who have observed ball lightning from a distance of less than one meter, only 22 reported the existence of a thermal flux [50], which accounts for 4.4% of the observations. Hence, it follows that the glow nature is nonthermal, since the color temperature of ball lightning is estimated at 1000–2000 °C and over;

(3) ball lightning may change its shape and has the ability to pass through openings and slits smaller in size than the lightning prior to the passage;

(4) the authors of Refs [50, 56, 57] and some others believe that ball lightning possesses an uncompensated electric charge;

(5) it is noteworthy that ball lightning, which does not differ in parameters from those indicated above, may turn out to be dangerous: it may burn and even kill [47, 50].

6. Specific properties of long-lived luminous objects

In the foregoing, we have already outlined several unusual properties registered in discharges and observed in natural ball lightning. The case in point is the interaction of a luminous object with conductors, which is attended by their melting or heating (Figs 14b and 17), and the absence of interaction with dielectrics (see Fig. 16).

The second specific property has to do with the temperature of the luminous object. The melting temperature of a thin fiber which was inside the object for more than 0.5 s (see Fig. 16) is below 250 °C, but the fiber undergoes no changes, although the color temperature is about 1000–2000 °C. The temperature of luminous objects is estimated, for instance, in Refs [25–27] at 900–2500 °C, depending on the time elapsed after discharge termination. The temperature issue was considered at length in Ref. [13], where the luminous object temperature was shown to depend on the time of discharge commutation and, naturally, the time elapsed after discharge termination. We next show that comparing the temperatures in this way is not quite correct, because the nascent objects, which bear or do not bear an uncompensated electric charge, follow different physical mechanisms of existence.

The excellent study [29] and our experiment may serve as illustrations of the specific discharge property related to temperature. Fantz et al. [29] determined the energy that went to plasmoid production. An energy of 19 kJ was deposited into the discharge, of which 4.2 kJ ($\sim$ 22%) was assigned to the energy accumulated by the plasmoid. The discharge duration (the commutation time) exceeded 150 ms, and the plasma heating was significant. In our experiment, the total energy imparted into the discharge amounted to about 7.2 kJ. If about 22% of the expended energy goes to the nascent luminous object, this energy amounts to about 1.6 kJ. We introduced the following modification into our experiment. A 0.1-mm thick aluminum disk approximately 120 mm in diameter was hung about 20 mm above the water surface with the use of dielectric threads. An opening approximately 30 mm in diameter was cut in the disk above the central electrode.

We intended to study the passage of a plasma jet through the opening in the conductor. On the face of it, nothing happened after usual discharge commutation. We supposed that the commutation had not occurred, but the residual capacitor voltage was about 2.5 kV, as usual. Stuck in our memory was a short high sound resembling a mosquito buzz. The experiment was repeated, with 7.2 kJ spent again. In the inspection of the aluminum disk, a small partially melted section was discovered in the opening. The melted metal measured 2–4 mg, which corresponds to 2–4 J of expended energy. There was no glow. We believe that the seemingly paradoxical discharge behavior is explained as follows.

Proceeding from the mechanism of plasma sheet formation [43] (processes of this kind are simulated in Ref. [58]), we assume that the displacement current, which heats the plasma, is hardly present in our discharges. The interaction with the conductors, as shown above, results in the liberation of a small amount of energy, 1–2 J. If the luminous object has had time to form, after the interaction attended by 1–2 J of energy liberation it vanishes immediately, without manifesting the presence of several kilojoules. The objects in Refs [1, 2] and Ref. [29] are therefore different in nature.

It is appropriate to cite here B M Smirnov's opinion in review [59] about the possible complexity of the phenomenon under investigation. Smirnov cited the example of ball lightning production by researcher Tuck of the Los Alamos National Laboratory (USA). For several years, Tuck performed experiments and took 30,000 photographs. Reproduced in four of them, in his opinion, was ball lightning. One can see from this example that the reproducibility of Tuck's experiments was low, and the same is also true, as a rule, for all other experimentalists. In Smirnov's opinion, the cause of such a failure lies with the complexity of this phenomenon, which prevents the establishment of linkage between the observable facts and the experimental modeling of ball lightning as a whole in a simple way.

However, the problems of reproducing ball lightning arose even for proven facilities that had produced it. K L Korum and J F Korum [60] decided to repeat Tesla's experiments on the generation of ball lightning. Until them, no one, with the exception of Tesla himself, had obtained ball lightning with the use of the Tesla generator. In the first experiments, ball lightning was not produced. The experimentalists encountered the fact that all work dedicated to the description and analysis of Tesla generator operation were based on an erroneous theoretical model. It was not until they took advantage of Shelkunov's concept of 'mean characteristic resistance' and applied to Tesla resonators the linear theory of slow wave propagation that they began to produce ball lightning. That is, the initial notions of K L and J F Korums [60] about the facility operation and the origination of ball lightning were incorrect. Unfortunately, on obtaining ball lightning, they only managed to take photographs of these objects. Due to the lack of more detailed diagnostics their work did not lead to a systematic investigation and, as a consequence, to the understanding of the nature of the nascent ball lightning.

As regards the theoretical model under formulation in our case, it is not without problems, either. In almost all work concerned with Gatchina discharge investigations, it is assumed that the luminous objects have a plasma nature [4, 12, 19, 22–38]. On the strength of its unpretentiousness, the discharge permits obtaining at least something round and luminous for rather serious changes in experimental conditions. In the first studies on the Gatchina discharge [1, 2], the resultant objects were termed luminous formations, since their plasma nature was not implied, at least in the classical understanding of plasma [7, 11]. The authors of Ref. [9] believe that dust-gas ball lightning is formed in the Gatchina discharge. "Simulation of the plasmoid produced by the Gatchina discharge" was performed in Ref. [20]. The term 'plasmoid' is put in quotes, which is reflective of the doubts about the plasma nature of the discharge. In Ref. [33], the object under study was termed 'Gatchina' water plasmoids, which *a priori* implies its plasma nature. The authors believe that, in any case, water plasmoid-ejection is a remarkable and beautiful phenomenon in its own right and that elucidating the mechanisms responsible for its origination, growth, and resultant plasma features may lead to a better understanding of plasma ejections.

The next specific property of the discharge is its interaction with low-intensity laser radiation. A laser beam less than 1 mW in power is directed to the jet, at an angle of 90°. It causes a giant macroscopic response of the jet, as well as of the luminous object (Figs 18a and 18b). A certain mechanical momentum is associated with the jet motion. In Fig. 18a, the jet changes the direction of its motion and a change occurs in this momentum. It may appear that the total momentum conservation law breaks down in the system. In this connection we considered the properties of the jet and the properties of the leader channel of a streak lightning. In Ref. [5], we showed that the jet models the leader channel of a streak lightning and outline experiments that illustrate this statement.

The experimental modeling of the leader of a streak lightning is represented in Fig. 19. We cite a statement from Ref. [61]: "We may hypothesize about the cause of the random origin of new heads. The surface of an equipotential plasma conductor-channel is unstable. At a random sharp spike there appears an enhanced field along the spike. Under its action the spike begins to grow, this growth being possible in any direction, including directions that make a large angle with a weak external field." That is, the intrinsic field of the jet

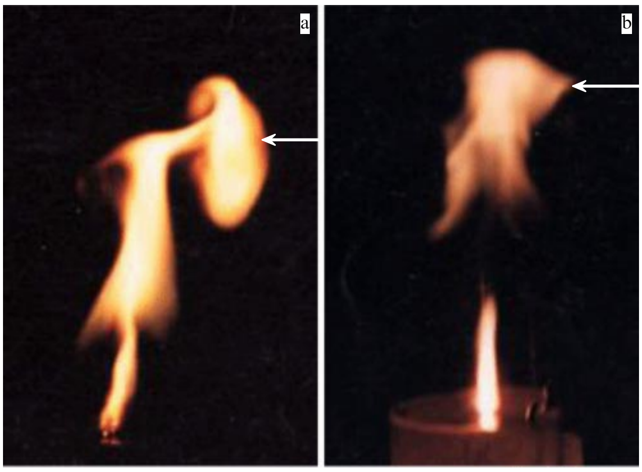

Figure 18. (a) Jet interacts with a laser beam. The laser beam (white arrow) is perpendicular to the discharge axis and propagates from right to left at a height of 22 cm above the electrode. (b) Luminous object interacts with a laser beam. The laser beam is perpendicular to the discharge axis and propagates from right to left at a height of 33 cm above the electrode.

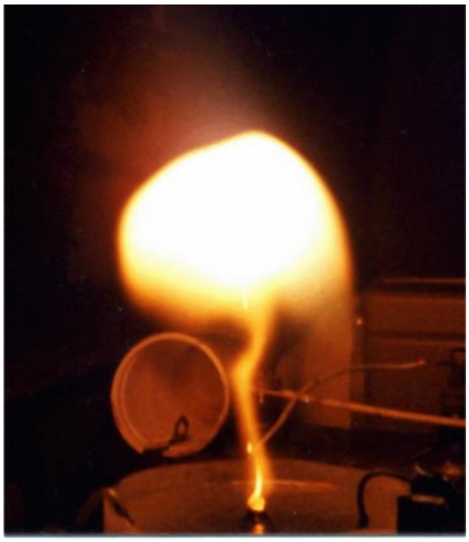

Figure 19. Modeling the leader of a streak lightning.

in circumstances where it interacts with the laser beam exerts a strong (determinative) effect on the jet motion. The total mechanical momentum is conserved: this is seen from the fact that the altered jet motion proceeds not at an angle of 90° but at a somewhat larger one. Different forms of the jet–laser beam interaction, which confirm the assumption in Ref. [61], are outlined in Ref. [13].

However, Noack et al. [26] failed to observe this effect. We believe that this is due to several reasons. A jet (Fig. 18a), a part of the jet [13], or an autonomously existing luminous object (Fig. 18b) may move counter to the laser beam only in the presence of an uncompensated charge and with increasing area of the jet surface or of the object surface. Furthermore, for the jet to move in one direction, the internal jet filling should be optically thick, which is achieved by adding, for instance, colloidal graphite into the discharge. Otherwise, the jet will move towards the laser beam at its point of entry and in the same direction as the beam at the point of its exit.

We also carried out experiments on the passage of luminous objects through an opening in cardboard. At the height at which the luminous object expands to a diameter of about 100 mm we placed a piece of cardboard with an opening 50 mm in diameter and shifted it by 50 mm aside from the discharge axis. The object passed through this opening. Due to volume limitations, the paper does not describe experiments with additions of various substances to the discharge, experiments involving the use of magnets, etc.

Another unusual property of luminous objects typical of ball lightning is the presence of an uncompensated electric charge. Nontrivial is the very fact that the macroscopic object exhibits this effect in a pulsed electric discharge. This property was considered adequately above.

7. Ball lightning model

Of the total number of descending lightning bolts, 90% bear a negative charge. A leader is the necessary element of the lightning. In our work (see, for instance, Ref. [11]), we hypothesize about the origin of ball lightning, which is formed in the stopping of the leader of a failed descending negative streak lightning. "The leader grows for a rather long time, up to 0.01 s — ages on the time scale of the transient phenomenon of a pulsed electric discharge'' [62]. The leader has a head, which 10^9 streamers per second start from. We are dealing with the stopping of the leader, when the charge continues to be delivered to the leader head, and it begins to grow in diameter. At the same time, the formation and growth of the ball lightning envelope occurs. At some point in time, the pressure of uncompensated charge will be balanced by the pressure of the envelope of a polar dielectric, the charge delivery will terminate, and the leader channel will disappear — this is how ball lightning originates.

The entire streamer zone is a highly nonequilibrium system because of the presence of a source of a strong electric field — the leader head. In the streamer zone, in the low-temperature air plasma, the formation of dipole radicals and molecules occurs against the background of plasmachemical, electrophysical and ionization–recombination processes. In the nonuniform electric field, they move towards a higher field (to the leader head), where the dielectric envelope forms and grows. Such highly nonequilibrium systems, when energy and substance fluxes circulate through the system, may be the site of collective processes and self-organization. According to the well-known notions of I R Prigogine [63], nonequilibrium, nonlinear, and irreversible processes are the source of coherence and give rise to spatially structured collective behavior and the self-organization of highly nonequilibrium macroscopic, dissipative structures. A spatio-temporal structure emerges, ball lightning in our case, which possesses a certain stability. The pressure of the dipole envelope is balanced by the Coulomb repulsion of similar charges [64]. At the instant of formation, the ball lightning inherits the potential corresponding to the leader potential at the instant of its annihilation.

There is an observational model of ball lightning whose parameters were obtained by averaging a large data array (average observable ball lightning, average ball lightning) [51]. The observational model of ball lightning is of great practical value. It is simple, and the proposed hypotheses are easy to verify with its help. Let us verify, in the framework of our hypothesis, the consistency between the (statistical) parameters of the average ball lightning and the statistics of average streak lightning or, to be more exact, with the average potential, which the leader of the average streak lightning delivers to the ground.

The uncompensated charge of the average ball lightning delivered by the leader may be estimated as

$$Q = 2W\varphi^{-1}\,, \qquad (1)$$

where W is the average energy of ball lightning (about 6 kJ, see Ref. [51, Table X]), and φ is the electric potential delivered to the ground by the leader of the average streak lightning (about 30 MV) [62]).

At the same time, the ball lightning potential inherited from the leader channel may be expressed in terms of the charge and diameter (D) of the average ball lightning:

$$\varphi = (4\pi\varepsilon_0)^{-1}\,Q(0.5D)^{-1}\,, \qquad (2)$$

where ε_0 is the dielectric constant.

From expressions (1) and (2) we obtain the diameter of the average ball lightning, which is equal to 24 cm for the above values of φ and W. This agrees nicely with the tabular diameter equal to 23 ± 5 cm (see Ref. [51], Table X).

Therefore, the statistical data on ball and streak lightning are consistent within the framework of our hypothesis. According to expression (1), the charge of the average observable ball lightning amounts to 4×10^{-4} C.

We compare our resultant value of uncompensated charge with the estimates of other researchers. In Ref. [64], the charge may be equal to 3×10^{-3} C. Reference [65] gives different estimates of the charge of ball lightning 10 cm in diameter. The author's calculations allow the conclusion that ball lightning may initially bear a charge ranging $10^{-6}\ \mathrm{C} < q < 10^{-4}$ C. The estimates of the ball lightning charge made by several other authors yield values on the order of $10^{-1} - 10^{-5}$ C. We assume that the ball lightning charge $q = 10^{-5}$ C and the radius $R = 10$ cm, then the voltage across its surface $U \approx 10^6$ V relative to Earth [65]. The author performed his calculations on the assumption that ball lightning has a positive charge and that the ground surface and wet grounded objects are also positively charged conductive equipotential surfaces. If the ground surface and wet grounded objects are negatively charged, the ball lightning charge reverses. When compared with the estimates of other researchers, our estimated uncompensated charge of the average ball lightning lies in the middle of its expected range.

We believe to have found good agreement between the statistical parameters of the average ball lightning (borrowed from the observational model) and the statistical data of average streak lightning or, to be more precise, the average potential delivered to the ground by the leader of the average streak lightning. We believe to have revealed this relation for the first time.

8. Some estimates

8.1 Luminous objects with and without uncompensated charge

The initial stage of discharge, which sees the envelope formation of the luminous object to be, is almost the same for different experimentalists. Due to this circumstance, an object of close-to-spherical shape appears. The existence mechanism may next be realized according to two extreme versions, which does not preclude the development of some intermediate scenario as well.

In the first version, the uncompensated electric charge is highest and the inner side of the envelope and the inner filling bear a charge of the same sign, due to which (and to Coulomb repulsion) the elastic envelope is observed and retains its size for a long time. The resultant object temperature is low: it is lower than 200 °C within 100 ms after discharge termination. The luminous object's rise is caused not by a high temperature but by the mechanical momentum obtained at the instant of discharge. In experiments, an object without additions is evidently decelerated and appears as a jelly-like vibrating (in the presence of air flows) body. When the momentum is perpendicular to the gravitational field of Earth, the addition-free object hangs in the air. With reference to Fig. 18a, after a change in motion, when the luminous object began moving parallel to the ground, the envelope started to expand primarily downwards, an indication that it is heavier than the displaced air at this point in time, and thousand-degree temperatures are ruled out.

In the second version, when the neutralization of uncompensated charge is underway, the object's temperature becomes high for the several reasons described above.

The pressure produced by the hot medium 'inflates' and expands the envelope, which breaks down rather quickly. There is no uncompensated charge, which might have served to keep the dipole envelope from expansion. This is the reason for the short lifetime of the emerging object according to the second version. Intermediate versions are also possible, when the object carries a small uncompensated charge; such objects will have intermediate properties between the two extreme versions.

A detailed understanding of the mechanisms occurring in the discharge calls for the development of new diagnostic techniques. It is believed that new information may be extracted from experiments with laser radiation by varying the energy input in the discharge, as well as the wavelength and power of the laser radiation. The results obtained in Ref. [13] on this topic have only brought out some dependences. Briefly discussed above interactions with conductors can serve, with their larger diversity, as one of the diagnostic methods. It might be beneficial to use noncontact methods of electric field measurements to continue the quest for diagnostic techniques commenced in Ref. [7].

8.2 Color of luminous objects and ball lightning

Of all the variety of observable effects, we return to the color of luminous objects and ball lightning. As noted at the very beginning of the paper, the color of a luminous object may be altered without varying any parameter of the facility used for its production. Figure 20 shows a photograph of an object of white color with a faint violet-red tint, which was taken in the mode corresponding to the production of a luminous object in Fig. 1. The violet-red tint is seen on closely located objects. The only difference was that the photograph in Fig. 20 was taken in a brightly illuminated room, an indication that the object has a high capacity for reflecting the incident light.

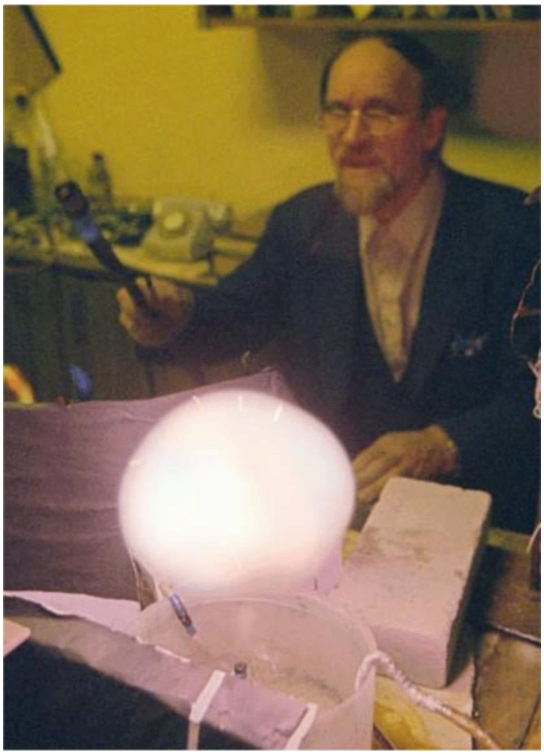

Figure 20. Color of a luminous object under bright external illumination.

The topic of color has long been considered and has numerous unobvious features [1, 2]. As we see, it is possible to obtain practically any apparent color, which is composed of the intrinsic luminosity (color), the light reflected from the available external illumination, and the light of the background against which we observe the object. In the passage through the luminous object, the background light mixes with the light it radiates to alter the color observed [1, 2]. The intensity of color of one of these components may turn out to be decisive and prevail over all other colors.

But let us consider an unusual case when the light emitted by the luminous object reflects from closely located bodies, for instance, red-scarlet on the wave crest (Fig. 1) or violet-red, as in Fig. 20. Of interest in this case is the color of the total lighting from the space that accommodates the luminous object or ball lightning, along with a large number of nearby light-reflecting bodies.

With reference to the spectra presented in Refs [22, 27], the intrinsic light has several colors in the visible range. Furthermore, spectroscopic measurements showed that luminous objects also emit light in the far ultraviolet and infrared domains of the electromagnetic spectrum invisible to the human eye. An important role in the observation of specific color is played by the visibility factor.

In a laboratory, it is easy to surround a luminous object by closely located bodies. The case in point is, for instance, water droplets in an artificial cloud. The effect of surroundings on the 'integral' color was experimentally modeled (Fig. 21). A small cloud of condensing water vapor was produced in the air. In Fig. 21, a white luminous object sinks into the cloud. The red color of the cloud (a halo) is observed on the side of its contact with the luminous object, while the red color is absent on the other side, where there is no cloud.

We compare the colors of luminous objects obtained in experiments with observations of ball lightning colors described in classical monographs [45–51]. There are no color photographs of ball lightning in these publications, and there are fewer than ten black-and-white ones. The situation has changed radically in the last few years. Video filming has become a common occurrence. It has become possible to compare the colors obtained in experiments with the colors of ball lightning observed in natural conditions. Let us revert to Fig. 21. The red color (the halo) is due to the

Figure 21. White luminous object flies into a cloud. Water droplets scatter red light well, and the cloud turns out red.

reflection from water droplets located close to the luminous object. Under natural conditions, these may be water droplets in a fog, clouds, or rain. Collected in the video material "Ball lightning — unique video witnesses" [66] are ten episodes, 12 min in total duration, of ball lightning filming. The ball lightning in Mitino (Moscow), which was observed on 27 July 2015, was filmed by three independent witnesses. In these videos, it was observed in rather clear weather, and its color was white. The video of 14 May 2013 was filmed during rain and the color was red. In the video of 28 October 2011, the ball lightning was in the clouds, and it has a large halo of red color. Since the halo radius is inversely proportional to the diameter of droplets in rain or a cloud, these videos bear out the evident fact that the diameter of rain droplets (the halo is hardly present) is much greater than that of cloud droplets, which lends credence to the entire presented material.

8.3 Infrequently observed specific properties of ball lightning

Several recent experimental papers [67–69] study the possibility of ball lightning passing through window glass. There are isolated instances of direct observation of this event. The passage of ball lightning through glass is interpreted primarily in connection with the detection of characteristic roundish holes in glass without direct observation of this event. The two main cases of ball lightning–glass interaction are the production of holes in the glass and the passage of the ball lightning allegedly without damaging the glass.

Nikitin et al. [67] outline numerous experiments to model the ball lightning–glass interaction. The authors of this paper admit that they failed to have consequences completely similar to those of ball lightning–glass interaction. More interesting from this point of view is the experimental paper by Bychkov et al. [68], who studied glass after allegedly damageless passage of ball lightning through them. A careful investigation of the spots of ball lightning passage through the glass revealed small defects (melting) several tenths of a millimeter in size. To some extent, this investigation bears out the conclusions of Ref. [69], where an artificially produced plasmoid interacted with a defect in glass with the formation of a burn-through hole. To unambiguously interpret this interesting experiment, it is necessary to determine at what point in time the interaction takes place. If the interaction takes place with the plasmoid devoid of galvanic coupling to the electrode (as, for instance, illustrated by our Fig. 17), this is undoubtedly the modeling of a ball lightning property unrelated to ordinary electrical breakdown.

The present paper is not concerned with the problem of uncompensated charge structure in a luminous object. In Ref. [7], we assumed that the uncompensated electric charge is mainly localized in a thin envelope-like layer, where charge carriers exhibit short-range order. The short-range order is possible when the potential energy of interparticle Coulomb interaction exceeds the kinetic energy of thermal motion, which may turn out to be sufficient for the displacement of the system as a whole under a weak external action. The existing experiments do not permit an unambiguous interpretation of such a behavior. The same applies to the interaction of ball lightning with glass. At present, the observational experimental data on the effect described above are too modest to make reliable conclusions. In this connection, our discussion here of the specific properties of ball lightning and luminous objects is limited to the list of generally accepted specific properties given below.

9. Conclusions

(1) Our developed facility has made it possible to produce, on the basis of a new electric discharge, 'long-lived spherical luminous objects,' which bear a striking resemblance to natural ball lightning. With a reproducibility close to 100%, it was possible to carry out systematic investigations of the physical properties of these objects and propose a physical model of the phenomenon.

(2) The results of investigations of the Gatchina discharge were so promising that they lent impetus to active investigations of the effects discovered in the discharge, which were undertaken by several research groups in Russia, Japan, Germany, the USA, Ukraine, and other countries. The prompt reaction to our work [6], which described the Gatchina discharge, was made possible due to the publication of the paper in the *Uspekhi Fizicheskikh Nauk* (*Physics–Uspekhi*) journal, which has a wide readership in Russia and abroad. According to the site Google Scholar, Ref. [6] is cited in more than 60 papers. The results obtained by independent research groups confirmed part of our experimental data and conclusions, and enabled working out in detail some physical processes that underlie the production and development of luminous objects.

(3) The objects produced in our laboratory resemble natural ball lightning in size, glow, and color, and exhibit the following extraordinary properties inherent in ball lightning:

- they interact with conducting substances and do not interact with dielectrics;
- their glow is nonthermal: the color temperature is estimated at 1000 – 2000 °C and above, while their temperature in reality is close to room temperature;
- they possess electrical properties and, in particular, carry an uncompensated electric charge;
- they can pass through openings with diameters two times smaller than their own;
- the color of luminous objects varies in relation to the varying observation conditions, similar to variation of the observable color of natural ball lightning under similar observation conditions.

(4) Proceeding from the resultant data, it is safe to say that the approach developed in our work has made it possible to produce an analog of natural ball lightning in laboratory conditions and thereby laid the foundation for its systematic study. The identical behavior of luminous objects and natural ball lightning leaves no room for doubt about their similar nature.

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Notes added in proof

The manuscript awaited publication for more than a year, and much new information about ball lightning saw the light of day during this period. It is pertinent to note immediately that the ball lightning research community's provision of information improved greatly. For instance, the VIth International Conference 'Atmosphere, Ionosphere, Safety (AIS-2018),' was held in Zelenograd (Kaliningrad region) in June

2018. This conference is held once every two years, and in 2018 it comprised the section 'Electromagnetic and Optical Phenomena in the Atmosphere, Including Long-Lived and Plasma Objects', Chair: V L Bychkov), where reports on ball lightning were heard, among other ones. Furthermore, AIS-2018 combined with the 14th International Symposium on Ball Lightning (ISBL-18). We note that the proceedings of AIS-2018 and earlier conferences are posted on the Internet for free downloading (http://ais2018.ru).

Held in October 2018 was the Russian Conference on the Problems of Cold Transmutation of the Nuclei of Chemical Elements and Ball Lightning (RCCTNandBL-25) (Adler, Krasnodar Territory). The materials of this and previous conferences are available on the Internet at http://lenr.seplm.ru.

Apart from these two important events, in 2018 (and earlier) two workshops ran (and continue running) in Moscow. One of them, the All-Moscow Workshop 'Physics of High-Current Discharges, Long-Lived Plasma Objects, and Electric Effects in the Atmosphere, the Physics of Ball Lightning and Physicochemical Processes in Long-Lived High-Energy and Plasma Objects', runs under the supervision of V L Bychkov and A F Aleksandrov at Moscow State University. The other, the International Workshop 'Cold Nuclear Fusion and Ball Lightning' runs at Russian RUDN University under N V Samsonenko's supervision. The workshop schedule is posted at http://lenr.seplm.ru.

There is another channel with information about ball lightning: YouTube. An excellent opportunity has evolved not to pore over dusty proceedings volumes but to plunge immediately into the whirl of opinions and debates about ball lightning and to sense the aura of this fascinating realm of science. As an illustration, we refer to the discussion of A I Nikitin's report to the International Workshop 'Cold Nuclear Fusion and Ball Lightning', which took place at RUDN University three days before the new year of 2018 (the video of the workshop entitled, 'Cold Nuclear Fusion and Ball Lightning –Nikitin–Parkhomov–RUDN–28.12.2017,' is posted on YouTube at https://www.youtube.com/watch?v=rGv4i1jqGhg). The speaker had engaged in the ball lightning problem for almost 70 years, and in his report entitled "Three sources and three constituents of the foundations of the ball lightning theory" he spoke about the present state of the ball lightning problem. Subsequent reports by workshop participants amazed even the highly experienced workshop supervisor Nikolai Vladimirovich Samsonenko, who noted with surprise that "everyone in this audience has his own ball lightning theory" (about 50 participants were present). Available on YouTube are the videos of the 24th and 25th RCCTN and BL-25 conferences and the videos of a rather large number of the workshops.

By and large, considering all above sources, it is pertinent to note that the content of the materials is rather traditional and that many papers have repeated themselves in different versions for decades. However, in our view, there are several studies that are a step forward in the theory of ball lightning.

A I Nikitin et al. [70] proposed a systematic approach in the construction of hypotheses about the nature of ball lightning. This issue has become not merely ripe but overripe. I P Stakhanov lamented in his monograph [71] that the number of various hypotheses about ball lightning is far greater than one hundred. Today, they number about 500, and over 1000 with the inclusion of their Internet versions.

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