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Progress in the creation of long-lived atmospheric luminous formations in a pulsed electric discharge with an electrolytic electrode

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Abstract

This work presents an analysis of the research conducted in many countries in recent years on the so-called Gatchina discharge. The findings indicate that the Gatchina discharge exhibits the majority of the characteristics of natural ball lightning, making it the most effective method for reproducing and studying this phenomenon. To a large extent, our new results are based on experiments performed for the first time to visualize dust particles arising in an erosive emission, as well as the formation of vortex flows. These experiments make it possible to explain the ability of the Gatchina discharge to maintain its shape for a long time in the afterglow.

Keywords: Gatchina discharge, ball lightning, self-organization, dusty plasma

(Some figures may appear in colour only in the online journal)

1. Introduction

The first scientific publication on natural ball lightning (BL) was published by Arago in 1838 [1]. Since then, numerous hypotheses about the nature of BL have been proposed, and various attempts have been made to reproduce it in laboratory experiments. However, BL remains largely mysterious, and, until recently, its reality has even been questioned by some. Various eyewitness accounts of BL have been reported in a number of books and reviews (see [2–6] and references cited therein). As a result, to date, many data have been accumulated on numerous observations of BL in natural conditions, various hypotheses about its nature have been proposed and the results of various attempts to create it in the laboratory have been published.

There now appears to be no scientific doubt about the reality of BL itself. However, its exact nature will become clear only after it has been created in the laboratory with clear control over the conditions and parameters. Thus, the creation of laboratory ball lightning (LBL) is a primary task of research on the nature of BL.

Since, as a rule, BL is observed during or after a thunderstorm, it is clearly related to atmospheric electricity. The search for LBL has therefore been focused on experiments with various types of electrical discharges in the atmosphere. Unfortunately, the reproduction of this phenomenon in the

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laboratory has consistently run into difficulties, including those caused by the lack of an adequate physical model of BL and therefore uncertainty about which experimental line to pursue.

Recently there has been significant progress in the experimental reproduction of BL in the laboratory. Based on the analysis of research by scientists from many countries-Russia, Japan, Germany, USA, China, Ukraine and others [7–16], it can be concluded that the Gatchina discharge (see [7–9]) is the best method for creating encapsulated laboratory electricity in which all the main features of BL are reproduced. Numerous experiments by various research groups have shown that long-lived luminous formations with physical properties strikingly similar to those of natural BL can easily be created and reproduced in the Gatchina discharge [7–16]. As the work reported here reveals, objects born in the Gatchina discharge reproduce not only the main properties of natural BL but also the unusual, specific properties that have been identified by numerous researchers. One can conclude that the autonomous luminous formations created by the Gatchina discharge are, in many respects, identical to natural BL.

In this study, based on both past results and new data, a comparative analysis of the properties of natural BL and LBL from the Gatchina discharge is carried out. It is concluded that the properties of this LBL are identical to those of natural BL, i.e. the Gatchina discharge generates all the main known properties of BL, but with one exception: the lifetime of LBL is less than what has been reported for BL. Based on the results of the analysis in this report, further studies of the LBL of the Gatchina discharge can be visualized, especially to increase its lifetime.

It should also be noted that in our discussions of BL and LBL, we avoid the kinds of unsubstantiated, unconfirmed hypotheses about the nature of these phenomena that are unrelated to electrical discharges in the atmosphere, yet have appeared in some reports (see, for example, reference [6]).

2. Results

2.1. Experimental setup

When setting up an experiment to create a laboratory analogue of BL, the original idea of the authors [7–9] was that natural BL is formed after the leader of the linear lightning stops (for more information about the properties of the leader see [17]). Further, the charge continues to flow into the ball's head, which leads to an increase in its diameter, with the simultaneous creation of the shell of future BL. The formation of this shell occurs from the extended streamer zone of the leader head in a strong electric field. It has been assumed that in such a strongly nonequilibrium plasma of moist air with impurities of complex molecules and macroparticles, dipole radicals and molecules are formed as a result of various plasma-chemical and electrophysical processes. In an inhomogeneous electric field they move in the direction of field amplification (to the leader's head). Due to dissipative processes of self-organization [18], a spatiotemporal structure appears, resembling the structure of a metamaterial that contains an uncompensated electric charge. That is BL, which has a degree of stability. It is assumed that the pressure of the dipole shell is balanced by Coulomb repulsion by charges of the same sign. In accordance with this hypothesis, the BL at the time of its formation inherits the potential corresponding to the potential of the leader at the time of its disappearance.

Based on the results of attempts made to create a laboratory analogue of BL [8, 10], a high-current pulse discharge (the Gatchina discharge) was created, the experimental setup for ignition of which is shown in figure 1. A similar scheme with slight variations has been used by all authors in studies of the Gatchina discharge [7–16].

The Gatchina discharge is a pulsed electric discharge carried out into the air half-space from a central metal or carbon electrode (usually a cathode) located above the surface of a liquid electrode made of water containing various dissolved additives. A typical experimental setup for igniting such a discharge is shown on the left side of figure 1. It uses a plastic polyethylene container, which is filled with water in which various additives are dissolved to increase its electrical conductivity. For galvanic contact with the conductive solution, a metal (copper) ring is located at the bottom of the vessel, connected to the positive side of a capacitor bank with a capacitance of about 600 μF. The left side of figure 1 shows the design of the central electrode in more detail. It is made of a quartz tube, into which a carbon or metal rod with a diameter of 5 mm is inserted, connected to a copper conductor made of high-voltage wire surrounded

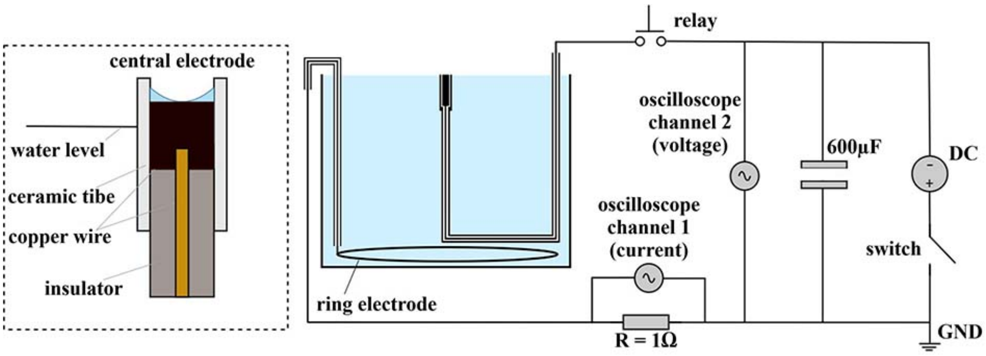

Figure 1. Electrical diagram of the experimental setup for ignition of a Gatchina discharge.

by a thick layer of insulation to prevent current between the conductor and the conductive solution. In some cases, drops of water with various additives can be applied to the surface of the rod to introduce them into the discharge.

After connecting a capacitor bank charged to 5.5–6.0 kV to the discharge gap, gas breakdown is accompanied by the germination of the leader-streamer system over the water surface. During the first 20–30 ms, an almost homogeneous ‘plasma sheet’ is formed on the surface of the water, and then a jet moving upwards appears from the central electrode located above the water (an analogue of the leader of natural lightning).

In accordance with the hypothesis stated above [8, 9], in order to simulate the leader stopping, the discharge circuit is forcibly opened using a high-voltage switch after about 80 ms (with a residual voltage of about 3 kV) and the discharge afterglow jet, breaking away from the electrode, transforms into a laboratory analog of BL, which glows due to its stored energy.

In the second phase, the discharge is not galvanically connected to the power source; the jet is completely detached from the water surface and is formed in the LBL, which glows due to the energy stored in the first phase of the discharge.

The experimental setup is simple and the Gatchina discharge is easily reproduced even in everyday home conditions (e.g. in a personal garage [10]). After publication of the first studies [7–9], this discharge began to be widely studied by various scientific groups around the world [7–16]. However, the optimization of the operating modes of the installation and the choice of materials is not obvious and has many subtle features, which are partially considered in reference [9].

It is also important to note a principal feature that distinguishes the Gatchina discharge device from other existing gas-discharge devices for achieving LBL. With the Gatchina device, almost 100% reproducibility of results is achieved with hundreds of discharge starts. This makes it possible to study the physics of the process and to confidently verify and analyze the results obtained.

Figure 2 shows photographs of a Gatchina discharge. As expected, at the active stage of the discharge, LBL is formed by a leader (the ‘leg’ in figure 2). After interruption of the current pulse, an autonomous luminous formation with a diameter of 12–16 cm is observed, which looks like ‘standard’ BL of typical size. In experiments with Gatchina discharges, by changing the operating modes of the experimental setup it is possible to obtain both truly round and ‘irregular’ shapes. It is also possible to obtain LBLs with diameters from 2 to 30 cm.

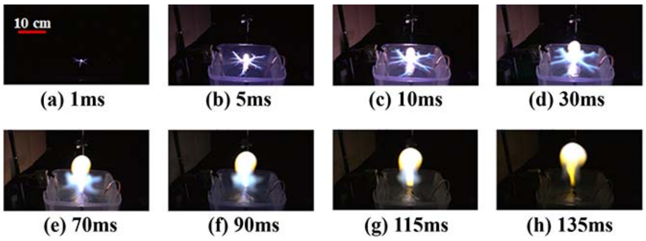

Figure 2. Photographs of a Gatchina discharge.

The large amount of video material obtained [7–16] shows that the LBL created in the Gatchina discharge visually corresponds in size and shape to natural BL. This makes these discharges favorably different from other objects created in gas-discharge plasma devices to simulate natural BL.

Next, we sequentially consider the correspondence between the properties of the LBL of the Gatchina discharge and natural BL.

2.2. The main properties of natural BL

Let us briefly recall BL observed in natural conditions. We first present a selection of parameters from data banks of observations of BL by eyewitnesses, the number of which is close to ten thousand. Observations show that natural BL most often has a spherical shape, but can sometimes have other shapes (pear-shaped, ellipsoidal, ring-shaped, etc.). The probability of observing BL in the form of a ball is about 90% (here and below, each parameter is accompanied by its observation probability). The observed BLs have a diameter of 5–50 cm (≈ 85%) and their brightness is comparable to that of an incandescent light bulb with a power of 10–200 W (≈ 83%). The color is white, red, orange or yellow (≈ 84%). They move horizontally (≈ 75%) and smoothly (≈ 83%), with a speed of 0.1–10 m s^{-1} (≈ 88%). The duration of BL observation in the range of 5–100 s is ≈ 70%, and in the range of 20–50 s it is ≈ 22%. BL generally looks like a glowing ball, calmly moving and rarely changing its parameters—brightness changes were observed in 3% of cases, shape changes in 6.5%, color changes in 2.5% and size changes in about 5% of cases. On the other hand, in the most cited of all publications on BL, the classic monograph of Barry showed that ‘the lifetime of BL is on average 1–2 s or less’ (reference [3], p. 39). This is, however, a shorter lifetime than was noted in 80% of the reported cases.

Later, in 1992, Smirnov [4] did considerable work on statistical processing and analysis of the eyewitness observations of BL available at that time. As a result, he created the ‘observational’ model of the average BL. The ‘average’ BL was described as an object of about 20 cm in size with a density equal to the density of air, but capable of having a surface tension like a liquid. The energy of this ‘average’ object was no more than 20 kJ and was compared with the energy of 10 matches; its energy density was about 30 J cm^{-3}.

The lifetime of the ‘average’ BL, according to reference [4], is about 4–16 s, much longer than what has been observed so far for LBL. To date, numerous experiments by various authors give the lifetime of the LBL of a Gatchina discharge as about 0.5–1.5 s. The maximum time known, 2 s, was reported by Shabanov [15]. As will be shown below, LBL with a lifetime of up to 1 s can demonstrate almost all the known properties inherent in natural BL. However, in order to be fully analogous to natural BL it is necessary to increase the lifetime of the LBL of the Gatchina discharge.

We believe that this is possible, since the times achieved so far are not limiting. Possible ways to increase the lifetime of LBLs are discussed at the end of this paper.

3. Discussion

Next, we compare, in brief, some of the known properties of natural BL and laboratory BL.

(1) BL has a low temperature, yet it glows. This means that the source of the glow is non-thermal, since the color temperature of BL is estimated at (1000–2000) °C or more. Of the 500 eyewitnesses of BL who observed it from a distance of less than 1 m, only 22 observers (4.4%) reported the presence of a heat flux [6]. It follows from this that BL has a low gas temperature, so that the source of the glow must be non-thermal (for more details see references [2–6]).

(2) BL interacts with conductors and does not interact with dielectrics.

(3) BL can change its shape and pass through holes and slits smaller than its size. After passing an obstacle, BL can sometimes regain its shape.

(4) It is assumed that BL has an uncompensated electric charge.

All these properties of natural BL are reproduced in experiments with Gatchina discharges.

We also note that natural BL can be dangerous; it can burn (and even kill). Its laboratory analogue obtained in Gatchina discharges can for example, melt and evaporate copper, nichrome and tungsten wires.

3.1. Charge of LBL of the Gatchina discharge

From analysis of the observational data [2, 5, 7] it can be seen that natural BL, as a rule, interacts with conductors and does not interact with dielectrics. In references [9, 19] it was shown that LBL based on the Gatchina discharge also has this property. In these works, the melting of an 80 μm diameter nichrome wire was observed when it was inside the LBL. The nichrome wire was suspended on thin synthetic threads that had a much lower melting point (about 200 °C). When these synthetic threads were placed inside the LBL, there was no effect on their tone.

Experiments were performed in the situation when the LBL flies past the end of a metal wire hanging on dielectric filaments and is attracted to the charge induced by it on the wire. This experiment shows that the LBL has an electric charge.

The following experiments show the sign of the charge and its distribution in the LBL. Figure 3 shows a graph of the time dependence of the current of negatively charged particles to the probe when a positive potential is applied to it. The Langmuir probe was located along the ascent path of the LBL at a height of about 20 cm above the electrode. The first current peak (5 μA) occurs after the probe touches the surface of the LBL. When the probe is inside the LBL, it registers a current that is several times less and is abruptly interrupted closer to the lower surface of the LBL. When the probe approaches the lower wall of the LBL, the second peak of charge arrival appears on the graph, which is half the size of the first peak. This dependence indicates that basically the charge of the LBL is concentrated in its surface layer.

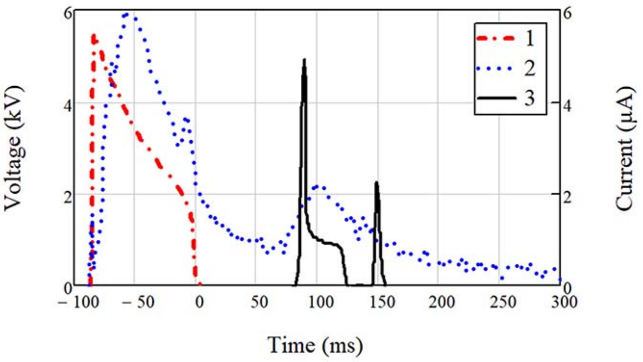

Figure 3. Probe current during passage of LBL. Curve 1 (red): discharge voltage drop. Curve 2 (blue): LBL luminosity in relative units. Curve 3 (black): probe current of the negative charge particle.

Thus, the LBL of the Gatchina discharge reproduces all the main properties of natural BL obtained from processing data in numerous observational accounts and presented in well-known monographs and reviews [2–6, 9].

However, the behavior of BL observed in nature, including its unique, specific physical properties, is richer and more diverse than that mentioned above. For example, BL tends to retain its spherical shape, yet easily turns into a snake-like form and back. When it encounters obstacles, it can melt or vaporize part of the metal and continue to exist.

This behavior of natural BL has also been reproduced in Gatchina discharges. Figure 4 shows the time dependences of LBL luminosity as it interacts with a small piece of thin nichrome wire installed on a dielectric suspension along the LBL path.

As a result of this interaction, an area of increased luminosity appeared on the optical radiation intensity curve. In

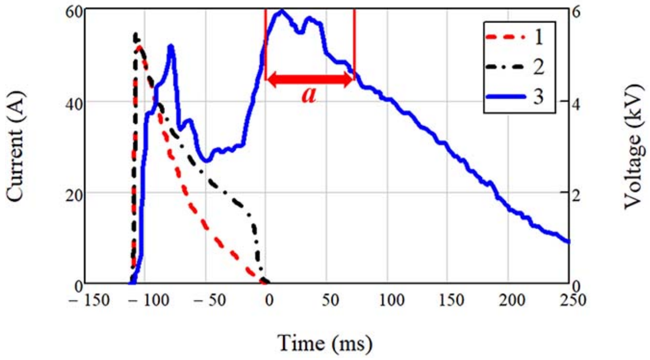

Figure 4. Experiment on the interaction of LBL with a thin nichrome wire 10 mm long and 0.08 mm in diameter. As a result of the interaction, the end of the wire melted and a ball with a diameter of 0.2 mm was formed. Curve 1 (red): current in the discharge gap (maximum value 52 A). Curve 2 (black): discharge voltage drop (~ 5 kV). Curve 3 (blue): LBL luminosity in relative units. In region ‘a’, there is a plateau with maximum luminosity at the moment of interaction of the wire with the LBL.

eyewitness observations of BL there are some properties that, although not always reported, are quite reliable, such as their transparency. This property is also reproduced in Gatchina discharges.

3.2. Influence of electron beam power

Experiments with various types of influence (mechanical, electrical, magnetic, optical (laser), etc.) on Gatchina discharge LBLs have shown that if the impact does not cause their destruction then they, like natural BL, restore their shape. In other words, these LBLs exhibit 'collective properties' and react to external influences as a whole [9, 15, 19, 20]—they behave like structures that strive to preserve their integrity.

In this regard, we recall that one of the main characteristics of a system with many interacting particles is the nonideality parameter Γ, defined as the ratio of the potential energy of interaction between neighboring particles to their average kinetic energy.

For the Coulomb interaction of particles of charge *Ze* and number density *n*

$$\Gamma = Z^2 e^2 / (T\varDelta), \tag{1}$$

where $\varDelta = n^{-1/3}$ characterizes the average distance between particles (the Wigner–Seitz radius) and T is their average kinetic energy. It is customary to call a system non-ideal, prone to self-organization, if $\Gamma \geqslant 1$ (see, e.g., references [21, 22]).

Since ensembles of electronic and ionic charges in a gas-discharge plasma are ideal, $\Gamma \ll 1$ (see, e.g., reference [23]). The fact of the formation of ordered structures suggests that there are factors in a Gatchina discharge plasma that contribute to its nonideality.

As already noted, in this work we do not consider hypothetical (unproven) conclusions and hypotheses about the discharge under study that have not been verified experimentally. Therefore, it is natural to assume that, along with the electrons and ions, macroparticles with a condensed dispersed phase (dust and aerosol particles) are present in Gatchina discharge LBL. The reason for their appearance in the discharge is both the sputtering of the cathode material (dust) and the formation of atmospheric hydrated aerosols from water vapor, as well as the possible formation of dozens of complex compounds in the electric field of the Gatchina discharge [13].

Due to their prevalence and the comparative simplicity of setting up an experiment, the issues of self-organization and the formation of ordered structures have been most studied for dusty plasma in classical plasma objects—low-pressure DC and RF discharges [21, 22]. Such work showed that micron-sized particles (dust grains) injected into a gas-discharge plasma acquire a large negative electric charge of the order of $10^4 e$, collecting very mobile electrons in the plasma. These highly charged dust particles can represent a strongly bound (non-ideal) component of the system and can produce organized structures in the form of liquid droplets and even crystals [21, 22].

In a dusty plasma, several mechanisms are known that can cause dust particles to behave like agents in an active substance (see, e.g., reference [24]). The macroparticles absorb the energy and momentum of the flowing plasma and transport it from a local scale to larger scales. Published reports include numerous experimental examples of self-organization and the formation of ordered structures in a dusty (complex) plasma.

As for the Gatchina discharge, microparticles are observed both in the discharge itself and in its autonomous phase; these result from the erosion of the central electrode and the evaporation of the conductive solution. To observe the erosive emission of macroparticles, video filming of the discharge was carried out using additional illumination of the discharge area with a laser light sheet, which was assembled using a 10 W green laser with a wavelength of 532 μm and a glass rod 6 mm in diameter. To minimize the influence of the bright glow of the discharge, the shooting was carried out through a green light filter, which transmitted the green light of the laser.

Figure 5 shows images of the discharge from 100 to 600 ms after the start of the discharge. In the first image, the glow intensity of the discharge and the emerging plasmoid is very high, significantly exceeding the intensity of the laser glow. Starting at about 200 ms, green laser light is visible, reflected from atmospheric dust particles, some of which are always present in the atmosphere. Starting at 250 ms, bright luminous points of upward-moving erosive particles also appear. As the plasma region moves upward, one can observe the movement of the erosion tail behind it. With a significant decrease in the intensity of the glow of the plasma region, it becomes clear that microparticles are also observed inside this plasma region. After the complete cessation of the glow from the laser light re-reflected by the

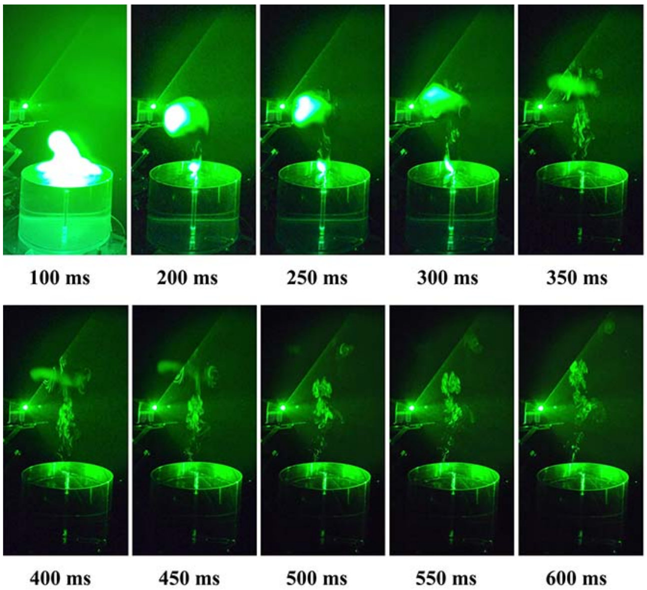

Figure 5. Discharge images at different times using additional illumination of the discharge area by a laser light sheet (shot through a green light filter).

microparticles, only a green glow remains.

At this stage, it is also seen that the microparticles are twisted into a toroidal vortex. This is an important mechanism for the formation of vortex rings (e.g. smoke rings), which are able to maintain their volume and structure for a long time.

Therefore, one can express cautious optimism that the previously developed apparatus for the formation of structures in dust plasma [21–24] could be applied and adapted to the atmospheric high-current pulse discharge under study. For a more detailed analysis, this issue requires further research.

Thus, laboratory BL is a complex plasma-gas-dynamic formation that changes its shape from spherical to vortex in various stages of existence.

Nevertheless, based on preliminary data, we propose two possible ways to increase the time of autonomous existence of LBL in a Gatchina discharge:

(a) Improving the possibility of the formation of ordered structures, possibly by increasing the density of solid dust particles and hydrated aerosols of humid air. Preliminary experiments have shown that the use of a Cu + Si electrode can increase the lifetime of the laboratory analogue of Gatchina discharge BL to almost 2 s. The introduction of an additional substance into the discharge should further increase the lifetime of the emerging laboratory analogue of BL to 2–3 s.

(b) Increasing the efficiency of vortex formation could also contribute to an increase in the lifetime of LBL. To achieve this, it is necessary to make the energy input into the discharge more inhomogeneous.

These proposals arose after analyzing the work in reference [25], where simulation of the Gatchina discharge was performed, and after analyzing references [26, 27], where experimental simulation of the Gatchina discharge was performed. In these works, it is shown that there is a gas-dynamic vortex in a Gatchina discharge, the captured images of which show a satisfactory match between calculation and experiment. It is noted in [27] that the existing model should be supplemented with more complex heat release processes for better agreement with experiment. A monograph [6] discusses these works in detail. Perhaps, as we hypothesize, increasing the degree of vortex formation will increase the lifetime of LBL. From this point of view, it is desirable to determine what changes in design and discharge mode are necessary to accomplish this task.

In reference [28], in addition to the vortex assumption, explosive evaporation of water from the central electrode feeding it into the LBL is discussed. A positive influence of this process on LBL formation is assumed. The additional introduction of substances into the LBL resembles the processes in erosive discharge, which are discussed in [6]. Recent work in this direction [29, 30] shows that it can also be significant. At the same time, it should be noted that the vortex LBLs obtained in Gatchina discharges are only one possible variant of the internal structure in a Gatchina discharge. As shown in [14], in Gatchina discharge imaging with a Sony FDR-AX700 500 fps video camera equipped with a 400–500 nm bandpass filter, it was determined that there is a luminous filling inside the LBL that relaxes and has no vortex structure. The shape (geometric dimensions) of the LBL did not change during the relaxation time of the inner filling. As shown in [31], a suspension consisting of micron-sized water droplets can be present inside the formed vortex structure. The internal structure of the LBL is not necessarily a vortex [32]. In other words, by changing the central electrode design or Gatchina discharge mode, it can transform into an LBL with a set of different properties. This is because LBL is a heterogeneous formation in the sense of a combination of the shell, charged particle structures of different degrees of non-ideality and additionally, in some cases, the presence of an internal gas-dynamic structure.

In addition, it is to be noted that the lifetime of the LBL depends on the electric charge stored in it. To achieve the goal of a longer lifetime, it is proposed to initiate a discharge from a source that is capable of raising the voltage applied to the discharge quite rapidly, from 5 kV to 12–20 kV in 30–100 ms. According to preliminary estimates, in this way it will be possible to increase the lifetime to about 4–5 s.

The experimental study of the Gatchina discharge by various laboratories around the world has revealed new unusual properties of this discharge, and various hypotheses about the nature of these properties have been proposed. However, a thorough analysis of both previously published results of Gatchina discharge studies and new data on the visualization of vortex structures and dust components in the discharge region shows that a comprehensive approach is necessary for a more complete and deeper understanding of the processes in Gatchina discharges. The latter should take into account gas dynamics, the influence of plasma nonideality due to the presence of dust components [21, 22], macroscopic charge separation processes [20] and the various plasma chemical reactions that occur. Although a complete analysis taking into account all these processes is very complicated, only such an approach will make it possible to analyze in detail the process of LBL formation on the basis of the Gatchina discharge and ultimately optimize the parameters of the discharge system elements in order to increase the lifetime of LBL on the basis of the Gatchina discharge. For example, it was noted in [15] that the choice of electrical parameters of the discharge system elements significantly affects the energy supplied to the discharge. In general, despite the fact that such a comprehensive analysis of the Gatchina discharge has not yet been carried out, the key problem of LBL generation has been solved as a result of Gatchina discharge research.

4. Conclusion

The failure of numerous attempts to create laboratory ball lightning (LBL) led to substantial discussion in published work of various hypotheses about natural ball lightning (BL), some of which are strikingly nonscientific, or even irrational. We believe that the nature of BL should be sought not by postulating dubious new mechanisms but in careful, thorough experiments with electrical discharges in the atmosphere. In this work, based on the available experimental results as well as new data, a comparative analysis of the properties of natural BL and LBL of the Gatchina discharge was carried out. It is found that the properties of LBL are essentially identical to those of BL: the Gatchina discharge reproduces not only the main parameters of natural BL but also its unusual, specific properties recognized by the majority of researchers. Based on the results of the analysis, prospects for further studies of the LBL of the Gatchina discharge are proposed, with a focus on increasing its lifetime.

Acknowledgments

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