Chapter 1
Unsolved Mystery of Ball Lightning

V.L. Bychkov

Abstract Ball lightning is an unusual phenomenon always drawing attention of people. There are still questions about its origination, features, interaction with environment, and phenomena related to it. On a way of studying this phenomenon, there are a lot of difficulties, the basic of them is insufficiency of authentic, scientific data. The chapter sets as the purpose to interest the reader in the problem, to describe conditions of ball lightning occurrence, theories, and its hypotheses explanation, to include readers in a circle of experimental searches in creation of a ball lightning and its analogues, and to describe fascination of a problem and difficulty of its solution.

1.1 Introduction

The term ball lightning (BL) is usually applied to an autonomous, stably shining ball-like object, which is observed in the atmosphere, and is connected usually with the thunderstorm phenomena, and the natural linear lightning. Under the autonomous feature, we understand its capability to move in space keeping its form, size, and color during a time compared with its lifetime. It is one of the most surprising natural phenomena, which on an extent of 1,000 years amazed the imagination of people. One of the first mentions about this phenomenon can be found in the Flavius Josephus's book "War of the Jews," written soon after 70 AD. In it, the garnet balls on the clothes of priests symbolized BL. First meeting of the scientists, investigating an atmospheric electricity, with BL was in 1753 [1–3]. Prof. G.W. Richmann was killed by stroke during a thunderstorm. He was measuring a potential of a metallic bar, placed on a roof of his house with a help of an electrometer—a metallic rod, which was placed inside the house. The rod was isolated from the ground by a crystal glass, and a silk thread was attached to the rod by one of its ends. He judged by an angle of the thread deflection about the value of the rod potential. In Fig. 1.1, one can see a picture of this event.

This event was soon investigated by M. V. Lomonosov. He revealed that the fireball was formed outside the house, and penetrated into the room through either

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Fig. 1.1 Death of professor G.W. Richmann after BL impact, the picture is taken from [1]

the door, or the window. The report of Lomonosov can be considered as the first qualified description of traces left by BL. Besides this event, Lomonosov knew also other cases of BL observations; about this, he wrote in his article [4] "combustion of fats, gathered together in air." In fact, this was the first model of BL with a chemical source of energy. Unfortunately, Richmann's death had for a long time retarded studies of the atmospheric electricity (including investigations of BL).

We can consider an activity of Francois Arago to be the next expression of interest in BL. He had collected and published 30 evidences of BL observations, explaining them as "lightning energy condensation" [5]. Later, BL observation cases and its models were discussed at Paris Academy of Sciences sessions.

An important milestone in BL investigation had become the Walter Brand's book "Ball Lightning," published in 1923 [6]. Brand in his book had represented 215 BL observations from 1665 to 1919 as described by eyewitnesses and indicated main 14 features of BL.

In the twentieth century after W. Brand worked and continue to work on BL problem many well-known scientists. They collect data on BL, analyze its properties, and carry out experiments on generation of its analogues. First of them was the Nobel Prize winner P.L. Kapitsa. He thought of its nature, and made the first plasma experiments on its origination. A hypothesis according to which BL is fed by the radio-frequency radiation energy of thunderstorms, P.L. Kapitsa [7] has proposed in 1955. Kapitsa with his coworkers realized a high-frequency constricted discharge in the atmosphere of helium, argon, carbon dioxide, and air at pressure from ten Torr to several atmospheres [8], but it proved to be a plasma, not BL.

J.D. Barry, G.C. Dijkhuis, M.T. Dmitriev, G. Egely, Ya.I. Frenkel, A.I. Grigor'ev, A. Keul, J.R. McNally, I.V. Podmoshenskyi, W.D. Rayle, S. Singer, B.M. Smirnov, I.P. Stakhanov, and many others made a considerable contribution in a solution of this problem. Nowadays, there exists an international Committee on ball lightning (ICBL), which was created in 1990 by S. Singer, B.M. Smirnov and Y.-H. Ohtsuki, and which holds International Symposia each 2 years.

During the twentieth century, collecting and analysis of observations by different investigators and research teams [9–15] was realized; many theories and experiments were made.

However, the problem of BL is still unresolved. There are many theories of BL, but none of them can explain all BL features. Many experiments and experimental approaches to this phenomenon have been realized. Some of them reproduce separate features of BL but cannot copy the phenomenon in the whole.

This chapter presents a short review of the state of the art in BL investigations.

1.2 General Ball Lightning Features

Intensive collecting of data and its analysis made in the twentieth century allowed to create a ball lightning image with averaged characteristics. These characteristics of BL are represented in Table 1.1.

Table 1.1 Average parameters of BL [16, 17]

Parameter	Value
Probability of spherical form	$89 \pm 1\%$
Diameter	24–32 cm
Lifetime	9–16 s
Motion velocity	3–5 m/s
Energy	12.6–31.6 kJ
Energy density	1.6–15.8 J/cm^3
Color	White ($24 \pm 2\%$), yellow ($24 \pm 2\%$), red ($18 \pm 2\%$), orange ($14 \pm 2\%$), blue and violet ($12 \pm 2\%$), others
Light flux	800–2,200 lm
Light output ratio	0.14–2.82 lm W^{-1}
Correlation with electric phenomena	$70 \pm 10\%$ BL appear during thunderstorms
Season	80% of BL appear in summer months (June–August)
Decay	$50 \pm 20\%$ explosion, extinction, decay
Probability of appearance	$10^{-9} - 10^{-8}$ km^{-2} min^{-1}

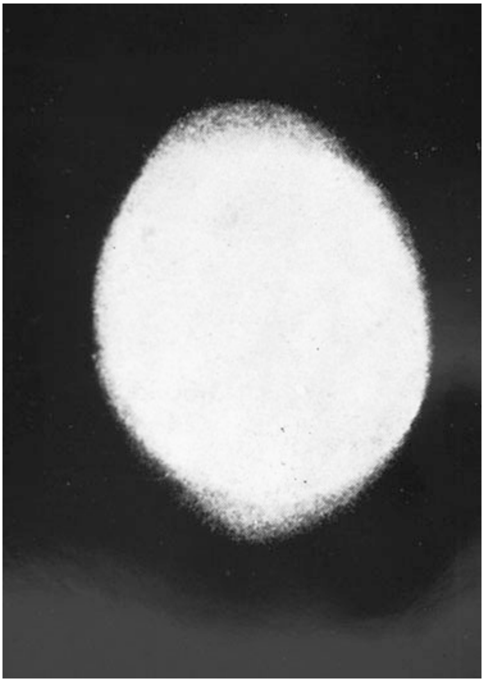

Fig. 1.2 Still photograph of falling-down BL taken during a thunderstorm in 1935 by Schneidermann [14]

To them, most known authors of the end of the twentieth century [11, 14, 16, 17] added the following. BL is observed indoors and outdoors, in airplanes and near them. It moves in horizontal and vertical directions (mostly downward). Its existence is often accompanied with hissing, whistling, and cracking. In most cases, BL thermal impact to objects is not revealed.

In Fig. 1.2, one can see a photo of a falling-down BL [14]. In [15], it is shown that an oval image of BL is caused by the motion of BL during shooting. In Fig. 1.3, we represent a still photograph of BL luminous trace from [14].

However, the collected data showed that BL can have an internal structure (as if it is made of honeycombs, or caviar) [11–13], sparks were observed inside and outside of it [13], and it can be surrounded by a halo much greater in size than BL itself [14]. It has also gray and black colors. Sometimes, it can appear in a form of a tape or a thread and transform it to the ball [13, 18]. In Fig. 1.4, one can see a photo of BL with luminous filaments (maybe emitted luminescent particles) [14].

BL exposes electric properties, making harmful influence on people and animals (similar to affection of the electric current). It often destroys electrical circuits and devices (computers, TV, and radio sets) [11–13]. In Fig. 1.5, we represent a photo of a falling-down BL [14], the validation that this was a real BL discussed in [15].

There are well-documented cases of pepole's death [13, 19] in the result of the electric or the thermal impacts caused by BL. Usually, these cases are biased, questioned [14], or disregarded [11, 14, 16, 17]. According to the authors of these papers, BL creates a path for a stroke of a linear lightning, which is the real reason

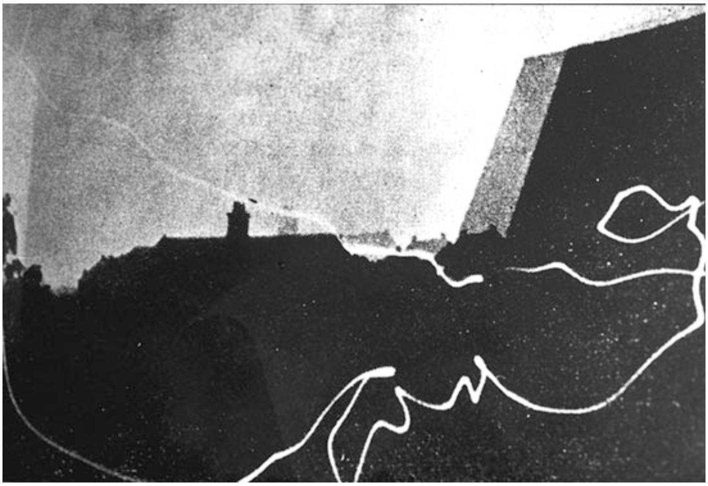

Fig. 1.3 Still photograph of a luminous trace of a moving-outdoors BL, taken by Bird [14]

Fig. 1.4 A fragment photo of BL with luminous filaments, the photo is taken from [14]

for the harmful events. However, there are reliable evidences that these cases were not connected with the linear lightning [13, 19].

BL can penetrate through window glasses in three ways: through existing holes, making a hole, and without any holes, leaving small or no traces [20–22]. A photo of the hole in the glass made by BL is represented in Fig. 1.6.

New analysis of BL properties made in the twenty-first century has shown new BL features, and emphasized the already known, but usually disregarded. In [20, 22] was shown that in about of 25% cases of BL observations from the close distance, the BL impact lead to arising of fires, injuries of people, and heating or melting of objects.

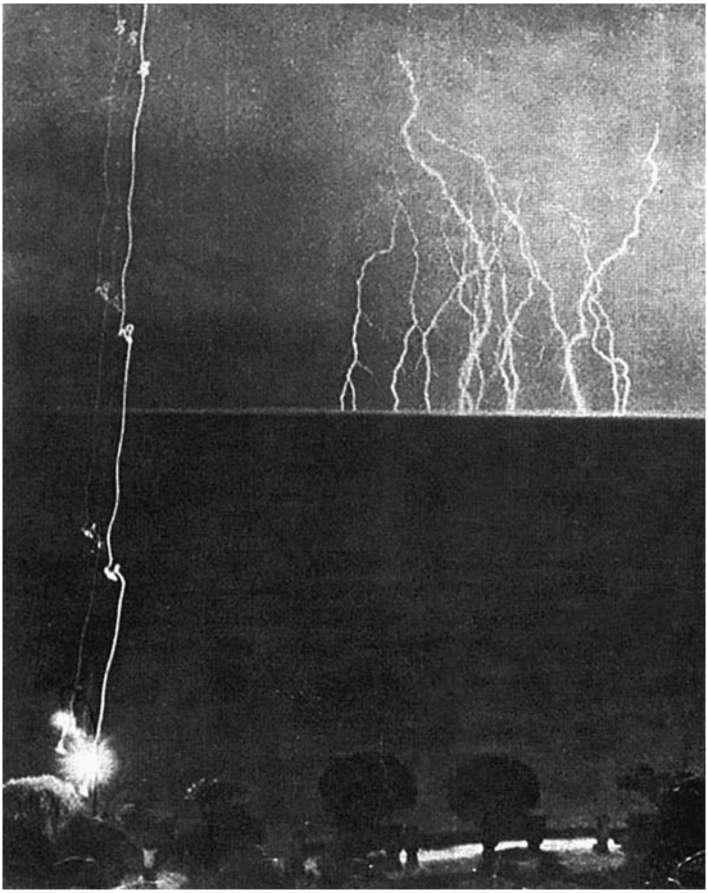

Fig. 1.5 Still photo of a falling BL taken by Shagin during a thunderstorm over the black sea near Sochi City [14]

Fig. 1.6 A *hole* in the glass made by BL [21]. To the *right*, there is a *hole* in the glass; to the *left*, there is the *disc* that had fallen out the *hole*. *Disc* (*hole*) axes sizes are 8.2 and 7.6 cm, respectively

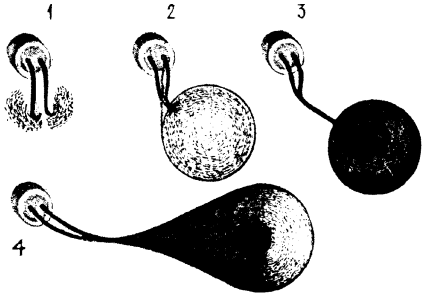

Fig. 1.7 An appearance of BL from a socket [19]

The idea about a hot flexible surface of BL leads also to the picture of BL in Fig. 1.7 where the BL blowing off from the socket is represented [19]. This BL capability is often described by the observers.

The photo in Fig. 1.8 shows a place of BL impact to the birch tree bark, which reveals the evident thermal effect.

Basing on the available data analysis, and especially on the analysis of works [12, 13, 15, 22–24], it was concluded that BL can store large amount of energy with the energy density up to 3×10^6 J/cm^3 and more in conditions of the linear lightning absence in immediate vicinity to BL.

Another outstanding BL feature [19,23,25] is its capability to drag heavy objects, such as metallic roofs (with weight about 10^4 kg) and metallic constructions (with weight about 10^2 kg), and to break large trees [26].

One has also to take into account that in a number of cases [12, 24, 26], tens or hundreds of kilograms of slad, carbonaceous steel with slag, and rocks at the places of large fireball explosions or falls were found.

These last two features first of all speak about a possibility of BL large momentum and mass. These cases were known long ago and were absolutely ignored in the twentieth century.

BL properties, described above, and a variety of its parameters define a complexity of BL phenomenon starting from the question “where does it from?” and “what is its composition?.”

However, parameters of this phenomenon averaged over a large number of events are not impressing, see Table 1.1. To say more, the given parameters are usually useless when one wants to have a reliable picture of the BL phenomenon, and prepare a new experiment on BL modeling. Collection and analysis of more than 3,000 cases of BL observations, and establishing of more than 80 BL features, put forward a multitude of questions. Some important and interesting of them are formulated in [15]. Majority of these features can not be included into the Table 1.1 because of its average character, as we have already indicated.

Nonimpressive average parameters of BL in the Table 1.1 have played an unkind joke with the BL problem in the twentieth century: the most interesting BL feature—its possibility to accumulate high values of energy stopped to be considered seriously [11, 14, 16, 17], and new investigators have lost their interest in BL researches. There still appear voices claiming that BL is an optical phenomenon or the effect of human perception.

Fig. 1.8 Still photograph of BL burn trace on a birch tree, taken by Yu. Kurilenkov in 2007 (with a permission of the author)

1.3 Energy Storage in the Ball Lightning

1.3.1 Hypotheses About BL Energy Sources

From the facts of BL observation presented above, one can have a general idea of this phenomenon. A desire of people to explain BL's nature and realize a similar object is understandable. Since BL observations have rich history, then there is a large number of hypotheses about its nature, many of them are discussed in [1, 2, 11–15]. On their basis, theoretical models of BL as a physical phenomenon are under a construction. In their basis lies the information on processes, which take place in air excited by a thunderstorm and the surrounding nature.

Concerning the hypotheses, it is necessary to note that their number is great. With time, some of them are forgotten—and then they appear again in works of new authors with new shades. Therefore, for an explanation of BL nature, following [16, 17], there is no sense to search for new physical principles inherent its nature, but is reasonable to use already existing ones. It is necessary to note that BL is a complex phenomenon, which combines at first sight inconsistent properties, so many existing models usually describe only the separate sides of the phenomenon.

One can stand on a view point of the corresponding model, and critically estimate other sides of the phenomenon, using the modern scientific information on the processes, the phenomena in the thunderstorm-excited air, and the nature surrounding the observed object. If it leads to principle contradictions between the used theoretical model and the observable facts, then it is necessary to conclude the inconsistency of the model.

Let us carry out the critical analysis of the existing hypotheses connected with BL energy accumulation. We concentrate our attention to this property most attractive for the autonomous objects. In the agreement with the conclusions of [11], BL has no constant external feeding with energy. Each of these hypotheses should explain, first of all, the energy of BL, and where it comes from. First, we divide existing hypotheses according to the supposed energy source. Then, following [16, 17] we can attribute possible hypotheses to one of the following types:

(1) Exotic
(2) Plasma energy
(3) Energy of excited molecular particles in the gas
(4) Electrical energy
(5) Chemical energy

Let us explain each of these types. We begin with the first one, which we conditionally name "exotic." To this type, we have included such assumptions, in which the BL energy is connected with dark and antimatter, X-ray radiation,, etc. Such type of the hypotheses is discussed in [1, 11, 15], where their inconsistency is shown.

1.3.2 BL Plasma Models

The plasma hypothesis is quite natural since BL is connected with electric phenomena in the thunderstorm atmosphere, with the usual lightning, by which a plasma is formed. An internal energy of such BL is reserved in different charged particles. This energy is released in the processes of their recombination. Depending on a type of the charged particles in the plasma—electrons, ions, complex and cluster ions, or aerosol-charged particles—there can be different versions of BL plasma models.

We consider that the energy in the BL plasma is not constantly delivered from the outside and the internal energy source exists. Thus, the BL temperature is insignificant (about of 1,000–2,000 K).

Let us consider that according to the observation data, the noticeable density of the internal BL energy is $W_{\mathrm{E}} = 10^2 - 10^6$ J/cm^3, and the average value of its lifetime is about of 12 s (see Table 1.1).

The energy reserved in such a BL plasma is connected with the ionization of atoms and molecules. In rough approach, the plasma energy density is

$$E = N_t I, \tag{1.1}$$

where I denotes the ionization potential of atoms or molecules and N_t is a number density of the charged particles. At the concentration of the charged particles in the plasma of $\sim 10^{19}$ cm^{-3}, created by the lightning, and the ionization potential of atoms, or molecules of $\sim$15 eV, from the expression (1.1) for the energy density reserved in the unit of the BL volume, we obtain the following value for the energy density of BL

$$W_{\mathrm{E}} \sim 24\,\mathrm{J/cm}^3.$$

As is known, the lifetime of the plasma is defined by the time of the charged particles elimination. The analysis of [16, 17] has shown, that the recombination time of the plasma consisting of the electrons and the positive ions, and consequently of BL, consisting of these particles (e.g., ions of nitrogen N_2^+ and oxygen O_2^+), is about of 5×10^{-13} s; the recombination time of the plasma, consisting of the positive and the negative ions, appears to be of the order of 5×10^{-14} s; and the recombination time of the plasma containing complex ions appears to be of the order of 10^{-13} s. The recombination time estimations [16] of the oppositely charged aerosol particles in air, when they approach each other due to the Coulomb attraction, and this motion is decelerated by the friction forces in the gas, show that the recombination passes quickly enough, with the typical time of $\sim$0.2 s.

From these estimates follows the inconsistency of the BL plasma models. Really, a process of the charged particles energy transformation in heat at the positive and the negative charges recombination in the plasma occurs too quickly, so appreciable energy cannot be kept in the plasma long enough.

1.3.3 The Long-Lived Excited Atoms and Molecules in Air

Another way of the energy storage in the linear-lightning-excited gas can be connected with a creation of a large number of the excited atoms or molecules. Two types of the excited particles—the metastable electronically excited atoms or molecules and the vibrationally excited molecules- are possible in air.

The energy store in them is about the given in the formulae (1.1), or smaller. The smallness of this energy density is true for any excited states in any gas. Even the increase of the energy by several times, does not lead to the observed numbers for real BL. At that, the processes with the participation of the excited atoms and molecules at the atmospheric air pressure proceed rather quickly [27].

Therefore, those models of BL, in which the excited particles are used as the energy source, appear to be also inconsistent by two parameters—the stored energy and the lifetime.

1.3.4 An Electric Way of Energy Storage

To electric hypotheses, we attribute such in which the BL internal energy is connected with the electric fields created by the charged particles. In this case, we initially have a system of the charged particles (electrons, ions, or aerosol-charged particles) collected in the set element of space. The energy used for placing there the charged particles, having overcome the Coulomb interaction forces between them, is the internal energy of the system interesting for us.

From the BL observation data follows, that it possesses rather high electric charge. An electric field created by the object's charge, can cause a luminescent discharge in air. So, we have to estimate an energy of such a system.

Let us consider that the full charge of BL is equal to q, and is located in a sphere of a radius R_0. Then, in the case the charge is uniformly distributed over the volume of the sphere, the electric energy of the sphere is equal to [16, 17]:

$$E = \frac{3}{5}\frac{q^2}{4\pi\epsilon\epsilon_0 R_0}, \tag{1.2}$$

where ϵ is the dielectric constant of BL material and ϵ_0 is the dielectric constant of vacuum. If the charge is uniformly distributed over the sphere surface, its electric energy is equal to [15–17]:

$$E = \frac{q^2}{4\pi\epsilon\epsilon_0 R_0}, \tag{1.3}$$

where ϵ is the dielectric constant of air. One can see that they are of the same order of magnitude. At that, an electric field strength value F is maximal at a surface of the sphere and is

$$F = \frac{q}{4\pi\epsilon\epsilon_0 R_0^2}. \tag{1.4}$$

As is known, at $F = 27 - 30$ kV/cm, the air breakdown takes place at the atmospheric pressure in dry or humid air. For such an electric field strength, the energy density of the surface-charged sphere is $W_E = 2 \times 10^{-4}$ J/cm^3. Even rise of the electric field on the ball surface by several orders of magnitude [15] does not save the situation. In this case, we also come to the conclusion, that by the electric interactions, it is impossible to explain the observable BL energy values.

Recently, Nikitin in [15] has published the concept of BL as a dynamic capacitor. As well as other authors of modern models, he had a predecessor—de Tessan—who proposed in 1859 a BL model in a form of a spherical electric capacitor. Even at replacement of air by an insulator with the electric field strength $E_{\rm brp} = 10^9$ V/m the energy stored in the capacity is insufficient for an explanation of the high energy density of BL. However, a strong dependence of the energy density on the electric field ($W_{\rm E} \sim E^2$) makes it very attractive to use, namely, this electric capacitor as the keeper of energy. The complexity consists in that in real electric capacitors the field pulls out electrons at the superstrong electric fields from the metal electrodes, and in the case of BL there are no solid electrodes. Therefore, it is necessary to search for a configuration, which existence would be supported by the moving separated electric charges of a different sign. The author has come to the model named "the dynamic electric capacitor." In it, the electrons are located in the center, moving on a ring orbit, and round them rotate the positive ions under the influence of the electric field, created by the charge of the electrons. The author met a problem of a cover of such BL, which protects moving electrons and ions from the collisions with the molecules of air. He supposes, that it is created of the raindrops water during the lightning discharge in the thunderstorm atmosphere. However, a possibility of such a cover creation simultaneously with the starting of the charged particles torsion is doubtful.

1.3.5 A Chemical Way of Energy Storage

The most ancient hypothesis of BL is connected with a chemical way of the energy storage [4, 5].

In the case of the chemical way of the BL energy storage, its energy is released at the chemical reactions. An elementary act of the chemical process is connected with a tunnel transition of atomic particles, and a reconstruction of an atomic system at a moment of the particles rapprochement. At the thermal energies, the probability of such a transition can be very small, so there are many examples with the large storage time of the chemical energy. The chemical way of the energy storage has one more advantage before others, providing the high energy density, considerably exceeding those of the electric processes and the plasma.

For a comparison, we represent values of the air energy density at the atmospheric pressure: the energy density of the completely dissociated and half ionized air is $W_{\rm E} = 0.7$ J/cm^3 [16, 17], and the energy density of air with a coal dust concentration greater than 0.08 g per 1 g of air is $W_{\rm E} = 3.6$ J/cm^3 [16, 17]. One can see high chemical energy density store with respect to those of the plasma. Even more energy is released at combustion of the solid materials. For example, if the silicon oxidation takes place in BL of 10 cm in radius filled with 1.0 g of the silicon, then the energy density released at the combustion would be about

$W_E = 2.2 \times 10^6$ J/cm^3, as it can be obtained from the data of [28], and it is considerably closer to the observed BL with high energy density.

In the case of the BL huge energy parameters, one can suppose a heavy weight of BL, and it in turn can explain the observed mechanical impacts of BL.

As the result of our analysis, in agreement with [16, 17], we come to the conclusion that the unique way of the energy conservation in BL is the chemical way.

At definite application, one can start at some model features of BL, so from the represented BL analysis we have to consider initially the ball-like, the high-energy, rather heavy, and the long-lived object.

One of the most consistently developed model was created in works of Smirnov [16, 17, 29]. According to his model, BL has the light aerosol framework with the specific weight of the atmospheric air. This framework is charged, that maintains its stability and rigidity. In the framework pores, there is a small amount of the active substance, which represents a mixture of a fuel and oxidizer. A weight of the active substance is by several times smaller than the weight of the framework. The active substance inside the framework has a fractal structure, and can be represented in a form of a large number of thin threads. The energy density of such BL is about $W_E = 30 - 50$ J/cm^3, this shows that such a model cannot be applied to the observed high-energy BL.

Articles [30, 31] have appeared to be important for understanding of a soil role in BL origination. In [30], it was proposed that BL appears as a result of the linear lightning stroke in the Earth. It releases high energy and creates the fulgurite area—a cavity in the Earth. In it, chemical reactions with participation of soil consisting of sand, organic, and other components take place. A sand includes silica (SiO_2) in its composition. A recovery of silica to metal silicon takes place, namely, in the reaction:

$$SiO_2 + 2C \rightarrow Si + 2CO. \quad (1.5)$$

Here, C is carbon and Si is silicon atoms.

At high temperature, this leads to the formation of metallic chains, and those, appearing in air, create a ball-like formation of the type predicted by Smirnov [29]. However, this model gives BL energy of the order of the model [29], so it cannot explain the features of the high-energy and heavy BL.

The model recently represented in [15, 32] continues the chemical approach to BL with the high-energy content, and it develops an approach of [30,31]. BL appears at an impact of either a linear lightning, or a high-power electric discharge to some melting and evaporating material. At this, hitting to some melting object a cavern (or a fulgurite area in case of the Earth) is created. There chemical processes occur at high temperature with the participation of metal, dust (mixture of sand and organic particles), rust, and water vapors in the case an impacted subject is over the Earth. Inside the soil components—silica [16, 17], atoms, and molecules of the dissociated organic—macromolecules including C and H_2 inside the Earth are participating.

At high temperature, the recovery processes of oxides take place in the cavern; they lead to creation of a metallic powder and accompanying gases. For example, inside the Earth they are [30, 31, 33, 34]:

$$SiO_2 + 2C \rightarrow Si + 2CO; \quad SiO_2 + 2H_2 \rightarrow Si + 2H_2O. \tag{1.6}$$

Here, H_2 denotes hydrogen molecules and H_2O are water molecules. Over the earth rust, Fe_2O_3, and other oxides can participate in the recovery processes. The cavern with the oxide surface filled with a metallic powder and gases is created: in the Earth—due to melting of SiO_2 on the surface of the cavern; over the Earth—due to oxidizing of the melted metallic surface at interaction with oxygen of air.

At the same time, the transportation of noncompensated charge to the particles of this cavern or a bubble takes place from the linear lightning or discharges. It is evident in the case of the linear lightning, which carries a noncompensated charge [35]. So, in the result of these processes, the charged sphere with the metallic powder and gases, such as CO_2 and H_2O inside, and the oxide cover layer outside is created.

Being charged, this bubble, created over the ground, separates from the place of its origination, if it has the same charge as the Earth. The linear lightning with average parameters transfers to the Earth about 10^{10} J [35], creating high pressure up to several hundreds of atmospheres in the cavity. After this, an ejection of a modified material part takes place. So, the bubble created in the earth is ejected into air. Bubbles can be light, heavy, hot, and highly charged objects, with respect to their composition. The oxide layer strongly decelerates an internal metal particle's oxidation due to prevention of oxygen penetration inside. The film has a rather high tensile strength [33, 34], so the cover can withstand development of hydrodynamic instabilities on the BL surface. The pressure of charges on the surface is initially compensated by the air pressure. Charged heavy object—the ball lightning moves in air. It does not fall down due to the Coulomb repulsion from the charged surface of the Earth. Due to the large charge of the object, a plasma layer originates on its surface [15]. The surface layer warms up the ball surface.

Slow combustion processes take place inside the reservoir of BL. They ensure not only an illumination of the ball, but its explosion, when the pressure of created gases inside the ball becomes comparable with the atmospheric one. Oxygen propagation into the reservoir sharply increases at break of the surface. Oxidation and release of energy takes place in different chemical reactions such as [30, 33]

$$Si + O_2 \rightarrow SiO_2, \quad SiO_2 + Si \rightarrow 2SiO. \tag{1.7}$$

The combustion takes place; the object explodes, and tears apart. For estimation of such a BL energy density, consider BL with the mass of 10 g ensured by the Si powder. It is in a sphere of 10 cm radius. The energy W_{ch} released at its oxidation in air is $W_{ch} = m_{Si} \cdot \Delta Q$, where m_{Si} is the mass of the silicon and $\Delta Q = 8.8 \times 10^6$ J/kg is the oxidation enthalpy of Si in air at typical combustion temperature $T = 2{,}000$ K, as it follows from [28]. So the chemical energy, which can be released at its combustion, is about $W_{ch} \sim 2.2 \times 10^7$ J/cm^3, that is even larger than the estimates of the BL energy density given above. BL lifetime can be limited by a number of processes, one of them the metallic powder material combustion. Absence in the literature of necessary data for Si combustion rate constants makes us use the data for the Al powder combustion [34]. The radial combustion velocity of Al powder (in H_2O and CO_2) is $V_{com} = 5-10$ mm/s. So, the BL lifetime estimate is ~75–150 s, which well fits to the observed lifetime of the large BL. We see that such BL can have high level of the chemical energy and live rather long.

This model considers BL as the object which can be hollow and can contain charged metallic particles inside it, that is can have the metallic core inside the oxide cover. The object's internal substance can represent a powder. The powder can be charged its motion inside the cover can lead to mechanical effects on BL motion and form. This object is alike a soft flexible cushion that can penetrate through holes. Its main energy is connected with a metal oxidation, but it also possesses a sufficiently large amount of the electrical energy.

Presence of the electric charges in this object represents its essential feature, since it determines its capability to fly, and to realize harmful impact to different electrical devices and people. So BL represents a unique joint of chemical, electrical, and mechanical features. BL studies require additional experiments, collection, and analysis of observation data, and field investigations to the places of its impact to Earth, objects, and people.

From the point of view of possible experiments, the presented model shows the productivity of the experiments with Si, rocks, metals, and metallic particles, as well as with natural organic materials in plasmas; some of them are discussed below.

1.4 Experimental Modeling

An attempt to understand the BL "construction" and create some working hypothesis on its nature was accompanied with attempts to realize a laboratory model of BL, or artificial ball lightning (ABL). In the past, there were many experiments undertaken on BL modeling in a laboratory. Some of them are described in [1, 2, 15, 36]. Experiments were realized by different types of gas discharges or plasma jets. It was defined by a convenience of the energy put by these means and the appropriate energy of existing discharges and plasma jets.

Following the accepted approach, we consider experiments that model the chemical nature of BL, when the realized long-lived object had a spherical form, which did not change into other forms (vortex or so).

In [1, 2] there is a description of H. Nauer's experiments on creation of luminescent balls at gas discharges in air with admixture of hydrogen and hydrocarbons, such as methane, propane, and benzene in concentrations somewhat smaller than those necessary for the inflammation of mixtures. The greatest effect was observed at the application of benzene. Bright luminescent balls were observed even at presence of tiny traces of it in the discharge chamber. At an explanation of the experiments, the author made a supposition that the glow appears on the tangle of thin threads, produced at benzene combustion. At that, the luminescence was considered as the result of an organic material combustion.

One can find descriptions of Barry's experiments with the pulsed discharge in air with propane admixture (with inter electrode voltage of 10 kV and energy in the pulse ∼250 J) in [2]. Air pressure was the atmospheric one, a volumetric propane concentration was 1.4–1.8%; it is smaller than the concentration necessary for an inflammation of the mixture. In the result a yellow–green ball appeared which lifetime was 1–2 s.

In the reference [37], that ideologically continued Barry's experiment [2], the pulsed discharge in air, was created between the copper electrodes, being at the distance of 3 mm. At that, the discharge voltage was changed in the range 8–10 kV, and energy in the pulse was 350 J. At Ethane content of 2.1% in mixture with air red balls with a diameter ∼4 cm and the lifetime of 0.3 s were observed sometimes. ABL of white color and 3 cm in diameter was observed in the discharge afterglow during 0.8 s at addition of 100 cm^3 of cotton fibers to the gas mixture. Appearance of the luminescent objects were observed several times in the mixture consisting of ethane 2.7% and 100 cm^3 cotton fibers processed into small particles. The maximum diameter of such an object was 5 cm, and its lifetime was 2 s.

Streamer discharges were used in [38] for a generation of ABL. For this purpose, a Tesla generator at the frequency of 67 kHz was used. A setup of Tesla [39] was reproduced in the smaller size [36]. The mean power delivered to the high-voltage electrode was 3.2 kW. This electrode was covered with a piece of wax or charred wood. It was experimentally revealed that a large number of hydrocarbon and metallic particles, evaporated from the electrode, appeared during the discharge. Their maximum number was observed in a small area near the electrode region with strong electric fields (of 10–20 kV/cm). ABL appeared near the high-voltage electrode as if "from nowhere" because they were absent at previous frames of video recoding. Their colors were different: red, yellow, blue, and white; their lifetime reached 2 s and size 1–5 cm. In the end of the existence, ABL often exploded with a loud bang, this effect we have to specially mark.

Tesla [39] had realized fireballs by himself, their sizes reached several centimeters. The high-voltage electrode in his case was covered with the isolation made of a natural rubber, and a layer of graphite powder was between the electrode and the isolation. Therefore, particles of metal, soot, carbon, and polymer evaporated from the electrode could take part in complicated processes of a structure formation and combustion.

To another popular investigations, one can attribute a formation of balls out of a metallic vapor, realized at closing of contacts of powerful electric batteries [40, 41]. Sizes of ABL were of several cm, and their lifetime reached tens part of a second.

Luminescent balls of 2–4 mm in diameter, and the lifetime of 2–5 s were obtained in [42] at short-circuit of two electrodes in water. The balls resembled drops of melted metal burning in air. After cooling, they represented metallic spheres of 2 mm in diameter with traces of oxides on the surface in a form of thin hair.

Experiments described in [43] were devoted to creation of regions with plasma conditions analogous realized at the linear lightning stroke to the soil, or at the explosion in a closed space. The discharge and the plasma were created in the closed volume of the organic tube. Then the created luminescent formation, consisting of a mixture of the vapor, particles of the electrode material melt, and the ionized air, went outside through a specially prepared hole, or a hole broken through in the tube due to the pressure rise during the discharge. The lifetime of such formations reached 5–7 s. They exploded after hitting an obstacle standing in front of it, leaving traces as from a multilayered object with the melted core. Sometimes, it was possible to find their remains, that resembled oxidized metallic shells. This was one of few experiments when there were detected an explosion and remains of ABL.

This direction had a development in the work [44]. It was discovered there that different ABL structures were formed at the application of organic plasma-forming materials and at injection of plasmas into air saturated with organic vapors. A plasma jet from the plasma generator passed over a cuvette, keeping melted paraffin or wax at undertaking of these experiments. At that, the plasma generator energy of about 200 J was delivered to the gas mixture during ~6–8 ms. A video recording had showed that the spheroid or mushroom formations were formed over the cuvette immediately after the "shoot" and rose up. Their size was 10–20 cm, and the temperature was $T \sim 1{,}500$–$2{,}000$ K (as it was estimated by their rising velocity), they existed up to 0.5 s. Luminescent objects in experiments [44] were created by the plasma stream. They appeared over a cuvette with a melted wax and a paraffin even 10 min after stopping of the cuvette heating. Such a long time of the vapors high-concentration existence proved that in real conditions gaseous hydrocarbons can be accumulated in some local places and ignited later. Appearance of such objects allows to explain a nature of the luminescent objects that lead to summer forest fires and are observed in coniferous forests in clear weather.

In the another experimental series in [44], with use of the capillary of 1–2 mm made in a material of a complex organic mixture consisting of paraffin, colophony and milled wood with average sizes of the "seed" $1 \times 0.3 \times 0.3$ mm were obtained luminescent objects with typical visible sizes 1–2 cm and the lifetime of 1–2 s. Several times, it was possible to find remains of these ABL. They were investigated with the electronic microscope, which showed their polymer fractal-porous structure. These ABL practically completely copied descriptions of the BL motion. They unexpectedly appeared from the channel of the plasma generator, usually 30 ms after the plasma flow. Visually, they unexpectedly disappeared, though the video record showed their gradual starvation during 0.3–0.4 s. In the reference [45], it was experimentally and theoretically was shown that analogous in sizes and the lifetime objects were observed at burning of small particles of wood with sizes of ~1–2 mm. Such particles could be formed in [44] at erosion of the channel wall, and later they could be ignited.

Abrahamson [31] has undertaken experiments on imitation of the lightning stroke to the Earth in order to verify his hypothesis [30], as described above. He passed a discharge current from the capacity 204 μF, charged to the voltage of 20 kV, through a layer of the humidified soil of 3 mm in the thickness. The soil filled the bottom graphite electrode; the graphite rod of 15 mm in diameter was used as the upper electrode located at a distance of 22–36 mm from the surface of an Earth layer on the bottom electrode. Energy released during the discharge was 110 kJ, and the charge of 1.3–3.4 C passed through the soil. At the highest power experiments, the negative potential was applied to the upper electrode. Products of chemical reactions were sucked away by a pump and deposited on the filter of quartz fibers and on a lattice of nickel. Fiber threads of 100 nm in diameter and to 7 microns in length were found on the filter by means of an electron microscope. Chains from 25 to 120 nm in length consisting of balls of 25 nm in diameter were found on a surface of a nickel lattice. However, authors of [31] did not manage to realize an appearance of large autonomous spheres similar to BL.

After papers [30, 31] several works [46–49] devoted to the combustion and explosion of porous silicon with the formation of ABL were published.

The work [46] was devoted to the explosion and combustion of nanostructured silicon in the presence and absence of the hydrogen on its surface. Special attention was paid to the investigation of spherical luminous structures formed in these processes. Porous silicon layers created as a result of the electrochemical anodizing of the single-crystal silicon were used as a source of the silicon nanoparticles. The explosion and combustion of porous silicon samples were initiated thermally, mechanically, electrically, and optically. For example, thermal initiation was made by a contact heating of the sample to 900°C. Visible differences in explosive reactions with respect to the way of their initiation were not revealed. The explosion and combustion of porous silicon were accompanied by the origination of luminous balls with a diameter of 0.1–0.8 m moving with a velocity up to 0.5 m/s. The lifetime of such objects could reach 1 s.

In [46], it was proposed a hypothesis of the appearance and development of BL. A linear lightning striking the Earth leads to creation of silicon particles including those whose sizes are equal to several nanometers. These nanoparticles appear in air in the form of a fractal cluster, and are not visible until their combustion or explosion is initiated by some impact. The hydrated silicon and humid air ensure the formation of the hydrated plasma in the processes of the combustion and the explosion, which increases the lifetime of such a plasma to several seconds.

However, this hypothesis based on the described experiments and the model [29] cannot explain the high energy of the real BL and its heavy weight.

In Fig. 1.9, one can see an example of realized luminescent structures obtained in [46].

In the work [47], were also tested the ideas of [30, 31] by vaporizing at normal atmospheric pressure of small pieces of highly pure Si wafers by an electric arc. The arc was generated by the interruption of the electric circuit. It realized high temperatures sufficient to melt and vaporize the Si pieces. Authors generated luminous balls that have long lifetime and several properties typical for natural BL. Their initial diameters were in the range from 1 to 4 cm, and the lifetime was up to 8 s.

We have to emphasize that the considered experimental works correlate with recent theoretical approaches [15, 32], though they did not represent high-energy

Fig. 1.9 Artificial ball lightning produced by thermal ignition of 100 μm thick 1 cm in diameter doped porous silicon: 0.5 s after formation [46]

objects and did not reveal a mechanism of BL flying or levitating in air, and there are doubts concerning the origination of the activated silicon in nature.

As we can see, our approach to the experimental revealing of the BL chemical nature has allowed us to select works devoted to the analysis of the combustion processes of different materials that can be under the lightning, discharge, and the plasma impacts. Their combustion is accompanied with complex gas-dynamic and radiation processes, which in many features resemble appearance of real BL. However, there was practically absent explosions of the created ABL typical for real BL.

1.5 Difficulties of BL Investigations

There is a complexity of BL events collecting since it is connected with several reasons. BL appearance is usually unexpected even if an observer is prepared to it theoretically: the observer becomes excited, so he can make mistakes in the observation details and believe in them. He can analyze it by himself, put it to some scheme, use some known hypothesis, and to misrepresent facts. It is true for events manifesting high BL energy, heavy weight, large momentum, and capability to take away golden adornments, change of BL form. So, the continuation of BL observation is required in order to eliminate ambiguity of observations, hence to simplification of experimental and theoretical modeling.

Difficulties of BL science development is strongly connected with the experimental realization of the observation events. It is well understood that the BL problem will be considered as solved only after the experimental realization of this object, having all indicated above features. Nowadays, there are problems with copying of BL impact to window glasses. Especially, it is true with their penetration through glasses without clearly detected traces. Available information about BL impact on glasses is insufficient for understanding of physical and chemical processes that take place.

There are difficulties with the experimental modeling of magnetic impact of BL on metallic subjects. There are only few descriptions left [3, 19] and no analysis of metals influenced by BL. So, we do not definitely know what to model. It is also difficult to imagine how to model BL impact on golden rings and bracelets leading to their disappearance. We understand that we can use high-frequency electric fields, but what else have we to foresee in experiments in order to realize these subjects disappearance? We have to understand a mechanism of BL transformation into a ball from a tape and back.

Generally speaking, there is a shortage of detailed observations showing how these effects are realized by nature. So, we have to continue collection of detailed descriptions of BL unusual events and analyze approaches to their experimental modeling.

New investigations are to be undertaken in modeling of BL appearance and creation of luminescent objects on a base of burning metals inside oxide covers. We have to understand and realize mechanisms of BL explosions. It is difficult to model BL levitation, though we can charge a rubber ball by the Van der Graaf accelerator. This can be another type of experiments. We have to continue experiments with combusting powders and jets, especially creating them in charged and excited states and so on.

1.6 Conclusions

In the given chapter, we have shortly looked at the BL problem as a whole. For better understanding of this phenomenon, we have represented its photos and descriptions of its properties.

We have presented an approach to hypotheses of BL origin which showed that BL most probably has a chemical nature.

Some known experiments on reproduction of BL analogues are described. They show various approaches to the experimental realization of this object and their results. These experiments show a complicated character of origination and elimination of the ABL of the plasma chemical nature.

Analysis of experiments demonstrates existence possibility of the ABL on a basis of heterogeneous structures (a mixture of a gas with solid or melted components) or an object with solid framework. They are formed at the destruction both of organic polymeric and inorganic materials, such as Si, SiO_2, SiC, Fe_2O_3, etc. In the plasma conditions, these objects can be highly excited and represent nonequilibrium electrically charged structures and melts that combust in air. Some models of this phenomenon, which have drawn the attention of the investigators, are named.

Unlike other directions of physics where theory development is based on the analysis of a large set of experiments with unequivocal and regularly reproduced results, such a possibility for BL theory construction at the moment is absent. Theories are born often in a random way, and are under the construction without accounting of all achievements of the predecessors. In these circumstances, the weakness consists of the BL physics.

One can conclude that BL is not only the physical phenomenon, but the geophysical, and the geochemical as well. BL appears over and from the Earth mainly after the lightning impact. It can be formed at its impact to metallic and organic subjects. It can be formed during the earthquakes and the volcano activity as well.

Therefore, laborious work on the further ball lightning data collection, on experimental and theoretical modeling of its properties, is necessary. As a whole the science of ball lightning has passed the long way which has led to accumulation of this phenomenon observations, results of many experiments, and theories. It has shown that this complex physical phenomenon is connected mainly with chemical and electric processes accompanying them in the atmosphere, over and in the Earth.

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