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Properties of Ball Lightning as a Basis for Creating Its Theory

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Abstract

Observational data of ball lightning often contradict each other, so it was sometimes proposed to build a theory of ball lightning based on only a small number of statistically reliable observations. Work on this principle did not bring results. The correct approach to creating the theory of ball lightning should be the desire to explain all of its properties, even those that are rare. In the database of ball lightning observations, the most valuable are the cases when it left traces available for quantitative analysis, or was filmed by video cameras. Ball lightning is a material body consisting of a shell and a multi-element core. Cases of water heating made it possible to determine energy density of ball lightning, which turned out to be higher than 10^{10} J/m^3. A study of results of ball lightning explosion, as well as its effect on snow, made it possible to assume that it is capable of generating radiation with a wavelength of about 10 cm, the power of which can be greater than 120 kW. Ball lightning has an electric charge of 10^{-3} - 10^{-1} C. The presence of an electric charge explains the complex nature of its movement in atmosphere. Ball lightning is formed under the action of magnetic field pulse and ultraviolet radiation of linear lightning channel. A model of ball lightning in the form of a core of charged "dynamic capacitors" and a shell of polarized water molecules is considered. It is shown that this shell is capable of withstanding the force of Coulomb repulsion of the core charges and the pressure caused by the movement of charge carriers. The glow of ball lightning core occurs due to orbital motion of electrons at a speed close to light speed. The intensity of the glow is determined by the degree of uniformity of electrons arrangement along the orbit.

Keywords

Ball Lightning Properties, Model, Core, Shell, Dynamic Capacitor

1. Introduction

Throughout human history, people have repeatedly observed glowing balls floating in the air during thunderstorms, called ball lightning. According to statistics, each of us has a chance to see ball lightning during our lifetime. I was lucky: when I was 10 years old, a red ball with a diameter of 20 cm flew past me. It moved silently above the wires of a telephone line [1]. Official science did not recognize the existence of such objects for a long time, considering them a figment of the imagination of poorly educated people. Incidentally, for the same reason, reports of "stones falling from the sky"—meteorites—were considered false. On July 26, 1753, in St. Petersburg (Russia), while conducting an experiment to measure the electric field strength under a thundercloud, Professor Georg-Wilhelm Richmann was killed by ball lightning [2]. Ball lightning flew out of a device that was attached to a metal tip of a mast on the roof of a house. The engraver Ivan Sokolov, who witnessed Richman's death, drew a picture of the event. Mikhail Vasilyevich Lomonosov conducted a study of the path along which the ball lightning moved, noting the stoppage of the clock and the scattering of sand on the stove. It can be considered that Lomonosov was the first scientist to study the action of ball lightning. He believed that ball lightning was an object of burning resin secreted by plants, which somehow thickened in the air. The tragic incident of the scientist's encounter with ball lightning became the reason for the ban on the study of atmospheric electricity [2]. It took 85 years for scientists to return to the study of ball lightning. François Arago, secretary of the Paris Academy of Sciences, published a review of 20 reports of ball lightning observations in 1838 [3]. In 1874, the French astronomer Camille Flammarion published a book [4], in which he included descriptions of 50 cases of ball lightning observations. In 1923, Walter Brand's book [5] was published. Brand collected 600 reports of ball lightning observations, which were stored in the libraries of Berlin, Marburg and Göttingen. For the book, he selected 215 of the most reliable reports. After processing them, he compiled a table of the frequency of manifestation of various properties of ball lightning. McNally [6] and Rayle [7] in 1966 published the results of a survey of people who observed ball lightning. In 1974, Stanley Singer's book [8] was published. He presented descriptions of observations of ball lightning and described models of its structure. Jorge Egely collected and processed 278 cases of observation of ball lightning [9]. Among them, of particular interest are reports of high energy of ball lightning. Yoshihiko Ohtsuki published a collection of reports on ball lightning, discussed at the International Symposium [10]. In 1999, a book by Mark Stenhoff [11] was published with an analysis of more than 200 reports of ball lightning observation. Russian scientists paid special attention to cases of anomalous behavior of ball lightning. In 1980, a book by Ilya Imianitov and Don Tikhiy [12] was published with descriptions of the actions of ball lightning, which seem incredible from the point of view of conventional scientific concepts. A description of the same extreme action of ball lightning on the soil can be found in the article by Mikhail Dmitriev *et al.* [13]. Igor Stakhanov collected over 1500 reports of ball lightning observations by surveying readers of the "Science and Life" magazine. After processing these observations, he published them in a book [14]. The results of the analysis of ball lightning properties were published in a book by Boris Smirnov [15]. In 2019, a book [16] was published by Alexander Grigoriev based on the analysis of 250 observations of ball lightning. Information about properties of ball lightning and its connection with bead lightning can be found in the book by James Barry [17]. Takaaki Matsumoto discovered extended traces on photographic films left by particles that appear during an electric discharge in water [18]. He suggested that these particles are micro-sized ball lightning. The books by Nikolaev [19] and Chernobrov [20] describe observations of luminous objects similar to ball lightning. A major contribution to the base of ball lightning observations was made by the book by Vladimir Bychkov [21]. Unlike some authors who "weed out" observations that cannot be explained, he also paid attention to such "incomprehensible" cases.

Based on observations, a "portrait" of ball lightning was synthesized. It is believed that ball lightning is a luminous spherical formation that usually appears during a thunderstorm. Its shape may differ from spherical—it can take the form of an ellipsoid or a cylinder. It can pass through holes that are much smaller than its diameter. In doing so, it changes shape and flows through the hole like a drop of liquid. It can pass through glass as if not noticing it. Ball lightning can move in the air in any direction. Sometimes it is carried away by the wind, and sometimes it can move against the wind. Once near the surface of a conductor (for example, the earth), it moves parallel to it, being at some distance from it. It can rotate, but can also suddenly stop rotating. It glows, and its color can be any. Ball lightning can exist from several seconds to several minutes, ending its life with an explosion or fading. Sometimes before disappearing, its color turns red. Ball lightning may not emit light at all, remaining "black". In addition to visible light, ball lightning emits radio waves. No traces remain where ball lightning disappears. Ball lightning can form at a great height near a linear lightning channel or where it strikes the ground. Ball lightning can penetrate into buildings through small openings. As a rule, a ball lightning explosion does not leave serious consequences. However, there are cases of ball lightning explosions inside closed buildings, which resulted in the walls of the buildings being pushed out. In this case, people who were near the exploding lightning stayed alive [22]. The listed properties of ball lightning made it possible to construct simple models of it. For example, the fact that it levitates in the air was explained by the fact that it is an object with a density close to the density of air (something similar to a balloon) [14] [23]. The glow of ball lightning was explained by the process of combustion of its substance [15] [24]. The presence of radio emission led to the construction of models of ball lightning in the form of a bubble filled with the energy of electromagnetic radiation [25] [26].

The attitude towards ball lightning changed dramatically in 1936 after an event that took place in London. Mr. W. Morris wrote to the editor of "The Daily Mail" newspaper that he had seen ball lightning that had fallen into a barrel with 18 liters of water and heated it to boiling [11]. Calculations showed that 10 MJ of energy was required to heat the water, which corresponds to the energy density contained in ball lightning, $\rho_E = 10^{10}$ J/m^3 [27]. Some scientists treated this "natural experiment" with distrust. They claimed that the water did not boil, but only foamed [14]. However, after some time, similar cases were repeated. A 6.5 cm ball lightning that fell into a cattle trough with 112 liters of water caused the water to boil away. Boiled frogs were lying at the bottom of the trough [12]. In front of numerous witnesses, a 25 cm ball lightning fell into a hole with 120 liters of water and evaporated it [9]. A 5 cm ball lightning "clung" to the hook of a fisherman's fishing rod. He lowered it into a bucket with caught fish. The water boiled, and the fish was cooked [28]. In all these cases, the energy density contained inside the ball lightning was higher than 10^{10} J/m^3. The fact that a large reserve of energy was recorded in ball lightning, on the one hand, led to the need to look for an explanation for it, and on the other hand, made ball lightning a prototype of a device for accumulating large amounts of energy. Pyotr Kapitsa suggested that ball lightning is an electric discharge in the air that receives energy from outside [29]. The authors of models of autonomous ball lightning believe that the energy of ball lightning is contained in the oscillations of electrons relative to the ion core [30] or that it receives energy due to the parametric resonance of its oscillations with oscillations of the external environment [31]. Models have been proposed with the accumulation of energy by electrons and ions separated in space and moving in coaxial orbits [32] [33]. Dijkhuis proposed a model of ball lightning consisting of tightly packed tubes of paired electrons around which ions rotate [34]. In all the proposed models, ball lightning is considered electrically neutral. This creates difficulties in explaining the case with which we began the article – people being struck by electric current.

In recent years, thanks to the widespread use of smartphones, videos have appeared, the study of which has expanded the possibility of refining the details of the properties of ball lightning. The advent of aviation and the exploration of outer space had significantly expanded the area of study of near-Earth space, in which luminous objects have been discovered whose characteristics turned out to be close to the properties of ball lightning. Long-lived luminous objects, called UFOs, have been discovered in the stratosphere [35], and in near space, astronauts have observed luminous objects accompanying spacecraft [36] [37]. In addition to an increase in the volume of space in which research is conducted, there has been a shift towards a decrease in the size of objects with unusual properties. In the experiments of Matsumoto, Shoulders and Urutskoev, "strange" particles with the properties of miniature ball lightning were discovered [18] [38] [39]. We have shown that all the properties of these particles can be explained by assuming that they are an ensemble of identical ions in a shell of polarized water molecules [40]-[42].

All information about properties of ball lightning was obtained by observing this phenomenon and traces of its impact on the environment. For centuries, the only "device" for obtaining this information was the human senses: sight, hearing, touch, smell. In addition, the obtained data was "processed" by the brain, which did not contribute to improving their reliability. In recent years, thanks to the appearance of videos about ball lightning, it has become possible to obtain reliable information about its structure and the details of its behavior. This article presents new results of filming ball lightning, which provides the basis for determining its basic properties.

2. Properties of Ball Lightning

Figure 1 shows ball lightning, filmed for the first time at close range. The typical shape of ball lightning is a sphere with sharp boundaries. It is evident that it consists of a luminous shell and a luminous core. The core is visible through the shell, which means that it is transparent, and its luminosity is less than the luminosity of the core. The shape of ball lightning is close to spherical. This is natural if we assume that the core for some reason tends to expand, and the shell prevents this. A rubber ball is constructed on the same principle. If the thickness of its shell is the same everywhere, it will take the shape of a sphere. If the thickness of the shell is not the same in different places, then its shape may change—it may take the shape of a melon or an elongated cylinder. The same can happen with ball lightning. This figure would seem to add nothing to the description of the properties of ball lightning. From its name it is clear that it is a ball. However, to this day, the opinion is still sometimes expressed that ball lightning does not exist, that it is an afterimage in the eye after observing a bright flash of lightning. Ball lightning captured on a video camera refutes this misconception.

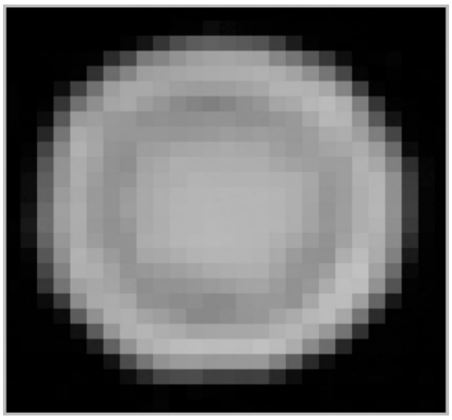

Figure 1. Ball lightning filmed in 2016 near Blagoveshchensk [43].

Observers sometimes say that the core consists of small, chaotically moving sparks. These sparks are trying to fly out, but the shell prevents them from doing so. The elements of the core are held inside the shell, but when it ruptures, they fly out of it and go out. Figure 2 shows the result of a collision of ball lightning with a car [22].

(a) (b)

(c)

Figure 2. The collision of ball lightning with a car. (a) The car approaches the ball lightning. (b) The moment of the collision. (c) The scattering of fragments of ball lightning.

The elements of the nucleus, repelling each other, fly out of the torn shell. The reason for their repulsion may be the presence of an electric charge of the same sign. The presence of a charge in ball lightning is confirmed by cases of electric shock to people and the observation of the hair rising of girls over whom ball lightning flew [16].

This gives grounds to believe that ball lightning has an uncompensated electric charge. This assumption is confirmed by the fact that sometimes ball lightning can split into parts (**Figure 3**).

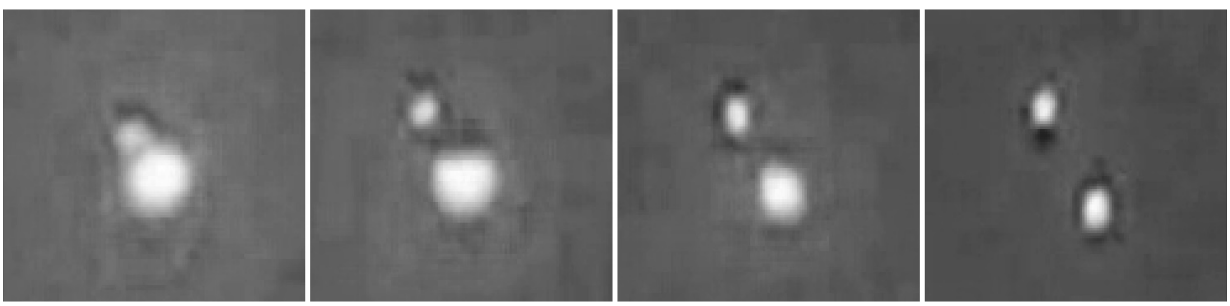

Figure 3. The frames of fragments scattering of separated ball lightning. 1st frame: $t = 0$ s; 2 − $t = 0.27$ s; 3 − $t = 0.40$ s; 4 − $t = 0.64$ s [44].

Let us assume that the scattering of ball lightning fragments occurred due to the repulsion of their charges q_1 and q_2 with a force

$$F_{\mathrm{rep}} = q_1 q_2 / 4\pi\varepsilon_0 x^2 , \quad (1)$$

here ε_0 is the dielectric constant and x is the distance between the centers of the spherical fragments. The fragments are slowed down in the air with a force

$$F_{\mathrm{fr}} = 0.5 \cdot C_{\mathrm{x}} \rho_{\mathrm{a}} \pi R^2 \left(\mathrm{d}x/\mathrm{d}t\right)^2 . \quad (2)$$

here $C_x = 0.3$, ρ_a is the air density, and R is the radius of the fragment.

Equating F_{rep} to F_{fr}, we find

$$x = \left[2q_1 q_2 / \pi^2 \varepsilon_0 C_x \rho_a R^2\right]^{1/4} \cdot t^{1/2} . \quad (3)$$

Analysis of **Figure 3** shows that the distance between fragments increases according to the law presented by formula (3).

Ball lightning can move with the wind, but it can resist the wind pressure for some time. The presence of an electric charge of ball lightning allows us to find an explanation for the reasons for the complex nature of ball lightning movement in the atmosphere. On July 27, 2015, in the Moscow district of Mitino, ball lightning was simultaneously filmed by three operators (**Figure 4**).

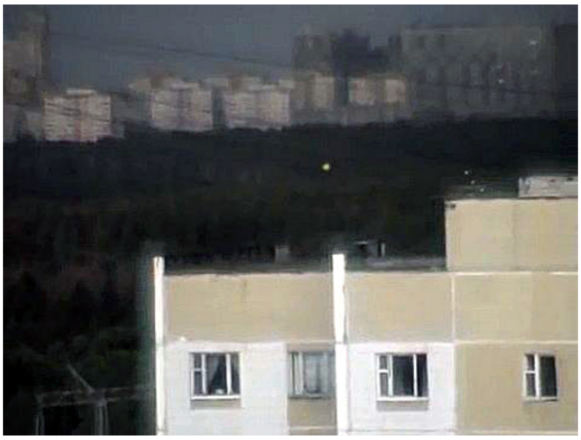

Figure 4. Ball lightning photographed in Mitino [45].

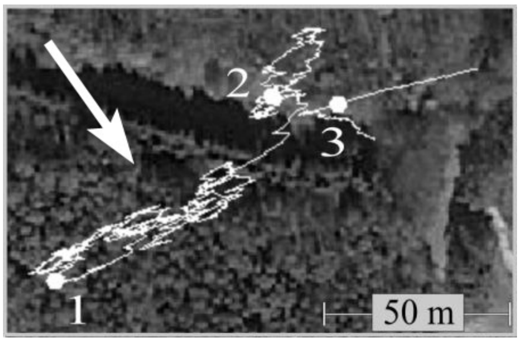

Figure 5. Horizontal projection of the trajectory of ball lightning caught in a "trap". The arrow shows the wind direction [47].

Using the triangulation method, we were able to calculate the trajectory of the ball lightning [45]. It turned out that, despite the strong wind, the ball was located in a 12 m wide zone, perpendicular to the wind speed, for 80 seconds (**Figure 5**). This was explained by the fact that the charge of the ball lightning was attracted to the charge of the approaching thundercloud. For some period of time, the force of attraction was compensated the wind pressure. When the cloud was above the location of the ball lightning, it rose to it and flew away with it. Usually, the lower part of a thundercloud has a negative charge [46]. Based on the event under discussion, we can conclude that the ball lightning in Mitino had a positive charge.

The presence of a charge in ball lightning is the reason for its movement in the atmosphere under the influence of electric fields. Roughly speaking, it moves along the lines of force of the electric field, which can penetrate into buildings. This can cause it to pass through small openings. In this case, it changes its shape and flows through the hole like a large drop of liquid. A strange feature of ball lightning is its ability to freely pass through glass without damaging it. This ability was absolutized and served as the basis for some hypotheses of ball lightning in the form of a tangle of self-consistent radio waves [48] [49]. However, information about the passage of ball lightning without leaving traces was always taken "on faith" without experimental testing of the glass. Our analysis [50] showed that after the passage of ball lightning, a trace remained in the glass in the form of a hole that was not completely sealed (**Figure 6**).

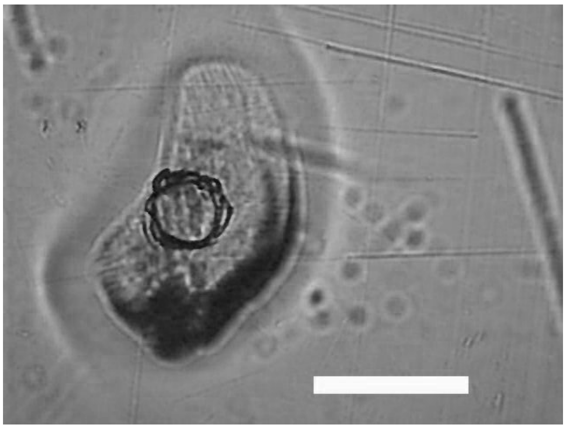

Figure 6. View of a section of glass from the street. The length of the white strip is 500 μm.

Thus, cases of the passage of elements of the core of ball lightning through molten glass should not be surprising, just as the "passage without a trace" of a stone through water does not seem strange. In both cases, the hole is "closed" by the tension force of the liquid. This case, as well as other cases of ball lightning passing through small holes, indicate that the elements of its core are no larger than 5 mm.

An analysis of the observation results suggests that there are at least two types of ball lightning in nature. These are low-energy ball lightning that does not leave much destruction when it disappears, and ball lightning with a large energy reserve. The former sometimes come out of household appliances (electrical outlets, landline telephones) [51]. The latter, as a rule, are formed at a high altitude near the linear lightning channel. Figure 7, Figure 8 show how ball lightning appeared after a linear lightning discharge [52].

Figure 7. The place of ball lightning observation in August 2022 in the city Tyumen.

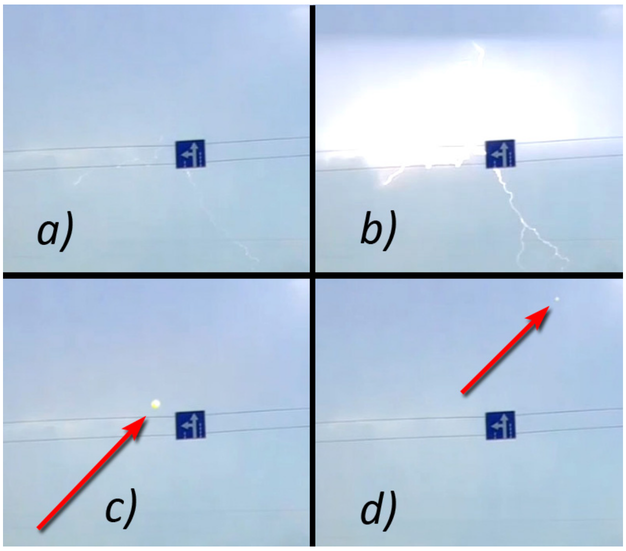

Figure 8. Frames of ball lightning filming. (a) View before the lightning flash. (b) Lightning flash. (c) Appearance of ball lightning. The repetition period of these three frames is 1/30 of a second. (d) Position of ball lightning after 12 seconds.

It is evident that the ball lightning was formed in less than 1/30 of a second (the duration of one frame of a video film). It is also important that the ball lightning appeared in a cloud containing a large number of water droplets. In contrast, low-energy ball lightning is "blown out" of the sockets within a few seconds.

Figure 9 shows the process of blowing out ball lightning from a socket.

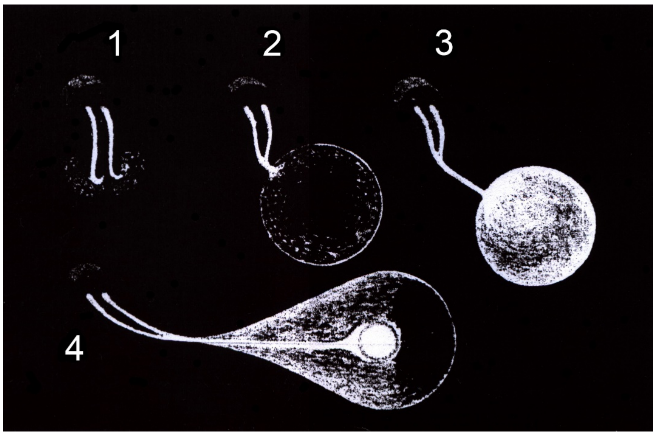

Figure 9. "Blowing out" ball lightning from an electrical outlet. 1 - 2—start of the process. 3—beginning of the ball formation. 4—lightning a "fire" [51].

It is natural to assume that in these cases the reason for generating the energy of the glowing balls was the electric current in overhead power lines or antennas. In the early and mid-20th century, telegraph and telephone communications, as well as radio broadcasting, were carried out using open wire lines. A linear lightning discharge into or near this line excited an overvoltage pulse in it, which could circulate in this line for quite a long time, reflecting from its ends. When reflected from an open end of the line (socket), the voltage doubled. The passage of a strong current in the presence of evaporated insulation material could lead to the formation of multi-charged clusters consisting of an ensemble of ions enclosed inside a dielectric shell. A set of such clusters can be accumulated inside a common large shell.

Thus, we come to the conclusion about the possibility of the existence of a type of ball lightning in which the charge carriers are not energy-intensive plasmoids of moving ions and electrons, but ordinary ions. The properties of this type of ball lightning should differ from the properties of high-energy ball lightning. And, indeed, ball lightning that appears from sockets is low-energy. It leaves practically no traces, and its explosion inside a room does not cause much destruction. The emitters of light in high-energy ball lightning are its core (relativistic electrons) and the corona discharge on its surface. For "ionic" ball lightning, the only source of light is the corona discharge. The emitter of light in a corona discharge is electronically excited molecules of nitrogen dioxide. Therefore, it can be expected that blue colors will predominate in the emission spectra of "low-energy" ball lightning, and the distribution of colors of "high-energy" ball lightning should be more uniform.

Ball lightning, which has a charge, is actually one of the electrodes of a capacitor, the second electrode of which is the surface of the earth. Therefore, it actively interacts with the external environment, changing its properties. When a grounded object is located near ball lightning, the charge flowing from ball will be between it and the object. Repulsion from this charge can create conditions in which ball lightning will levitate above the surface of the earth or become part of a group of ball lightning [47].

When in the electric field of a thundercloud, ball lightning actually forms a single connected system with it. This system (cloud + ball lightning + object) can move together for some time. This can explain cases when ball lightning lifted people up and even dragged a freight train along with it [53]. Pilots who accidentally flew inside a thundercloud report that there is a large number of ball lightning there [16]. A group of ball lightning that finds itself in a common shell can be perceived by an observer as an unidentified flying object [35].

The most mysterious property of ball lightning is its ability to accumulate a large amount of energy in a small volume. In 1936, ball lightning the size of a large orange hit a barrel with 18 liters of water and heated it to boiling. Based on this, it was found that the energy density in it was not less than $\rho_E = 10^{10}$ J/m^3 [27]. According to the virial theorem, to hold particles with such an energy density inside a container, it must withstand a pressure of $P = \rho_E/3 = 3.3 \times 10^9$ Pa $= 3.3 \times 10^4$ atm. Ball lightning leaves no material traces after it disappears [54]. Therefore, the material for creating this container should not be a super-strong solid shell, but a simple natural material, such as water. In the case under consideration, ball lightning heated the water. This means that it is capable of transferring energy directly to water. The first thought is to assume that this occurs because ball lightning has a high temperature. However, witnesses report the absence of a sensation of heat emanating from ball lightning [5] [11] [12] [14] [16]. There is a known case when ball lightning, having fallen on snow, did not melt it [55] (**Figure 10**).

Figure 10. Ball lightning lying on snow [55].

A possible explanation for this may be that the water was heated by radio frequency centimeter radiation (as happens in a household microwave oven). We conducted an experiment that showed that snow placed in a microwave oven does not melt [55].

Sometimes ball lightning emits a bright flash of light at the end of its life, and then goes out after 1/2 a second [43] (**Figure 11**).

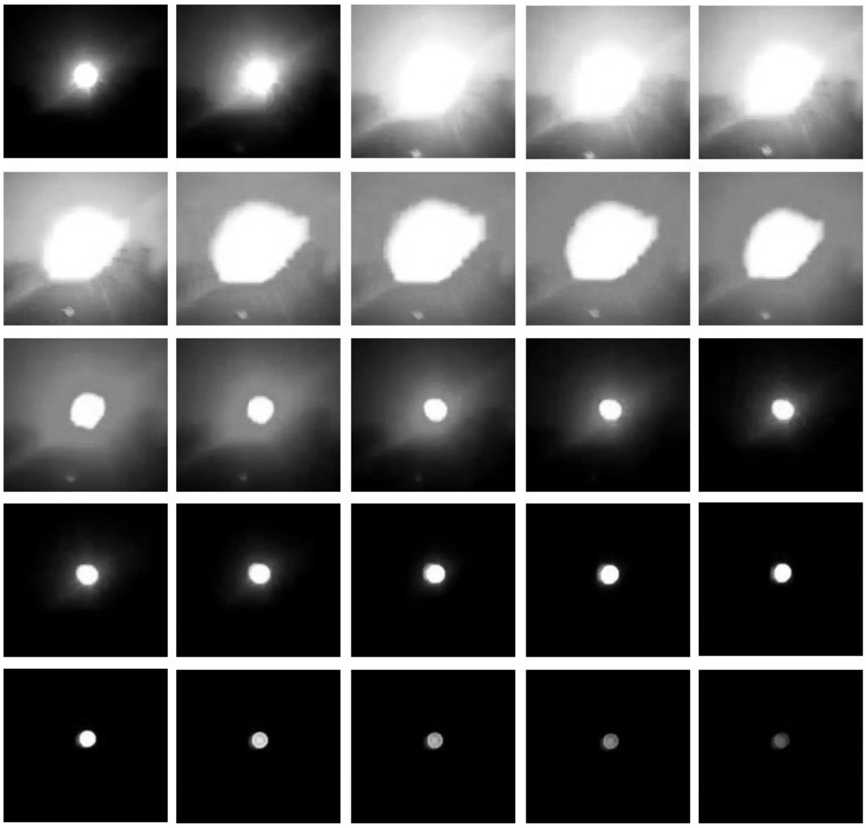

Figure 11. Flash of ball lightning. The sequence of frames is from left to right and from top to bottom. The time between adjacent frames is 1/30 s. The large size of the flash image is explained by overexposure of the frame. The ball lightning itself retains its shape and size during the flash.

There is a known case when after a ball lightning explosion near a man, a gold chain hanging from his neck disappeared (**Figure 12**). Similar cases are described in books [12] [16], which tell about the disappearance of a gold bracelet and the loss of gold rings from women who encountered ball lightning.

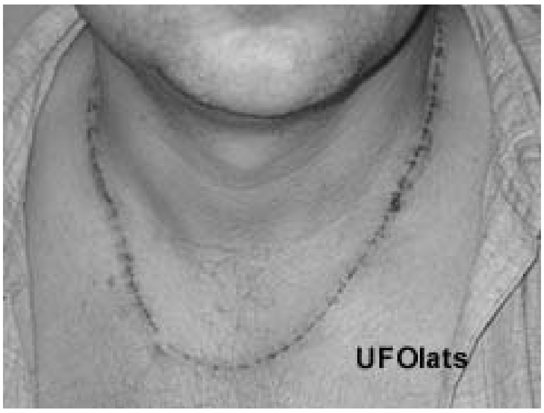

Figure 12. Burn mark from evaporated gold chain [55].

Apparently, simultaneously with the flash of light, ball lightning emits a pulse of radio frequency radiation, and the energy of this pulse is enough to evaporate a gold chain weighing 17 g. To evaporate the chain, the energy of 36 kJ is required. If we assume that the flash lasted 0.3 second (see **Figure 11**), then the power of this radiation was 120 kW.

3. Ball Lightning Model

Let's discuss whether it is possible to create a container that can withstand the pressure of the energy core of ball lightning (3.3×10^3 MPa) and, in addition, the force of Coulomb repulsion of charges. Only "at hand" material, such as water, is allowed to be used to create the container. We will begin the discussion with the problem of holding motionless charge carriers $Q = 5 \times 10^{-3}$ C inside a spherical shell with an internal radius $R_{in} = 5 \times 10^{-2}$ m. The charge carriers stretch the sphere with a force

$$F_Q = Q^2 / 8\pi\varepsilon_0 R_{in}^2 = 4.496 \times 10^7 \text{ N}. \quad (4)$$

here $\varepsilon_0 = 8.854 \times 10^{-12}$ F·m is the dielectric constant. The electric field strength created by a charge $Q = 5 \times 10^{-3}$ C at a distance of $R_{in} = 5 \times 10^{-2}$ m is:

$$E = Q / 4\pi\varepsilon_0 R_{in}^2 = 1.798 \times 10^{10} \text{ V/m}. \quad (5)$$

Here it is necessary to make a lyrical digression in order to overcome a certain psychological barrier. It is generally believed that when the field strength on the surface of a charged ball exceeds 3×10^6 V/m, an electrical breakdown should occur. Let us see if this rule is applicable to ball lightning. It is known that the path along which the spark discharge should pass is laid by the leader—a thin channel with a fairly high temperature of 3000 - 6000 K [56] [57]. In order to maintain a high temperature and, consequently, high conductivity of the leader during the time of its "germination" (10^{-4} - 10^{-3} s), it is necessary that a current flow through this channel with a power release of at least 130 W per centimeter of the channel length. At lower power values, the channel will cool down, its conductivity will decrease, and the advance of the leader will stop. For typical cases of spark development in air at atmospheric pressure, the current flowing through the leader cannot be less than 1 A [56] [57]. In ball lightning, due to the extremely low electrical conductivity between the core and the shell, the current is limited to 1 - 10 mA. This cannot become an obstacle to maintaining a corona discharge on its surface, but, however, it prevents the possibility of forming a spark channel.

Let's place a water molecule (an electric dipole with a moment $p_w = 6.327 \times 10^{-30}$ C·m) on the surface of the sphere of radius R_{in}. The condition for complete polarization of the dipole is the requirement [58]:

$$E > E_{min} = 3k_B T. \quad (6)$$

Substituting into formula (6) $k_B = 1.38 \times 10^{-23}$ J/K, and $T = 300$ K, we find $E_{min} = 2 \times 10^9$ V/m. Condition (6) is satisfied, and the water molecules on the surface of the sphere will be oriented along the electric field strength vector. In a non-uniform electric field E, a water molecule will be attracted to the center of the sphere with a force of:

$$f_q = p_w \cdot \mathrm{grad} E = -2 p_w Q / 4\pi\varepsilon_0 R_{in}^3 . \quad (7)$$

Let's imagine a water molecule as a ball with a diameter of $d_w = 4 \times 10^{-10}$ m. On the surface of a sphere with a radius of R_{in}, $n_w = 4\pi R_{in}^2 / d_w^2$ water molecules can fit. A shell consisting of one layer of water molecules will be attracted to the center of the sphere with a force

$$f_w = f_q \cdot n_w = 2 p_w Q / \varepsilon_0 d_w^2 R_{in} = 8.93 \times 10^{-1}\ \mathrm{N} . \quad (8)$$

The force f_w is less than the force F_Q by $F_Q/f_w = 5 \times 10^7$ times. The force F_Q can be compensated by a shell of 5×10^7 layers of water molecules. Its thickness is $a = 5 \times 10^7 \cdot d_w = 2 \times 10^{-2}$ m.

Now let's consider ball lightning with an "active" core consisting of particles with a kinetic energy density of $\rho_E = 10^{10}$ J/m^3. Let the inner radius of the shell be $R_{in} = 5 \times 10^{-2}$ m, and the charge of the core be $Q = 5 \times 10^{-3}$ C. The pressure of the core on the surface of the shell is $P = 3.3 \times 10^9$ N/m^2, and the force acting on the shell is $F_E = P \cdot 4\pi R_{in}^2 = 10^8$ N. To compensate for this force, $n_E = F_E/f_w = 1.12 \times 10^8$ layers of water molecules must be added to the shell. Its thickness will increase by $b = n_E \cdot d_w = 4.48 \times 10^{-2}$ m. The total thickness of the shell will increase to $a + b$ = 6.48 cm, and the radius of the ball lightning will become equal to $R_{bl} = R_{in} + a + b = 11.48$ cm.

Let's assume that the shell is filled with a gas whose density is equal to the density of air at normal pressure. One gram-molecule (6.023×10^{23} molecules) occupies a volume of 22.41×10^{-3} m^3. In 1 m^3 there are $N_m = 2.688 \times 10^{25}$ molecules, each of which has the energy $E_m = \rho_E/N_m = 3.72 \times 10^{-16}$ J $= 2.325 \times 10^3$ eV. Molecules with such energy will be ionized, and the shell will be filled with plasma with a temperature $T_p = E_m/k_B = 2.69 \times 10^7$ K ($k_B = 1.38 \times 10^{23}$ J/K) is the Boltzmann constant). No shell can withstand such a temperature. It is more realistic to assume that systems with rotating particles serve as energy accumulators. An element capable of containing a large amount of energy can be a dynamic electric capacitor, the basic diagram of which is shown in **Figure 13** [59]-[61].

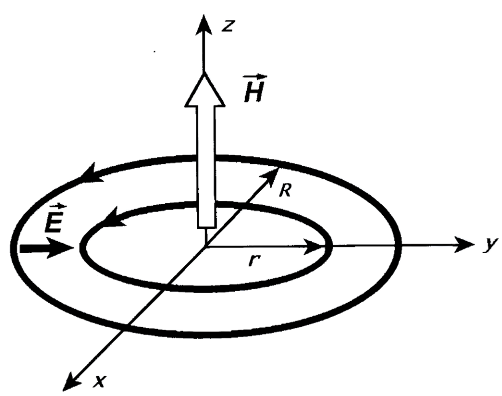

Figure 13. Dynamic electric capacitor.

In the center of the system are electrons moving in a ring orbit of radius r. Protons move around the electrons in an orbit of radius R. The combination of the magnetic field H created by the movement of the protons and the electric field E causes the electrons to drift in the direction perpendicular to the vectors $\boldsymbol{E}$ and $\boldsymbol{H}$. The movement of electrons in a dynamic capacitor is similar to the movement of electrons in a magnetron. The speed of the electrons is close to the speed of light. Moving along the orbit, they oscillate in the direction perpendicular to their velocity vector. To create the magnetic field needed to hold electrons in orbit, the number of protons must be greater than the number of electrons, so this system has a positive electric charge. A large number of dynamic electric capacitors are located inside a spherical shell of polarized water molecules. In reality, the dynamic capacitor has a more complex structure [59]-[61]. Protons rotate in orbits whose planes are inclined to the plane of the electron orbit. Their movement creates a barrel-shaped magnetic field. Due to this, a force arises that stabilizes the position of the electron orbit. A similar scheme for holding electrons in orbit is implemented in betatrons. A dynamic electric capacitor, like any system of electrons and positive ions held by their own fields, tends to expand [62]. It can exist only in a device that creates a force that prevents its expansion. The action of the expanding dynamic capacitor on the shell wall turns out to be "softer" than the action of randomly moving particles can be. This is due to the fact that the protons during contact with the shell move parallel to the shell plane and transfer to it not all the kinetic energy they possess, but only part of the energy associated with the radial expansion of the capacitor.

The movement of electrons along a closed orbit may be the cause of the generation of synchrotron, undulator and radio-frequency radiation. The radiation power depends on the degree of uniformity of the electron distribution along the orbit. With a uniform distribution, the radiation power is low, and when the uniformity is violated, it increases. Because of this, the intensity of the glow of ball lightning oscillates chaotically (**Figure 14**).

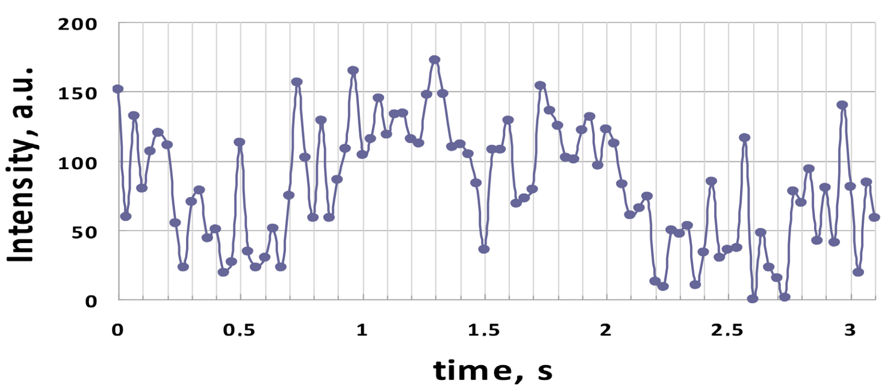

Figure 14. Graph of the change in glow intensity of ball lightning filmed in Blagoveshchensk [43].

Another source of the glow of ball lightning is a corona discharge on its surface.

The result of this discharge is the formation of nitrogen dioxide NO_2 and ozone O_3 [8] [63]. Ball lightning, possessing high energy, may be formed near the turn of the linear lightning channel through which the current pulse passes. The current causes the appearance of a magnetic field and a vortex electric field. Ultraviolet radiation of the channel ionizes the air. Due to the combined action of the electric and magnetic fields, a spatial separation of charges and their acceleration occurs. In this case, some of the electrons leave the place where the core of the ball lightning is formed, and it becomes positively charged. In the presence of a sufficiently large number of water drops, a shell is formed around the core [64].

Let's discuss whether the principle of the device of ball lightning can be useful for explaining the phenomena described in the articles [36] [37]. The authors of these articles said that the astronauts saw some luminous objects flying around the spaceships. Hope for the validity of this assumption is given by the method used by nature: it "loves" to create objects of different scales, which are based on the same principle. The atom, the solar system and the galaxy are essentially in Roman: built on the same scheme. Let us assume that an object with the properties of ball lightning, discussed above, is near a spaceship. Let the radius of its inner sphere be $R_{in} = 5 \times 10^{-2}$ m, the charge $Q = 5 \times 10^{-3}$ C, and the thickness of the shell $a = 2$ cm. If the density of the shell material is equal to the density of water ρ_w, then ball lightning mass is $M = 4\pi R_{in}^2 a \rho_w = 0.628$ kg. Let's assume that an object with a positive charge $Q = 5 \times 10^{-3}$ C is at a distance $L = 5$ m from the surface of the spaceship—a metal sphere with a radius $R_{sh} = 5$ m. Under the action of the electric field created by the charge Q, a negative charge $-q$ will accumulate on the side of the ship closest to the object, and a positive charge $+q$ will be displaced to the opposite side of the ship. For simplicity of analysis, charges Q, $-q$ and $+q$ will be considered point charges. The force F_{at} attracting the object to the ship is equal to

$$F_{at} = \frac{Qq}{4\pi\varepsilon_0} \cdot \left[\frac{1}{L^2} - \frac{1}{\left(L + 2R_{sh}\right)^2} \right] = 1.6 \times 10^6 q \text{ N} \tag{9}$$

Let the object have a velocity $v = 10$ m/s, directed perpendicular to the line connecting its center with the center of the ship. The centrifugal force acting on the object is equal to

$$F_{cp} = Mv^2 / \left(L + R_{sh}\right) = 6.28 \text{ N}. \tag{10}$$

Equating F_{cp} to F_{at}, we find $q = 3.92 \times 10^{-6}$ C. The period of the object's revolution around the ship will be equal to $T = [2\pi(L + R_{sh})]/v = 6.28$ s.

4. Conclusion

Based on the above, we can assume that the described model is capable of explaining almost all the details of the properties of ball lightning. In addition, it may be useful for understanding the nature of multi-charged clusters and objects discovered in near space. The main property of ball lightning is its ability to hold an electric charge of 10^{-3} - 10^{-1} C inside itself. The charge carriers can be either stationary ions or structures of moving electrons and positive ions. Accordingly, it can be considered that there are two types of ball lightning: 1) ball lightning with a low-activity core and 2) ball lightning with a core of moving charges. The container for holding electric charges in ball lightning of both types is a shell of water molecules. In a strong non-uniform electric field created by the charge of the core, polarization of water molecules occurs and a gradient force arises, compressing the shell in the direction of the center of the charge area. For some time, this system is in a state of stable equilibrium [59]-[61]. With the above-mentioned charge values and a ball lightning diameter of 2×10^{-1} m, the electric field strength on its surface significantly exceeds the breakdown field strength in air $E_{br} = 3 \times 10^6$ V/m. The development of spark breakdown is prevented by the low conductivity of the ball lightning shell. However, the shell still has conductivity. Due to this, its charge gradually flows into the atmosphere. The lifespan of ball lightning, which can be from 1 second to 10 minutes, depends on the rate of charge flow. Small ball lightning has the shortest lifespan, while large ones live longer [65]. In nature, there are multiply charged water clusters 5 - 50 μm in size, arranged according to the type 1 ball lightning scheme. They are formed when a strong current passes through water [39] [40]-[42]. These clusters can penetrate deep into a solid body [66]. They pose a danger to human health [67]. Due to the conductivity of the shell, charges penetrate through it, and a corona discharge exists on its surface. The glow of the first type of ball lightning (with stationary ions) is provided only by the corona discharge. In ball lightning of the second type (with an active core), the glow of the shell is supplemented by the glow of the core. It occurs due to the movement of charges (mainly electrons) along circular orbits with centripetal acceleration. Apparently, there are some mechanisms for transferring energy from ions (the main energy keepers) to electrons. Electrons move along a closed orbit, oscillating in the direction perpendicular to this orbit. According to observations, large ball lightnings (probably UFOs) are capable of emitting light in the form of a narrow beam. The beam directed at the observer looks like a white dot surrounded by concentric rings of different colors [55]. It is possible that synchrotron radiation may be the cause of this. The hypothesis of the existence of structures in the core of ball lightning that have a mechanical torque (dynamic electric capacitors) allows us to find an explanation for cases of ball lightning rotation. The occurrence of rotation and its stop can occur due to a change in the orientation of the moments of rotation of the elements of its energy core [68]. Pilots who accidentally fly into a thundercloud report that it contains a large number of ball lightning. They can become the basis for the formation of UFOs [35]. The area of existence of objects similar to ball lightning extends to near space [36] [37]. The question of how they appear there and how they behave remains open.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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