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The Physical Theory of Ball Lightning

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The analysis of modern models of ball lightning displays, that they are unsatisfactory on a series of tests. The model of ball lightning is offered, which exterior electronic envelope is retained by interior volumetric positive charge. The compounded electron motion in an outer envelope creates the strong magnetic field driving a state of ionized hot air inside ball lightning. The conditions of origin surveyed, the estimates of parameters of ball lightnings of different power are made.

1. Introduction

Among rare and so far unexplained natural phenomena one of the first places rightfully belongs to ball lightning (BL). Indeed, BLs have quite a considerable amount of controversial properties. We shall list them according to the data from [1–3]:

1. BLs appear either in the clear skies or during heavy rain, either near the ground or falling from the clouds.

2. Their color can be red or blue, sometimes both or other colors.

3. BLs are sometimes motionless, sometimes are moving rather fast.

4. They can soar in the air or roll along wires or the edges of some objects.

5. They can disappear quietly or explosively, sometimes damaging the things around them.

6. The shape of BL can be clearly defined or vague.

7. Sometimes BLs avoid good conductors and sometimes are attracted to them.

8. During observation BLs can be either quiet or sparkling, making a lot of crackling and hissing or leaving strong odor.

9. Most often BLs are observed in connection with discharges of streak lightning during thunderstorms, hurricanes, storms, tornadoes, blizzards of snow or sand, earthquakes, but sometimes BLs themselves are divided into smaller BLs. Sometimes even structures of two BLs take place, which are connected by a chain of glowing beads.

No wonder, that in the presence of dozens of models explaining certain properties of BLs, still there is no single comprehensive model of their internal structure. The situation is complicated by the fact that we do not have experimental technical equipment that would allow at any time to create artificial ball lightning, not differing by their properties from natural analogues.

The purpose of this paper is to analyze some models of BL by a number of criteria in order to select the models that best reflect the basic properties of BL.

2. Observation conditions and characteristic parameters of ball lightning

The lifetime of the observed BLs reaches tens of seconds, and given their sudden appearance it is too little for detailed study. Hence, the main sources of information on BLs are the consequences of their interaction with the surrounding objects and the evidence of eyewitnesses. According to the survey conducted by the magazine "Science and Life" in 1976 [4], BL usually is a glowing spherical formation with diameter of 10 – 40 cm. According to [2], the average diameter of BL is 28 ± 4 cm. Appearance of BLs repeats well the distribution of thunderstorm activity during the day and the frequency of storms by months during the year in almost all countries, which indicates close relationship between BLs and streak lightnings.

The probability of observing BL is little, according to statistics one BL is recorded per 1000 – 2000 common lightnings, which is due to different scales of the phenomena and different observation conditions. On average, only one out of 300 people during their lifetime can see a BL. Surveys of NASA employees [5] show that 409 people have seen a place where a streak lightning hit the ground, and 180 people saw a BL. It means that the probability of observing a BL is only 2.5 times less than the probability of observing a point of strike of a streak lightning. Then, if a BL occurs during a streak lightning discharge, we can expect BL appearance during each discharge of this kind. And indeed, there are direct observations of formation of one or several BLs at the place of a streak lightning strike, in its channel or near it. In many cases, it is recorded on high objects, towers, power transmission towers, lightning rods. Besides, special experiments were carried out for using natural lightning to form a BL, for example, by means of rockets, connected to the ground by wire in order to set the path of the lightning [1].

According to the data from [1–2], the characteristic parameters of a streak lightning are as follows: the main channel section is about 10^{-2} m^2; main discharge currents are from 10^4 A up to $5{\cdot}10^5$ A; during short discharge of about 10^{-3} s 20 C of electricity can be transferred; the temperature of the air in the lightning channel reaches 25000 K; the thermal velocity of ions is not less than 10^4 m/s, of electrons – over 10^6 m/s. Glowing of a streak lightning occurs mainly due to neutral or singly ionized atoms of nitrogen and oxygen, its channel contains $4{\cdot}10^{18}$ electrons in 1 cm^3 [3]. Ion pressure reaches 18 atm, electron pressure – 14 atm, so that the rapid decay of the channel is accompanied by the sound effect like a thunderbolt. If the voltage between the cloud and the ground is 10^8 V and the transferred charge is 20–30 C, then the energy of the lightning is (2–3) · 10^9 J [4]. With an average length of the lightning 3–5 km, the energy per unit length is $5{\cdot}10^5$ J/m, which is sufficient to provide energy to the resulting BL. Observations show that 68 % of BL move horizontally, 18 % – downwards, 5 % – upwards, and 17 % of BL move spasmodically, while 83% move smoothly. Speeds vary from 0.1 to 10 m/s, which is, according to [5], 70 % of all cases, and for the rest 30 % the speed does not exceed 40 m/s.

Soaring BLs are usually red, avoid good conductors and often get into closed houses through windows, doors, chimneys, narrow channels and cracks. BLs attached to objects are mainly dazzlingly bright, white or blue, staying on good conductors (water, metal surface, wires) or can roll over them. They heat the objects that come in contact with and often disappear as if boiling and throwing sparks. Transformation of soaring BL into the attached one and vice versa is quite possible and can occur suddenly.

Numerous evidences suggest that even near a brightly glowing BL there is no heat, but there is strong radio emission, fixed as cracking noises in radio receivers and handsets, when BL is passing near them. In the visible range the radiation power of BL equals several watts, as visually it corresponds to a light bulb with power of about 100 watts. Sometimes irregularity of glow and flash is recorded, and change of BL's color usually is accompanied by its explosion. According to the data from [4], in 335 reports of BL explosions, in 34 cases damage of objects was observed, and in 19 cases they were wooden objects or poles. Often BLs punch holes in plywood partitions and doors or in clay walls, vaporize small amount of substance being in contact with metal objects, burn clothing, carpets and leave other traces. In particular, it is reported that BLs knocked pans and telephones to the floor, penetrated into houses through the glass, damaged electrical wiring and electrical equipment, melting their parts.

In [1-3] there are descriptions of various emergency situations, in which BL arose spontaneously. As it follows from the experience of contacts with BL, they usually are formed near the sources of strong electromagnetic discharges – at lightning strikes, at short circuit-disconnection of high-voltage or high-current electrical equipment of AC or DC, at high-frequency pulses of high-power generators. For example, BLs were obtained at voltage of 12 kV and power of 10^7 W at a discharge during time of 10^{-3} s. According to the data from [6], during emergency shutdown of batteries in a submarine, a BL with diameter of 12 cm appeared near the switch contacts, and the current flow reached the value $1.6 \cdot 10^5$ A.

The results of experiments, in which glowing plasma formations were created similar to BL by their shape, are presented in [1], [3] and [7]. If gas or liquid are located in the contact area with dischargers with high voltage or high current, the discharge often takes a spherical shape. In experiment [8] a discharge of two curved electrodes in gases at different pressures was used. In this experiment a luminous cloud appeared, the glow of which greatly increased by addition of low concentrations of hydrocarbons. The authors of [9] produced a discharge in a chamber at a pressure of 10^{-5} atm so that the dielectric walls of the chamber were destroyed, turning into glowing plasma with a lifetime of 10 ms. At the photos we could see that first the plasma had the shape of a ball and then becomes vortexlike. The story of electrodeless discharges apparently begins with Tesla's experiments with high-voltage transformers in the late 19th century. In other experiments powerful focused microwave pulses with frequency of 75 MHz and power of 30 kW stirred the air up to the temperature of 2500 K, and its afterglow time reached 2 s [10]. Nevertheless, it should be stated that the results of these and many other experiments can not fully simulate all the basic properties of BL. For example, although 59 % of BLs live on the average 3 s, and 26 % – 29 s, but in 15 % of cases the observed time is 213 s [11].

3. BL models and the criteria of their analysis

Since the number of different models of BL is large enough, further we will briefly present only the main and the most developed models. Analyzing them we will base upon the following criteria [4]:

1. The mechanism of BL formation, relation to atmospheric electricity.
2. Energy source and method of energy storage.
3. The nature of motion, shifting and balance of BL in the atmosphere.
4. Stability of shape and its transformation, characteristic dimensions.
5. The mechanism of glow and radio emission, emerging of sparks and characteristic sound of BL, as well as the peculiar odor.
6. The cause of explosion or quiet disappearance, the lifetime.

Some calculation examples from [1-2] of damage of objects after contact with BL allow us to assess its internal energy. In case when BL melted clothing on the body and the ring on the finger, the required energy was 440 J. With the diameter of 10 cm the energy density of BL is 0.8 J/cm^3. In another case, BL got down on the asphalt and made a hole in it. Assuming that the asphalt heated to 170° C, with the apparent diameter of 14 cm, the energy of BL should reach 3 kJ. From V.V. Varsonofev's report [4] it follows that BL discharged into a water-heating radiator. The result is a hole with diameter of 4 – 5 cm and depth of 0.5 mm. The mass of evaporated metal was 0.08 grams, which required 700 J.

In case of Ya.V. Berezovskiy BL with diameter of 10–20 cm vaporized metal with mass 0.22 grams on the rifle rod, spending energy up to 2 kJ. The minimum energy density of BL can be estimated by the acoustic noise of its explosion, as well as by its radio emission and luminosity with the lifetime of 1 s. In the first case, we obtain the value of more than 0.006 J/cm^3, and in the second case – of the order of 0.2 J/cm^3, which gives for a BL with a radius of 1 cm the energy 0.8 J.

Let us now review the models of BL. In some plasma models it is assumed that BL consists either of positive and negative ions or of electrons and positive ions. The energy density of a fully ionized air plasma can reach 180 J/cm^3 (of which 30 J/cm^3 is used on dissociation of molecules and 150 J/cm^3 is used on single ionization), which is sufficient to explain the BL energy. However, the concept of BL as of a bunch of recombining nonideal plasma hardly complies with the criterion of lifetime – the plasma under influence of Coulomb forces would disappear too fast, in no more than 10 ms. The situation is not solved by the cluster model [4], in which ions are surrounded by shells of neutral particles (such as water) that prevent recombination. This model assumes the ion temperature 500–700°C, and to explain the explosions of BL existence of two recombination channels, slow and fast, is postulated. Too fast release of energy also takes place in the aerosol model, in which positive and negative charges are concentrated on the particles of dust, smoke or on drops.

The quantum-mechanical model is described in [12], where quasi-neutral plasma of ions and electrons is considered. If electron spins are directed in opposite ways, then kinetic forces of gas expansion could be balanced by the forces of exchange interaction of electrons. However, in this model explanation of many features of BL requires additional assumptions.

In neutral gas with long-lived excited atoms and molecules there can be enough energy (the volume of a ball with a radius of 20 cm contains up to 10 kJ) but its luminescence, as it follows from the experiment, lasts not more than 0.1 s. The lifetime is short in models in which BL is considered as a glowing sphere of substances vaporized by streak lightning.

There is a wide variety of chemical models. In one of the old models [13] it is assumed that combustion of hydrocarbon mixtures takes place in BL. A glowing yellow-green ball with the size 4 cm with a lifetime up to 2 s was obtained in [14] using electric spark ignited mixture of air and 1.4–1.8% propane, the energy density equaled $7\cdot10^{-3}$ J/cm^3. Among other candidates for the active substance were hydrogen, methane, coal dust or reactive aerosol, which may either have existed or be formed at the place of a lightning strike (for example, in bogs area or coal mines). The disadvantage of these models is that for unrelated particles it is difficult to explain the stable form of BL while moving against the wind and passing through glass, the electrical phenomena of BL, and also the fact that during combustion the radius tends to increase rapidly. In addition, BLs are formed in those areas which are definitely devoid of the sources of combustible substances. The energy source of BL could be the reaction of ozone decomposition. When the ozone concentration is 2 %, the density of its chemical energy in the air is equal to 0.13 J/cm^3 [2], but the lifetime of such BL is too short, taking into account that the reaction rate increases due to increasing of the temperature.

To explain the stability of BL's shape in [15] a filamentary model of BL based on aerogels of SiO_2 or Al_2O_3-type was suggested, which was further developed in [2], [29]. To maintain the shape and the surface tension, which is necessary to explain the elasticity of BL, the filaments should be charged up to 10^{-6} C. Since the frame is heated to a high temperature, the Archimedes buoyancy occurs. Along the filaments the chemically active substances are located which are responsible for light emission. The questions in this model which need to be improved are the following: aerogel and active chemical substance's composition, explanation of radio emission, sparks, the odor of BL and its possible explosion. A model similar by the structure is a bubble model [16], where BL has a core similar to a bubble of metal or silicate, and its buoyancy in the air is due to the Archimedes force. In one variant of the bubble model, BL is a bipolarly charged bubble which has a shell of water with ordered position of molecules and with thickness 10 microns. [17]

There are BL models in which the main energy is the electric field energy. The total charge of BL may not exceed a value at which the electric field strength at its surface is more than E_0 = 30 kV/cm to avoid atmospheric air breakdown. Hence, with the radius of BL r = 0.07 m we find its charge and electrical energy:

$$Q_0 = 4\pi\varepsilon\varepsilon_0 E_0 r^2 = 1.6\cdot 10^{-6}\ \text{C}, \qquad W = \frac{KQ_0^2}{4\pi\varepsilon\varepsilon_0 r} = 0.34\cdot K\ \ \text{J}, \qquad (1)$$

where ε_0 is vacuum permittivity, ε is dielectric permittivity (here we take $\varepsilon = 1$), the coefficient K is 0.5 or 0.6, respectively, for the cases when the charge is distributed either over the surface of the sphere or in the volume of a ball.

As we can see from (1), the electrostatic energy is too little to explain the energy content in BL. This difficulty is avoided by considering not one charge, but two opposite charge as in a spherical capacitor or volume charges. However, there is still the problem of BL's stability in case of rapid discharging of these charges as a result of Coulomb forces. In one model [18] inside the plasmoid there is a positively charged core, outside of which there is a layer of negative ions and the area of electron impact ionization, and then the area of gas ionization by UV radiation and of ion recombination. From here electrons and negative ions move inwards and positive ions go outwards. According to the author, BL must be formed from positively charged lightnings, or in the areas with a positive charge.

Increase of stability can be achieved in vortex models. A rotating circular plasma vortex with a frozen-in magnetic field is described in [19]. In model [20], the charged particles rotate along the surface of the torus in the meridional direction, creating a magnetic field inside the torus like in the solenoid. Calculations show that if the energy of the plasmoid consists of the kinetic energy of the particles and the magnetic field energy, then the total energy by the virial theorem does not exceed $3PV$, where V is the plasma volume, P is the external pressure. If P = 1 atm, the radius of BL is 10 cm, then its energy can be up to 1000 J. However, according to researches on the theory of stability of magnetohydrodynamic configurations [21], the system, held by its own magnetic field, is stable only in the presence of external pressure.

One of the most developed models of BL with an external energy source is Kapitsa model [22], according to which the observed constant luminosity intensity of BL is due to the energy input from the thunderstorm clouds by the radio waveguide. In support of the model experiments were conducted [23], which showed the principal possibility of existence of luminous plasma formations in the radio-frequency field. Nevertheless, the problem of energy has not been solved, since strong radio emission from lightnings lasts only a few thousandths and hundredths of a second, and in the range, necessary for the resonance with BL volume, at wavelength of 30–70 cm, the energy density is too low. There is a number of models with an external energy source, for example, [24], but behavior and motion of BL is often of such a kind that it seems autonomous and independent of any channels or waveguides.

The electron-ionic model of BL, presented in the next section, contains many positive aspects of earlier theories and, in principle, allows experimental proof.

4. The scheme of formation and the structure of ball lightning in the electron-ionic model

If we do not take into account the emergence of BL at operation of powerful electrical equipment, almost all other cases BL is observed in connection with ordinary streak lightning or just in thunderstorm-cloudy weather. In the framework of the electron-ionic model the natural BL can be a direct consequence of streak lightning when the storm cloud is discharged to the ground, passing its negative electricity to it (or in case of discharge of neighboring clouds). Fig. 1a shows the secondary branches and the main lightning channel, filled respectively with stationary and moving electrons. The rapid motion of electrons and the main flash of lightning start after connecting of the main channel with the ground, thus the luminous part of lightning increases from the ground to the cloud. Electrons in the secondary branch are also moving to the main channel and fall through it to the ground. In this case, almost a closed loop of electron current (Fig. 1b) is possible, when in its center a magnetic field with induction B appears. In the electrified air there are many positive ions around the lightning, which start to swirl around the magnetic field lines, and thus are fixed in the center.

In turn, the electron current from channel 2 can jump over to branch 1 through region 3 forming then a closed current. A necessary condition for this is the force holding the electrons on a closed orbit. If there is a sufficient amount of positive ions in the center, they can attract the electrons and thus ensure their stable rotation. This process can occur in a relatively weak secondary channel, which explains the occurrence of BL away from the brightly flashing main channel of streak lightning. In addition, formation of BL is possible not only near the ground or near tall objects, but also along the entire channel of streak lightning, the beginning of which is lost in the clouds. In some cases, when a streak lightning struck a conductive wire, BL was observed coming out of telephone apparatuses, radio outlets, counters, bulb holders. As we can see BLs occurred due to the closure of current pulses of streak lightning through the air near the contacts in the form of an electric arc.

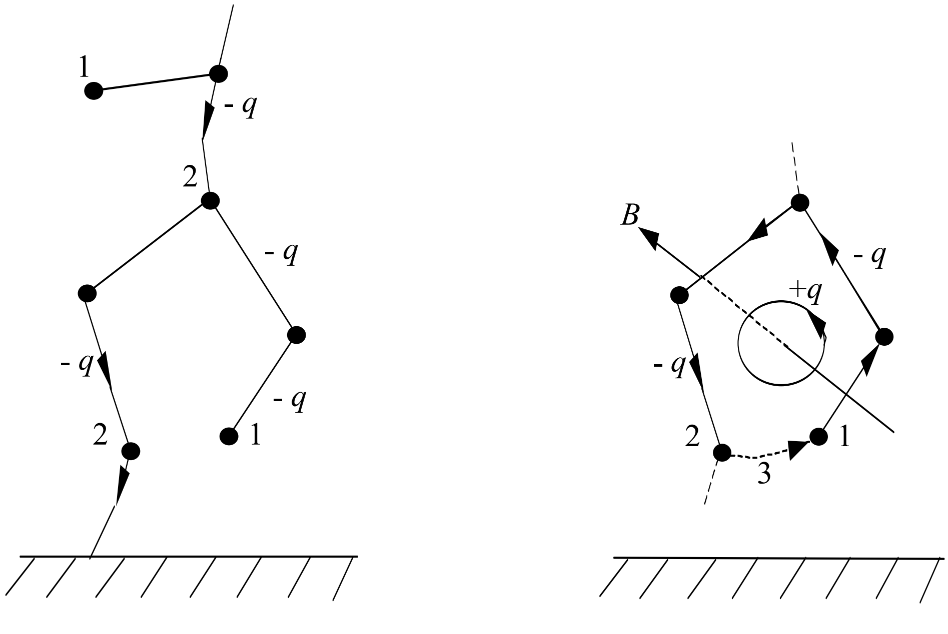

Fig.1. a) 1 – secondary lightning branches, 2 – the main channel, in which electrons are moving (marked as $-q$).

b) Moving of electrons from secondary branch 1 to the main channel 2 of the lightning can be closed through region 3. B is the magnetic field induction from electron current. Ions with the charge $+q$ are rotating along the magnetic field lines.

Based on this pattern, Fig. 2 shows the equatorial section of BL's model as an axially symmetric configuration with parallel spherical currents. The positive ions at atmospheric pressure are located in the very hot air inside BL, left after a streak lightning strike. Fast-moving electrons in the outer shell generate a magnetic field with induction *B*, which holds the positive ions in orbits inside BL. At a certain radius *R* the rotational speed of the ions becomes equal to the thermal velocity, which allocates a separate equilibrium shell in BL. Finally, the electrical attraction of positive ions and negatively charged electrons holds electrons in the outer shell from expansion, being the main part of the centripetal force. Due to approximately spherical shape of BL, the radius *r* of rotation of the outer electron cloud around the common axis decreases moving from the equator to the poles.

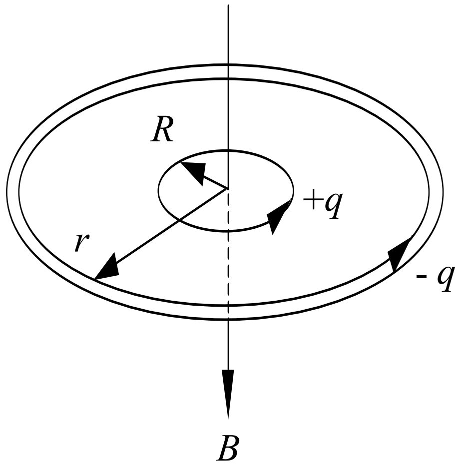

Fig.2. The equatorial section of the BL model, forming rings on current shells of spheroidal shape. R is the rotation radius of ions in equilibrium shell around the magnetic field with induction B, r is the radius of external electron shell.

This relatively stable configuration can explain the observed lifetime of BL, significantly exceeding the lifetime of uniform ion-electron plasma at atmospheric pressure. Electron shell effectively isolates the air heated to a high temperature inside the BL, slowing the energy transfer to the environment. Positive ions inside the BL are almost not attracted by the electrons from the outer shell, since the electric field of the electrons inside the sphere is zero because of the balance of all electrical forces. Therefore, the ions can be distributed evenly throughout the BL, and recombination of ions and electrons slows down significantly.

As we can see in Fig. 1b, BL is actually a small piece of streak lightning, spun into a ball with a characteristic size 10 – 40 cm. Accordingly, in both types of lightning currents and magnetic fields can be similar in magnitude.

In order to present the structure of BL more clearly, we will cite very detailed evidence of M.T. Dmitriev, a chemistry specialist, who had experience of work with low-temperature plasma, and who witnessed the phenomenon of BL [25]:

"The lightning luminosity was significant, particularly at a distance of several meters, nevertheless it could be observed freely without much effort. The central part represented a ball with a diameter of about 6 – 8 cm, somewhat elongated in the vertical direction. This part was the brightest and its external view (except the shape) quite resembled electric-discharge torch in the air, obtained in the plasmatrons, with plasma temperature of the order of 13,000 - 16,000°. The central part of the lightning was surrounded by the area with thickness of 1 – 2 cm, with thick violet glow similar to air glow at a pressure of 0.1 mm Hg, bombarded by electrons with energy of several tens of electronvolts. The next outer shell with thickness of about 2 cm was also nonuniform, resembling by color a quiet electrical discharge at atmospheric pressure or peripheral glow of an electron beam with energy of several tens of kiloelectronvolts, coming from the vacuum tube in the air at normal pressure. Light blue glow of this part of lightning decreased rapidly with increasing distance from the central ball, gradually fading away. Lightning shells were easily observed only in the horizontal direction. In the lower part they were compressed and could only be discerned when compared with the side parts of lightning. Above the lightning the shells were significantly thicker, but not as distinct. In addition, some bright convective jets could be seen in them (as over the ordinary fire, only their color had a whitish tint). The overall diameter of the ball was about 11−12 cm in the horizontal direction and about 14−16 cm in the vertical direction. From a distance of several tens of meters, presumably, only the central part of the ball could be observed. From a distance the lightning had a bluish tint ... In the lightning, apparently, the energy was released all the time. This was indicated by the continuous rustling and some strong cracklings. Its charge leakage probably was going on continuously. The energy release increased dramatically when the lightning contacted the surfaces (leaves or twigs) and it was accompanied by louder crackling and sparking. The lightning left a strong smell by its character almost coinciding with the smell of the air after being exposed to ionizing radiation."

As we see from the text, Dmitriev's ball lightning had a vertical symmetry axis coincident with the rotation axis of the electron cloud in our model of BL and with the direction of the internal magnetic field. The internal ion cloud of the lightning was extended in the vertical direction, and all the shells were well seen only in the horizontal direction. The rotation of the particles in the shells at the differential speed was indicated by separate bright convective jets. The presence of high electric field strength near BL and the energetic particles was proved by numerous observations of their hissing, crackling and emission of sparks as in case of the electric discharge. In addition, air samples taken after the passage of BL showed increased content of ozone and nitrogen oxides (about 50−100 times more than normal). According to the data from [25], the required ratio of the ozone and nitrogen oxides concentrations can be obtained by an electric discharge in the air with the strength of up to 400 kV per 1 m, and assessment of the required electrical energy in such an equivalent discharge for the total lifetime of BL gives the value of 530 J [1].

We will further denote by M, V, R and m, v, r the masses, motion velocities and rotation radii of ions and electrons, respectively; B is the magnetic field induction; N_i is the amount of uncompensated positive ions inside BL; N_e is the number of free electrons in the outer shell of BL; q is the elementary charge; i is the electron current at the orbit with radius r; μ, μ_0 are relative magnetic permeability of the medium and the vacuum permeability.

The shell formed inside of BL is the boundary where the ion thermal velocity is aligned with the rotational speed of ions in the magnetic field. At this point, the relation holds:

$$\frac{MV^2}{R} = qVB, \tag{2}$$

and the ions rotate by the circle with radius R in the plane which is perpendicular to the magnetic field. On the other hand, the charged particles can move freely along the magnetic field lines. Consequently, at the radius R, ordered, mutually perpendicular ion fluxes take place instead of random motion of ions, which is accompanied by strong friction in the gas and the corresponding energy release in the form of emission.

The characteristic energy U_i of the air molecules ionization amounts to about 13 eV. If we assume that there is thermal equilibrium between the ions and electrons inside BL, we can find their temperature on condition:

$$U_i = \frac{3}{2}kT,$$

where k is the Boltzmann constant. Hence, we obtain the temperature $T = 10^5$ K, which is required for complete air ionization, but given that not all of the gas was ionized during the formation of BL from the heated air near a streak lightning, the average temperature $1.4 \cdot 10^4$ K of the inner shell with the radius R is possible according to Dmitriev's observation.

The upper values of BL's parameters can not exceed the corresponding parameters of streak lightning. Near the main channel of the lightning at the current $I_M = 2 \cdot 10^5$ A and the radius $R_M = 0.1$ m the magnetic field induction reaches the value: $B = \frac{\mu \mu_0 I_M}{2\pi R_M} \sim 0.4$ T. If an electron rotates in such a magnetic field with the orbit radius r_e, its speed must be less than the speed of light:

$$v = \frac{Bqr_e}{m} < c, \qquad r_e < \frac{mc}{Bq} = 4 \cdot 10^{-3} \text{ m}.$$

Since $r_e << R_M$, even relativistic electrons can be held and accumulated in the magnetic field near the lightning channel. On the other hand, at currents of more than 1000 A in pulsed vacuum discharges the electron temperature in energy units reaches 1 keV and the speed of electrons' motion reaches up to 10^7 m/s [26]. As the upper value of the current in the plasma the value $1.4 \cdot 10^6$ A should be used according to [27], since further increase the electric field strength leads to compression of the current filament and to increase of emission at constant current and temperature of the particles.

To simplify the calculations, we assume that charges and currents are mainly concentrated near the equatorial plane or have cylindrical symmetry, and the ions are singly charged. We will express the electron current in the outer shell and the magnetic field of this current acting on the ions:

$$i = \frac{qN_e v}{2\pi r}, \qquad B \approx \frac{\mu\mu_0 i}{2r} . \tag{3}$$

The velocity of ions in the inner shell V can be assessed by the average glow temperature T using the relation between the kinetic and thermal energies:

$$\frac{MV^2}{2} = \frac{3\kappa T}{2} .$$

When $T = 1.4 \cdot 10^4$ K and the average ion mass $M = 4.7 \cdot 10^{-26}$ kg, as in a nitrogen molecule, the velocity of ions is equal to $V = 3.5 \cdot 10^3$ m/s. Solving now (2) – (3), with a radius of BL $r = 7$ cm and the radius of the formed shell $R = 4$ cm we find the magnetic field induction and the electron current:

$$B = 2.6 \cdot 10^{-2} \text{ T}, \qquad i = 2.9 \cdot 10^3 \text{ A}.$$

At the air temperature in BL is $T = 1.4 \cdot 10^4$ K and the atmospheric pressure, the concentration of particles is $n = 5.2 \cdot 10^{23}$ m^{-3} and their total number in BL reaches $7 \cdot 10^{20}$. When the ionization degree is 22 %, the number of charges will be $1.5 \cdot 10^{20}$, which is significantly more than the number of electrons N_e in the outer shell of BL or the uncompensated positive charge in BL. The equilibrium condition for the electrons, moving in the outer shell, connects the centripetal force and electric forces:

$$\frac{mv^2}{r} = \frac{N_i q^2}{4\pi\varepsilon\varepsilon_0 r^2} - \frac{N_e q^2}{4\pi\varepsilon\varepsilon_0 r^2} . \tag{4}$$

The first expression in the right side of (4) describes the attractive force between the electron and the internal volume ion charge, the second describes the repulsive force of repulsion of the electrons in the outer shell from each other. The balance of forces (4) will be satisfied in case when the total number of uncompensated positive charges N_i exceeds slightly the number of free electrons in the outer shell N_e. Therefore, BL in general must be positively charged. We will assume that the following relation exists between the number of ions and electrons:

$$\Delta N = N_i - N_e = \frac{1}{50} N_e .$$

Then from the expression of the found current (3) and using (4) we can estimate the velocity of the electrons in the outer shell, the number of ions and electrons, and the effective charge of BL:

$$v = 8.7 \cdot 10^7 \text{ m/s}, \qquad N_i \approx N_e = 9.2 \cdot 10^{13}, \qquad Q = q\Delta N = 2.9 \cdot 10^{-7} \text{ C}. \qquad (5)$$

The kinetic energy of the electrons in the outer shell of BL will be:

$$E_k = \frac{N_e m v^2}{2} = 0.3 \text{ J}. \qquad (6)$$

Multiplying the volume of BL by the magnetic energy density, we estimate the magnetic field energy:

$$E_m = \frac{4\pi r^3}{3} \cdot \frac{B^2}{2\mu\mu_0} \approx \frac{\pi\mu\mu_0 r i^2}{6} = 0.4 \text{ J}. \qquad (7)$$

The electrostatic energy of BL is calculated as the integral of the energy density of the electric field u over the volume:

$$W = \int_0^\infty u\, dV, \quad \text{where} \quad u = \frac{\varepsilon\varepsilon_0 E^2}{2},$$

E is the electric field strength.

Outside BL the field strength E is low due to partial compensation of the positive ionic charge and the negative charge of the electrons in the outer shell. In the electron shell itself the field is rather large but the volume of the shell depends strongly on its thickness; if the thickness is small the energy in the shell can be small. The energy of the field inside BL can be easily calculated; with uniform distribution of positive charges over the volume, with their total charge qN_i, the energy of the ball taking into account (5) is equal to:

$$W_+ = \frac{q^2 N_i^2}{40\pi\varepsilon\varepsilon_0 r} = 2.8 \text{ J}. \qquad (8)$$

The total electrostatic energy of BL will be slightly larger than the value (8).

According to the data from [25], the plasma energy density in BL at the temperature $T = 1.4 \cdot 10^4$ K equals 0.35 J/cm^3. Multiplying this density by the volume of our BL model with its radius 7 cm, we find the maximum possible energy of the plasma, including the kinetic energy of the particles:

$$E_i = 500 \text{ J}. \qquad (9)$$

Thus, the most energy in BL of a medium size according to (6) – (9) consists in the energy of the ionized particles.

The charge Q that we found in (5) is 5.5 times less than the maximum charge of BL according to (1). We will find the electric field strength E near the surface of BL and the corresponding electric potential:

$$E = \frac{Q}{4\pi \varepsilon \varepsilon_0 r^2} = 530 \text{ kV/m}, \qquad \varphi = \frac{Q}{4\pi \varepsilon \varepsilon_0 r} = 37 \text{ kV}. \tag{10}$$

This field strength is sufficient to cause in the air around BL appearance of ozone and nitrogen oxides, the smell of which usually accompanies the phenomenon of BL. Since the charge of BL is positive, it will be bombarded with electrons and negative ions from the surrounding atmosphere. The energy acquired by them in the electric field of BL according to (10) can reach the values up to 37 keV, in energy units. It is known that the path of electrons in the air is limited by different losses and starting with the initial energy of electrons equal to 40 keV, it does not exceed 2 cm. Actually, the initial energy of the air's electrons is low and in the electric field of BL they will acquire substantially less energy. If we assume that the area of acceleration of electrons near BL is $\Delta r = 1$ cm, then from (10) for their energy we obtain:

$$q\Delta\varphi = \frac{qQ\,\Delta r}{4\pi \varepsilon \varepsilon_0 r^2} = 5 \text{ keV},$$

which corresponds to Dmitriev's observations [25] on the glow of BL's shell similar to the peripheral glow of an electron beam in the air.

In order to estimate the stability of BL we should estimate the pressure is exerted on the outer electron shell by electric repulsive forces of uncompensated positive ions inside BL. Near the electron shell at radius *r,* the positive ion with charge *q* is influenced by a force from all the uncompensated ions, the total number of which N_i is almost exactly equal to the number of electrons N_e in the outer shell:

$$F = \frac{N_i q^2}{4\pi \varepsilon \varepsilon_0 r^2} \ .$$

Using the known concentration *n* of air particles inside BL at atmospheric pressure and temperature $T = 1.4 \cdot 10^4$ K, we can write the characteristic volume per particle as $\frac{1}{n}$ and the area per particle as $\sigma = \left(\frac{1}{n}\right)^{2/3}$. Dividing the force F by σ, we obtain the additional pressure exerted on one ion:

$$\overline{P_i} = \frac{F}{\sigma} = 2.8 \cdot 10^4 \text{ Pa}.$$

This quantity is an order of magnitude less than the atmospheric pressure, so that in view of the small number of ions N_i in relation to the total number of gas particles in BL and the holding effect of the magnetic field with respect to the plasma, the electron shell must hold ions inside.

We will estimate the thickness d of the outer electron shell of BL using the condition for the pressure in the plasma in the magnetic field: $P_m + P_\perp = const$,

where $P_m = \dfrac{B^2}{2\mu\mu_0}$ is the magnetic pressure, $P_\perp$ is the pressure of plasma across the magnetic field lines. We will assume that the main pressure in the outer shell is maintained by the air itself, and the magnetic pressure equals the additional pressure P_e from the motion of electrons:

$$P_e = n_e kT = \frac{N_e kT}{4\pi r^2 d}, \qquad \text{where} \qquad \frac{3\kappa T}{2} = \frac{mv^2}{2}.$$

Provided $P_m \approx P_e$ we obtain d = 1.3 cm. In another limiting case, when the pressure P_e is equal to the atmospheric pressure and exceeds the magnetic pressure, the thickness of the electron shell must be less, reaching the value $3 \cdot 10^{-5}$ m.

Electrons, moving at high velocities in the outer shell, colliding with the air particles must ionize them, which is the main reason of the small path of electrons in the air at the considered energies. However, the secondary electrons resulting from ionization due to the effect of the electron avalanche can completely replace the primary electrons, moving under influence of the centripetal force of the internal positive charge of BL. In addition, between the external pressure, the electron current and the magnetic field in the plasma there is an inverse relation – compression of BL (for example, when it cools) increases the currents and the magnetic field and the magnetic field due to self-induction tries to maintain the initial current.

Because of its charge (5) BL can move under influence of electric fields. As it is noted in [3], BLs sometimes fall out of the clouds and move quickly to the ground, hit it and explode. Often this motion occurs along the channel of the streak lightning which has just emerged. The close relation between emerging of BL and streak lightning strikes is indicated by the evidence of the physicist Loeb, a famous expert in the field of gas discharge [4]. In the summer of 1898 or 1899 in Springfield (MA), there was a heavy thunderstorm, which he was watching from the window of his parents' house. He noticed a ball, glowing in a way as excited nitrogen atoms did. The ball was moving down slowly from the roof of the neighboring house along a smooth curvilinear trajectory. Its diameter was equal to the diameter of two children's balloons. It fell on the lawn in front of the house, jumped up and disappeared. After that, the house was struck a streak lightning.

It is noted that in some cases BL is formed from one streak lightning and is destroyed by another streak lightning. BLs that are formed near the ground tend to move slowly and can stop near some objects, move against the wind, or even get up to the clouds. These features of BL behavior can be explained by the influence of strong electric fields between the clouds and protruding objects on the ground, which are periodically oscillating during discharges of streak lightnings and motion of clouds, and even the direction of the field strength can be changed. Besides, due to the high temperature inside BL its average density differs from the density of the ambient air, so that Archimedes buoyancy force must be added to the electric forces. It should be noted that due to the different air density at the level of clouds at a height of 300–500 m and near the ground, the buoyancy force changes by about 6 %. The balance of these forces takes place, apparently, in tied or attached BLs, or in hovering motionlessly, or in BLs connected with objects.

During the lifetime of BL its charge can change due to interaction with the environment or in the partial decay, leading to a change of the equilibrium state. Thus, changing from a fixed to free BL, it usually goes up, and then by a sloping line it goes to the clouds. We will consider the process of balancing of BL in the atmosphere in more detail. If the air inside BL is really hot, the Archimedes force is much greater than the weight of BL. On the other hand, during formation BL is usually located at the place of streak lightning going into the ground or near tall objects that bear the ground potential. Due to its charge BL creates in the ground, as in a conductor, induced charges and is attracted to them. The attraction force can be determined by the image method from electrostatics. We will find the height h above the ground, at which BL is in equilibrium, from the equality of the Archimedes force and the electric force:

$$\rho g V_b = \frac{Q^2}{4\pi\varepsilon\varepsilon_0 (2h)^2}, \qquad (11)$$

where ρ = 1.29 kg/m^3 is the air density around BL,

g = 9.81 m/s^2 is the gravity acceleration,

V_b = $1.43\cdot10^{-3}$ m^3 is the volume of BL.

At the charge Q from (5) the height h = 10 cm, which is close to the size of BL. As the air cools down, BL's volume decreases, and in case of loss of electrons from the outer shell the charge Q can increase. Therefore, BL can go up above the ground and then move smoothly depending on the ground relief, wind and electric fields from the storm clouds. As an example, we will calculate the electric field which would counterbalance the Archimedes force:

$$E = \frac{\rho g V_b}{Q} = 6.2\cdot10^4 \text{ V/m}. \qquad (12)$$

It is known that the difference of potentials between the clouds and the ground can reach up to 10^8 V, which at an altitude of the cloud above the ground of 1 km gives the field strength 10^5

V/m (instead of the 100 V/m, which are observed during clear weather). Comparison with (12) shows that the electric fields of thunderclouds can direct the motion of BL.

5. Ball lightnings of extremely low and high energy

The potential energy of BL by its absolute value can not be less than the kinetic energy of electrons, which is the condition of BL's integrity as well as of any other object. One of the extreme states of BL corresponds to the approximate equality of the magnetic, electric and kinetic energies of moving charged particles (for example, during formation of a plasmoid of BL type in the focus of concentrated electromagnetic wave). For this state we can find the number of charges from the equality of magnetic and kinetic energy of the electrons taking into account (7), (3) and the formula for E_k from (6):

$$E_m = \frac{\pi \mu \mu_0 r i^2}{6} = \frac{\mu \mu_0 q^2 N^2 v^2}{24 \pi r} = E_k = \frac{N m v^2}{2}, \qquad N = \frac{12 \pi m r}{\mu \mu_0 q^2}.$$

At the radius of the smallest BLs of the order of $r = 1$ cm we will obtain the value $N = 10^{13}$ for the number of charges. Substituting the value N instead of N_i in (8), we find the electrical energy: $W_+ = 0.23$ J. At the same energy density of plasma, as in (9), the energy of BL's plasma is about 1.5 J. Given for BL of the smallest we assumed $E_m \approx W_+ \approx E_k$, the total energy of this BL will not exceed the value of 2.2 J.

Now we will consider BL of high energy. The total charge of BL can not exceed the value at which the electric field strength at its surface is greater than $E_0 = 30$ kV/cm, in order to avoid atmospheric air breakdown. Hence, we find the maximum charge of BL:

$$Q_0 = 4 \pi \varepsilon \varepsilon_0 E_0 r^2. \qquad (13)$$

Expressing BL charge as $Q = q(N_i - N_e)$ from (4) and equating to (13), we obtain:

$$\frac{v^2}{r} = \frac{q E_0}{m}. \qquad (14)$$

In the right side of (14) there are constants. Assuming that the maximum possible velocity of electrons v equals the speed of light c, we find the largest BL radius with the limiting value of the electric charge Q:

$$r = 17 \text{ cm}, \quad Q = Q_0 = 9.6 \cdot 10^{-6} \text{ C}, \qquad (15)$$

on condition $v \approx c$.

We will assume that the electron current in the outer shell of BL is so large that the magnetic pressure P_m becomes equal in magnitude with the atmospheric pressure P_a:

$$P_a = P_m = \frac{B^2}{2\mu\mu_0}, \quad \text{where} \quad B = \frac{\mu\mu_0 i}{2r}, \quad i = \frac{qN_e v}{2\pi r} \quad \text{as in (3).}$$

From these relations, taking into account (15), we find the limiting values of the magnetic field, the current and the number of electrons in the outer shell of BL:

$$B = 0.5 \text{ T}, \qquad i = 1.4 \cdot 10^5 \text{ A}, \qquad N_e = 3.1 \cdot 10^{15}. \qquad (16)$$

We assume, according to [25], as BL temperature the quantity $T = 1.4 \cdot 10^4$ K and the corresponding ion velocity $V = 3.5 \cdot 10^3$ m/s. Then, from (2) it follows that the ions must rotate by circles with radius $R = 2$ mm in the plane, which is perpendicular to the magnetic field. On the other hand, the charged particles can move freely along the magnetic field lines. Consequently, in the model of BL with a strong magnetic field the charged particles move along helical lines and periodically are reflected from the outer electron shell. In magnetic fields, which are the order of magnitude less than that in (16), the rotation radius of ions R will grow approximately to half the value of the BL radius. Thus there is only one stable ion orbit, which specifies the position of BL core.

The estimates of kinetic, magnetic and electric energies of high-energy BL (6–8) give: E_k = 0.13 kJ, E_m = 2 kJ, W_+ = 1.3 kJ. Since the energy density of BL at temperature $T = 1.4 \cdot 10^4$ K is 0.35 J/cm^3, we can find the maximum possible energy of plasma multiplying by the volume of this BL model, with its radius equal 17 cm: E_i = 7.2 kJ. Thus most of energy in a high-energy BL consists in the energy of ionized particles and the energy of electromagnetic field, and the total energy of 10.6 kJ falls in the range of upper values for BL energies, calculated based on the results of their impact on the surrounding objects.

Using the formula (11), the known charge of BL (15) and BL volume V_b = 0.02 m^3 we can estimate the height h above the ground, at which BL is in equilibrium in case of balance of the Archimedes force and the electric force: h = 90 cm. Using (10) we find the value for the electric potential of high energy BL, which is about 500 kV. Under influence of the electric field the electrons and negative ions are accelerated towards BL. Assuming that the particle acceleration area near BL is Δr = 1 cm, corresponding to the breakdown interval at the field strength of 30 kV/cm, we calculate the energy of particles:

$$E_k = q\Delta\varphi = \frac{qQ\,\Delta r}{4\pi\varepsilon\varepsilon_0 r^2} = 30 \text{ keV}.$$

According to the data from [25], the light-blue glow of the outer shell of BL really resembles a quiet electric discharge with electron energy of tens of keV. If BL charge is sufficiently large, then its observed radius can be larger than the actual due to the glowing corona around it.

6. Some cases of ball lightning emerging

BL emerging often takes place after a lightning strike into a tree, telephone pole, metal structures, power lines, as well as when lightning passes near antenna and telephone wires, melting and evaporating them. In these cases, we should expect emerging several channels of lightning discharge and additional number of positive ions in the air due to substance evaporation, which increases the possibility of BL emerging. Streak lightning striking the transmission tower was observed in 1973 by V.V. Venderevskih [4]: "A shaft of fire and sparks appeared, from which a ball of fire jumped out, glowing like burning magnesium. The ball (with diameter 20–25 cm) started moving along the wire from the place of emerging to the next tower, then jumped to the same wire on the other side of the tower, and after passing some distance, it got to the top wire (apparently, a grounded one). After that, the ball disappeared, and the part of the wire near the place of the ball's disappearance got heated and became red and yellow. During the ball's disappearance a little glowing ball separated from it, that fell down and faded out."

In [28] emerging of BL is described during closure of the contacts of electric power lines of 110 V by a piece of copper wire. BL was yellow-white in color, with diameter of about 3 cm, it rolled over the table and disappeared, leaving the copper ball of the size of 1 mm. Apparently, inclusion of evaporated metals in BL increases its weight, so that BL from the start has strong connection with the objects near which it was formed. If a hole appears in the shell of BL, then outflow of hot air plasma can take place, effectively heating the object with which BL is in contact. In the described above case, BL heated an electric wire emitting to it all its energy.

According to [29], the light flow from an average BL is about 1600 ± 200 lm. This luminosity can be explained by the radiative transitions of atoms and molecules and gradual recombination of air ions inside BL, so that its energy decreases continuously at a speed up to 2 joules per second just due to radiation. The ratio of the surface area to the volume increases with decreasing of radius, therefore, small BLs would spend all their energy on radiation faster, in seconds or fractions of seconds, and it is actually observed in both natural and artificial BLs in case of short circuits in electrical equipment.

BL is rarely a perfect sphere, in 91 % of cases it is an object of irregular spheroidal shape, sometimes with a few bulges. Some BLs seem hollow, oval (2.7 %), ribbon (2.6 %), amorphous (1.4 %), occasionally there are heart-shaped, pear-shaped, egg-shaped or in the form of a torus, disk, cylinder, spindle, ring [29]. One observation is described in [3]: After a thunderstorm BL appeared over a square stone with sides of 80 cm, which 4 people were trying to lift, at the height 90 cm from the stone. It was a transparent yellow ball with diameter of 20 cm, it was swinging uniformly with an amplitude of 4 cm. In the center of the ball there was a bluish pear-shaped flame with the length of about 4 cm, with the sharp edge turned down. The flame was rotating by a vertical circle with diameter of 7 cm inside the large ball. After a few seconds BL disappeared with cracking. Later it was found out that at 100 meters the lightning struck a stone quarry.

According to [2], BLs can resemble a snake, a rope, a string, a sausage, a stick with thickness of 1–4 cm and length of 30–60 cm. Fibrous structure of radiation is observed as well. Sometimes BL is transformed into a ball from this shape. A typical example of BL transformation is given in [4], according to reporting of K.K. Poters from Nizhneudinsk: “The ball was in 10–15 cm from our faces and we saw very well as it began passing through the hole, taking the form of a melon. It stretched, got smaller in diameter and passed through the hole. When the ball was going through the hole and decreasing in size, it seemed to be shaking all the time, and it seemed that it consisted entirely of jelly, and blue rays with length of about 1.5 cm were constantly coming from its surface and ended with bursts of sparks.” In the case of S.B. Sergieva in 1943 BL went through the hole in the window with width 1 cm, “stretching as a sausage.” Often, after BL’s passing through glass small melted cracks appear. Several cases were recorded of BL’s penetration into aircrafts [30]. One BL was formed after a streak lightning had struck into the nose of a plane, later a hole of 8 mm was found there and a lot of small holes. Another BL appeared in IL-18 which is a completely hermetic aircraft, and it was found out that the plastic radome of the radio locator had a lot of holes like a flour sieve.

In connection with the structure of BL we will consider several particular cases. Here is an excerpt from a letter from Mrs. Esper to F. Arago [31]: “The weather was stuffy and the sky seemed calm at that moment, but flashing of lightning was seen from all sides. Passing near my window, which was very low, I was surprised to see a large red ball quite similar to the moon, which was colored and increased under influence of vapors. This ball was going down slowly and perpendicularly from the sky to one of the trees of Beaujon. My first thought was that it was Grimm’s balloon, but the color of the ball and the time of day soon convinced me I was mistaken, and while my mind was looking for a solution of this phenomenon, I saw that there was fire at the bottom of the ball, that was hanging at a height of 5 to 7 meters above the tree. It seemed as if paper was burning slightly with small sparks and flashes, then when the hole became two or three times larger than a hand, a sudden violent explosion ripped the whole shell, and a dozen serpentine lightning rays flew out of the center of this infernal machine, which were scattered in different directions, and one of them hit House № 4 and broke a hole in the wall, as a cannonball. This hole exists until now. Finally, the rest of the electrical matter started to burn with white, bright and glowing flame and to spin like firework wheel.” In the case that took place in Germany in 1949 [3], after the collapse of BL a part of it was left, shaped like a new moon, with horns turned down. The collapse of BL was accompanied by sparks of up to 30 cm. In the case which took place in Ljuberetsky district of Moscow in 1973, BL was observed going down from the height of trees [4]. Its color changed from dazzling white turning to yellow, bright red and then to dark red, after that a black spot appeared in the center and BL disappeared. While falling it was losing pieces of matter and emitted sparks.

In our model, the properties of BL described above can be explained by the fact that the outer shell can have not only spherical, but also stepped shape, showing some independence and flexibility of particular electron rings and thus the variability of BL shape while passing through narrow openings. It is logical to suppose that while going through narrow channels, BL goes so that the rotation axis of its particles is directed along the velocity. During BL lifetime, due to interaction with air and the surrounding objects some rings get broken and fluxes of fast electrons are emitted in the form of sparks from the outer electron shell of BL, creating characteristic crackling, the smell of ozone and radio emission. At the same time BL also emits air heated to a high temperature, in which the energy is released due to recombination of ions. The air temperature can reach the temperature of air in the channel of a streak lightning, captured during the formation of BL, that is, up to the order of tens of thousands degrees. At this temperature, it is easy to explain such effects of BL as glass melting and evaporation of metal objects. Release of energy can have explosive character, destroying the outer electron shell, which protects BL from contact with the surrounding atmosphere. Sometimes BL is just divided into several BLs. At a certain equilibrium form, sparks and sound of BL are minimal.

We should expect that vagueness or distinctness of BL shape is related to the configuration of current shells, the strength of current flowing in them and the gap between the shells. According to statistics, 50 % of all observed BLs disappear with a small explosion, which apparently is connected with their instability due to loss of charge and energy for radiation, and with disbalance of electromagnetic and centrifugal forces and with the gas pressure acting on the particles. Low-energy BLs in the absence of interaction with the environment will simply discharge, almost without noise and special effects.

7. Conclusion

According to observations, 30 % of soaring BLs spin in the air and part of attached BLs roll along the objects which attract them. When going down to loose soil or peat, BLs can dig a hole or scatter the ground. Fast motion of electrons in BL shell and high velocities of heated air particles in BL are indicated by the fact that in some cases of contacts with it, people got injures similar to those from electricity, and objects got heated or melted. According to the data from [32], the lethal dose of electric shock to persons is about 2 kJ, which falls in the range of energies of BL. According to our proposed model, the physical nature of ball lightning is the same as that of ordinary streak lightning. Since the motion of particles in BL is mainly rotational, and in streak lightning – it is translational, then from a philosophical point of view, both types of lightning give another example of the complementarity principle in nature. A peculiar feature of BL is the fact that its total energy is positive and BL itself is relatively stable. Another contradiction is gravitationally bound bodies, the stability of which is accompanied by the negativity of their total energy. In both cases the total energy increases in absolute value with decrease of the object volume at a constant number of particles. Thus, as in BL as in plasma object, the additional external pressure leads to increase of currents and the magnetic field (this is a characteristic property of plasma), and in case of volume decreasing the electrostatic energy increases. It should be mentioned that for construction of this model of BL the same ideas were used, as those used in [33] for describing the scheme of emerging of the electric charge in elementary particles.

In Table there are parameters of BL of different sizes. The radius of the small BL is near 1 cm, and kinetic energy of electrons approximately equal to magnetic energy. Almost all energy of BL with radius 7 cm (500 J) is consisting of plasma energy, including the kinetic energy of particles. The most power BL with radius 17 cm has total energy by quantity 10.6 kJ, and only part of it (3.3 kJ) is electromagnetic energy.

Parameters of ball lightnings of different sizes

r , cm	i , A	B , T	W , J
1	20	$1.3\ 10^{-3}$	2.2
7	$2.9\ 10^{3}$	$2.6\ 10^{-2}$	503
17	$1.4\ 10^{5}$	0.5	10600

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