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Electron - Ionic Model of Ball Lightning

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ABSTRACT

The model of ball lightning is presented where outside electron envelope is kept by inside volume of positive charges. The moving of electron in outside envelope is a reason of strong magnetic field, which controls the state of hot ionized air inside of ball lightning. The conditions of origins of ball lightning are investigated and the values of parameters for ball lightning of maximum power are calculated.

INTRODUCTION

Practically not decaying concern to a ball lightning (BL) is stipulated apparently by that till now there is no one conventional model of their interior constitution. Precisely also there is no also experimental technique, which one would allow at any moment of time to create simulated BL, not distinguished on the properties from natural analogs. The chemical BL models have apparently greatest variety. In one of the oldest model [1] it is considered, that in BL there is burning hydrocarbonaceous intermixtures. A luminous yellow-green blob by the size 4 cm at a lifetime up to 2 second was obtained in [2] at firing by an electric spark of an intermixture of air and 1.4 – 1.8 % of a propane, density of energy has come to $7 \cdot 10^{-3}$ J/cm^3. As other candidates as an active substance were termed hydrogen, methane, braize or reactive an aerosol, which one could be or be formed in a place of shock of a linear lightning (for example, in region of swamps or collieries). A deficiency of these models is that for disconnected among themselves of particles it is difficult to explain a stable BL form at a motion into the wind and at passage through glasses, electrical effects of BL, and also that at burning radius aspires promptly to increase. Besides, BL will be formed and in those places, which one are certainly dispossessed of sources of combustible matters. Energy source of BL could be a decomposition reaction of ozone. At concentration of ozone in 2 % in air density of its chemical energy is peer 0.13 J/cm^3 [3], but the lifetime BL is gained too small if to take into account, that the reaction rate is incremented at the expense of temperature rise.

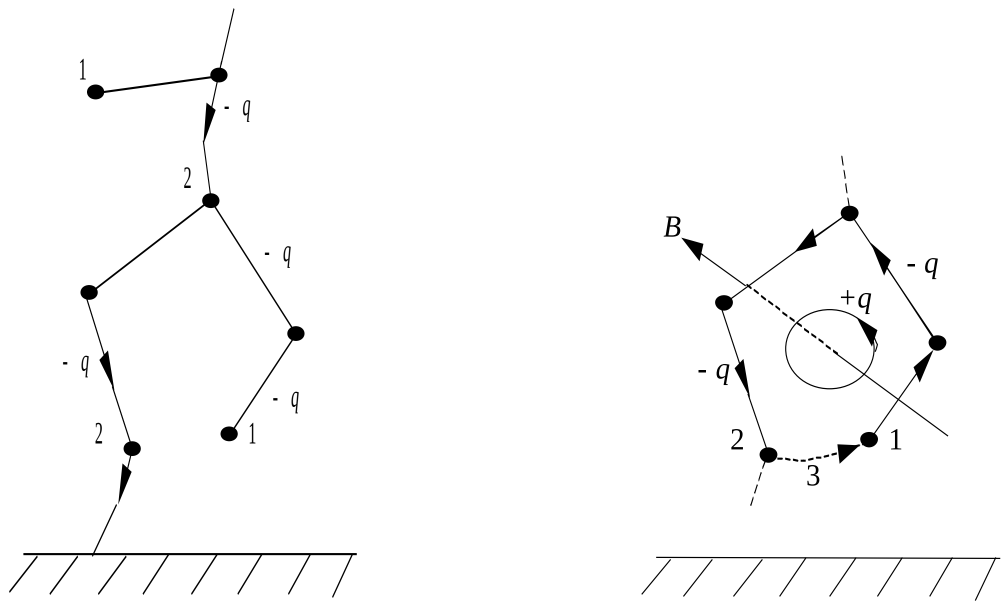
For explanation of stability of the shape BL in [4] the filamentary model BL was offered on the basis of aerogels such as SiO_2 or Al_2O_3, further developed in [3], [5]. For maintaining the shape and interfacial tension indispensable for explanation of elasticity BL, the hairlines should consider as charged up to 10^{-6} C. That the skeleton heated to high temperature, there is a lifting force of the Archimedes. Reactive the matters, accountable for a thermal radiation, place along hairlines. The problems exacting finishing in this model, are those: a composition of an aerogel and active chemical agent; explanation of a radio-frequency radiation, sparking and odor from

BL and its possible explosion. Similar on a construction the bubble model is [6], in which one BL has a core such as a bubble from metal or silicate, and its buoyancy in air arises at the expense of force of the Archimedes. In one of modifications of bubble models BL represents the charged bubble having a shell from water with a ranked arrangement of molecules and width 10 microns is bipolar [7]. The brief review of some other models BL is presented in [8].

The lifetime apparent BL reaches tens seconds and taking into account their sudden occurrence too little for detailed examination. From here basic sources of information about BL become consequences of their interaction with surrounding objects. Some examples from [3], [9] damages of subjects after contact with BL allow making estimation of an internal energy contained in BL. In [10-12] the results of experiments are presented, in which one there were luminous plasma formations recalling on the shape BL. Here there are expositions of different emergencies, at which one spontaneously arise BL. As follows from experience of contacts with BL, they are usually shaped near to radiants of the strong electromagnetic discharges – at a lightning discharge, at closure opening of high-voltage or high-current electrics, at high-frequency impulses of power generators. The exhibited further electron- ionic model of BL has that feature, that in BL the currents of considerable quantity flow past, and model supposes experimental checkout.

THE SEQUENCE OF FORMATION AND STRUCTURE OF BALL LIGHTNING

If not to take into account occurrence BL at actuation of a power electrics constant or alternating-current, practically in all remaining cases BL is seen in connection with usual linear lightnings or at a cloudy-thunderstorm weather. Within the framework of electron-ionic model natural BL can be an immediate corollary of a linear lightning, when the thunderstorm cloud is discharged on ground, transmitting it negative electricity (or at the discharge of adjacent clouds). In a fig. 1a the secondary branches and main channel of a lightning charged accordingly with sluggish and promptly migrated electrons are exhibited. A prompt electron motion and basic flash of a lightning start after linking a main channel with ground; thus luminous part of a lightning grows from ground to a cloud. The electrons, which are taking place in secondary branches, also move to a main channel and are poured through it on ground. Thus the almost closed circuit of an electronic current is possible (fig.1b), when at its centre there is a magnetic field with an induction B. In electrified air around of a lightning there are many positively ionized atoms, which one start to be torqued around of lines of a magnetic field and by that are arrested at centre. In turn current of electrons from the channel 2 can skip on a branch 1 through area 3, supporting the further close current. An indispensable requirement for this purpose should be the force retaining electrons on a closed orbit.



a) b)

Fig. 1. a) 1 – secondary branches of lightning, 2 – primary channel, in which the electrons are moving (are marked $-q$).
b) The electron motion from a secondary branch 1 in a primary channel 2 of lightnings can be made through area 3. B – induction of a magnetic field from an electron current. The ions with a charge $+q$ are spun around lines of the magnetic field

At sufficient quantity of positively ionized atoms at centre they can attract to itself electrons and by that to provide their inconvertible gyration. Outgoing from an offered picture, in a fig. 2 the equatorial section of BL model by the way of rotationally symmetric configuration with a spherical electronic current is presented. The positively ionized atoms are at atmospheric pressure in very hot air inside BL after shock of a linear lightning. Promptly migrated electrons in an outer envelope generate a magnetic field with an induction B, which one retains positively ionized atoms on orbits inside BL. At last, the electrical attraction of positively ionized atoms and electrons with negative charge retains electrons in an outer envelope from dispersion, being by a main body of a centripetal force. In view the spherical shape of BL the radius of gyration r of exterior electron atmosphere around of a general axis diminishes in accordance with transition from equator to poles. This specified rather inconvertible configuration allows explaining an apparent lifetime BL, which essentially exceed lifetime of homogeneous ion-impact plasma at atmospheric pressure. The electronic envelope efficiently isolates of high-temperature air inside BL, retarding transport of energy to a surrounding medium. The positively ionized atoms inside BL practically are not attracted by electrons from an outer envelope, as the electric field from electrons inside an orb is equal to null because of an equilibration of all electrical forces. Therefore ions can be proportioned uniformly on all BL volume, and the recombination of ions and electrons is essentially retarded.

As it is visible from a fig. 1б, BL as a matter of fact there is a small part of a linear lightning, twisted in a skein with the typical size 10 – 40 cm. Accordingly in both types of lightnings currents and the magnetic field can be close on quantity.

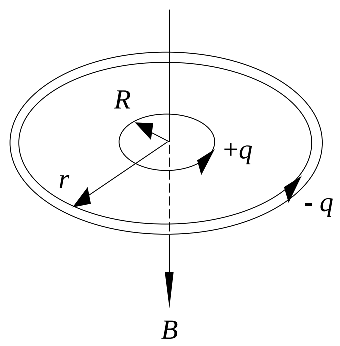


Fig. 2. Equatorial section of model of ball lightning select ring on electronic envelop of the spheroidal shape. R – radius of gyration of ions around of a magnetic field with an induction B, r – radius of exterior electronic envelop

On data from [3], []9-10], the typical parameters of a linear lightning are those: section of a main channel about 10^{-2} m^2; currents in the main discharge from 10^4 A and up to $5\cdot 10^5$ A; during the short discharge about 10^{-3} s may be transferred 20 coulombs of an electricity; temperature of air in the channel of a lightning reaches 25000 K; an electron concentration in the channel of a linear lightning up to $4\cdot 10^{18}$ in 1 cm^3; velocities of heat motion for ions not less than 10^4 m/s, for electrons more than 10^6 m/s. The probability of BL observation is insignificant and on a statistician one BL is noted against 1000 usual lightnings.

Let's estimate parameters most power BL with the help of data about linear lightnings. Near to a main channel of a lightning at a current $I_l = 2\cdot 10^5$ A and radius $R_l = 0.1$ m induction of a magnetic field reaches quantity:

$$B = \frac{\mu\mu_0 I_l}{2\pi R_l} \approx 0.4 \text{ T}.$$

If the electron is spun in such magnetic field with radius of an orbit r_e, its velocity should be less speed of light:

$$v = \frac{Bqr_e}{m} < c, \qquad r_e < \frac{mc}{Bq} = 8\cdot 10^{-3} \text{ m}.$$

As $r_e << R_l$, that in a magnetic field near to the channel of a lightning even relativistic electrons can be retained and accumulate. On the other hand, at currents more than 1000 A in the pulsing vacuum discharges the energy of electrons reaches 1 keV, and travelling speed of electrons up to 10^7 m/s [13]. As the upper value of a current in plasma it is necessary apparently to utilize quantity $1.4\cdot 10^6$ A agrees [14], as the further amplification of an electric intensity gives in squeezing a current cord and increase of radiation at an invariable current and temperature of particles.

Let's designate through M, V, R and m, v, r masses, travelling speeds and radiuses of gyration of ions and electrons accordingly; B – induction of a magnetic field; N_i – quantity of uncompensated positively ionized atoms inside BL ; N_e – quantity of mobile electrons in an outer envelope of BL ; q – unit electrostatic charge; i – current of electrons on an orbit of radius r; $\varepsilon, \varepsilon_0$ – relative complex dielectric constant and permittivity of vacuum; μ, μ_0 – relative magnetic conductivity of medium and permeability of vacuum. For simplification of calculations we shall to consider, that the charges and currents in basic are massed near to an equatorial plane or are disposed like the cylinder, and ions are singly.

The equilibrium condition for electrons moving in an outer envelope, relates axipetal and electrical forces:

$$\frac{mv^2}{r} = \frac{N_i q^2}{4\pi\varepsilon\varepsilon_0 r^2} - \frac{N_e q^2}{4\pi\varepsilon\varepsilon_0 r^2}. \qquad (1)$$

The first expression in a right member (1) features an attractive force between an electron and volumetric interior ionic charge, second – repulsive force of electrons in an outer shell from each other. The balance of forces (1) will run in the case, when the total number of uncompensated positive charges N_i will be insignificant to exceed number of mobile electrons in an outer envelope N_e. Therefore, BL as a whole should be charged positively, having a charge $Q = q(N_i - N_e)$. On the other hand, the total charge of BL can not exceed such quantity, at which intensity of an electric field on surface of BL exceed $E_0 = 30$ kV/cm in order to prevent a disruption of ambient air. From here we calculate a maximal charge of BL :

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

The availability of a major electric intensity near BL and vigorous electrons confirms by numerous observations of their fizz, scratching noise and emission of sparks as at electric discharge. Besides, the samples of air taken after passage BL, have shown the heightened content of ozone and nitric oxides (approximately in 50 – 100 times above than norm). On data from [15], the demanded relation of concentrations of ozone and nitric oxides can be received at electric discharge in air with intensity of electric field up to 4 kV/cm, and the estimate of indispensable electrical energy in such equivalent discharge for full lifetime of BL gives value 530 J [9].

Expressing a charge Q from (1) and equating to (2), we gain:

$$\frac{v^2}{r} = \frac{qE_0}{m}. \qquad (3)$$

In a right member (3) there are stationary values. Accepting, that the greatest possible velocity of electrons v is peer to speed of light with, we discover greatest BL radius with limiting quantity of electric charge:

$$r = 17\,\text{cm}, \qquad Q = Q_0 = 9.6 \cdot 10^{-6}\,\text{C}, \tag{4}$$

under condition of $v \cong c$.

Let's suspect, that the electronic current in an outer envelope of BL so large, that magnetic pressure P_m is compared on quantity to atmospheric pressure P_a:

$$P_a = P_m = \frac{B^2}{2\mu\mu_0}, \quad \text{where} \quad B = \frac{\mu\mu_0 i}{2r}, \quad i = \frac{qN_e v}{2\pi r}. \tag{5}$$

From (5) and (4) are calculated limiting quantities of an induction of a magnetic field, current and number of electrons in an outer envelope of BL:

$$B = 0.5\ \text{T}, \qquad i = 1.4 \cdot 10^5\ \text{A}, \qquad N_e = 3.1 \cdot 10^{15}. \tag{6}$$

The velocity of ions V inside BL can be estimated on medial temperature of glow T with the help of a relation between kinetic and thermal energies:

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

Shall accept according to [15] as BL temperature quantity $T = 1.4 \cdot 10^4$ K, then at medial mass of an ion $M = 4.7 \cdot 10^{-26}$ kg as for a molecule of nitrogen the velocity of ions will be peer $V = 3.5 \cdot 10^3$ m/s. A radius of gyration of ions in a magnetic field we shall calculate from expression:

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

so that taking into account (6) ions are spun on circles of radius $R = 2$ mm in a plane, perpendicular magnetic field. On the other hand, the charged particles easily can slide along lines of a magnetic field. Therefore, in BL model with a magnetic field charged particles are slide on circular helixes and are periodically reflected from outside electronic envelope.

The kinetic energy of electrons in outer envelope of BL will be equal to:

$$E_k = \frac{N_e m v^2}{2} = 0.13\ \text{kJ}. \tag{7}$$

Multiplying a volume of BL $V_b = \frac{4\pi r^3}{3} = 0.02\ \text{m}^3$ on density of magnetic field energy, we shall estimate energy of a magnetic field:

$$E_m = \frac{V_b B^2}{2\mu\mu_0} = \frac{\pi\mu\mu_0 r\, i^2}{6} = 2\ \text{kJ}. \qquad (8)$$

The electrostatic energy of BL is evaluated as integral from density of energy of electric field u on volume:

$$W = \int_0^\infty u\, dV\,, \quad \text{where} \quad u = \frac{\varepsilon\varepsilon_0 E^2}{2}, \qquad E \text{ – intensity of an electric field.}$$

Outside BL intensity of a field E is small because of partial neutralization of a positive ionic charge and negative charge from electrons in an outer envelope. In the electronic envelope field is large enough, but the volume of the envelope essentially depends from its width; at small width the energy in the envelope can be insignificant. Energy of a field inside BL is evaluated precisely, at a uniform distribution of positive charges on a volume with their common charge qN_i the energy of the sphere is equal:

$$W_+ = \frac{q^2 N_i^2}{40\pi\varepsilon\varepsilon_0 r} = 1.3\ \text{kJ}, \qquad (9)$$

here it is accepted $N_i \approx N_e = 3.1 \cdot 10^{15}$ agrees (6). The complete electrostatic energy of BL will be more, than quantity (9).

On data from [15], density of energy of plasma in BL at the temperature of $T = 1.4 \cdot 10^4$ K constitutes 0.35 J/cm^3. Multiplying this density on a volume of our BL model at radius 17-cm, we calculate the greatest possible energy of plasma, including a kinetic energy of particles:

$$E_i = 7.2\ \text{kJ}. \qquad (10)$$

Thus basic energy by ours power BL agrees (7) − (10) is energy of the ionized particles and energy of electromagnetic field, and the aggregate energy by quantity 10.6 kJ hits in a gamut of the upper values of energies for BL, computed by results of their action on surrounding objects.

Curious feature of BL is that the total energy is plus, and at the same time BL is relatively stable. Other contrast are the gravitation-bound bodies, the stability which one is accompanied negativity of their total energy. In both cases the total energy grows modulo at diminution of a volume of object at invariable quantity of particles. In BL as in plasma object the additional external pressure gives in amplification of currents and magnetic field (this is characteristic feature of plasma), and at diminution of a volume electrostatic energy is growing.

Due to the charge (4) BL can be slid under influence of electric fields. As it is mentioned in [10], BL sometimes fall out of clouds and are promptly guided to ground, there are impacted and blast out. Frequently this motion happens along the channel just of arisen linear lightning. Close connection between places of occurrence of BL and shocks of linear lightnings directs at that, that in some cases BL is derived from one linear lightning and is erased by other linear lightning. BL, arisen in proximity of the ground, are usually slid slowly and can stop for some subjects, move into the wind or even to be lifted in clouds. These features of behaviour can be quite explained by activity of strong electric fields between clouds and salience subjects on ground, periodically oscillating at the discharges of linear lightnings and a motion of clouds down to a veering of a field gradient. It is known, that the potential difference between clouds and ground can reach quantity up to 10^8 V, that at a cloud height above ground in 1 km gives intensity of a field 10^5 V/m instead of those 100 V/m, which one are supervised at a clear weather. Besides, owing to a heat of air inside BL its medial density differs from density of an ambient air, so that to electrical forces it is necessary to add lifting force of the Archimedes. The balance of the indicated forces is carried out, apparently, for bound either attached BL, or soaring fixed, or bound with subjects. During life of BL its charge can vary because of interaction with encirclement or at partial decay, giving to change of equilibrium state. So, at transition from attached BL to free it is usual soar up and then on a slanting line leaves to clouds.

Let's consider process of an equilibration of BL in an atmosphere in more detail. If air inside of BL hardly heated, the force of the Archimedes is much greater of a weight itself BL. On the other hand, at the formation BL usually is in region of entrance of a linear lightning in ground or for high subject's carrier an earth potential. Due to a charge BL creates in ground as in a conductor the directed charges and is attracted to them. The attractive force can be spotted with the help of a method of images from an electrostatics. Let's find height h above ground, at which one BL is in equilibrium, from equality of electrical force and force of the Archimedes:

$$\frac{Q^2}{4\pi\varepsilon\varepsilon_0(2h)^2} = \rho g V_b = 0.25 \text{ N}, \quad (11)$$

where $\rho = 1.29$ kg/m^3 – density of air around BL,

$g = 9.81$ m/s^2 – acceleration due to gravity,

$V_b = 0.02$ m^3 – volume of our BL model.

At the charge Q from (4) heights $h = 90$ cm. In accordance with a cooling of air volume of BL is diminished, and at losses of electrons from an outside envelope charge Q can be incremented. Therefore BL can float above ground and further smoothly to move depending on a contour of terrain, wind and electric fields from thunderstorm clouds. It is easy to calculate electrical force effective on BL at a field gradient $E = 10^5$ V/m from hardly of charged thunderstorm clouds: $F = QE = 1$ N that is close to force of the Archimedes (11).

To present the structure BL more visually, we shall give the rather detailed testimony of M. Dmitriev, expert-chemist possessing experience of operation with a low-temperature plasma and becoming the eyewitness of an BL appearance [15]:
"The brightness of the lightning was considerable, specially at distance in some meters, nevertheless it was possible freely to view, without particular effort. Was noticeably, that the colour of the lightning is nonuniform. The central part represented a ball a dia about 6 – 8 cm, a little bit prolate in a vertical direction. This part was also brightest, on the appearance (except for the shape) rather resembling an electrodischarge plume in air gained in plasma generators, with temperature of plasma about 13000 – 16000 K. Central part of the lightning was enclosed area width 1 – 2 cm with heavy-bodied violet glow very similar to air glow at pressure 0.1 mmHg, bombarded electrons with energy in some tens eV. The next outside envelope, width about 2 cm, also was nonuniform, resembling on colour silent electric discharge at atmospheric pressure or peripheral glow of electron beam with energy in some tens kiloelectronvolt hitting from a vacuum tube in air at usual pressure. The light blue glow of this part of the lightning promptly descended with enlargement of distance from a central ball, gradually descending on is not present. Envelopes of the lightning were well scanned only in a horizontal direction. In bottom they were, probably, squeezed also it was possible to distinguish them only by comparison to lateral parts of the lightning. Above the lightning envelopes were considerably to strata, but not so are sharply expressed. Besides in them it was possible to see separate bright convective jets (as above a usual campfire, only colour them was with whitish tone). The overall diameter of the ball constituted about 11 – 12 cm in a horizontal direction and about 14 –16 cm in vertical. From distance in some tens meters the central part of the ball was visible, apparently, only. Have issued the lightning had a bluish tone…. In the lightning, apparently, all the time the energy was oozed. It directed continuous rustle and strong separate scratching noises. Probably, continuously there was also leakage of its charge. The energy liberation was sharply incremented at touch of the lightning with surfaces (leaves or brushwood) and was accompanied by more strong crash and sparking. The lightning has kept after itself a strong odor, on the character almost conterminous with an odor of air subjected action of ionizing radiation".

As it is visible from the text above, the ball lightning of M. Dmitriev had a vertical symmetry axis conterminous to a spin axis of electron envelope in our model of BL and to a direction of an interior magnetic field. In magnetic fields, on the order smaller, than in (6), the radius of gyration of ions R grows approximately up to quantity of half of BL radius. On the other hand, the charged particles easily can move along lines of magnetic field. Therefore, at radius R instead of a random motion of ions there are ranked orthogonally related ionic streams, that is accompanied by strong friction in gas and relevant energy liberation by the way radiation. Thus there is only one inconvertible ionic orbit, which one scores a standing of a core of BL. The interior ionic cloud of the lightning was prolated in a vertical direction, and all envelopes were well scanned only in a horizontal direction. About gyration of particles in envelopes with differential velocity spoke separate bright convective jets. Under the guess in [15], the light blue glow of an outer envelope resembles silent electric discharge with energy of electrons in tens keV. Let's calculate potential of our model BL at its radius and charge agrees (4):

$$\varphi = \frac{Q}{4\pi\varepsilon\varepsilon_0 r} = 500 \text{ kV}. \tag{12}$$

As the BL charge is positive, it will be bombarded by electrons and negatively ionized atoms from an environmental atmosphere with energy, gained by them, from passage of a potential difference right up to quantity (12). It is known, that the run of electrons in air is restricted to different losses and at initial energy of electrons in 500 keV the run does not exceed 1 m. Actually initial energy of electrons of air is small also they in an electric field of BL will gain essentially smaller energy. If to consider, that the band of acceleration of electrons close BL is peer $\Delta r = 1$ cm (that corresponds to an electric intensity punching air, from a charge Q of our model of BL), from (12) follows:

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

that corresponds to observations in [15]. If the BL charge is great, the apparent radius can be more present at the expense of a luminous corona around it.

It is possible to explain a brightness usual medium-sized BL by emission transitions of atoms both molecules and gradual recombination of air ions inside BL, so that the energy only at the expense of radiation continuously descends with velocity up to 2 J per one second. The relation of a surface area to a volume grows in accordance with diminution of radius, therefore, small BL will spend all energy for radiation and convective heat exchange in an environmental atmosphere faster, during the order of a fraction and unities of seconds, and it really detect both for natural, and for simulated BL at short circuits of an electrics.

In connection with BL structure it is interesting to consider some cases from [10]. BL rather seldom represents an exact orb; it is mass ungeometrical, sometimes with several salients. Some BL seem hollow, oval, heart-shaped, pear-shaped, egg-shaped or by the way of torus or ring. In a case in Paris in 1849 for BL there were sparks and fiery tongues, which one as though were pulled out from a hole in the ball. At enlargement of the hole BL has blown up with lightning-like discharge. After that was visible some bright glow.

In case of 1949 in Germany after decay BL has remained a part recalling on the shape young month, turned around horns downwards. The decay by this BL was accompanied by sparks of length up to 30 cm. Attached to subjects BL fade usually as though boiling and throwing out sparks. On a statistician up to 50 % all apparent BL end the life with small explosion. Within the framework of our model it is possible to explain the circumscribed BL properties to that the outer envelope can have not only spherical, but also staircase form, demonstrating thereby some independence of separate current rings. During BL life separate rings by virtue of instability or the interactions with surrounding objects are torn and from BL the streams of high-velocity electrons and plasma by the way of sparks take off. Sometimes BL is simply parted on a few small BL. Low-current BL in absence of interactions with encirclement will simply be discharged almost silently and without the special effects.

CONCLUSION

Under the observational data BL frequently are spun in air or are bowled in subjects. At omitting on loose ground or peat BL are capable to dig holes or to scatter ground. A prompt motion of particles in BL directs at that circumstance, that in some cases of contact with it the people gained burn as from an electric current, and the subjects heated up or fused. According to model, offered us, the physical nature of BL the same, as well as for a usual lightning.

As motion of particles in BL in basic rotary, and in a linear lightning translational, from a philosophical point of view both types give an example of action of the complementarity principle in the nature. It is necessary to tell that for build-up of the BL model the same ideas, as in [16], were utilized at exposition of the scheme of origin of electric charge for fundamental particles.

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