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Birthplace of ball lightning

Abstract

Examples of ball lightning formation at high altitude near a linear lightning channel are considered. A photograph of ball lightning emerging from a linear lightning channel is shown. It is shown that the process of ball lightning formation lasts no more than 30 ms. A model of ball lightning formation due to the action of a magnetic field pulse of a linear lightning current on the ionized volume of space is described. A scheme has been proposed to explain a rare event - the gathering of ball lightning from sparks. Cases of the formation of ball lightning at a large distance from the site of a linear lightning strike, when energy was transferred through wires, are considered. It is noted that the process of formation of such ball lightning and their properties differ markedly from ball lightning appearing near the channel of linear lightning. This made it possible to distinguish these objects into a special type of ball lightning. A model of the process of formation of such ball lightning is described, according to which their core consists of ions flowing from the electrode of an air electrical capacitor (antenna, power line), and the shell material is dust particles. Cases of observation of objects with a size of 50 microns - 1 mm appearing during electrical discharges in water are considered. The analogy of these objects with miniature ball lightning is shown.

Keywords: formation of ball lightning; two types of ball lightning; miniature ball lightning

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Relationship between the place of ball lightning formation and the place of linear lightning discharge

According to statistics, the formation of ball lightning in nature is associated with thunderstorm activity. The summer months of June-August account for 83% of their observations, and if we add May and September to them, then this period will account for 93% of the total number of events.[1] In the Stakhanov's study, in 45 cases out of 1500, witnesses reported the formation of ball lightning near the channel of linear lightning. For example, one day student Sazonov saw how "three balls of bright white color separated from the middle part of the linear lightning channel and began to slowly fall. Their diameters were 30-50 cm".[1] In August 1970, "unusual lightning was observed in Pyatigorsk. Its main branched channel seemed quite "thick" and glowed for an unusually long time - about 1.5-2 seconds. After this, only the central channel of the lightning was remained, which in one or two seconds turned into a dotted line, slightly thinner. Then, within 5-7 seconds, the "strokes" of this dotted line gradually shortened, the distance between them became larger, but the brightness remained high... Then, at about the tenth second of the entire process of lightning evolution, the "strokes" completely contracted, turning into white balls with a diameter of 70-100 cm. After the formation of the balls for 10-15 seconds, the picture remained the same, only the brightness of the balls fell, and they decreased, becoming red. So gradually they went out. All this took 20-30 seconds".[2] A similar case was described by Brand:[3] "After a very powerful lightning discharge, a bead lightning passed through its channel. Individual luminous points, identical in shape, began to increase without changing their position in space until they became invisible. A few seconds later, a new lightning bolt passed through the same channel. Immediately after this, at the upper end of the lightning channel, just under the cloud, a luminous spherical mass appeared, which began to descend at low speed to the ground. A short time later, also after a powerful lightning discharge, the phenomenon repeated. However, this time the movement of the luminous mass was too fast for its shape to be determined." "During a bright flash of short linear lightning (cloud-to-cloud discharge), a ball appeared at one of its ends with a diameter of about one meter. Ball lightning began to fall down in a concave arc, gradually turning into a horizontal trajectory. Approximately ten seconds later, the ball lightning exploded like fireworks".[1] "A thunderstorm was starting, the clouds were hanging very low. It became dark as night. Suddenly lightning struck parallel to the ground, everything around was illuminated with light. Suddenly a second lightning struck the same place and, as if it had hit something, it crumbled into many balls that scattered in different directions. The lightning flashed somewhat flat and was almost parallel to the surface of the earth. Each time, after the lightning, balls the size of a child's ball or smaller appeared. It was difficult to determine their number - something around 50-100".[2] During a severe thunderstorm, unusual lightnings were observed: "At first, ordinary linear lightning of a reddish color appeared. Then, along the entire length of the horizontally located lightning channel, identical red balls with a diameter of about 20 centimeters appeared, reminiscent of the full moon in brightness. They flashed simultaneously, being at an equal distance from each other (10-15 diameters), then the lightning channel itself (the bridges between the balls) disappeared. Without changing their spatial position, dimming and throwing out sparks, the balls fell down and disappeared. The sparks also tended downward: those that were thrown upward changed their trajectory and, falling, went out at a distance of 2-3 ball diameters, their color did not change. It seemed that the balls always appeared at the slightest bend in the lightning channel, and in straight sections they were simply located at equal distances. This wasn't just one random lightning bolt. All this happened for a long time - 10-15 minutes. Lightning appeared for about 5 seconds, went out and after 2-3 minutes reappeared in the same place. About ten such discharges were observed. In total, about 40 balls were born in the garland; with each subsequent outbreak, the number and size of the balls were approximately the same".[2] "One of the branches of the lightning strike struck towards the ground at an angle of approximately 45^0, but did not reach the ground. This branch seemed to spin tangentially, and within a few fractions of a second a ball with a diameter of 30-40 centimeters was formed. The ball slowly floated downwards along the same tangent, and then in the direction of the wind, like a soap bubble.

Its speed was 1-2 m/s. The ball was reddish in color with a bluish halo around it, and its brightness resembled a candle flame".[2] "Lightning flashed in the form of two winding lines emanating from one point in the cloud. A fiery spiky ball with a diameter of about 8 centimeters flew off from one of the lines with a hiss. From the place where the ball separated, sparks fell and attached to the ball. At first, it seemed to hang in the air 20 centimeters from the linear lightning channel and 50 centimeters from the treetops. Then it began to slowly descend and disappeared behind these trees. All this lasted 5 seconds".[2] On February 1, 2002, during a very strong thunderstorm in Melbourne, Australia, Ern Manka, while photographing lightning, accidentally photographed ball lightning flying out of a linear lightning channel (Figure 1). The exposure time was several minutes; ball lightning appeared towards the end of the shot. Manka also observed ball lightning visually. Through television and newspaper advertisements, he found witnesses to this phenomenon. According to their testimony, ball lightning, after formation, remained motionless for a short time, and then suddenly rushed to the ground at a speed of about 720 km/h (200 m/s). The diameter of its crown was about 45 m. Having hit the ground, it divided into spheres of an indeterminate color, similar to the thread of a necklace.

Figure 1 Ball lightning emitted from a linear lightning channel.[4]

Jumping on the ground, it covered a distance of about 12 km. When faced with obstacles, it decreased slightly in size. The movement of the ball ended with a loud explosion and the appearance of a large area (30 m) of orange glow, which lasted about 5 seconds.[4] Figure 2 shows ball lightning captured by a car's video recorder. In Figure 3 the process of ball lightning formation is shown. The shooting frequency was 30 frames per second. After a flash of lightning, which lasted no more than 1/30 of a second, an image of ball lightning appeared in the next frame. From this we can conclude that the time of its formation was also no more than 1/30 of a second. The resulting ball lightning rose to the cloud within 12 seconds, moving away from the observer, and disappeared from view. Let us pay attention to the fact that in the frame b) it is clear that the linear lightning channel passed next to the left side of the road sign, where ball lightning then appeared. This indicates that it was formed near the linear lightning channel. The dimensions of the road sign are 70×70 cm. The diameter of the ball lightning after its appearance is 0.35 of the length of the side of the sign, and before disappearing it is 0.15 of this length. There are 5 cars between the sign and the camera. The length of the car is 4.5 m, the distance between them is 1 m, hence the distance between the sign and the camera $L = (4.5 + 1)\cdot 5 + 1.5 = 29$ m. The angular size of ball lightning at the beginning of movement is $\theta_i = 0.7\cdot 0.35/29 = 0.008448$ rad, and at the end of the movement – $\theta_c = 0.7\cdot 0.15/29 = 0.003621$ rad. Let us assume that the diameter D_{bl} of the ball lightning was equal to one meter. In this case, the distance to it was: at the beginning $L_i = D_{bl}/\theta_i = 118.4$ m, and at the end – $L_c = D_{bl}/\theta_c = 276.2$ m. Thus, ball lightning traveled a distance of 157.8 meters in 12 seconds with speed $v_{bl} = 13.15$ m/s. A ball of radius $R = 0.5$ m moving in the air is acted upon by a frictional force:[5]

$$F_t = C_x\cdot(\rho_a v_{bl}^2/2)\cdot\pi R^2 = 23 \text{ N}. \quad (1)$$

Figure 2 Location of observation of ball lightning in August 2022 in Tyumen. URL (31.08.2022) https://rutube.ru/video/cef51a778cd2419e0220d4f95ec29178/

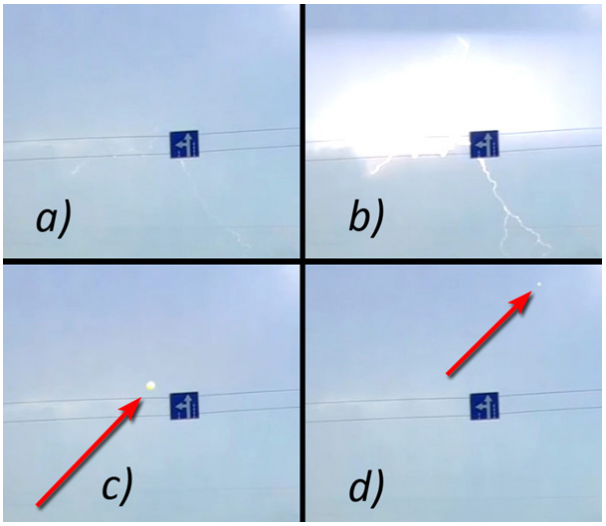

Figure 3 The sequences of ball lightning shooting. a) View before the lightning flash. b) Flash of lightning. c) The appearance of ball lightning. The repetition period of these three frames is 1/30 of a second. d) Position of ball lightning after 12 seconds.

Here $C_x = 0.3$ is the dimensionless coefficient, and $\rho_a = 1.13$ kg/m^3 is the air density. Let us estimate the minimum charge value of this ball lightning. Let's assume that its shell consisted of polarized water molecules. The condition for complete polarization of molecules is the requirement that the electric field strength at the location of the shell is not less than $E_{min} = 2\cdot 10^9$ V/m.[6] This condition can be met if the charge inside the shell of ball lightning is no less than

$$Q_{min} = 4\pi\varepsilon_0 R^2 E_{min} = 5.56\cdot 10^{-2} \text{ C}. \quad (2)$$

Charge carriers stretch the shell with a force[7]

$$F_Q = Q_{min}^2/8\pi\varepsilon_0 R^2. \quad (3)$$

This force is counteracted by the compression force of the shell in a non-uniform electric field[7]

$$F_{sh} = \sigma a\cdot 4\pi R^2\cdot \text{grad}\, E_{min} = 2\sigma a Q_{min}/\varepsilon_0 R. \quad (4)$$

Here $\sigma = 1$ C/m^2 is the density of dipole charges on the surface of the shell, and a is the thickness of the shell.[7] Equating F_Q to F_{sh}, we find

$$a = Q_{min}/16\pi R\sigma = 2.2\cdot 10^{-3} \text{ m}. \quad (5)$$

The volume of the shell $V_{en} = 4\pi R^2 a = 6.9 \cdot 10^{-3}$ m^3, and its mass $m_{en} = 6.9$ kg. The ball lightning rose to the cloud due to the action of the cloud's electric field E_{cl} on its charge. The friction force F_t and the force of gravity $F_g = m_{en} \cdot g$ acted opposite to this force. Equating $F_E = E_{cl} \cdot Q_{min}$ to the sum $F_t + F_g$, we find $E_{cl} = 1.63 \cdot 10^3$ V/m. This value of electric field strength is typical for the pre-thunderstorm period.

The above examples suggest that the main thing for the appearance of ball lightning is its proximity to the energy source - linear lightning. At its birth, it "uses" lightning energy and material found in the moist air. The above-mentioned observations about the connection between the place of its formation and the bends of the linear lightning channel are interesting. This is consistent with the fact that sometimes when shooting linear lightning with a Boys's camera (time sweep image), the curved sections of the channel glow longer than the main channel.[8]

Let's discuss how ball lightning can form inside the ring loop of a linear lightning channel.[9-12] During a discharge, near the channel atmospheric air is ionized under the influence of ultraviolet radiation. The resulting plasma is exposed to radiofrequency radiation from the discharge, the intensity of which is maximum at the center of the loop. This radiation pushes it from a region with high electromagnetic field strength to a region with low field strength.[13-15] High frequency radiation only causes electrons to move. However, when electrons are displaced, a polarization force appears, which drags positive ions along with them. The movement of plasma from the center of the loop to its periphery will also cause air movement. As a result, a cavity with reduced air pressure and a pressure gradient at its boundary can form in the center of the current loop. Typically, several successive discharges pass through the same lightning channel. Let a current pulse with a rise time of 10 μs and a fall time of 50 μs pass through the channel loop after the formation of a vacuum cavity. As the current increases, a magnetic field will be generated inside the loop, the vector of which is perpendicular to the plane of the loop, and an eddy electric field, the vector of which is directed opposite to the direction of the current flowing through the loop of the lightning channel and lies in the plane of the loop, will appear. Electrons located at the periphery of the vacuum cavity, under the influence of a magnetic field and an electric field orthogonal to it, in the presence of collisions with air molecules, will drift towards the center of the cavity. Positive ions (most likely protons) will also move in this direction, but due to the fact that their mass is much greater than the mass of an electron, their drift speed will be 10^6 times less than the electron drift speed.[12] Therefore, during the time the lightning current increases, only electrons will have time to reach the center of the cavity. Charge separation will occur and a radial electric field will appear in the space between the areas occupied by electrons and protons. When this field appears, protons will drift towards the center of the cavity. Some of them may get inside the cavity and begin to move in a circular orbit. The electrons, in turn, will drift in a closed orbit in mutually perpendicular electric and magnetic fields. During the period of decreasing current in the lightning channel, the direction of the vortex electric field vector will change to the opposite. In this case, the drift of charged particles to the center of the vacuum cavity will stop, but the process of accelerating protons will begin. It will occur due to an increase in potential as the proton orbit approaches the electron orbit. This can lead to an increase in the proton energy to 10^6 eV.[12] As a result of the described processes, a "dynamic electric capacitor" can be formed - a ring of electrons drifting under the action of orthogonal fields - a magnetic field created by the movement of protons, and an electric field in the space between the orbits of electrons and protons, rotating around the electron ring. However, the formation of a system of moving charges does not end there. Electrons and protons are "magnetized" only in a plane perpendicular to the magnetic field vector, but they can move in the direction of this vector. Electrons, due to their high mobility, can move away from the place of formation of the "dynamic capacitor" to a much greater distance than protons. The result of this will be the appearance of an uncompensated positive charge of the "capacitor". The expansion of this system can be stopped if, in a short time, a shell of polarized water molecules manages to form around it.

Many cases have also been described in which ball lightning occurred at the site where linear lightning struck objects on the ground. In 1953, a witness, who was at a distance of 10 meters from a lightning strike into the ground, saw how "a light yellow ball lightning with a diameter of 30-40 cm jumped out of the ground. Having risen to a height of 6-8 meters, it began to move parallel to the ground at a speed of about 1 m/s. Having walked 70 m, it came across a pine tree and exploded".[1] In May 1938, "after a lightning strike, multi-colored "splashes" of flame ran across a plowed field, so that it seemed as if the ground had "caught fire." After 3-5 seconds, the "splashes" gathered in a heap, forming a white fireball with a diameter of 50-70 cm. The ball broke away from the arable land, rose two meters above the surface of the earth and began to move along it. Its surface seemed to be boiling and seemed shaggy, and the "coats" on one side were longer than on the other".[1] "Linear lightning struck the same place in the ground twice with an interval of 15 minutes. Both times, after the discharge, a sheaf of sparks appeared, which then collected into a ball. The balls were a bright greenish-blue color with a diameter of 30-50 cm. Sparks flew from them in different directions. The balls moved, rising up approximately 5 meters, and then began to move horizontally. After 5-10 seconds, the balls disintegrated with the ejection of matter and went out".[1] "Linear lightning struck the wires not far from the pole. Following this, a yellow-green flash appeared on the wire near the pole, which began to "flare up". A ball with a diameter of about 15 cm was formed from it, which began to slowly roll along the sagging wire".[1] "After a discharge of linear lightning into a steel power transmission pole, a luminous purple ball with a diameter of 10-15 cm flew up from the site of the strike, which moved up in a straight line at high speed".[1] "Lightning struck a tree 20-25 m high, knocking off the top and splitting it. Simultaneously with this blow, a ball with a diameter of about 40 cm was formed one meter from the ground and approximately two meters from the tree. The color of the ball was white-yellow in the middle and orange on the edge".[1] "During a thunderstorm, lightning struck the lake. Ball lightning jumped out of the water at the site of the impact. It was 10-20 cm in size and orange in color. Having jumped to a height of 30-50 cm, it began to move horizontally along the surface of the water".[1]

Among these cases, observations of the formation of ball lightning from a cloud of sparks are of particular interest. Considering that ball lightning has an uncompensated electric charge, and the sparks from which it was collected were, in all likelihood, also charged, this process seems unlikely. However, cumulation processes are known, when a system is capable of significantly compressing a small part of its volume by dumping part of its mass. The idea of inertial thermonuclear fusion is based on this principle.[16] A target containing deuterium and tritium is irradiated symmetrically from all sides by laser beams. The resulting plasma scatters in the direction of the radius, and the recoil pulse of the plasma flow compresses the target core. Let us discuss whether a similar process is possible in a cloud of charged sparks. Let this cloud have the shape of a ball with radius $R = 0.5$ m, and the distance between neighboring sparks is 10 cm. In this case, $n = 10$ sparks can fit on a length of 1 meter, $n^2 = 100$ on an area of 1 m^2, and in a volume 1 m^3 – $n^3 = 1000$. Let the charge of each spark be $q = 10^{-5}$ C, and the mass be $m = 1$ g. The volume of a ball with

a radius R = 0.5 m is equal to V_b = 0.523 m^3, it contains $N_V = V_b \cdot n^3$ = 523 sparks. The surface area of the ball is $S_b = 4\pi R^2$ = 3.14 m^2, $N_S = S_b \cdot n^2$ = 314 sparks are located on it. A charged spark located inside a ball is subject to repulsion forces from neighboring charges, the resulting force being zero. In contrast, charges located on the surface of the sphere are subject to a force that forces them to fly away in the direction from the center of the ball. Inside the sphere there are $N_{in} = N_V - N_S$ = 523 – 314 = 209 sparks, the total charge of which is $Q_{in} = N_{in} \cdot q = 2.09 \cdot 10^{-3}$ C. This internal charged nucleus presses on the surface of the ball with a force:

$$F_e = \frac{Q_{in}^2}{8\pi\varepsilon_0 R^2} = 7.85 \cdot 10^4 \text{ N}. \quad (6)$$

Let the charge located on the surface, under the influence of this force, break away from the cloud and fly in the direction from the center of the ball. Force acting on the total charge of the "shell" $Q_S = q \cdot N_S = 3.14 \cdot 10^{-3}$ C:

$$F_S = \frac{Q_{in} Q_S}{4\pi\varepsilon_0 R^2}. \quad (7)$$

The work done by this force on the path from R to $R + L$:

$$A = \int_R^{R+L} \frac{Q_{in} Q_S}{4\pi\varepsilon_0} \cdot \frac{dR}{R^2} = \frac{Q_{in} Q_S}{4\pi\varepsilon_0} \left(\frac{1}{R} - \frac{1}{R+L} \right). \quad (8)$$

The moment of momentum of the detached sparks is $P = M_S \cdot v$ = 222.3 kg·m/s. The distance L = 1 m of the spark flew in time $\tau = L/v = 1.41 \cdot 10^{-3}$ s. The force with which the escaped sparks acted on the remaining core of charges is equal to $F_r = P/\tau = 1.58 \cdot 10^5$ N. This force is greater than the force $F_e = 7.85 \cdot 10^4$ N. The result of this will be compression of the core. This process can be repeated: new charges found there will fly away from the surface of the ball, which will lead to further compression of the core. If by this time a dielectric shell appears around it, ball lightning may form.

Thus, the presence of an object at the site of a lightning strike does not lead to a significant difference in the appearance of ball lightning from balls that appear at a great distance from the ground. At the same time, thanks to the proximity of the object, it is possible to notice the details of the process of its formation: the collection of "sparks" and the appearance at some distance from the place where the current passes (when lightning strikes a tree). However, there is no doubt about the source of its energy - this is the energy of linear lightning. In this regard, cases of formation of ball lightning far from the site of a linear lightning strike remain a topic for discussion.

The case of the appearance of several ball lightnings after a positive lightning strike with a current of 370 kA near the city of Neuruppin in Germany is described in detail in the article[17] and book.[4] "In Neuruppin, a small town northwest of Berlin, January 14, 1994 was a fairly warm winter day. There were clouds in the sky, but there was no rain, except for a light drizzle. Th. Hinz, who was on duty at the weather station, described the event that occurred after 16 hours of Universal Coordination Time (UTC): "An exceptionally bright flash of light was visible in the north, followed 10 seconds later by a very loud clap of thunder." An entry appeared in the station's diary: "Thunderstorm (light) northeast (NE) 16.06-16.28" (UTC time). The thunder was indeed very strong, as people compared it to a bomb explosion. The location of the lightning strike to the ground was 5 km east of the city. A large number of ball lightnings have been observed in Neuruppin. Two large ball lightnings were outside the premises: one of them stood motionless over the roofs, and the other moved over the bridge. Smaller ball lightnings were seen both indoors and outdoors: two moved from outside into houses, one through a window through which it then left the house, and the other entered an open window and passed through the curtain. Two ball lightnings were inside the room all the time, but lived for a short time and did not move at all. The total number of objects recorded was 11, but it is possible that the number was higher.

Here are some examples of observing ball lightning in Neuruppin. "The woman was sitting in the room doing needlework. The door to the balcony was open, but the curtains were closed, as usual. Suddenly, a bright ball flew into the room through the window and instantly disappeared. It happened so quickly that she did not have time to remember the color of the ball and its other features. Shortly thereafter, an extremely strong clap of thunder sounded outside, stunning her".[4] "A boy sitting at the table saw a very bright white ball the size of a football approaching him. It moved very quickly. Immediately after this, there was a strong clap of thunder, which made the cups in the buffet rattle".[4] "The driver was driving with his wife in the car. They noticed a pale white ball hanging motionless over the rooftops. Then the object disappeared, as if it had been "turned off." A few seconds later, there was a strong clap of thunder".[4] "The young man and his friend were riding bicycles. Suddenly they heard a strong clap of thunder, which frightened them. Following this, they saw a round white or yellowish object approaching from above. Having touched the ground, this object silently disappeared. At that moment, one of the street lights went out".[4] "While talking on the phone, the man noticed a bright light outside the window on the roof near the chimney. A luminous object descended from the roof along an inclined path and approached the window. The object looked like a flying saucer and did not have a clear boundary. After a short time, the "plate" flew vertically upward. Following this, a strong clap of thunder was heard".[4] "A man and a friend were driving to the city center by car. Suddenly something very bright approached them. Everything around them was illuminated with a bright light, so that they could not see anything through the car window. The object may have passed directly over the car's roof. Shifting to the right, it either disappeared into the lake or simply disappeared into thin air. Only then did they stop the car. The driver accidentally touched the car's roof with his hand. Before this, the car had been driving for about two minutes, and the air was cold. However, the roof seemed warm to him. Suddenly, after this, there was a strong clap of thunder. The car radio was not damaged".[4] "Suddenly, a luminous object with a diameter of 50-60 cm appeared in the workshop, one meter from the floor, filling the room with a bluish light, bright as the sun. The glow lasted no more than a second. Shortly after this, a loud, terrible crash was heard that pinned the observers to the wall. The workshop equipment was not damaged. All windows in the room were closed".[4] "The woman was talking to a friend on the phone, who asked her why the line was crackling. Suddenly the entire sky lit up with a strong blue light. It pulsed, flaring up and dying out. Suddenly she noticed blue sparks flying out of the telephone receiver's microphone. Frightened, she asked her friend if she saw something like that. She replied that no. After this, a terrible thunder was heard, which made the woman jump, and everything became silent".[4]

As we can see, in all cases of the observation, ball lightning or other light phenomena appeared in Neuruppin before the arrival of the sound of thunder. This means that the energy required to create them was transferred to the site of their formation at high speed, most likely the speed of light. Electromagnetic radiation generated by the linear lightning channel propagates at this speed. It seems natural to assume that energy transfer occurred along waveguides that permeate the territory of industrialized countries. In other cases, such "waveguides" could serve, for example, underground water flows.

A striking example of the delivery of energy to create ball lightning through electrical wires is the observation described below. "In calm, clear, windless weather the observer's attention was attracted by the sounds of some shots similar to rifle shots. He saw fiery bright yellow balls with a diameter of about 30 centimeters flying along high-voltage wires. The balls were born one after another 4-5 meters from the pole and slid along the upper wires at the speed of a thrown stone. In about two seconds, three balls were born and, maintaining a distance of five to six meters, they rolled with a hiss and crackle, rather than sliding along the wire. So they moved until the next pole, then the wires went into the ground. Not reaching the cup of the insulator about seventy centimeters, the balls jumped over the pole with a margin of 50-60 centimeters and, once behind the pole in the air, abruptly stopped and lazily floated near the pole within a radius of 5 meters for 3-5 seconds, and then collapsed as if then inside with a bang-shot. Not a single spark or ash fell to the ground. Each individual ball was formed as follows. Approximately four meters from the pole, a flame appeared on the top wire on a section of wire 1.5 meters long. The height of the flame at the very beginning was 7 cm, and then downward towards the end it decreased to zero (came to naught). The flame was not on the wire, but seemed to hang about a centimeter above it. Suddenly this flame sharply curled up into some kind of lump, not much like a ball: hooked, angular, full of holes, yellow-brown red in color. Having rolled about four meters, this lump grew into a perfect ball of bright yellow color with a diameter of 30 centimeters. Then it rolled without changing either color or shape. The flame that curled up was only enough for a ball the size of a chicken egg, and from it a ball the size of a football was inflated. All this lasted for about five minutes according to a completely unchanged scenario: the first ball is jumping through the insulator, the second is on its way, the third is just being formed, and more than four balls are lazily flying around the pole. This performance had stopped as suddenly as it began".[2]

As you can see, ball lightning can be formed due to the energy of linear lightning transferred over a long distance along electrical wires. However, in contrast to ball lightning born near linear lightning, which is formed within a fraction of a second, the process of formation of such ball lightning lasts several seconds. This gives reason to assume that such ball lightning has properties that distinguish them from ordinary ball lightning.

Formation of ball lightning inside electrical appliances. Two types of ball lightning

Among the reports about ball lightning, a fairly large part is occupied by descriptions of its appearance from electrical sockets, telephone sets, loudspeakers, and even electric irons. Typically, these events occurred during a thunderstorm, and electrical appliances were connected to overhead electrical lines. Here are typical examples of describing these phenomena. "It was raining and thunderstorm outside the window. There was a loudspeaker in the form of a black plate hanging on the wall. Due to the thunderstorm it was turned off. A crash was heard, and at the same time a spark appeared in the center of the loudspeaker. It began to grow, and after 3 seconds a fiery yellow ball with a diameter of 25-30 centimeters was formed. The ball slowly and smoothly floated across the room for 7-8 meters and went through the broken glass into the garden. From a distance, it looked somehow faded, dim".[2] "A thunderstorm has just thundered. Suddenly, a luminous point appeared in the center of the loudspeaker connected to the network. It increased, then its brightness weakened, and clouds of purple dirt crawled out of the loudspeaker. The clubs formed into a clear outline of a ball with a volume of half a soccer ball. The ball rose up 50-70 centimeters, after that it floated horizontally (in a parallel stream of air from the window). Its color changed all the time: from a dark dirty purple it became like the color of an anthracite flame, then it turned pale and became golden-cream color... The whole phenomenon lasted 10 seconds. The loudspeaker remained operational.[2] "An antenna was stretched over the roof of the house on poles about twelve meters high. There was a detector receiver with headphones on the window. On the window frame there was a primitive lightning protection switch: one plate was "ground", the second was "antenna", in the middle was a switch key (usually during a thunderstorm the antenna was connected to ground using a switch, but in the case under discussion this was not done). Suddenly lightning flashed brightly, a strong clap of thunder was heard, and two or three seconds later a fireball began to grow between the ridges of the lightning protection plates, crackling and hissing. An unfamiliar smell began to spread in the room, sharp and stinging in the nose. We looked, spellbound, at the growing ball of bluish-yellow color, bright as a 100-150 W electric light bulb. Its surface seemed matte, and around there was a halo up to one centimeter thick with a bluish tint. Having reached a size of 12-15 centimeters, the ball stopped growing, and then began to shrink with a hiss and disappeared. We observed it for 5-6 seconds. The lightning switch was placed on the "antenna". A gap between both plates was about three millimeters".[2] "After a close, deafening lightning discharge from a semaphore electrical inductor... a bright blue ball with a diameter of 1.5-2 centimeters slowly separated with a click. Very slowly this ball floated through the air to the middle of the room. As it moved, the ball increased in size to 6-7 centimeters. Its color became bluish-light. So a minute and a half passed, during which time the ball moved about two meters. And suddenly the ball disappeared - just as suddenly as it appeared".[2] "During a thunderstorm, the owner of the apartment pulled the plug of the loudspeaker out of the socket, and I turned off the switch. At that moment, in two places at once: in the radio socket and inside the switch, a strange hissing sound was heard, slight sharp clicks, and rapidly two bright purple balls measuring 6-7 centimeters fell from the socket and from the switch to the floor. Throwing diagonally across the kitchen, both balls at the moment of contact made another click, similar to a spark discharge, and jumped out through the window glass into the street. After a second or two they disappeared. The socket and the switch were charred".[2] "Almost simultaneously with the flash of a very strong lightning discharge, an orange glowing ball began to blow out of the electrical outlet (like a soap bubble from a straw). When the ball reached the size of a football, it came off the socket and floated across the room to the window. Having flown up to the window, the ball, without slowing down its movement or changing its shape, passed through the glass, as if there was no glass at all. In a yard the ball exploded with a roar".[2] One day, the attention of a married couple "was attracted by a luminous ball floating out of a socket. The ball seemed to be freed from captivity - it floated out, increasing in size to 4-5 millimeters and taking on an ideal spherical shape. In 2-3 seconds, it swam a little in the plane of the socket holes, moving 1 cm away from the wall, then returned and disappeared into the second socket hole. While moving the ball trembled and swayed, as if on a stretcher. The most surprising thing was the color of the ball. In the initial phase, when leaving the hole, the ball had a deep orange color. When it was fully formed, it became transparent orange. Then, as the ball moved, its color changed to lemon-yellow, from which a piercing, juicy green color (the color of fresh greenery) suddenly emerged. When moving to the second hole, the color of the ball changed from green to pale blue, and just before the entrance to the socket it became dull gray-blue".[2]

"Along with a strong lightning discharge, a cracking sound was heard near the radio socket, into which the loudspeaker plug was

not plugged in. Raising his head, the witness noticed that a dark red ball was hanging at a distance of less than a meter from the socket. The ball floated to the open door and went out into the street. There it exploded. The external input of the radio wiring was burned out, the socket was melted".[1] During a thunderstorm, "a hissing was heard from the loudspeaker. From the socket terminal into which the loudspeaker plug was inserted, a yellow stream about 10 cm long began to flow out, which quickly twisted into a ball. Irregularities similar to thorns formed on the surface of the ball. The core glowed orange, and the spikes were somewhat darker. Within 2-3 seconds, the hissing stopped, and a luminous spherical mass formed, from which a faint rustling sound emanated. The ball made a circle around the room and, returning to the socket, disappeared with a crash and a bright flash. There was a spot of burnt paint with a diameter of 25-30 cm left on the floor, and soot on the stone wall".[1] Figure 4 shows the process of formation of a ball from a luminous mass emerging from a socket. The picture was drawn based on the witness's story.[18] It can be seen that the luminous mass in the form of cords comes out of the socket holes, and then forms a ball, which after some time begins to glow. Sometimes luminous balls appear without the participation of a thunderstorm when there is a short circuit in the ordinary electrical network. One day, from an electric iron, "which usually sparked when turned on, instead of sparks, a luminous bluish-white ball with a diameter of about 1.5-2 cm flew out and disappeared, colliding with an iron stove. A surface of the ball was mirror-smooth".[1] In the engineer's apartment, during a short circuit, "a luminous ball with a diameter of 10-15 cm appeared. It rolled across the floor for about a meter and went out, leaving no consequences. During a short circuit, an insulation at the point of contact caught a fire".[1]

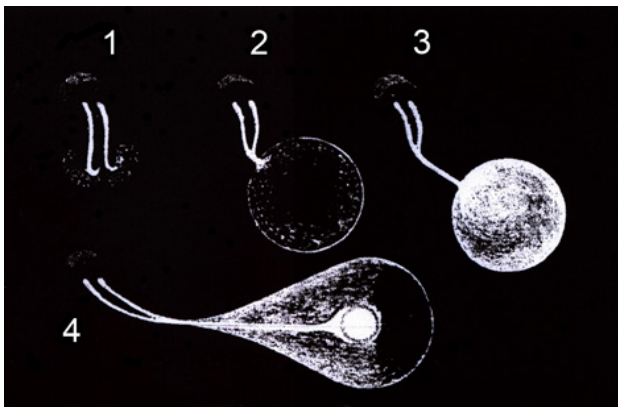

Figure 4 "Blowing" ball lightning out of an electrical socket. 1-2 – start of the process. 3 – a beginning of ball formation. 4 – an ignition of a "fire".[18]

According to the electrodynamic model,[10-12] to create an object with the properties of ball lightning, it is necessary to have a certain number of charge carriers of the same sign and material to create a shell that restrains the Coulomb repulsion of charges. Charge carriers can accumulate in some kind of capacitor, for example, in an overhead power line or in an outdoor radio antenna, if a part of the linear lightning charge hits them. In the early and mid-20th century, telegraph, telephone, and radio communications were carried out using open wire lines, so they could also act as this capacitor. In the above description[2] a story about blowing a luminous ball from the gap between the metal plates of the lightning switch of the detector receiver antenna is talked. One plate was attached to the wire leading to the antenna, and the second was connected to a metal object buried in the ground. Let the horizontal part of the antenna be a wire with a diameter of 2 mm, suspended on insulators to poles 12 m high, and the length of the wire was equal to L_a = 20 m. The antenna can be represented as a coaxial capacitor with a central wire of radius r_c = 1 mm and an outer electrode of radius R_c = 12 m. The capacity of such a capacitor is $C_a = \pi\varepsilon_0 L_a/\ln(R_c/r_c) = 5.92\cdot10^{-11}$ F. Let us assume that linear lightning transferred a negative charge $Q_a = 10^{-2}$ C to this capacitor. Then the potential of the capacitor will become equal to $U_a = Q_a/C_a = 1.7\cdot10^8$ V, and the electric field energy accumulated in it will be $W_{ea} = Q_a^2/2C_a = 8.4\cdot10^5$ J. A corona discharge will appear at the edge of the lightning switch plate connected to the antenna.[19] If it lasts τ = 10 seconds, the average value of the current will be equal to $I_{av} = Q_a/\tau = 10^{-3}$ A. An electron, gaining speed in a strong electric field, when colliding with an air molecule will ionize it, as a result of which a new electron and positive ion will appear. This electron, accelerated in an electric field, will create a new electron upon collision with a molecule. That is, an avalanche increase in the number of electrons will occur. The development of this is hampered by the process of attachment of some electrons to oxygen molecules. At a negative potential of electrode, the number of electrons increases in the direction away from the electrode. In this direction, the field strength decreases, and at the certain distance from the electrode the process of avalanche formation stops. Trichel[20,21] found that the negative corona discharge current is intermittent. During the development of an electron avalanche, almost the same number of electrons and positive ions are formed near the negatively charged electrode (cathode). The ions move towards the cathode. When the distance between the ions' cloud and the cathode becomes too small for the process of avalanches developing, the current stops. An electric field with a strength value sufficient to form a new avalanche can be restored only when the electrons leave the ionization zone. The pulse repetition rate depends on the rate at which electrons leave this zone; typical values of this frequency are 1-3 MHz.[22] Estimates show that the negative charge is transferred both by O_2^- ions and free electrons.[23]

Let us assume that dust particles move simultaneously with the electrons in the direction from the cathode. We will consider these dust grains to be balls with a diameter of $d_d = 4\cdot10^{-6}$ m. In the electric field created by the charge Q of the cloud of negative ions, the dust grains will be polarized, and from them a spherical shell with a radius $R = 5\cdot10^{-2}$ m can be formed around this cloud. The charges inside the shell stretch it with force:

$$F_Q = Q^2/8\pi\varepsilon_0 R^2. \quad (9)$$

The force of compression of the shell by a layer of polarized dust grains can be determined by the formula:[7]

$$F_{sh} = \sigma_d \cdot a \cdot 4\pi R^2 \cdot \text{grad}\, E = 2\,\sigma_d \cdot a \cdot Q/\varepsilon_0 R. \quad (10)$$

Here σ_d is the charge density of the ends of the dipoles on the surface of the shell, a is the thickness of the shell, and E is the electric field strength created by charge Q at a distance R. For a shell of water molecules σ = 1 C/m^2.[10-12] For a shell of dust particles we take $\sigma_d = 10^{-1}$ C/m^2. Let the shell consist of 100 layers of dust grains, then $a = 100\, d_d = 4\cdot10^{-4}$ m. Equating F_Q to F_{sh}, we find:

$$Q = 16\pi\sigma_d \cdot a \cdot R = 10^{-4}\ \text{C}. \quad (11)$$

With a discharge current of $I_{av} = 10^{-3}$ A, a charge of 10^{-4} C can accumulate in 0.1 seconds. The volume of the shell is equal to $V_{en} = 4\pi R^2 a = 1.26\cdot10^{-5}$ m^3. If the dust was laying in a layer 1 mm thick, then it was collected from an area of 100 cm^2. The electric field strength created by a charge of 10^{-4} C at a distance of $5\cdot10^{-2}$ m is equal to $3.6\cdot10^8$ V/m. At such field strength, a corona discharge can appear on the surface of the shell, supported by a current of electrons "leaked" through the shell. In the corona discharge, electronically excited molecules of nitrogen dioxide NO_2 are formed.[24]

Thus, we come to the conclusion about the possibility of the existence of a new type of ball lightning, in which the charge carriers are not energy-intensive structures consisting of moving ions and electrons, but ordinary ions. The properties of ball lightning of this type should differ from the properties of high-energy ball lightning. Apparently, Stakhanov's assumption[1] about the existence of two types of ball lightning with different values of the duration of existence is somehow consistent with our conclusion. And, indeed, ball lightning that appears from sockets is low-energy. They leave virtually no traces, and their explosion indoors does not cause much destruction. The light emitters in high-energy ball lightning are its core (relativistic electrons) and the corona discharge on its surface. For "ionic" ball lightning, only the corona discharge remains the source of luminescence. The main emitter of light in a corona discharge is electronically excited nitrogen dioxide molecules, the emission spectrum of which lies in the short-wave region. Therefore, we can expect 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.

The Table 1 shows the probability of observing the color of ball lightning coming out of the "socket", obtained based on processing 26 messages from the Grigoriev's book.[2] The second column of the table presents the color probability distribution found by Grigoriev for an array of 1803 descriptions of ball lightning. From a comparison of the rows of the table, it is clear that in the spectra of "low-energy" ball lightning observed indoors, the colors of the "blue" part of the spectrum predominate. The green color appears to be due to the presence of copper atoms created by the evaporation of wires connected to sockets.

Table 1 Probability of observing the color of ball lightning

Color	Part, BL from "sockets"	Part, all BL[2]
Red	0.111	0.136
Orange	0.037	0.351
Yellow	0.259	0.17
Green	0.074	0.012
Bluish	0.148	0.081
Blue	0.111	0.027
Purple	0.148	0.027
White	0.111	0.137

According to the hypothesis described above, to create ball lightning, a source of electric charges of the same sign is required. However, there are known cases when luminous balls appeared during malfunctions of power electrical circuits powered by alternating voltage. It can be assumed that in these cases ball lightnings with an "ionic" energy core were formed. To create them, you need a strong current and a material to form the shell (water, plastic, etc.). "Ionic" ball lightning can occur at both positive and negative electrodes, so its charge can be of any sign. However, it is unlikely that ball lightning with charges of different signs could form in 1/50 of a second. It is more logical to assume that there was some kind of valve in the electrical circuit that passed current in one direction (rectifier). Apparently, this can explain the cause of the incident that happened in January 1954 in the village of Rodinskaya, Donetsk region. "At school, something happened to the firebox and pipes burst in the attic. Water penetrated the ceilings of the second floor classrooms. Wires ran to nine light bulbs in each classroom. The wires were inside the plaster, but the insulation was fabric at that time. The ceiling was not completely wet, but dry areas alternated with wet ones. When we opened the classroom doors, we saw hundreds of ball lightning of blue, azure, greenish colors, there were fewer yellow and orange balls. They jumped out of the wiring and wet areas of the ceiling. Some balls moved towards each other, others - in opposite directions. Some, colliding, formed a large one out of two, and some were repelled and rolled in different directions. All this resembled a large anthill. At the junction of the wires near the corner light bulbs there were garlands of balls of different colors, the largest ones were orange and red. As the balls moved, a faint cracking sound could be heard from wherever they were. There was a faint smell of ozone".[2]

Micro-sized ball lightning that appears during electrical discharges in water

Matsumoto[25] studied the results of the action of electric discharges in an electrolyte. A solution (1.5 mol/l) of potassium carbonate or bicarbonate (K_2CO_3; $KHCO_3$) in tap water was used. Wires with a diameter of 0.1-2 mm made of palladium, platinum, nickel, cadmium, iron, gold or lead were used as a cathode. The anode was a polished copper plate partially immersed in liquid. Pulses of direct or alternating (50 Hz) current with a voltage above 40 V were applied to the electrodes. The current-voltage discharge curve demonstrated a strong nonlinearity of the process, from which it was concluded that there was compression of the current channel due to the pinch effect. When the discharge was powered by alternating current, a voltage of 120 V was applied to the electrodes, which was periodically turned on for 20 ms and then turned off for 20-30 seconds. When voltage was applied, small sparks were observed on the surface of the cathode, and traces of round objects measuring about 50 microns in size were found on the copper plate. The same traces were recorded on X-ray photographic film located near the discharge site (Figure 5). Matsumoto believes that these traces were left by clusters of hydrogen atoms, which are highly compressed by degenerate electrons that interact strongly with each other.

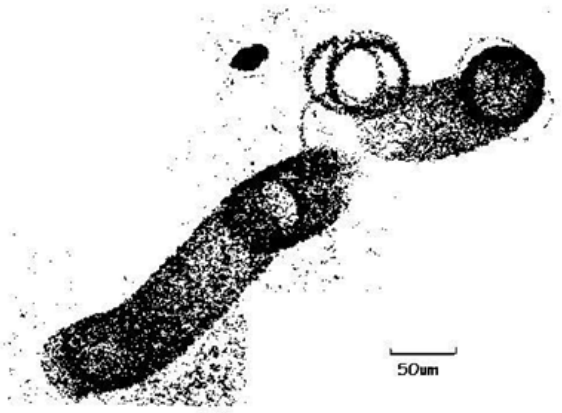

Figure 5 Traces of objects appearing during electrical discharges in water.[25]

The article[26] describes the properties of long-lived luminous objects that appear during electrical discharges in water. The average size of these objects was 1 mm; when leaving the water into the air, their size increased to 5 mm. They looked like orange spheres. Their glow time (up to 0.1 s) was four orders of magnitude longer than the characteristic recombination time of the discharge plasma. The spheres were formed from amorphous luminous clouds during the period when the discharge plasma had time to completely recombine. Experiments have shown that the luminous objects are not particles of hot electrode material, pieces of non-ideal plasma, or a chemical reaction zone. All this indicates that long-lived luminous objects were formed not from the discharge plasma, but from its decay products. Figure 6, taken from the article,[26] shows 9 frames of a film about the

movement of spherical objects in the air. The sequence of frames is from left to right and from top to bottom. The frame exposure time was 5 μs, the interval between frames was 100 μs. The first four frames capture the process of condensation of the left sphere from the cloud. In the next five frames, these spheres move away from each other. The graph of changes in the distance x between them (points) is shown in Figure 7. The dependence of distance on time is well approximated by the curve $x = k \cdot t^{1/2}$. This suggests that each sphere has an electrical charge. Indeed, the repulsion force of charged spheres is $F_{rep} = A/x^2$, and their braking force in the air is $F_{fr} = B \cdot (dx/dt)^2$. Equating F_{rep} to F_{fr} and solving the equation, we get $x = (4A/B)^{1/4} \cdot t^{1/2} = k \cdot t^{1/2}$.

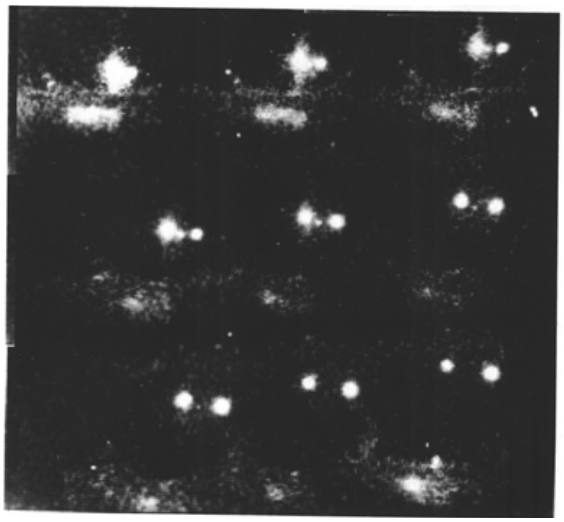

Figure 6 Film footage of the movement of luminous objects in the air.[26]

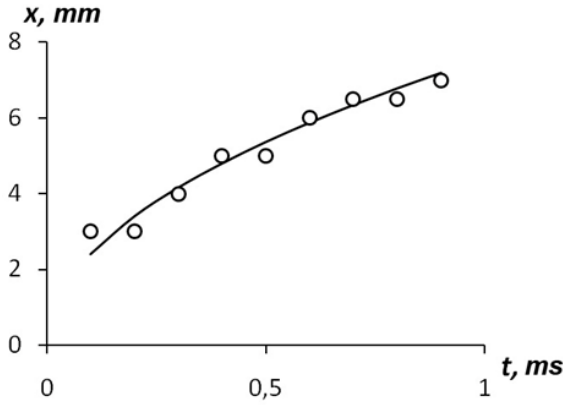

Figure 7 Graph of the dispersion of luminous objects. Circles – the distance between neighboring objects. The curve is constructed using the formula $x = k\,t^{1/2}$.

Let us take the diameter of the sphere as a scale to be 5 mm. In $8 \cdot 10^{-4}$ s, the two spheres diverged by a distance of 8 mm, hence the speed of each of them is $v = 0.5 \cdot (8\text{ mm}/8 \cdot 10^{-4}\text{ s}) = 5$ m/s.

Edward Lewis,[27] analyzing the traces left by objects such as "microscopic ball lightning" on photographic films and other materials, saw their analogy with the traces left by tornadoes. However, he sees many more analogies in the behavior of microscopic and ordinary ball lightning. They are capable of making holes, passing through materials without leaving traces, possessing abnormally high energy, and demonstrating an unusual pattern of movement. In the experiments of Urutskoev et al.,[28] these microscopic objects left traces in the form of chains and lines in the emulsion of photographic films and on the surface of various materials.

We have shown that the properties of objects that appear during electrical discharges in water are similar to the properties of a "multiple charged water cluster" - an ensemble of ions of the same sign located inside a shell of polarized water molecules.[12,29-32] These clusters form near the electrode, where the density of ions that transfer charge in the liquid increases. The likelihood of this process increases when using electrodes with a small area (thin wires). Clusters with a positive charge are formed near the cathode, and clusters with a negative charge are formed near the anode. The material for creating the shell is water surrounding the current channel. The details of this process remain to be explored.

Conclusion

One of the main reasons that were preventing us from understanding the nature of ball lightning for more than a hundred years is its "many faces character". On the one hand, it is a harmless glowing flashlight that looks like a balloon. On the other hand, it is a "dangerous beast" that can cause electric shock and explosion. Among the ancient Slavs, ball lightning was even a symbol of the stern pagan god Rod.[33] "Many faces character" has led to the emergence of a large number of models of ball lightning, capable of explaining only a small part of its many properties. As a rule, the process of its formation lasts a fraction of a second, and the naked human eye cannot notice the details of this process. The time and place of the appearance of ball lightning is unpredictable, which makes it impossible to use instruments to study the process of its birth. Scientists who have studied ball lightning have repeatedly suggested that in nature there are several types of ball lightning.[1,34,35] This article shows that this is indeed the case. All ball lightnings are built on the same principle - it is a unipolarly charged core enclosed in a shell of polarized particles. However, in some of them the charge carriers are structures with high kinetic energy. Such ball lightning is formed in the immediate vicinity of the linear lightning channel. Ball lightning of the second type can be formed at a great distance from the linear lightning channel during the discharge of an electrical capacitor (aerial antenna, power line) that has received a charge from linear lightning. The charge carriers in such ball lightning are low-mobility ions. Accordingly, the energetic effect of such ball lightning turns out to be weaker than the effect of ball lightning of the first type. The size range of ball lightning of both types extends from tens of microns to several meters, and the lifetime is from several seconds to several minutes. The authors of the article[36] showed that the lifetime of ball lightning increases with its size. An approximation of this dependence shows that the lifetime of ball lightning 10-20 m in size can be 1-2 hours. This gives grounds to include unidentified flying objects in the category of ball lightning.

Acknowledgments

None.

Conflicts of interest

None.

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