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How does ball lightning work?

Abstract

The results of observations are described when ball lightning left material traces in the form of stone, metal balls, and molten metal after disappearing. There are also cases where ball lightning moved heavy objects over long distances: iron cages, people, magnets and even a train. This is explained by an assumption that the attraction of objects to ball lightning proceeds due to their polarization in its electric field and action of the electric field of clouds on it. Events are described when ball lightning dug trenches in wet soil and made deep holes in the ground. An explanation for these actions is given.

Keywords: ball lightning, carrying objects, ball lightning charge, atmospheric electric field

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Ball lightning can carry objects

In the article[1] we talked about the fact that, according to observations, the materials for ball lightning formation in nature are water and air. From the point of view of an ordinary designer, this state of affairs seems absurd: why was the choice so poor given the enormous wealth of possibilities (the use of metals, ceramics, etc.). This is probably why cases where solid materials were found in the traces left by ball lightning are of particular interest. The most "famous" case (on the basis of which several models of ball lightning were even created) is the discovery of ball lightning with a stone. "In 1953 we lived in a one-story house in Budapest. One day after a summer thunderstorm, when I was in the room with my grandmother and younger sister, ball lightning flew through the window. It flew with a whistle along the wall at a height of one and a half meters from the floor. A stone with a diameter of 10-15 cm fell out of it. It was black, smooth and approximately spherical in shape. The stone fell on the floor near an electrical outlet and remained in the room. The electric wire burned out and the apartment was left without electricity. We kept this stone for several years. Later, when we moved, we lost it. Then we had never seen such a stone anywhere near us. There were flowers growing in our garden and there were no stones on the ground. I am sure, that it was not iron, it was an ordinary stone".[2] The mass of a stone with a diameter of 15 cm is about one kilogram. Thus, it turns out that ball lightning should "be able" to carry heavy objects. The fact that such an action is possible is proven by other cases of observation of ball lightning. "One hot day in 1934, a group of young people were getting ready to go to a dance. There was a small cloud in sky and lightning flashed occasionally. Suddenly, after a strong thunder, ball lightning flew into the room through the open window. It threw one of the guys out of the room into the garden and knocked the rest down. Then it quickly flew around the room, pulled the fork towards it and disappeared. No one was hurt and everyone went to the dance. All this lasted 3-4 seconds".[2]

"On July 19, 2003, ball lightning the size of a soccer ball flew into the kitchen where two women were sitting. It exploded and hot metal balls spilled onto the floor. They quickly went out, leaving burn marks on the linoleum. There was an ozone smell in the room. Analysis showed that the balls were hollow spheres made of pure iron with a diameter of 0.3-1.2 mm and a wall thickness $a = 10$ μm".[3] The volume of the wall of a ball with a diameter $d = 1.2 \cdot 10^{-3}$ m is $V_b = \pi D^2 a = 4.52 \cdot 10^{-11}$ m^3, and its mass $m_b = V_b \cdot \rho_{Fe} = 3.36 \cdot 10^{-4}$ g. 15 balls were collected. Let's assume that there were 10 times more of them, then their total mass was $M_b = 5 \cdot 10^{-2}$ g. In[4] a case is described when ball lightning left behind fragments of an unknown nature. "The event occurred on one of the days in the spring or summer of 2011 in the village of Gofitskoye, Labinsky district, Krasnodar region, Russia. In the interval of 15-17 hours, a ball with a diameter 25 cm was seen flying at an altitude of 7-8 m at a speed 4-8 m/s. The ball looked like red-hot metal. It sparkled like a fire, but there was no flame. The observation lasted several minutes. The ball approached the courtyard gate and "leaked" through the gap between the gate frame and the support with hinges, changing its shape like a liquid substance. Then the ball came out entirely from the other side of the gate and took its previous shape. Having flown another 1.5-2 meters, it landed on the asphalt scaffolding of the building and burned with a hiss. There were no traces of impact left on the gate or asphalt. At the landing site, small fragments similar to slag were found, the total volume of which was about 100 cm^3. On the surface of the cooling ball, the witness noticed three symmetrically located bulges the size of half a pea. A smell emanated from this place, similar to the one that appears when using a flint (when you hit a flint on a stone to create sparks) or when doing electric welding. This smell was felt in the yard for several days. The fragments left by ball lightning were shivers of 0.5-1.5 cm in size. The material crumbled easily, and its surface was covered with many cracks. The pieces were attracted to the magnet. Analysis showed that the substance of the fragments consisted of iron oxide in combination with silicon and calcium. It contained traces of carbon, zinc, magnesium, aluminum, phosphorus, sulfur, chlorine, potassium and titanium." "Approaching the town of Cancil Bluff (USA), the driver and passenger saw a red ball falling to the ground ahead, half a mile away from them. Having approached the place where the ball fell, they discovered a thick layer of molten metal on the frozen ground. The red-orange layer glowed for more than 15 minutes. After cooling, the metal was taken for analysis. Its weight was about 20 kg, it was a carbon steel with slag".[5]

The described and similar facts were warmly welcomed by the authors of ball lightning models, according to which it is formed when linear lightning strikes the ground. For this reason, its composition must include silicon, carbon and other solid components of the soil.[6] These models were also supported by the observation of Chinese scientists who recorded the optical spectrum of a luminous ball formed near the earth after a linear lightning strike.[7] Lines of silicon, iron and aluminum were detected in the spectrum. However, a more

thorough analysis of this event showed that the researchers recorded not the emission spectrum of ball lightning, but the spectrum of an arc discharge between the wires of a power line. The intensity of the ball's glow pulsed at a frequency 100 Hz, which is exactly twice the frequency of electric current in China (50 Hz). Despite this, work[7] is constantly cited as evidence of the observation of ball lightning.

Let us discuss the results of observations of the ball lightning disappearance. The overwhelming majority of them indicate that the substance of ball lightning cannot contain solid substances - silicon oxide, metals or organic compounds. Of the condensed substances, it can only contain water.[1] This composition of ball lightning corresponds to its model in the form of a "balloon" or in the form of an electrical discharge in the air. But these models cannot explain how ball lightning jumps and why it sometimes leaves behind traces of solid matter. In models of ball lightning with a hard shell of metal or silicon oxide,[6,8,9] questions about the mechanisms of its levitation and passage through small holes remain unanswered. Therefore, it seems strange that instead of searching for ways to explain the typical behavior of ball lightning, the isolated cases in which it left behind "material" traces are of hypertrophied interest, and on this basis models of ball lightning are "built." Ball lightning, observed in the village of Gofitskoye, gave the author of the article[4] reason to assume that "the elements which were founded in the fragments ... can react in the combustion of thermite mixtures with the release of colossal amounts of thermal energy." Gromyko[3] believes that the hollow iron balls discovered during the explosion of ball lightning "are the remnants of "ectons" and were formed during the discharge of positive linear lightning onto a metal conductor. Before cooling, the hollow balls were a vaporous metal." (Ecton is "a package of charged particles (10^{10}-10^{12} elementary charges), existing about 10^{-9} – 10^{-8} s and appearing during micro-explosions on electrodes due to the high concentration of energy in the micro-volume of their surface").[10]

The electrodynamic model[11-13] allows us to explain the above properties of ball lightning. According to this model, ball lightning is a positively charged energy core located inside a shell of polarized water molecules. The core is an ensemble of dynamic capacitors - objects made of moving electrons and protons. These capacitors have a charge, so to overcome the Coulomb repulsion force they must be placed in a vessel that can withstand high pressure. A shell of water serves as such a vessel. In the electric field created by the charged nucleus, the shell tends to contract towards the center and creates a force that compresses the nucleus. When the shell is destroyed, dynamic capacitors fly out along radial trajectories and disintegrate into elementary charges. The shell, having lost its strength and shape due to the disappearance of the force that formed it, disintegrates into drops of water. Thus, when ball lightning disappears, neither the rigid frame nor the substance from which its energy core was formed remains.

In the space around ball lightning there is a non-uniform electric field created by its charge. For ball lightning with a charge $Q = 10^{-3}$ C, the electric field strength at a distance $R_{bl} = 0.1$ m from its center is $E = Q/4\pi\varepsilon_0 R_{bl}^2 = 9 \cdot 10^8$ V/m. (Here $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m is the dielectric constant). Suppose that next to ball lightning with a radius $R_{bl} = 0.1$ m, a round stone with a diameter $d_{st} = 0.15$ m and a mass 1 kg accidentally appears. In a strong electric field, the material of the stone will be polarized and the stone will "stick" to the ball lightning. The force with which the stone is attracted to ball lightning is $F = D$ grad $E = D \cdot Q/2\pi\varepsilon_0 R^3$. Here D is the dipole moment of the polarized stone, equal to the product of the magnitude of the charge q induced on its surface and the diameter of the stone d_{st}. To hold a stone weighing $m_{st} = 1$ kg in a canopy, a force greater than $F_{st} = 10$ N is needed. Equating F_{st} and F at $Q = 10^{-3}$ C and $R = R_{bl} + d_{st}/2 = 0.175$ m, we find $D = 3 \cdot 10^{-9}$ C·m. At $d_{st} = 0.15$ m $q = 2 \cdot 10^{-8}$ C. If charge q is distributed over a surface of 10^{-2} m^2, then the charge density will be equal to $\sigma_{st} = 2 \cdot 10^{-6}$ C/m^2. This value is significantly less than $\sigma = 1$ C/m^2 – the limiting value of the charge density for complete polarization of a layer of water molecules.[11-13] Therefore, it can be assumed that ball lightning can attract not only a stone, but also an object heavier than the stone. Therefore, it is not surprising that a piece of iron or scale could "catch" to the ball lightning. Most of the observations described above say nothing about the "adventures" in the life of ball lightning before its disappearance. The exception is its behavior in the village of Gofitskoye. Shortly before its death, ball lightning "squeezed" through the gap between the gate frame and the support. It is quite possible that this place was located near the steel loop. Passing by it, ball lightning could scrape off a layer of rust from it. One day, flying over a stream, ball lightning heated a layer of sand to the melting temperature.[2] This was made possible due to its ability to generate powerful electromagnetic radiation, which most often occurs at the moment of ball lightning death. Exploding over the kitchen floor,[3] it could turn an iron nail captured somewhere along the way into steam. As the steam cooled, balls with metal boiling inside were formed, which then turned into hollow spheres. In the town Cansil Bluff,[5] it was able to bring with it and melt a steel part weighing about 20 kg.

Ball lightning can attract objects to itself not only due to the action of an electric field, but also a magnetic field. This is evidenced by the following message. "In 1950, I studied at the Suslonger seven-year school in the Mari Autonomous Soviet Socialist Republic. On June 12 we took a physics exam for the 7th grade. I took the second session. A thunderstorm was approaching. There were magnets of various shapes and various devices on the table. Suddenly something made a noise. We raised our heads. Physics teacher Dmitry Dmitrievich pressed himself against the cabinet and shouted: "Don't move!" We froze in our seats. A cloud, it seemed bluish-violet in color, flew in through the window, approached the table where the school supplies were lying, immediately rose and flew out of the window again without breaking the window. And then a miracle happened that remained in my memory for the rest of my life. When the cloud rose from the table, we all saw how the magnets, as if alive, rose and flew out the window. One horseshoe-shaped magnet pierced the wall of an iron tank that stood on the opposite side of the railway line, the other fell near the line and went deep into the ground."[14] As you can see, ball lightning was able to lift only two magnets into the air. Other physical instruments remained on the table. A possible reason for this could be that they were much heavier than magnets. But another reason is also possible: ball lightning "chose" them because it itself became a magnet. According to our model, the core of ball lightning consists of many "dynamic electrical capacitors" - electrons and protons, rotating around a common center.[11-13] The movement of charges results in the generation of a magnetic field, causing each capacitor to become a magnetic dipole. If the magnetic moments of pairs of dipoles are oriented in opposite directions, then the core as a whole will have no magnetic moment. But in the magnetic field of a permanent magnet lying on the table, polarization of the core of ball lightning could occur, and it, too, became a permanent magnet.

The described cases of carrying light objects are surprising, but seem quite understandable. If ball lightning weighing several kilograms can float in the air, held by the electric field of the atmosphere, then it can do this by becoming one kilogram heavier.[15] But in the literature there are descriptions of cases when ball lightning lifted much heavier objects into the air.

Carrying of heavy objects. "Dragging" people

Cases are described when ball lightning, which appeared over some object or person, lifted it into the air and carried it some distance. Such cases are not discussed in the general literature, since the possibility of lifting a heavy object by "light" ball lightning is fundamentally rejected.

"Once on a clear July day, a man was fishing on the Samara River. Suddenly, on the opposite bank (70 meters from him), a bright yellow ball appeared and quickly approached the fisherman. The ball was slightly flattened on the sides, and there was some kind of boiling going on inside it. The man lost consciousness. When he came to his senses, he discovered that he was a hundred meters from the previous place where he had been fishing. The ball was next to him. It hung near a large tree at a height of one meter from the ground. The fisherman lost consciousness again and woke up in a new place 50 meters from the tree. The ball was not nearby".[16] "In 1966, near the village of Voronovo, Tomsk region, Russia, ball lightning, moving at a high altitude along the road, stopped above two Chirikov brothers and began to descend. The brothers felt an electric shock on their arms and legs (their muscles cramped), and some unknown force began to press on them from above. It was difficult to raise their arms; there was some kind of weight pressing on their shoulders, as if somebody was sitting on them. The ball descended, and the thermal effect of this object increased. It became stuffy, the brothers unbuttoned their sheepskin coats and took off their mittens. When the angular size of the object increased to 0.17 radians (at this angle, a 1-meter object is 6 meters away), it stopped descending. The forceful pressure on the brothers stopped, but the thermal impact and brightness of the object became difficult to bear. After this, the object began to move away. The brothers were shocked again, and some unknown force pulled them up. They grabbed each other's arms, but the force lifted them up, greatly reducing their pressure on the ground. As the object moved away, the force decreased. Having risen to a great height, the object flew away. Within a radius of 70 meters from the site of the object's descent, the snow melted and became loose".[17] On January 1, 1985, in the Progress newspaper, published in the city Zmeinogorsk, Altai Territory, Russia a note appeared about an event that happened on November 30, 1984 in the village of Galtsovka (Goltsovka), located 12 km from Zmeinogorsk. It reported that on this day at 19.30 a bright object with a diameter of 1.5 m flew over the village. The central part of the ball glowed bluish-violet, and the edges were yellow-red and sparkled. The path of the ball was tortuous; it moved as if diving. After this, Goltsovka was visited by journalists and scientists who talked with witnesses. Based on these conversations, the history of this event was reconstructed.

"The luminous body approached Goltsovka from the southwest. Before this, it carried a haystack across the road leading to Zmeinogorsk at a distance 300 m and lowered it to the ground without stirring up the stems. A tractor carriage parked next to an electrical substation was overturned. Having flown into the village, the object passed by the house of the tractor driver Makarov, who perceived it as a luminous ball the size of a soccer ball, the flight of which was accompanied by a loud sound, like from a flying airplane.

Flying near a private house, the ball tore off its hinges and moved the door of this house by a distance of 5-7 cm, and a crack formed in the ceiling of the house. Flying over an eight-apartment two-story building, the object tore sheets of slate from its roof and scattered them behind the house (Figure 1). The slate was torn off along with the nails and was not damaged by the nail heads. One intact sheet was found on the ottoman of an apartment located on the second floor of this building. Ball lightning cut off a picket fence on the front garden fence at a length about 2.5 m. After this, the ball moved to the territory of the engine yard. At this time, the mechanic Portnov, dressed in a padded jacket, was walking through the yard. As the ball approached him, the padded jacket on his back rose up and pulled Portnov back. He fell to the ground. Being above the tractor station, ball lightning crushed the frame welded from steel corners. It first dragged another similar frame along the ground, and then lifted it into air and carried it 300 meters. The weight of this frame was at least 100 kg. Finally, a luminous object appeared above the barn and destroyed its western wall (Figure 2).

Figure 1 The roof of a two-story house destroyed by ball lightning.[17]

Figure 2 A barn destroyed by ball lightning.[18]

A concrete pillar with a cross section 50 cm × 60 cm, holding the roof, was smoothly cut at a height 1.2-1.3 m from the ground (Figure 3). After this, the luminous body flew away to the hills in a direction to the northeast. After some time, people saw a flash of light there and heard the sound of explosion".[18]

Figure 3 Concrete pillar torn by ball lightning.[18]

"On October 1, 1978, a luminous ball with a diameter of 7 meters flew over a one-story house at an altitude of about 15 meters. At the same time, bricks were torn out of the wall of the house and smoothly fell to the ground. Flying over the apple trees, the ball uprooted them and gently laid them on the ground. Flying over the next house, the ball tore off sheets of slate from its roof, which flew after it. In the third house, when a ball passed over it, an old woman, knitting a stocking, soared to the ceiling and then gently sank back down".[17] "In February 1985, near Petrozavodsk, Russia drivers of a diesel locomotive driving a train of empty freight cars saw a luminous ball with a diameter of 2 meters. The ball was flying next to the diesel locomotive. When the train began to slow down on a steep climb, the ball suddenly moved across the train and ended up in front of the locomotive at a distance of several meters from it. The train began to involuntarily pick up speed. The driver began to slow down and turned off the fuel supply to the engine, but the locomotive did not slow down. The ascent gave way to descent. The driver turned on the braking system, but this did not help. The ball continued to drag the train at a speed of about 50 km/h. The driver radioed to the station that, due to the interference of an unknown object, he could not brake. Since, fortunately, there were no obstacles for the traffic, the station duty officer gave the train the green light. Coming out onto the platform, she saw a strange sight: a bright white ball was attached to the diesel locomotive, in the center of the ball a fiery red disk stood out just to the right of the axis of movement. Just before the station, the ball flew off to the side for a few seconds. But when the train entered a dead section, it again settled in front of the diesel locomotive. A sharp braking followed, the train's speed dropped from 50 to 20 km/h, and then the train began to accelerate again. The driver's attempts to slow down the train led to nothing. The ball dragged the train for several tens of kilometers, all this time the controller in the car's cabin was at zero, so the locomotive did not have its own traction. As a result, the strange object saved 300 liters of fuel. At a distance 50 kilometers from the station, the ball broke away from the diesel locomotive and flew away".[17]

The facts stated above indicate that ball lightning can perform mechanical work - lift heavy objects into air and carry them to long distances, tear up trees and even drag a heavy train behind it. In addition, it is capable of the opposite effect - creating a force that presses people to the ground. Let's try to find the reasons for this complex behavior of ball lightning. Let's start with its ability to lift a heavy object into air, for example, a man in a padded jacket. In the strong electric field of a ball lightning charge, polarization of objects occurs - on the surface located near the charge, charges of the opposite sign are collected, and on the far surface - charges of the same sign. An electric dipole is formed, the moment of which is determined by the product of the charge value at its end and its length. If ball lightning has a charge Q, then in the non-uniform electric field E created by this charge, a force will act on the dipole, causing it to move towards the charge (this process is similar to the attraction of a piece of paper to an electrified comb). Let the dipole be an item of clothing (a cotton padded jacket), extended in the direction of the electric field of the charge to a length $l = 0.1$ m, and the center of the dipole is at a distance $R = 2$ m from the center of the ball lightning. The force, acting on the dipole, is:

$$F_l = D \cdot gradE = D \cdot \frac{d}{dR}\left(\frac{Q}{4\pi\varepsilon_0 R^2}\right) = 2,25 \cdot 10^9 D \cdot Q. \quad (1)$$

Here $\varepsilon_0 = 8.854 \cdot 10^{-12}$ F/m is the dielectric constant, $D = q \cdot l$ is the dipole moment, and q are the charges of different signs at its ends. The weight of a person weighing 90 kg is $P_m = 883$ N. Let us take the charge of ball lightning to be $Q = 10^{-2}$ C. Equating F_l to P_m, we find $q = 3.9 \cdot 10^{-4}$ C. If the surface area of the quilted jacket is $S \sim 1$ m^2, then the charge density on it is about $4 \cdot 10^{-4}$ C/m^2.

With this value of the surface charge density at the ends of the dipole, ball lightning can lift not only a man into air, but also a steel cage, and can also tear a tree out of the ground. Usually, when trying to explain such an effect of ball lightning, a psychological barrier arises: it is considered impossible that "light" ball lightning can lift an object heavier than itself into air. This barrier is easily overcome: in fact, ball lightning is held in space due to the attraction of its charge to the charge of the cloud. Thus, we must consider not the system: light ball lightning + a load suspended to it, but a massive cloud + ball lightning + load. In this case, ball lightning plays the role of a crane hook. Let us pay attention to the fact that ball lightning, having lifted someone up, does not throw him from this height, but smoothly lowers him to the ground. This is explained by the fact that the distance between ball lightning and the lifted object increases smoothly, and, therefore, the "lifting force" also decreases smoothly.

Now let us turn to the analysis of the event that occurred in the village of Voronovo.[17] Ball lightning, approaching the Chirikov brothers, began to put pressure on them with a force equal to the weight of a person (about 500 N). Let's find out the reason for the origin of this force. According to our model, ball lightning constantly loses its charge. As it approached the brothers standing on the road, a stream of charge carriers escaping from the surface of the ball lightning was directed directly at them. Let us assume that the charge of ball lightning was equal to $Q = 10^{-1}$ C, and the brothers acquired a charge $q = 10^{-5}$ C during the "irradiation with charges". Ball lightning, being at a distance $H = 5$ m from the brothers, pressed on them with a force $F_Q = Qq/4\pi\varepsilon_0 H^2 = 400$ N, that is, like a person weighing 40 kg sitting on their shoulders. After some time, the charge q drained from the surface of the brothers' bodies, and a "lifting" force caused by the polarization of their bodies began to act on them. The brothers' sensation of a flow of heat and the formation of melted snow was apparently somehow connected with this flow of charge carriers and the radio frequency radiation of ball lightning.

Let us evaluate the force with which ball lightning acted on slate sheets located on the roof of the house in Goltsovka. The sheet area is $S_{sh} = 1$ m$\times$1.5 m = 1.5 m^2, its thickness is $a_{sh} = 4$ mm, and its weight is 20 kg. Let us assume that in the electric field of a ball lightning flying at a distance 10 meters from the roof, polarization of a slate sheet occurred. Let the charge density of the ends of the dipoles on its surface (as for water) be equal to $\sigma = 1$ C/m^2. Then the dipole moment of the slate sheet will be equal to $D_{sh} = \sigma \cdot S_{sh} \cdot a_{sh} = 6 \cdot 10^{-3}$ C·m. Ball lightning with a charge $Q = 10^{-2}$ C, located at a distance $H = 10$ m from the roof, will attract a slate sheet with a force $F_{sh} = D_{sh} \cdot 2Q/(4\pi\varepsilon_0 H^3) = 1200$ N. This force is 6 times the weight of the sheet (200 N). Under the influence of this force, the sheet along with the nails will come off the roof and rise into the air.

Now let's discuss the event when ball lightning with a diameter 2 meters dragged a train of freight cars at a speed of 50 km/h.[17] The traction force required to move the train decreases with increasing speed. For a diesel locomotive moving at a speed of 50 km/h, it ranges from 10^4 to $4 \cdot 10^4$ N.[19] Let us assume that the ball lightning attached to the diesel locomotive had a charge $Q = 0.1$ C. Being at a distance $l = 2$ m from the diesel locomotive, it was attracted to it with a force $F_{at} = Q^2/4\pi\varepsilon_0(2l)^2 = 5.6 \cdot 10^6$ N. Now let's imagine that in front of the diesel locomotive at a distance $L = 1$ km from it there was a thunderstorm cloud with a negative charge $Q_{cl} = 50$ C. The force of ball lightning attraction to the cloud is $F_{cl} = Q \cdot Q_{cl}/4\pi\varepsilon_0 L^2 = 4.5 \cdot 10^4$ N. This force is sufficient to create the required amount of traction force for the diesel

locomotive. If a cloud flies in the direction the train is moving at a speed 50 km/h (14 m/s), it will drag the train along with it. What is surprising about this story is that ball lightning dragged the train over a distance of 50 km. If we take into account that the speed of the train was 50 km/h, we find that ball lightning "was working" for about 60 minutes. This time significantly exceeds the average lifetime of ball lightning (20 seconds).

In the event that occurred in Goltsovka, the cause of the destruction of the concrete support of the barn roof is of particular interest.[18] People who studied this event suggested that this work was not done by ball lightning, but by an accompanying tornado (vortex). Let us offer our explanation of this action. There is some discrepancy in the descriptions of the event: the size of ball lightning was indicated in the range from 0.3 to 1.5 m. Let us assume that this was, in fact, the case, and ball lightning gradually lost its size and charge (as in the case of ball lightning, digging ditches in Ireland in 1868).[20] Let's assume that ball lightning that flew into the barn struck a column and transferred part of its charge to it. Let these be two portions of $q = 10^{-3}$ C each, located at a distance $r = 10^{-1}$ m. The Coulomb repulsion force of these charges is $F_c = q^2/4\pi\varepsilon_0 r^2 = 10^6$ N. The tensile strength of concrete σ_B does not exceed 6 MPa.[21] Thus, the breaking force of a column with a cross section $S_b = 0.5$ m×0.6 m = 0.3 m^2 is equal to $F_c = \sigma_B \cdot S_b = 1.8 \cdot 10^6$ N, which is comparable to our estimate.

Ball lightning digs ditches in the soil

In[22] it is told that in 1900 in Norway, during a thunderstorm, a dazzling yellow ball the size of a cricket ball approached the hotel window. This ball had exploded with a terrible crash, throwing out long tongues in all directions purple flame. The next day, a hotel guest discovered a footprint in the ground on the lawn in front of the window, starting at a distance of 20 m from the window. It was a furrow 44 m long, 7-24 cm wide and 4-12 cm deep. The furrow went around a large granite boulder, from which two pieces were broken off. A large piece with a mass of more than 100 kg was thrown at 5 meters. In several places the trail disappeared underground, but then came to the surface again. The average width of the furrow was 15 cm, its average depth was 8 cm, hence the volume of ejected soil V = 0.15 m × 0.08 m × 44 m = 0.5 m^3. With soil density $\rho = 3 \cdot 10^3$ kg/m^3, the mass of ejected soil is $M = \rho \cdot V = 1.5 \cdot 10^3$ kg. If we assume that the soil was thrown to a height $H = 0.5$ m, then the work done by ball lightning was $A = MgH = 7.3 \cdot 10^3$ J.

In[20] impressions of Mr. Fitzgerald's walk at August 6, 1868 are described. When the surrounding area was cleared of the dense black clouds hanging over the mountains, he rode on horseback along the mountain valley to look for something worthy of observation. The sky above the mountains was very black and lightning and thunder followed each other continuously, so he decided to turn home. But, looking back, he suddenly saw a fireball in the air. Having passed the ridge of the mountain, the ball smoothly descended into the valley, maintaining a constant distance from the surface of the earth. Suddenly the ball hit the ground, and a minute later it reappeared and began to move along its surface. So it moved a distance about 180 meters. Then it disappeared again, plunging into the swamp soil, and, having walked 100 meters along the stream, reappeared on the surface. After that, it again began to move along the surface, and then plunged again, this time into the bank of the stream. After that, it flew to the opposite bank, making a hole in the peat slope, and finally buried itself in the ground. At the point where it first touched the ground, a square hole measuring 6 m × 6 m appeared, around which lay peat, as if cut out with a large knife. The ball did this work in one minute. Then it dug a ditch about 100 meters long and 1.2 m deep, and after that it plowed the soil to a depth of about 30 cm. Having turned the bank of the stream to a length of 15 m and a depth 1.5 m and throwing a huge mass of earth into the bed of the stream, it moved to the opposite peat slope. No more than 20 minutes passed between the appearance and burial of the ball, during which it moved smoothly, as if floating, having traveled through the air and ground for about a mile. At first it looked like a bright red round fireball with a diameter of about 60 cm. However, its volume quickly decreased, especially after each dive into the soil, so that its diameter before disappearing was reduced to 8 cm. The sky above was clear, but an hour after that it became dark as night. Thus, we can assume that ball lightning dug a ditch measuring 1.2 m × 1.2 m and about 300 m long. The volume of ejected earth V = 1.5 m × 1.5 m × 300 m = 675 m^3. Taking the density of peat equal to $\rho_t = 3 \cdot 10^3$ kg/m^3, we find the mass of the earth $M = \rho_t \cdot V = 2 \cdot 10^6$ kg. If we assume that the height to which the soil was thrown was $H = 1$ m, then the work done by this ball lightning was $A = MgH = 19.6$ MJ.

Stenhoff[23] believes that channels can leave currents flowing in the ground after a linear lightning strike. Soil release occurs due to the rapid evaporation of water from the soil. A similar explanation can be applied to cases such as the Norwegian's,[22] when the effect of ball lightning was not visually observed, but it is not applicable to the case of digging a ditch in Ireland in 1868. In 2006, a group of Irish scientists carried out a study of the site where Mr. Fitzgerald observed the action of ball lightning.[24] Surprisingly, after 138 years, traces of the "work" of ball lightning are still preserved on the earth. According to these scientists, the ditch was dug by a miniature black hole weighing from $2 \cdot 10^4$ to 10^6 kg, which levitated due to the generation of an alternating magnetic field with an induction of more than 0.7 Tesla. Models of "average" ball lightning[25,26] do not offer options for explaining the sequence of its action in Ireland.

According to the electrodynamic model,[11-13] ball lightning can have a large supply of energy, which is stored in the form of kinetic energy of ions undergoing orbital motion. There is some mechanism for converting the energy of ions into the energy of electromagnetic radiation with a wavelength of 1-10 cm. This radiation is absorbed by the water with which the soil is saturated. Water evaporates, steam expands and pieces of soil are released. To perform this action, the ball lightning must be in close contact with the soil. This occurs due to the presence of an electric charge in ball lightning. Due to the polarization of moist soil, ball lightning is attracted to the ground and can even burrow into it, forming a channel or tunnel. The horizontal movement of ball lightning along the surface of the earth occurs under the influence of electric field of atmosphere.

Holes in the soil and ball lightning

Several cases have been described of discovering holes in fields with a diameter of up to 50 cm, the depth of which reached several meters. "In July 1886, people working in a barley field heard a loud sound similar to the sound of a train. The sound came from the sky from a rapidly descending "giant ball of smoke." The ball fell onto the field and sank deep into the ground. A hole with a diameter 30 cm was formed, the depth of which could not be measured even with the longest poles".[5] "On October 24, 1989, at about 6 p.m., a strange luminous spherical object measuring at least fifty meters in size appeared in the sky above the village of Vladimirovsky in Russia. The object landed on a field and left a hole 6 meters deep in it, deeper the channel curved and went to the side. There were no remains of excavated soil, as happens during drilling, near the well. The shape of the well was elliptical, measuring 40 cm×60 cm. It seemed that the ground was not drilled, but pierced with some kind of giant rod".[27] "In April 1990, a resident of the village of Kostenki, Voronezh region,

Russia saw at night that a bright red ball was hanging over her garden. In the morning she discovered a deep hole in the garden. It was a perfectly round hole with a diameter of 10 cm with smooth walls. The depth of the hole was 5.4 m. There was not a crumb of soil on the ground near the hole. It is estimated that the mass of earth occupied by the well volume was about 120 kg. A few months later, an area with a diameter 8 meters with denser vegetation appeared around the well. The potato tops were 10-15 cm higher, and the leaves were more juicy compared to potatoes in the other part of the garden".[28] "At about two o'clock in the morning on June 9, 1996, near the village of Knishtin in the Krasnodar Region, Russia an unidentified flying object (UFO) landed on a wheat field. During its landing, a bright light appeared from it, and the object began to land, as it were, on this beam. At the landing site, circles of stacked ears with a diameter 15 m, 10 m and 5 m were found. In the center of each circle there was an oval hole about a meter deep. All circles were connected to each other by a straight line. The wheat stalks were not crushed, but inclined to the ground and seemed to be twisted or intertwined".[27]

Circles of stacked plants, in the center of which there were "holes" in the ground, were also observed in other areas of the Krasnodar Region of Russia. Figure 4 shows a snapshot of such a "hole" with a diameter 8 cm.[29] It is quite possible that these holes were made by ball lightning. The laying of the ears in a circle was apparently carried out by an air whirlwind (tornado). It can be assumed that the ball lightning was in the center of the vortex in a zone of low pressure and was attracted to the ground by the action of a "mirror" charge.

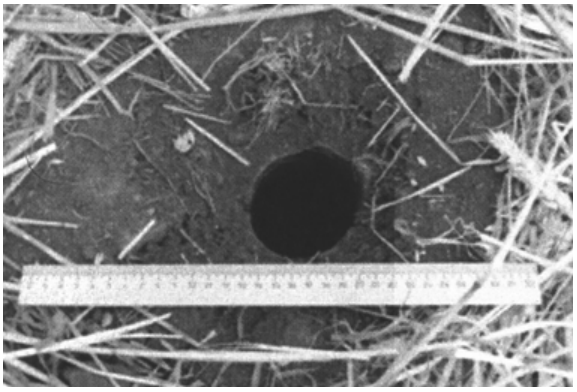

Figure 4 A hole in the soil in the center of a circle of stacked ears of corn.[29]

Let's estimate the pressure required to squeeze out a hole in the soil. An ordinary shovel with a width 20 cm and a blade thickness 1 mm enters the ground under pressure with a force 500 N. Hence the pressure of the shovel P_{sp} = 500 N/(2·10^{-4}) m^2 = 2.5·10^6 Pa. Let us assume that ball lightning had a radius r = 4 cm. Its cross-sectional area is $S = \pi r^2$ = 50.24 cm^2, and the force with which it was pressed into the soil is $F_{bl} = P_{sp} \cdot S$ = 1.256·10^4 N. In the paper[29] the results of a study of a cylindrical piece of soil dug out of a field with a radius R = 20 cm and a height H = 20 cm, in the center of which there was a hole with a radius r = 4 cm are described. The volume of the monolith was 21.56·10^{-3} m^3, mass – 28.59 kg, average density ρ_0 = 1.33 g/cm^3. Figure 5 shows how the soil density changed in the direction from the hole's wall to the monolith's boundary.

It can be seen that at a distance of about 2 cm from the wall the density increased to 2.1 g/cm^3, after which it dropped to 1.8 g/cm^3, and again increased to 2 g/cm^3 at a distance 6 cm - the soil was compressed by waves of length 4-6 cm. Let us assume that the earth from the hole was pressed into the wall of the cavity. The volume of the extruded earth is $V_h = \pi r^2 H$ = 1004.8 cm^3, and its mass $m_h = \rho_0 \cdot V_h$ = 1336.4 g. Let the extruded earth take the form of a pipe with an internal radius r = 4 cm, an external radius r_x and a height H = 20 cm, and the density of the soil in it became ρ_t = 2 g/cm^3. Mass of soil in the pipe $m_t = \rho_t \cdot \pi(r_x^2 - r^2)H = 125.6 \cdot (r_x^2 - 16)$ g. Equating m_t to m_h, we find r_x = 5.16 cm, that is, the thickness of the pipe is 1.16 cm. This value is consistent with the half-width of the first maximum of the radial density distribution in Figure 5. It is likely that the process of pressing ball lightning into the ground occurred in the form of a strike. This impact generated standing waves in the ground, causing compaction of areas of the soil. Let us determine the minimum value of the charge of ball lightning. Let us assume that a well-conducting aquifer of soil was at a depth l = 1 m. For ball lightning with charge Q lying on the surface, the force of attraction to the earth is $F_{at} = Q^2/4\pi\varepsilon_0(2l)^2$. Equating F_{at} to F_{bl}, we find Q = 2.36·10^{-3} C. This value is typical for ball lightning.

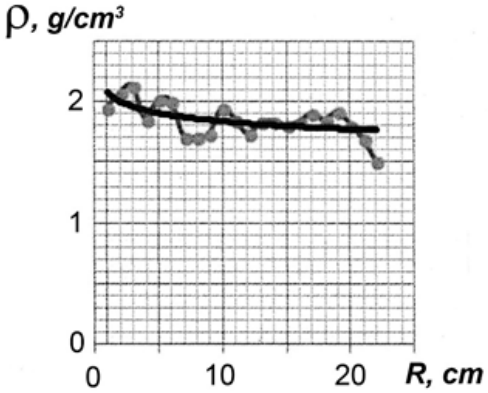

Figure 5 Change in sample density at different distances from the hole's wall.[29]

Conclusion

In[30] the history of developing of the electrodynamic model of ball lightning is briefly outlined. We used the de Tessan's idea that ball lightning is an electric capacitor.[31] We built a model of such a capacitor in the form of electrons moving in a circular orbit under the influence of mutually orthogonal electric and magnetic fields. The magnetic field was created by positive ions moving around the electron ring. It turned out that to create a sufficiently strong magnetic field, the number of ions must be greater than electrons, and this system of charges, which we called a "dynamic electric capacitor," turned out to be positively charged. This can be called the first stage in the implementation of the de Tessan's idea. To prevent the "dynamic capacitors" from flying apart due to Coulomb repulsion of charges, they had to be placed in a container that could withstand high pressure. We have shown that a spherical shell of polarized water molecules can serve as such a container. As a result, we came to a new form of implementation of the de Tessan's idea - the representation of ball lightning in the form of one of the electrodes of a large capacitor, the second electrode of which is the surface of the earth. The observations presented in this article indicate that ball lightning is an object closely connected not only with the earth, but also with other objects that form the electric field of the atmosphere. Such a giant capacitor can be considered the third implementation of the de Tessan's idea. The cases of "work" of ball lightning described above were performed not by an isolated charged ball, but by the clouds to which this ball was attached. The model of ball lightning in the form of an open capacitor allows us to find answers to the cause of many observations that remain unexplained for many decades. In[22] it is told how in 1904 a German engineer and his wife, during a strong storm with rain, hail and snow, saw a bright ball with a diameter of 4 meters flying at an altitude of 6 meters. "The

ball descended, passing through the telegraph wires, which began to glow, and enveloped the couple. They stood in a dense mass of white light, feeling neither smell nor heat. The movement of the ball did not cause the slightest movement of air. They did not even feel the outside wind and saw only the cobblestones under their feet. Nothing happened to the engineer's lit cigar. Then the ball jumped across the road, began to rise and disappeared at a distance of 10 meters behind a dense wall of hail." A possible reason for this event could be that the couple was trapped inside a large electrical capacitor. A strong electric field could cause the air to shine and changed the conditions of air movement.

Acknowledgments

None.

Conflicts of Interest

None.

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