Review Article

The danger of ball lightning

Abstract

Ball lightning in close contact with living beings can strike them with electric current or high-frequency radio emission. The current, passing through the surface of the skin, can cause it to burn. The entry of current into the region of the heart or the respiratory center of the brain can lead to death. High-frequency radio emission from ball lightning occurs in the wavelength range of 1-10 cm and can be absorbed by liquid water. When ball lightning comes into close contact with the body, blood heating and muscle rupture can occur. Cases of the indicated action of ball lightning on people are given. It is shown that the charge of ball lightning can be kept in a shell consisting of polarized water molecules. The reason for the generation of electromagnetic radiation of ball lightning is the cyclic movement of electrons in closed orbits. The radiation power sharply increases when the uniform distribution of electrons along the orbit is violated. It had been proven that dashed traces that appear on photographic films during electrical discharges in water are created by the action of multiply charged clusters having the structure of ball lightning. These clusters can penetrate the skin into living organisms and remain in them for a long time. The biological effect of these clusters has not yet been studied, but there is evidence that they are hazardous to health (causing cancer and liver damage).

Keywords: Ball lightning; Electric shock; Defeat by high-frequency radiation; Danger of multiply charged clusters

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Introduction

Ball lightning is a natural phenomenon known to man during the entire time of his existence on Earth. And, if a related phenomenon - ordinary linear lightning - has now ceased to be a mystery, then its sister - ball lightning, despite the successes of science, still remains unknown. Ball lightnings are luminous spheres that appear during thunderstorms and range in size from a few centimeters to several meters (Figure 1).[1,2] They strangely move in air and exist from a few seconds to tens of minutes. Their unexpected appearance near a person has a strong emotional impact on him. Personally, I experienced this action in childhood when I saw a red luminous ball next to me.[3] This property of ball lightning was used by adherents of ancient religions. In pagan pre-Christian Rus', a certain Rod was considered the supreme god, which appeared before people in the form of ball lightning. Ball lightning itself was called "rodia" in the language of the ancient Slavs.[4] An important stage in the formation of a database on the properties of ball lightning can be considered 1937, when a letter was published in the Daily Mail newspaper about how a red fireball descended from the sky during a thunderstorm. This ball fell into a barrel with water and heated it to a boil. Based on this event, the ball lightning energy was estimated to be 10 MJ, and the energy density was 10^{10} J/m^3.[5,6] This gives reason to consider ball lightning as an energy accumulator with a capacity exceeding the specific capacity of chemical accumulators.

Over two centuries of research, a large number of descriptions of ball lightning observations have been collected. The main inconvenience in collection of information was the short lifetime of ball lightning. In recent years, thanks to the widespread use of smartphones, reliable video footage of observations of ball lightning has become available. This allows examine in details the fine features of its behavior. As a result of the work of data collectors published in books,[6-13] there has been a noticeable progress towards solving this problem. In this article, we will consider cases of harm to people by ball lightning. Similar studies were carried out before us by many researchers.[6-8] Stenhoff[6] considered the question of the action on living beings a current of ball lightning discharge, which in general is similar to the action of an ordinary linear lightning strike. This means that ball lightning has a fairly significant electric charge, which it can transfer to a person by touching him. We will give examples of another type of ball lightning action on people, when it, while maintaining its structure unchanged, acts on a person, being in direct contact with his body. This can be explained by the fact that ball lightning is capable to generate powerful radio frequency electromagnetic radiation. After that, we will consider the danger posed by micro-sized ball lightning - multiply charged water clusters - particles, the study of which is just beginning. Based on the electrodynamic model of ball lightning,[14-16] we will present an explanation of the effects of ball lightning and discuss whether there are ways to protect against its harmful action.

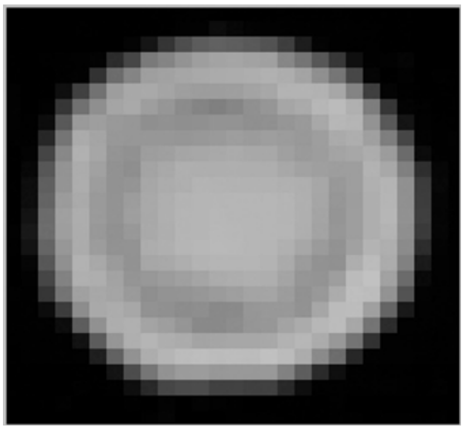

Figure 1 Ball lightning with a core and a shell. Photographed in 2016 near Blagoveshchensk.[1,2]

Cases of people's strikes by ball lightning

A) Electric shock

The case of the defeat of Professor Georg-Wilhelm Richmann by ball lightning on July 26, 1753 in St. Petersburg was widely known.

Richmann conducted experiments with a “thunder machine”. A pole with a metal tip was installed on the roof of the house, from which an iron wire was laid inside the house. The wire was connected to an “electric force indicator” - a copper rod, the bottom of which was in a crystal glass with copper filings. A thread was glued to the upper part of the rod, which, when the charge of the rod increased, deviated from it. An eyewitness to the event, engraver Ivan Sokolov, reported that during a thunderstorm, “a pale blue fiery lump the size of a fist” separated from the rod. The lump hit the professor on the forehead. The professor fell on his back on the chest behind him. A “red spot the size of a silver ruble” was found on the victim’s forehead, and his left shoe was torn in two places. The cause of death was an electric current that passed through the body of a scientist.[17]

“In August 1979, ball lightning exploded in a tent in which a husband, wife and their four-year-old daughter were lying. A dry wound from a burn formed near the woman’s elbow, after that the current passed through her arm and went into the ground through the fingers. A current, which had killed her husband, passed from his left hand into the body, through the heart and then through the right leg. His body was covered in dark lines, as if his nervous system had been burned from the inside. The daughter received a chin burn, but remained alive”.[18] In 1977, in the vicinity of the city Mednogorsk, Orenburg Region of Russia, a motorcycle driver and a man sitting behind him were killed by a ball lightning discharge. The passenger in the wheelchair survived. According to his story, “A button-sized ball sat on the handlebars of a motorcycle. There was a click, and the engine turned off. The right side of the driver’s helmet was torn off, and his right ear was cut off. The electrical charge entered his ear and exited through his left leg, just above the knee. The man sitting behind the driver had his whole body burned. His skin became black as coal, it was impossible to touch it, it stuck to any object like jelly. The motorcycle remained unharmed”.[12]

Stenhoff[6] noted the similarity between ball lightning’s action on people and that of linear lightning. Those who survived a linear lightning strike were observed to have rather insignificant wounds: loss of consciousness, memory loss, burns, temporary paralysis, and treelike patterns on the skin. Loss of consciousness could last from several minutes to several hours; after treatment, relapses were occasionally observed. Memory loss concerns a so-called type of “retrograde amnesia” when the victim does not remember that the lightning strike and retains only sensation of heat and light. Memory is usually restored within several hours. At the passage of a lightning current through the feet band the lower portion of the body, death is impossible. However, at that finiteness, the feet are usually paralyzed. The paralysis typically lasts from several hours to approximately one day. Victims can feel numbness and even have full loss of sensitivity below waist. Burns usually occur at the point of current input. The treelike changes of skin color in the areas of the body where the electric current entered appear because of the movement of electric sparks over the body’s surface. They usually disappear within several hours. Most dead occasions produced by typical lightning are caused by a blow to the head. A shock by a lightning current can cause ventricular fibrillation or respiratory arrest. Ventricular fibrillation or asphyxia can occur when the electrical current passes through the heart. In the case of respiratory arrest, dead can also be caused by the current passage through the respiratory center of the brain, which is located at the base of the skull. Asphyxia can result from currents of 40-60 mA.

As one can see, the consequences of people being struck by the discharge current of linear and ball lightning turn out to be the same. However, Stenhoff noticed that a ball lightning strike is less dangerous than a linear lightning strike. After being struck by lightning, a victim can be rescued if the current passed through the body without going through the heart. The duration of current from a strike of linear lightning is 40-250 μs.[19] We can imagine ball lightning as a spherical capacitor that has an electric charge. The electrical capacity of a sphere with radius $r = 10$ cm (the typical size of ball lightning) is $C = 4\pi\varepsilon_0 r = 10^{-11}$ F (here ε_0 is dielectric constant). If we accept the resistance of a person’s skin equal to $R = 1$ kΩ, the typical time of ball lightning discharge is $\tau = RC = 0.01$ μs. This means that because of skin-effect there is a probability that the current discharged by the ball lightning will just pass over the skin, but not enter the body.

B) Damage to people by electromagnetic radiation of ball lightning

The literature describes many cases of tragic consequences of ball lightning impacts on people, which cannot be explained only by the action of an electric current. On August 16, 1978, a group of five climbers camping at 3,900 meters were attacked by a bright yellow ball the size of a tennis ball. The ball successively descended into the climbers’ sleeping bags, causing wild cries of pain. One of the climbers died, the rest were taken by helicopter to the hospital. The victim V. Kavunenko conveys his feelings in this way: “When the ball burned through my bag, I felt hellish pain, as if several welding machines were burning me. I fainted. When I came to, I could not move my arm or leg. The body burned, it turned into a hearth of fire. In the hospital, they counted seven wounds. Those were not burns: just pieces of muscle were torn to the bone. It was the same with my friends. None of them showed signs of burns. The entrance holes in the bags were no larger than a tennis ball, but a size of our wounds reached 15-18 centimeters”.[20,21] The doctor of the burn center Yu. M. Panova noted that “the wounds of the climbers had a rounded shape, and coagulation, usually associated with thermal exposure, penetrated deeply into the tissues of the body. Perhaps this was due to the explosion of fluid in the tissues of the body under the influence of induced currents.[18,22]

In July 2011, ball lightning with a diameter of 3-4 cm penetrated into the garage of E. Chesnokov. The ball was white on the outside, and its inside glowed blue, yellow and red. When moving, it crackled and threw out sparks 1.5-2 cm long. The ball pulsated with a frequency of about 1 Hz. Chesnokov began to drive the ball towards the door with a broom. The ball stopped, flew around the observer and began to move along his back and arm to the elbow at a distance of 1-1.5 cm from the surface of the body. Chesnokov began to drive the ball away more actively and ran to the garage door. As he unlocked the door, the ball went from his buttock to his foot and jumped over to the other leg. The ball penetrated into swimming trunks made of synthetic fabric, then flew out of them and flew to his calves, forming two holes in them with a diameter of 2-2.5 cm. The ball burned both legs. On the left leg, in the place where the shin passes into the calf, the ball burned the leg to the bone. During treatment, this part of the bone was removed and replaced with a plastic prosthesis. 30% of the skin was burned. The treatment took 6 months.[18] The wounds on Chesnokov’s body look like climbers’ wounds. The reason for them could be the boiling of blood in the tissues due to the action of high-frequency radiation from ball lightning.

C) Danger of micro-sized ball lightning

In the cases discussed above, ball lightning acted as a “clear killer”, but it can also be harmful as a “silent killer”. About 30 years ago, researchers discovered that during electric discharges in water, traces appear on photographic films in the form of imprints of objects 50 μm in diameter or dashed lines several millimeters long and about 10 μm wide.[23–25] These traces were left by unknown particles with energies greater than 100 MeV. Moreover, it turned out that such particles filled the space of scientific laboratories and industrial workshops where electrical equipment is used. The situation turned out to be similar to the one that arose 400 years ago after the invention of the microscope. Then people suddenly discovered that they live in a vast world of micro-organisms, both friendly and dangerous. We have shown that all the details of the traces of these "strange" particles can be explained if we consider them as small ball lightnings – clusters consisted of an ensemble of ions enclosed inside a spherical shell of water molecules.[26-28] Health monitoring of researchers working with such particles showed that in some cases they are life-threatening.[29,30]

Electric charge of ball lightning

Some cases of ball lightning influence on people allow us to estimate the magnitude of its charge. In[12] it is described how, at pre-stormy weather, the hair of girls sitting in the room, when a luminous ball with a radius R_{bl} = 4 cm passed over their heads, rose up. When the ball lightning flew off to the side, the hair fell off. To raise hair, it is necessary that the electric field strength in the head area is not less than 1–2 kV/cm.[31] In order for ball lightning to create an electric field with a strength higher than $E_{up} = 2\cdot10^5$ V/m at a distance R = 1 m, its charge must be greater than $Q = 4\pi\varepsilon_0 R^2 E_{up} = 2.22\cdot10^{-5}$ C (here $\varepsilon_0 = 8.854\cdot10^{-12}$ F·m is the dielectric constant). With such a charge, the electric field strength on the surface of ball lightning (at $R_{bl} = 4\cdot10^{-2}$ m) is equal to $E = Q/4\pi\varepsilon_0 R_{bl}^2 = 1.25\cdot10^8$ V/m. This is 42 times more than the air breakdown intensity $E_{br} = 3\cdot10^6$ V/m. On July 27, 2015, ball lightning with a diameter of 0.75 m for about 80 seconds resisted the pressure of the wind due to attraction to the charge of the approaching cloud. Based on this, its charge was estimated as $Q_{bl} = 10^{-3}$ C.[32] The electric field strength on the surface of this ball lightning was 20 times greater than E_{br}.

Thus, the charge of a rather significant value is one of the properties of ball lightning that cannot be ignored. Figure 1 shows a photograph of ball lightning. It can be seen that it consists of a spherical core and a shell. Let there be a charge Q in the core (in a sphere with an inner radius R_i = 5 cm) and a shell of thickness a. Let us discuss whether it is possible to create a container capable of withstanding the Coulomb repulsion of charges located inside the core of ball lightning. Charge carriers Q press on the wall of the sphere with the force $F_q = Q^2/8\pi\varepsilon_0 R_i^2$. If $Q = 10^{-3}$ C, then $F_q = 1.8\cdot10^6$ N. Let the shell consists of water. Let us imagine a water molecule as a ball with diameter $d_w = 4\cdot10^{-10}$ m, which has a dipole electric moment $p_w = 6.327\cdot10^{-30}$ C·m. A water molecule located at a distance R_i from the center of the sphere will be attracted to it with the force $f_d = p_w\cdot\text{grad}\,(Q/4\pi\varepsilon_0 R_i^2) = -2p_w Q/4\pi\varepsilon_0 R_i^3$. At $Q = 10^{-3}$ C, $f_d = 9.1\cdot10^{-19}$ N. The area occupied by a water molecule on the shell surface is $s_w = d_w^2 = 1.6\cdot10^{-19}$ m^2. The area of a sphere of radius R_i = 5 cm is $S = 3.14\cdot10^{-2}$ m^2. It can fit $n_w = S/s_w = 1.96\cdot10^{17}$ water molecules. The compression force of the shell, consisting of one layer of water molecules, is $F_d = f_d\cdot n_w$ = 0.178 N. This force is less than the force F_q by $N = F_q/F_d = 10^7$ times. The Coulomb force of the charge carriers' repulsion F_q can be compensated by the contraction force of the shell, which consists of 10^7 layers of water molecules. The thickness of each layer is $d_w = 4\cdot10^{-10}$ m, and the thickness of the shell is $a = d_w\cdot N = 4\cdot10^{-3}$ m. Thus, the charge $Q = 10^{-3}$ C can be kept in a sphere with an inner radius R_i = 5 cm with a shell of water 4 mm thick. The electric field on the surface of this sphere is $3\cdot10^9$ V/m. Langevin had shown, that for complete polarization of a water molecule, the electric field strength must be at least $E_{min} = 3k_B T/p_w = 2\cdot10^9$ V/m.[33] (Here $k_B = 1.38\cdot10^{-23}$ J/K is the Boltzmann constant, and the temperature is T = 300 K). The value of the field strength obtained by us on the surface of the shell satisfies the Langevin criterion. But at the same time, this field exceeds the value of the breakdown field $E_{br} = 3\cdot10^6$ V/m by 1000 times.

Breakdown creation can be prevented by significantly reducing the value of current flowing from the shell into the atmosphere. Usually, the path along which the spark discharge must pass is laid by a leader - a thin channel with a rather high temperature of 3000–6000 K.[34] To maintain a high temperature (and, hence, a high conductivity of the leader) during the time of its "germination" (10^{-4}–10^{-3} s), it is necessary that a current was flowing through its channel with release a power of at least 130 W per one centimeter of the channel length. At lower power values, the channel will cool down, its conductivity will decrease, and the advancement of the leader will stop. For typical cases of spark development in air at atmospheric pressure, the current in the leader channel cannot be less than 1 A.[34,35] In ball lightning, due to the extremely low electrical conductivity of the space between the core and shell, the current is limited to 1–10 mA. This cannot become an obstacle to maintaining a corona discharge on its surface, but, however, suppresses the possibility of the formation of a spark channel.[31] This is true for ball lightning, which is in an equilibrium state. If the insulation between the core and the shell is broken, ball lightning can be discharged to the ground through the spark channel. Indeed, such cases have been observed.[6–8,10]

RF radiation from ball lightning

Ball lightning can affect the operation of electronic devices. Dmitriev, who observed ball lightning on the Onega River, noticed that as it approached the transistor radio receiver, the noise sharply increased, which then turned into a continuous rumble.[8,36,37] The engineer, who was resting on the shore of the lake, listened to the radio in the evening. Suddenly, a cloud of luminous balls with a diameter of several millimeters to 50 centimeters appeared next to him. It became as bright as day. The receiver did not work, but only cracked.[12] On the evening of June 31, 1969, several cars stood at the railway crossing in the Kuntsevsky district of Moscow, waiting for the passage of an electric train. At this time, two disk-shaped "apparatuses" flew over the crossing. When the barrier opened, the engines of all the cars would not start. Drivers were able to do this only after a few minutes. Similar cases occurred repeatedly, however, it was noticed that only car engines were turned off, while tractor engines continued to work. It can be assumed that the reason for this is the effect of RF radiation on the electronic ignition system of the car. There is no such system in a tractor diesel engine.[38]

These observations can be explained by the fact that ball lightning is a source of radio emission. The power of this radiation can be quite large. In Chernovtsi in the summer of 1947, ball lightning about 8 centimeters in diameter flew through a window into a small room in which two girls were sitting. In the center of the room, a 40-watt light bulb hung on a long cord. When the ball lightning flew past the light bulb, "the filament of the incandescent was glowing reddish, although the switch was turned off. When the ball had flown away from the lamp, the filament shining went out".[12] A similar incident occurred in 1981 in Odessa. When the trolleybus' yoke was separated from the wires, a round bright ball with a diameter of 15-20 centimeters separated from "the total mass of sparks, resembling an electric arc in color and brightness ... The ball crossed the road, ... landed on the wires of the opposite trolleybus line and began to move along them. The wires were fixed on poles with lighting lamps. As the ball passed under the lamps, they flashed in turn. So the ball floated past three or four lamps. Then, having separated from the wires, the ball flew under the ceiling of the lamp, and it began to burn: sparks fell, smoke was coming".[12] It is natural to assume that such a transfer of energy from ball lightning to electric lamps occurred due to radio emission, the power of which was from 10 W to 100 W. Ball lightning can transmit energy over a distance in the form of a radio emission pulse. In,[11] a case of evaporation of a gold bracelet by ball lightning is described. "There was a thunderstorm. The woman slept in a house whose doors and windows were locked from the inside. She was awakened by the sound of a lightning stroke, similar to a shot. Going to the window, she was surprised to find in it a small hole. And suddenly she noticed that the golden bracelet had disappeared from her hand. Only a dark band remained on the wrist". Let us take the mass of the bracelet as 50 g. To evaporate the bracelet, it must be heated to a gold melting point of 1063.4^0 C, which will require an energy $6.78 \cdot 10^3$ J, melt it and bring it to a boiling point of 2887^0 C (which will require an energy of $3.2 \cdot 10^3$ J + $11.8 \cdot 10^3$ J = $15 \cdot 10^3$ J) and then evaporate (with an energy consumption of $8.4 \cdot 10^4$ J). To evaporate one gram of gold, the energy of $2.11 \cdot 10^3$ J is required, and the total energy required to evaporate the bracelet is 10^5 J. If we take the evaporation time of the bracelet to be 10^{-2} s, then the pulsed power of the radio emission source must be at least 10 MW. On July 10, 2006, in Jurmala, near Oleg Andreyev "a bright yellow-orange ball the size of a tennis ball exploded ... After the explosion, Oleg's face was covered with black soot, and the gold chain around his neck evaporated, leaving a burn in the form of a dotted line" (Figure 2).[18]

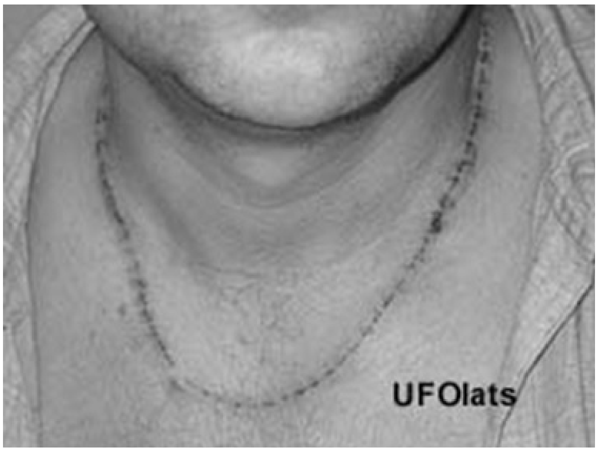

Figure 2 Burn trace from the evaporated chain.[18]

Evaporation of a chain with a mass of 17 g requires the energy 36 kJ. With the pulse duration of 10^{-2} s, the power of the radio wave generator was at least 3.6 MW. In,[22] the case of "abduction" of ring metal objects by ball lightning is described. A white-hot ball lightning about 5 cm in size flew up to a man and a woman sitting in the threshing floor on hay. When it approached them at a distance 1 m, the woman's hair stood on end (fan), and the man's hair moved under his cap. When the ball lightning flew away, the woman discovered that rings had disappeared from her fingers, and "the man had lost the chain from the folding knife, the metal tip from the fountain pen and the metal rims on the shoes that secure the edges of the holes for the laces". Note that, having performed these actions, ball lightning did not die. In August 1978, in Khabarovsk, in front of many witnesses, ball lightning 50 cm in diameter flashed above the ground, and then, rising several meters, exploded.[39] Under the flash point, 0.4 m^3 of slag was formed - pieces of sintered soil with an average size of 5-6 cm. It was shown that a similar effect on the soil can be exerted by a high-frequency radiation pulse with a power of at least 10^{10} W.

The described cases mean that the release of a large amount of ball lightning energy in the form of radio emission can occur not only at the moment of its death, but also be an "ordinary" episode of its life. Having emitted a pulse of electromagnetic radiation (in the form of light and radio waves), it returns to its original state and exists for some more time. Figure 3 shows frames of a video film about the observation of ball lightning near Blagoveshchensk in 2016. The flash of light lasts for ten frames (1/3 of a second), after which the ball lightning continues to exist for some time. This behavior, apparently, explains the action of ball lightning in the case in the climbers' tent or in Chesnokov's garage.

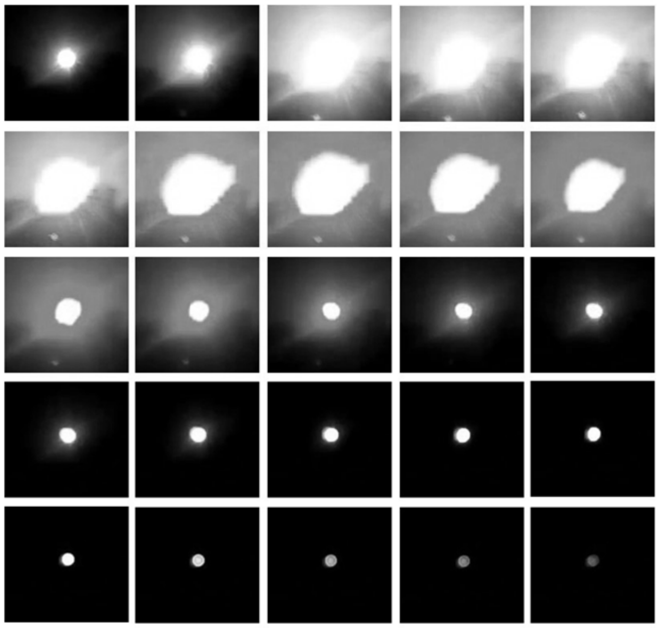

Figure 3 A flash of ball lightning. The frame sequence is left-to-right and top-to-bottom. The time between adjacent frames is 1/30 s. The large size of the flash image is due to overexposure of the image. Ball lightning itself retains its shape and size during a flash.[1-3]

The cases described above allow us to conclude that ball lightning is capable to generate high-frequency radio emission. The energy of the radiation pulse in some cases exceeds 10^5 J, which is 1-10% of the energy of a medium-sized ball lightning (10-20 cm). The classical cases of measuring the energy of ball lightning by heating water[5,11,40,41] indicate that the radio waves emitted by it are absorbed by water. Some idea about the range of wavelengths of radio emission of ball lightning can be given by the case of its observation by the Popele spouses on January 6, 2011 near Budapest (Figure 4).[18] The diameter of the ball lightning lying on the snow was about 50 cm.

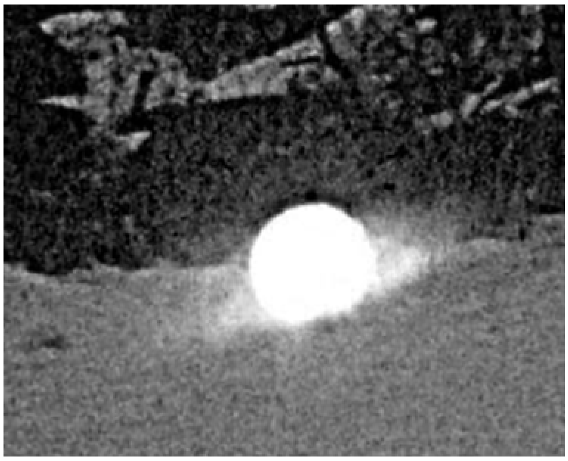

Figure 4 Ball lightning lying on the snow.[18]

The most surprising thing about this event was that the couple, who investigated the place where the shining ball was located after the disappearance of the ball lightning, did not find any traces of snow melting. The reason for this may be that the radiation of ball lightning lies in the range of radio waves that are not absorbed by snow. To test this idea, we put a plastic box with a snow in the microwave oven. (A household microwave oven operates at a wavelength 12.25 cm). When exposed to snow for 30 seconds of radio emission with a power of 850 W, it remained untouched. Therefore, it can be expected that the range of wavelengths emitted by ball lightning may lie in the region of 1-13 cm.[18] Based on the observations described above, it can be assumed that in a "calm" state, ball lightning emits radio waves with a power of 10–100 W in the decimeter range, and at the moment of emission of an optical radiation pulse, it generates a radio pulse with a power of up to 10^{10} W. Such high powers of pulsed radio emission cannot be explained by the corona discharge mechanism. Consider a ball lightning with a radius $R = 5$ cm, holding a charge $Q = 10^{-3}$ C inside. If the characteristic drain time of this charge is equal to $\tau = 100$ s, then the average current strength will be $I = Q/\tau = 10^{-5}$ A. The potential on the surface of the ball is $U = Q/4\pi\varepsilon_0 R = 1.8\cdot10^{8}$ V. From here we find the average corona discharge power $P = U\cdot I = 1.8\cdot10^{3}$ W. Our experiments have shown that the efficiency of corona discharge power conversion into radio emission does not exceed 10^{-4}.[31] Therefore, the average power of corona discharge radio emission cannot be higher than 0.2 W. In the electrodynamic model of ball lightning,[14-16] the source of radio emission is electrons and ions moving in orbits with a radius of $r = 10^{-3} - 10^{-1}$ m. The radiation power is minimal with a fairly uniform distribution of charges along the orbit. Indeed, let us consider the trivial case when there are only two electrons in the orbit, separated from each other by a distance of the diameter of the orbit. These electrons will emit two waves in antiphase, and these waves will cancel each other out. If the uniformity of the distribution of charges along the orbit is disturbed, the radiation power increases sharply. Often this happens before the death of ball lightning. The characteristic wavelengths of radio emission are comparable to the size of the orbits - $\lambda \approx 1$ mm-10 cm. The energy for radiation is drawn from the kinetic energy of moving charges, mainly ions. The mechanism of energy conversion is still not well understood.

Micro-sized ball lightning

In 2000, a group of researchers[25] discovered "strange" particles that appear during the electrical explosion of titanium foil in distilled water. These particles left dotted or continuous traces from 0.1 mm to 3 mm long on the X-ray film. The trace width was about 20 µm, and the dotted trace pitch was about 12 µm (Figure 5). The speed of these particles was estimated to be 20-40 m/s, and the energy, determined from the blackening area of the film, turned out to be about 700 MeV. Similar traces have been repeatedly observed by other researchers. Matsumoto[23] saw them during electric discharges in water, and Shoulders[24] saw them during discharges along the surface of metals and dielectrics. It was found that discontinuous traces appear not only on photographic films, but also on any objects with a smooth surface - on polycarbonate disks or on mica plates.[42] It was found that "strange" particles can penetrate into solid materials.[43,44] In this case, the titanium surface was hardened, and copper crumbled into a fine powder. Sections of copper plates were pierced with channels: sometimes straight, sometimes curved, sometimes helical. Often the traces were in the form of lines with sharp breaks. The strangest thing was the discovery of "twin tracks", when several identical copies of the track were observed on an area of several square centimeters.

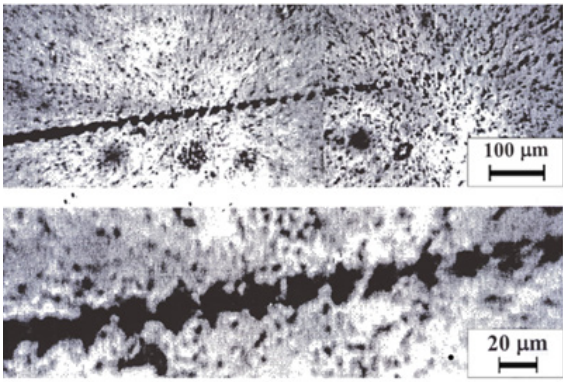

Figure 5 Trace of a "strange" particle on photographic film.[26,27]

We have shown[26-28] that the appearance of traces can be explained if we consider them as multiply charged clusters built like ball lightning. Let us assume that such a cluster contains $n = 2.8\cdot10^{7}$ ions with a total charge $Q = 4.5\cdot10^{-12}$ C. Let's take the ion diameter equal to $d = 4\cdot10^{-10}$ m, then the area occupied by one ion is $s = 16\cdot10^{-20}$ m^2. Let the ions be placed on the surface of a sphere of radius r. The surface area of the sphere is $S = 4\pi r^2 = s\cdot n$, hence $r = (s\cdot n/4\pi)^{1/2} = 6\cdot10^{-7}$ m. The ions stretch the sphere with a force:

$$F_Q = Q^2/8\pi\varepsilon_0 r^2 = 2.53\cdot10^{-1}\ \text{N}. \quad (1)$$

Let us place a water molecule on the surface of the sphere. It will be attracted to the charge Q, located inside the sphere, with a force:

$$F_a = p_w Q/2\pi\varepsilon_0 r^3 = 2.37\cdot10^{-12}\ \text{N}. \quad (2)$$

(Here $p_w = 6.327\cdot10^{-30}$ C·m is the dipole moment of the water molecule). On the surface of a sphere with a radius $r = 6\cdot10^{-7}$ m, one can place $n_w = 2.82\cdot10^{7}$ water molecules (we consider a water molecule as a ball with a diameter $4\cdot10^{-10}$ m). The force of compression of the sphere by one layer of water molecules is $F_1 = F_a\cdot n_w = 6.68\cdot10^{-5}$ N. This force is 3800 times less than the force F_Q. The F_Q force can be compensated if the number of layers of water molecules in the cluster shell is increased to 3800, while its thickness will be equal to $a = 4\cdot10^{-10}\times3800 = 1.52\cdot10^{-6}$ m. As a result, we have obtained a cluster with a cavity radius $r = 6\cdot10^{-7}$ m and with outer radius $R = r + a = 2.12\cdot10^{-6}$ m. The mass of the cluster is equal to the mass of its shell. The shell volume $V_{sh} = 4\pi(R^3 - r^3)/3 = 4\cdot10^{-17}$ m^3, and its mass $M = \rho_w\cdot V_{sh} = 4\cdot10^{-14}$ kg. (Here $\rho_w = 10^3$ kg/m^3 is the density of water). Fig. 6 shows the process of a trace formation on photographic film.[26,27] It is accepted that the initial values of the charge and mass of the cluster are $Q = 4.5\cdot10^{-12}$ C and $M = 4\cdot10^{-14}$ kg. It is believed that at a height $L = 15\cdot10^{-6}$m above the level of the film plane, a small cluster with charge $q = Q/100$ and mass $m = M/100$ separates from it. A small cluster, moving in the electric field of the large cluster, picks up speed and, hitting the film emulsion, creates a latent image in it. The large cluster, having received a recoil momentum, takes off above the film. But, since the material of the film is polarized in the electric field created by the cluster, it attracts the cluster to itself (the process is similar to the attraction of a piece of paper to an electrified comb). The cluster again "falls" onto the film, and the process is repeated. Since the cluster has a charge, an external electric field directed along the surface of the film will cause it to move parallel to its surface. As a result, a dotted trace will appear on the film, similar to the trace shown in Figure 6.

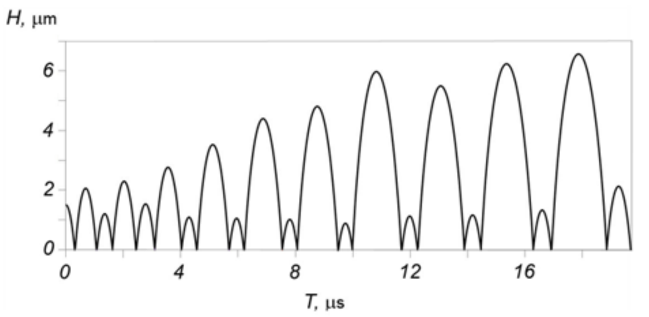

Figure 6 Change in the height of the rise of the charged cluster above the level L = 15 μm, at which a small charge was separated from it (Calculation result).[26,27]

The force acting on the cluster from the external electric field E is equal to $F_E = E{\cdot}Q$. Moving at a speed v, a cluster with radius R experiences the action of a decelerating force

$$F_D = (\pi C_D \rho_m R^2 v^2)/2, \quad (3)$$

where $\rho_m = 1.205$ kg/m^3 is the air density and $C_D = 5.8$ is the drag coefficient of the medium.[45] With $F_E = F_D$ the speed

$$v = (2QE/\pi C_D \rho_m R^2)^{1/2} = A{\cdot}(QE/R^2)^{1/2}. \quad (4)$$

It follows from this formula that all clusters with the same value of the Q/R^2 parameter will move in an electric field with the same speed. For the cluster considered above, $Q/R^2 = 4.5{\cdot}10^{-12}$ C/$(2.12{\cdot}10^{-6})^2$ m^2 = 1 C/m^2. The same value of this parameter is obtained for other clusters built according to the scheme described above.

A cluster with a radius $R = 2.12{\cdot}10^{-6}$ m and a charge $Q = 4.5{\cdot}10^{-12}$ C located on the metal surface is attracted to it with the force:

$$F_{mt} = Q^2/4\pi\varepsilon_0(2R)^2 = 10^{-2}\ \text{N}. \quad (5)$$

Cluster pressure force on the surface is:

$$P = F_{mt}/\pi R^2 = 700\ \text{MPa}. \quad (6)$$

This pressure exceeds the strength of steel (330 MPa) and should push the cluster into the solid body. Thus, we can assume that our assumption about the identity of "strange" particles and micro-sized ball lightning has a solid foundation.

Conclusion

Summing up, we are forced to admit that we do not yet know a reliable way to protect against the action of ball lightning. Methods of protection against linear lightning strikes are based on the knowledge of its nature and the predictability of its behavior. It is known that danger always comes from above and the damaging factor is a strong electric current. Therefore, grounded conductors that divert current from the protected object (lightning rods) and electrical shielding of premises (Faraday cages) can protect against it. These protective measures do not affect ball lightning: it is able to penetrate into a shielded room through narrow holes (and even right through the windows). Until we reproduce ball lightning in the laboratory and study it, we still have to use a simple recommendation: try to avoid contact with it. As you can see from the descriptions above, sometimes this is not possible.

The above applies to typical ball lightning 10-100 cm in size. As it turned out in recent years, we are constantly in the world filled with microscopic ball lightnings. This is natural, since we live inside a giant capacitor (earth-ionosphere) with an electric field strength of 100 to 1000 V/m. Inside this capacitor, electric currents flow - both strong (lightning) and weak (St. Elmo's fires). We are exposed to electrical shocks every time we take off our wool sweater or nylon shirt. In these discharges, charged clusters are constantly formed, which, as we believe, sometimes take the form of microscopic ball lightnings. These clusters can penetrate into condensed bodies (including organisms) and remain there for a long time. What consequences this may lead to is unknown. The only thing that saves us is the thought that living organisms have been in the "sea" of micro-lightnings for the entire history of their existence on Earth, but we did not suspect this. It is possible that these organisms have found ways to protect themselves from their harmful effects, such as a mechanism for "repairing" DNA molecules damaged by the action of ionizing radiation. At low levels of radiation, the body copes with its action, but at high doses of radiation it dies. It is possible that a similar thing happens at excessively high concentrations of micro-lightnings - their action causes cancer and liver damage. Ways to protect against them have not yet been found. Therefore, the only thing that can be recommended is good ventilation of the working premises.

Acknowledgments

None.

Conflicts of Interest

None.

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