# Traces of the action of ball lightning as material for studying its structure 


#### Abstract

According to observations, at the site of the ball lightning disappearance there are no traces left except a cloud of vapor. This reduces the number of materials for its formation in nature to air and water molecules. It is shown that, using these materials, it is possible to create a model of ball lightning with an energy reserve with a density up to $10^{10} \mathrm{~J} / \mathrm{m}^{3}$. Ball lightning has an electrical charge and mass. It is capable of heating water, tearing off bark from trees, jumping on the ground, cutting discs in glass, and melting holes in metal barriers. An explanation for this behavior of ball lightning is given.


Keywords: ball lightning, electric charge, shell, energy, effect on trees and glass

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## What is ball lightning made of?

Ball lightning is a mysterious natural phenomenon that people have been familiar with throughout human history. Glowing balls suddenly appear during thunderstorms; they "float" in the air, avoiding obstacles. These are not harmless balls, but objects that can have a large supply of energy. If they come into contact with a person, they can give him an electric shock. Exploding near a person, ball lightning can vaporize the gold chain around his neck. ${ }^{1}$ According to eyewitness accounts, during its short life, ball lightning behaves like a material body. It can spin like a regular ball, bounce off obstacles and jump on the ground, leaving holes. ${ }^{2}$ Therefore, it would be natural to expect that after its disappearance, fragments of its "framework" should remain on the earth. By studying them, we could understand how it works. However, in reality this is not at all the case: after disappearing, ball lightning turns into "nothing". No material traces remain of it. Here are typical examples of the end of ball lightning life.
"The ball seemed to be boiling inside... It touched the ground and crumbled into fiery sparks, which immediately disappeared"3 "Small balls separated from the ball. They, glowing, rolled in different directions and then went out"." "The ball, the size of a soccer ball... broke up into small balls the size of a children's ball. The balls rolled on the grass and disappeared there".3 "The balls fell from the sky, jumped on the ground, covering a distance $30-50$ meters, gradually decreasing in size, and went out. These balls had the appearance of blue-hot iron and they radiated radiance". "The ball "floated" a distance of about 40 meters at a speed $2 \mathrm{~m} / \mathrm{s}$, hit the wall and suddenly exploded with a deafening sound, leaving no traces behind". ${ }^{3}$ "The balls moved to the side $50-60$ meters and there, in contact with the snow, they disappeared with a slight spark. Some of them, upon contact with the snow, were crushed into smaller ones... The guys came closer to the place where the balls fell, wanted to find out what was happening with the snow, but did not notice anything significant". ${ }^{3}$ "Having touched the ground, the ball exploded with a strong roar, even the earth trembled under our feet... There were no traces left on the ground". 3 "The ball, 10 cm in diameter, hit the electric switch, exploded and disintegrated. For a moment, each point of the ball turned into a small lightning-spark, causing the ball to sharply increase in volume and crumble without a trace. There were no traces left on the switch". "The ball fell on the pavement, scattering sparks around it, and began to jump like a
ball, jumping up $10-15 \mathrm{~cm}$. Doing several jumps, it fell into pieces, which immediately went out". "Ball lightning...having touched a tree branch, with a crash, crumbled into sparks and disappeared. There were no traces left at this place". "The ball lightning hit the floor and jumped to a height 80 cm . Then it hit the floor and jumped several more times, each time lower and lower. Finally, it fell to the floor and, without separating from it, began to roll around, crumbling into small balls. They, in turn, fell apart into even smaller balls, similar "to mercury." The balls ran across the floor and went out". ${ }^{4}$ All these are cases of "premature" death of ball lightning from a stroke. But it can fade away without leaving traces, and on its own. "The ball rolled along the path five meters... and disappeared silently". ${ }^{3}$ "The ball disappeared as suddenly so as it appeared". ${ }^{3}$ "The ball looked as if it was entirely woven from sparks. Everything in it was rotating... The ball noticeably decreased in size and went out with a slight bang... There were no traces left on the floor". ${ }^{\text {" }}$ In the partition between the two windows, two yellow-orange balls the size of a human head slowly floated... the balls were opaque with clear boundaries. There was an impression that a flame was boiling in a flexible transparent shell, filling the entire volume. It was clear that the entire mass was in continuous motion. They hovered for a moment at a height of about one meter above a puddle in the middle of the room... and seemed to burn without smoke. These balls disappeared without leaving a trace"." "I saw about five or six meters from me at a height of about two meters something resembling a sheaf, consisting of many balls of seemingly molten metal... The sheaf, moving away, dissolved in air in front of my eyes, as if it had gone into nothingness". ${ }^{3}$ " $A$ fireball with a diameter $10-15 \mathrm{~cm}$ slid along the surface of the stream. Having walked 30 meters in 30 seconds, it "calmly disappeared". "A homogeneous yellow ball with a diameter 20 cm floated in the air, like a body floats inside a liquid... The ball became inhomogeneous and began to appear grayish. Then, without breaking into pieces or falling, it quietly, without a sound, disappeared. There was nothing in place of the ball: no heat, no drops of liquid". " "A "golden" ball with a diameter of about 15 cm flew into the room through an open window. Having flown at a height 2 meters into the middle of the room, it stopped one and a half meters from me. So, shining and vibrating, it stood for $10-15$ seconds. Then it began to shrink: first to the size of a nut, then to the size of a pea, and finally completely disappeared into the air right before my eyes. I stood there without moving. I felt as if
 unrestricted use, distribution, and build upon your work non-commercially.
millions of ants were swarming on my body". ${ }^{5}$ Sometimes a cloud of smoke or steam appears at the point where ball lightning disappears. "The ball exploded with the sound of a gunshot. Sparks scattered all over the hall, clicking. The hall was filled with smoke, and there was a smell of burnt straw". "The ball resembled a white cloud on a blue background - some kind of white smoke or gas. The ball, without moving from its site, dissolved in air, and disappeared, leaving the smell of burning sulfur". "'A luminous purple ball with a diameter $10-15 \mathrm{~cm}$, having flown about 30 m in a few seconds, disappeared, leaving behind a faint luminous cloud that quickly melted away". ${ }^{4}$ "Light yellow ball lightning with a diameter $30-50 \mathrm{~cm}$... exploded with a strong bang. At the same time, it broke up into small sparks. A small cloud of steam formed at the site of the explosion. It was quickly melted away". ${ }^{4}$

Finally, traces sometimes remain at the site of the ball lightning explosion. But these are not the remains of its substance, but traces of its thermal effect on nearby objects. "There was an explosion... In the air... there was a smell of ozone and a slight smell of burning... A burnt paint and a scorched wood at the site of ball explosion were found". " "The fireball exploded 1 meter above the floor. A burnt spot with a diameter $5-7 \mathrm{~cm}$ and a depth of about 0.5 cm appeared on the painted floor, around which there were many small dark spots". ${ }^{4}$ "The ball fell into a corner and disappeared with a crash and a bright flash. There was a spot of burnt paint with a diameter $25-30 \mathrm{~cm}$ left on the floor, and soot on the stone wall". " "A bright "sun" the size of a ball... sank along a curve to the ground and scattered into a million sparks. After the rain, I decided to return to the impact site and look at these sparks. But instead of sparks, I found only burnt black grass. It looked as if there had been no rain. It was dry in a circle with a diameter 60 cm . In the center of this dry circle I saw a gray bundle of wire. I wanted to pick it up, but as soon as I touched it, it turned to dust" ${ }^{5}{ }^{5}$ "A ball with a diameter 10 cm appeared on the crown of the tree. Jumping from branch to branch, it fell to the ground and disappeared. At the place where it fell, a hole the size of a nut was discovered in the ground overgrown with short grass. The grass around the hole was scorched and smoking. The air smelt of sulfur". 5 "Some red object in the shape of a potato descended to the ground and flew along the ditch. As it moved, it melted the sand and left behind a section of hard, shiny material several centimeters thick, 10 centimeters wide and 70 centimeters long". ${ }^{5}$

As one can see, ball lightning does not seem to use for its creation any "structural" material other than the one that turns into steam or smoke. This is understandable, since ball lightning, which is formed at a great distance from the ground, only has air and water "at hand." Therefore, most likely, ball lightning is "made" from molecules of water, oxygen and nitrogen, as well as from ions of these substances. The possibility that it contains flammable gases and metal atoms is extremely low. Nevertheless, having such a "modest" supply of substances in its composition, ball lightning is capable of exerting a strong thermal effect on water and sand, stimulating chemical reactions leading to the formation of ozone or soot. Information on observing the structure of ball lightning is very important. According to it, ball lightning consists of small elements (luminous sparks), capable of "living" only inside an intact shell. When the shell breaks, they go out. Among the listed properties of ball lightning, the greatest interest is caused by its ability to accumulate large amounts of energy within itself.

## Cases of measuring the energy of ball lightning

Thus, we are forced to build a model of ball lightning based on the study of indirect traces of its effect on the environment: the results of
its energetic impact on materials, the reasons for the appearance of odor, its glow, etc. The ability to accumulate large energy in a limited volume is the most difficult to explain property of ball lightning. Therefore, the desire of many researchers to explain the destruction caused by ball lightning by the action of linear lightning becomes understandable. ${ }^{4,6,7}$ However, attitudes to the problem of ball lightning changed dramatically on November 5, 1936, when The Daily Mail (London) published a letter to the editor about "a red hot ball that fell from the sky into a barrel containing 18 liters of water. The water heated up and boiled for several minutes." The specific heat of water is $C_{w}=4200 \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$; heating $M_{w}=18 \mathrm{~kg}$ of water by $\Delta T=80 \mathrm{~K}$ (from $20^{\circ} \mathrm{C}$ to $100^{\circ} \mathrm{C}$ ) required energy $E_{b}=M_{w} \cdot C_{w} \cdot \Delta T=6 \mathrm{MJ}$. Latent heat of evaporation of water $L_{w}=2.26 \mathrm{MJ} / \mathrm{kg}$. If we assume that $m_{w}=1.8 \mathrm{~kg}$ of water evaporated, then the energy $E_{e v}=L_{w} \cdot m_{w}$ $=4 \mathrm{MJ}$ was spent on this. In sum, we find that the total energy of the red ball was $E_{t}=E_{b}+E_{e v}=10 \mathrm{MJ}$. The diameter of the ball was 10 cm , and its volume $V_{b}=0.523 \cdot 10^{-3} \mathrm{~m}^{3}$, hence the ball lightning energy density $\rho_{E}=E_{t} / V_{b}=1.9 \cdot 10^{10} \mathrm{~J} / \mathrm{m}^{3} .^{6,8}$ It is interesting that the author of the letter, after the water cooled, tried to find the remains of ball lightning in the barrel, but found nothing. In August 1962, ball lightning with a diameter 6 cm fell into a trough with water for drinking live-stock. The water in the trough had almost completely boiled away, and boiled frogs lay at the bottom. ${ }^{9}$ Boiled frogs were also found in two other troughs. The mass of water in the trough was $m_{1}=112.5 \mathrm{~kg}, m_{2}=100 \mathrm{~kg}$ evaporated, the water was heated from $10^{\circ} \mathrm{C}$ to $100^{\circ} \mathrm{C}(\Delta T=90 \mathrm{~K})$. Hence the energy transferred by ball lightning to water was $E_{t}=m_{1} \cdot C_{w} \cdot \Delta T+m_{2} \cdot L_{w}=268.5 \mathrm{MJ}$. The volume of a ball with a diameter 6 cm is $V_{b}=113 \mathrm{~cm}^{3}$, hence the energy density of this ball lightning was $\rho_{E}=E_{t} / V_{b}=2.38 \cdot 10^{12} \mathrm{~J} / \mathrm{m}^{3}$. Note that this is a minimum estimate of the energy of ball lightning: in the other two troughs, the water also heated up, for which some of the energy was spent. It is possible that the observer underestimated the size of the ball. If its diameter were 28 cm , then the energy density of ball lightning would be $\rho_{\mathrm{E}}=2.4 \cdot 10^{10} \mathrm{~J} / \mathrm{m}^{3}$. In July 1972, during a lunch break in Hungary, in front of numerous factory workers, a brightly glowing ball the size of a soccer ball fell into a pit with 120 liters of water. The water boiled and evaporated. ${ }^{5}$ To heat 120 kg of water at $\Delta T=80 \mathrm{~K}$ and evaporate it, energy $E=311 \mathrm{MJ}$ is required. Taking the diameter of the ball equal to 25 cm , we find the energy density of this ball lightning $\rho_{E}=3.8 \cdot 10^{10} \mathrm{~J} / \mathrm{m}^{3}$. In July 1964, a technical school student was fishing on the Ucha River in the morning. A luminous ball with a diameter 5 cm suddenly "attached" to the fishing hook. The fisherman lowered the hook with the ball hanging on it into a galvanized bucket of water, in which there were caught fishes. The water bubbled and boiled for several minutes. All the fishes were cooked. The bucket contained $m_{\mathrm{w}}=5 \mathrm{~kg}$ of water and $m_{f}=0.9 \mathrm{~kg}$ of fishes. Heating the fish soup to a boil ( $\left.\Delta T=80 \mathrm{~K}\right)$ required energy $E=C_{w}\left(m_{w}+m_{f}\right) \Delta T=1.98 \mathrm{MJ}$. Some of the energy was spent heating the metal bucket and evaporating some of the water. The volume of a ball with a diameter 5 cm is equal to $65 \mathrm{~cm}^{3}$, hence we find that the energy density of ball lightning was no less than $\rho_{E}$ $=3 \cdot 10^{10} \mathrm{~J} / \mathrm{m}^{3}$. ${ }^{10}$

In addition to the cases of direct measurement of the energy of ball lightning discussed above, other cases of estimating its energy based on the destruction it produces are described in the literature. The energy of the ball lightning that caused the splitting of the wooden pier pile was determined to exceed $130 \mathrm{MJ} .{ }^{11-13}$ The energy of a ball lightning with a diameter 1.5 m , which melted $0.4 \mathrm{~m}^{3}$ of wet soil before the explosion, was estimated to exceed $1000 \mathrm{MJ} .{ }^{14}$ The article ${ }^{15}$ reports observations of ball lightning with energies $100-1000 \mathrm{MJ}$ and even large ball lightning with energies of up to $10,000 \mathrm{MJ}$.

The high energy of ball lightning cannot be explained by any model where it is considered an object with a density close to the density of air. In this case, the energy per one air molecule should be no less than $1.4 \cdot 10^{3}-4.4 \cdot 10^{3} \mathrm{eV}$. This value is 2-3 orders of magnitude greater than the ionization energy of an atom or molecule. The only way to increase the energy reserve of "chemical ball lightning" is to increase the density of its substance by 1000 times. In this case, models with an energy source in the form of a solid or liquid explosive can "survive". However, a new problem arises - a significant increase in the mass of ball lightning. For example, a trinitrotoluene ball lightning with the energy 10 MJ should have a mass 2.5 kg . For models in which ball lightning is considered electrically neutral, the problem arises of explaining the mechanism of its levitation. In addition, there is the problem of preventing the detonation of an explosive and creating conditions for maintaining its slow combustion for several minutes.

In the examples of the thermal effect of ball lightning described above, the mechanism of energy transfer from ball lightning to water also requires explanation. The typical mechanism of energy transfer from a body heated to a high temperature (for example, in a chemical combustion reaction) is unlikely for this case. In this case, ball lightning should emit a large flow of energy in the infrared range of the spectrum. However, according to numerous observations, ball lightning located at a close distance from the observer does not emit heat. It would be more natural to assume that ball lightning heats the water while remaining "cold." This is possible, for example, if the heating is caused by electromagnetic radiation in a narrow range of the spectrum, for example, in the radio range (this is how water is heated in household microwave ovens). In a microwave oven, radio waves are generated by the movement of electrons. If the same reason operates in ball lightning, we must assume that charge movement also occurs in its core. The facts of the above observations also speak in favor of the presence of radio frequency radiation from ball lightning. The energy of ball lightning that fell into a trough with water was somehow transmitted through the wooden walls to other troughs, ball lightning melted the sand, being at some distance from it, a ball lightning was able to heat a coil of wire until red hot. ${ }^{5}$

## Damage to trees by ball lightning

Another source of information useful for estimating the energy of ball lightning and analysing the process of transferring its energy is the results of its action on trees. Since the wood structure of all trees is, in principle, the same, the results of such an action should be similar. Here are typical examples of this action. "Ball lightning with a diameter 50 cm struck a poplar. An explosion tore a "chip" 20 meters long, 35 cm wide and 10 cm thick from the poplar trunk, split it and scattered it over an area $1000 \mathrm{~m}^{2}$. At this time, two pieces of wood weighing 20-25 kilograms were thrown at a distance 40-45 meters from the poplar"." "A yellow fireball with a diameter of about one meter exploded near a large spruce tree. As a result of the explosion, the tree was split, and a long scar, about 10 meters long and about half a meter wide at the bottom, formed along the trunk". "Ball lightning the size of a man's head struck a very tall white poplar tree. It cut a vertical groove 2 cm deep, 20 cm wide and 10 m long in the bark and wood". ${ }^{16}$ "A reddish-purple ball lightning the size of a hat, hissing, hit the top of a tall oak tree and tore it into splinters to the root". ${ }^{16}$ The article ${ }^{17}$ describes the case of the action of ball lightning on a tree, when it had not yet exploded, but remained intact. Ball lightning, about 15 cm in size, appeared on the trunk of a pine tree at a height $h=12 \mathrm{~m}$. It descended along a vertical line, cutting a groove in the bark, the width of which was about 5 mm at the top, and 5 cm at the bottom near the root of the tree. After that, the ball lightning flew by along the surface of the earth 62 m and exploded. The event was
observed for $\tau_{t}=8-9$ seconds. The path traveled by ball lightning was $l=12 \mathrm{~m}+62 \mathrm{~m}=74 \mathrm{~m}$, its average speed was $v=l / \tau_{t}=8.7 \mathrm{~m} / \mathrm{s}$, and the sliding time along the tree trunk was $\tau=h / v=1.4 \mathrm{~s}$. Similar events occurred repeatedly. The report ${ }^{18}$ describes a case when at night during a thunderstorm an observer managed to photograph ball lightning that moved over a fence for one minute (Figure 1). In the morning, he discovered a mark on a pine tree in the backyard of the property (Figure 2). A strip of "cut" bark appeared on the tree, to the surprise of the observer, which had no signs of "burning" (Figure 3).


Figure I Ball lightning flying over the fence.


Figure 2 A trace left by ball lightning.
Another similar incident occurred on July 13, 2018 in Gorny Altai. ${ }^{19}$ The builders, sheltering indoors from the rain, saw how ball lightning, like a cutter, passed through the tree, leaving a notch about 3 centimeters wide on the trunk (Figure 4).


Figure 3 Shape of the trail of ball lightning.


Figure 4 The result of the action of ball lightning.
Let us estimate the energy spent by ball lightning on the detachment of bark in the event described in the article. ${ }^{17}$ It is natural to assume that the peeling off of the bark could have occurred due to the boiling of the sap between the bark and the wood. Let the length of the mark on the pine tree be 10 m and its width 3 cm . From here we find its area $3000 \mathrm{~cm}^{2}$. Let us take the thickness of the sap layer to be 1 mm , then the volume of evaporated liquid $V_{b}=300 \mathrm{~cm}^{3}$, and its mass $m_{b}=0.3$ kg . Let the air temperature be $T_{0}=20^{\circ} \mathrm{C}$. To heat 0.3 kg of water to $T_{b}=100^{\circ} \mathrm{C}$, the energy required is $W_{1}=m_{b} \cdot C_{w} \cdot\left(T_{b}-T_{0}\right)=10^{5} \mathrm{~J}$. (Here $C_{w}=4.2 \cdot 10^{3} \mathrm{~J} / \mathrm{kg} \cdot \mathrm{K}$ - specific heat capacity of water). In order to turn 0.3 kg of water into steam, energy is needed $W_{2}=m_{b} \cdot L_{w}=6.78 \cdot 10^{5} \mathrm{~J}$. (Here $L_{w}=2.26 \cdot 10^{6} \mathrm{~J} / \mathrm{kg}$ is the specific heat of evaporation of water). The work done by ball lightning is $A_{b l}=W_{1}+W_{2}=7.78 \cdot 10^{5} \mathrm{~J}$. If we take the time of ball lightning movement along the barrel equal to $\tau$ $=1.4 \mathrm{~s}$, then the power of the ball lightning action was $P_{b l}=A_{b l} / \tau=$ $5.56 \cdot 10^{5} \mathrm{~W}$. The calculations performed can be treated as an estimate of the energy reserve of ball lightning. It is quite possible that the mechanism of "shaving" of the bark could be different. Suppose, for example, that ball lightning acted like an ordinary mechanical cutter. But in this case, it had to cut the nylon rope with which the hammock was tied to the tree (Figure 4). For the same reason, it is
necessary to exclude the possibility that the tree was affected by "hot" ball lightning. (The idea that ball lightning has a high temperature is sometimes used by some authors of ball lightning models to explain its glow, which, in their opinion, is of a thermal nature). The hot ball lightning should have melted the rope.

## Explanation of the reasons for the energetic action of ball lightning

Let's start by explaining the mechanism of concentration of large energy in a limited volume of space. It is known that the energy density of molecules located inside a certain vessel and the pressure they exert on the walls of the vessel are measured in the same units $\left(\mathrm{M} / \mathrm{LT}^{2}\right)$. This is no coincidence; there is a close connection between them. Let us consider the motion of a group of particles moving with an average speed $V$ inside a cube with edge length $L$. Let $1 / 3$ of them, having a mass $M$, move between the left and right walls of the cube, and the remaining $2 / 3$ move between the other walls. The total mass of particles is $3 M$, their kinetic energy $E_{c}=3 M V^{2} / 2$, and energy density $\rho_{c}=E_{c} / L^{3}=3 M V^{2} / 2 L^{3}$. Let us determine what pressure particles with mass $M$, moving at speed $V$, exert on the left and right walls. When they collide with the left wall, particles with a total mass $M$ transfer momentum $p=2 M V$ to it and change the direction of their movement to the opposite. Having reflected from the right wall, after a time $\Delta t=2 L / V$ the particle again collides with the left wall. The force of action of particles on the wall is $F=p / \Delta t=M V^{2} / L$ , and the pressure is $P=F / L^{2}=M V^{2} / L^{3}$. From here we find the connection between pressure and energy density: $\rho_{c}=3 / 2 P$. This is a simplified derivation of the so-called virial theorem. A more accurate calculation leads to the result $\rho_{c}=3 P$. This means that to keep an ensemble of particles with an energy density $\rho_{\mathrm{E}}=10^{10} \mathrm{~J} / \mathrm{m}^{3}$ (typical for ball lightning) in a limited area of space, a vessel is needed that can withstand a pressure $P=1 / 3 \rho_{\mathrm{E}}=3.3 \cdot 10^{9} \mathrm{~Pa}=3.3 \cdot 10^{4} \mathrm{~atm}$. Let's discuss whether it is possible to create such a vessel from simple materials - water, air molecules and ions. At the same time, let us remember that ball lightning has a unipolar electric charge $Q$, the carriers of which must also be kept inside a certain container. First, let's consider the situation when charge carriers "sit" motionless on the inner wall of a sphere with radius $R_{i n}=5 \cdot 10^{-2} \mathrm{~m}$. Let's place one water molecule on the outer wall of the sphere. A water molecule is an electric dipole with a moment $p_{w}=6.327 \cdot 10^{-30} \mathrm{C} \cdot \mathrm{m}$. In an electric field, such a dipole will turn in the direction of the field vector and will maintain this position if the field strength is not less than: ${ }^{20}$

$$
\begin{equation*}
E_{\min }=3 k_{B} T / p_{w} . \tag{1}
\end{equation*}
$$

Substituting $k_{B}=1.38 \cdot 10^{-23} \mathrm{~J} / \mathrm{K}$ and $T=300 \mathrm{~K}$ into this formula, we obtain $E_{\text {min }}=2 \cdot 10^{9} \mathrm{~V} / \mathrm{m}$.

The electric field strength created by the charge $Q$ at a distance $R_{i n}$,

$$
\begin{equation*}
E=Q / 4 \pi \varepsilon_{0} R_{i n}^{2} \tag{2}
\end{equation*}
$$

Here $\varepsilon_{0}=8.854 \cdot 10^{-12} \mathrm{~F} / \mathrm{m}$ is the dielectric constant. At a value of $R_{\text {in }}=5 \cdot 10^{-2} \mathrm{~m}$, an electric field with intensity $E_{\text {min }}$ can be created by a charge

$$
\begin{equation*}
Q_{\text {min }}=4 \pi \varepsilon_{0} R_{\text {in }} \cdot E_{\text {min }}=5.56 \cdot 10^{-4} \mathrm{C} . \tag{3}
\end{equation*}
$$

Let us assume that the charge value of the ball lightning core was 10 times greater than $Q_{\text {min }}: Q=5 \cdot 10^{-3} \mathrm{C}$. In this case, the electric field strength at $R_{\text {in }}=5 \cdot 10^{-2} \mathrm{~m}$ is equal to $1.8 \cdot 10^{10} \mathrm{~V} / \mathrm{m}$. Charge carriers collected inside a sphere with radius $R_{i n}$ will stretch the wall of the sphere with a force: ${ }^{21-23}$

$$
\begin{equation*}
F_{Q}=Q^{2} / 8 \pi \varepsilon_{0} R_{i n}{ }^{2} . \tag{4}
\end{equation*}
$$

At $Q=5 \cdot 10^{-3} \mathrm{C}$ and $R_{\text {in }}=5 \cdot 10^{-2} \mathrm{~m} F_{Q}=4.496 \cdot 10^{7} \mathrm{~N}$. A water molecule located on the surface of a sphere with radius $R_{i n}$ will be attracted to the center of the sphere with a force

$$
\begin{equation*}
f_{q}=p_{w} \cdot \operatorname{grad} E=-2 p_{w} Q / 4 \pi \varepsilon_{0} R_{i n}{ }^{3} . \tag{5}
\end{equation*}
$$

We will consider a water molecule to be a ball with a diameter $d_{w}=$ $4 \cdot 10^{-10} \mathrm{~m}$. On the surface of a sphere with radius $R_{i n}, n_{w}=4 \pi R_{i n}{ }^{2} / d_{w}{ }^{2}$ water molecules can fit. A shell with one layer of water molecules will be attracted to the center of the sphere with a force

$$
\begin{equation*}
f_{w}=f_{q} \cdot n_{w}=2 p_{w} Q / \varepsilon_{0} R_{i n} d_{w}^{2}=0.893 \mathrm{~N} \tag{6}
\end{equation*}
$$

The tensile force of the shell $F_{\mathrm{Q}}$ is greater than the force of its compression by one layer of water molecules $F_{Q} / f_{w}=Q d_{w}{ }^{2} / 16 \pi R_{\text {in }} p_{w}=5 \cdot 10^{7}$ times. To compensate for the force of repulsion of charges by the compression force of the shell, its thickness $a$ must be $5 \cdot 10^{7}$ times greater: $a=5 \cdot 10^{7} \times 4 \cdot 10^{-10} \mathrm{~m}=2 \cdot 10^{-2}$ m . A shell of this thickness can prevent the scattering of stationary charges. Now let's discuss how we can create counteraction to the force that stretches the shell due to the movement of charge carriers. We found that when the kinetic energy density of particles inside the shell is equal to $\rho_{c}=10^{10} \mathrm{~J} / \mathrm{m}^{3}$, the pressure inside the sphere is $P=$ $3.3 \cdot 10^{9} \mathrm{~Pa}$. The area $S$ of the internal surface of a sphere with radius $R_{i n}=5 \cdot 10^{-2} \mathrm{~m}$ is equal to $3.14 \cdot 10^{-2} \mathrm{~m}^{2}$. From here we find the force that stretches the shell, $F_{\text {rep }}=P \cdot S=1.036 \cdot 10^{8} \mathrm{~N}$. Above we found that one layer of polarized water molecules can create a compression force of the shell of 0.893 N . To compensate for the force $F_{\text {rep }}=$ $1.036 \cdot 10^{8} \mathrm{~N}$ will need to be added to the shell another $N=1.036 \cdot 10^{8}$ $\mathrm{N} / 0.893 \mathrm{~N}=1.16 \cdot 10^{8}$ layers of molecules. Taking the diameter of a water molecule equal to $4 \cdot 10^{-10} \mathrm{~m}$, we find that the thickness of the additional layer should be equal to $b=1.16 \cdot 10^{8} \times 4 \cdot 10^{-10} \mathrm{~m}=4.64 \cdot 10^{-2}$ m . As a result, we find that the thickness of the shell of ball lightning, which has a charge $Q=5 \cdot 10^{-3} \mathrm{C}$ and an energy reserve with a density $\rho_{\tilde{\mathrm{n}}}=10^{10} \mathrm{~J} / \mathrm{m}^{3}$, is equal to $d=a+b=6.64 \mathrm{~cm}$. The radius of such ball lightning is equal to $R_{b l}=R_{i n}+a+b=11.64 \mathrm{~cm}$. Shell volume $V_{e n}=(4 / 3) \pi\left(R_{b l}{ }^{3}-R_{i n}{ }^{3}\right)=6 \mathrm{dm}^{3}$, and mass $M_{b l}=6 \mathrm{~kg}$. Such ball lightning can rise into the air if the electric field strength in the atmosphere is greater than $E=M_{b l} \cdot g / Q=1.18 \cdot 10^{4} \mathrm{~V} / \mathrm{m}$. The above calculations are extremely simplified to improve understanding of the physics of ball lightning. For thick shells, it is necessary to take into account the weakening of the gradient force of attraction of water molecules as the distance to the center of the sphere increases. It was proven $\mathrm{in}^{21-23}$ that the configuration of ball lightning in the form of an energetic core with a charge and a shell of water is stable. Moreover, the stability of the system is maintained despite the simultaneous loss of charge and energy. The loss of charge leads to a decrease in the force compressing the shell, and the loss of energy leads to a decrease in the pressure of the core on the shell.

So, we found that a sphere with a diameter 23 cm and a mass 6 kg , which has an uncompensated electric charge $Q_{b l}=5 \cdot 10^{-3} \mathrm{C}$, can be a reservoir for storing kinetic energy 10 MJ . This ball is a spherical capacitor with an internal electrode of radius $R_{\mathrm{in}}=5 \cdot 10^{-2}$ m and a second electrode (earth) removed to infinity. The capacity of such a capacitor is $C=4 \pi \varepsilon_{0} R_{\text {in }}=5.56 \cdot 10^{-12} \mathrm{~F}$, and the energy of the electric field accumulated in it is $W_{E}=Q^{2} / 2 C=2.25 \cdot 10^{6} \mathrm{~J}$. This is approximately 4 times less than the kinetic energy of the particles contained in ball lightning core ( 10 MJ ). Heating of water in a barrel and in troughs, as well as heating of sap in trees, in principle, could be carried out either by direct current or by high-frequency radiation. Let us estimate the power of ohmic heating of a liquid when passing the
current of a ball lightning slow discharging. Taking the characteristic lifetime of ball lightning equal to $\tau=100 \mathrm{~s}$, we find that the average value of its discharge current $I_{a v}=Q_{b l} / \tau=5 \cdot 10^{-5} \mathrm{~A}$. Potential $U$ on the surface of ball lightning $U=Q / 4 \pi \varepsilon_{0} R_{\text {in }}=3.75 \cdot 10^{8} \mathrm{~V}$, and the power of this current $P=U \cdot I_{a v}=2 \cdot 10^{4} \mathrm{~W}$. Thus, the heating of water. in principle, can be explained by the direct effect of current. However, the cases of ball lightning energy transfer over a long distance (through the walls of the trough or through air during evaporation of the chain ${ }^{1}$ ) forces us to give preference to the explanation of water heating through the electromagnetic radiation of ball lightning. The generator of this radiation is the electrons that are part of the "dynamic electric capacitors" that make up the core of ball lightning. ${ }^{21-23}$ In such a capacitor, electrons move in closed orbits, and several electrons can move in the same orbit. When electrons are evenly distributed throughout the orbit, their radiation is suppressed due to interference. However, when the "order" of electron arrangement is violated, electromagnetic radiation occurs, the power of which can reach several megawatts.

Let's consider the behavior of ball lightning above the treetops. As shown in article, ${ }^{24}$ ball lightning has a positive charge. The electric field of the ionosphere-earth capacitor is directed from top to bottom (the earth is negatively charged), so ball lightning, moving along the field line, will move down. If there are vertical conductors (tree trunks), the power lines will become denser near them. Therefore, the ball lightning will be attracted to the tree trunk. Touching the trunk, due to polarization of the wood, it will be attracted to it. The force of attraction to a conductor of a sphere of radius $R_{b l}=R_{i n}+a+b=11.5$ cm with a charge $Q=5 \cdot 10^{-3} \mathrm{C}$ is equal to

$$
\begin{equation*}
F_{a c}=Q^{2} / 4 \pi \varepsilon_{0}\left(2 R_{b l}\right)^{2}=4.26 \cdot 10^{6} \mathrm{~N} \tag{7}
\end{equation*}
$$

Let us assume that the force of attraction of the ball to the dielectric $F_{a d}$ is 10 times less than the force of attraction to the conductor. Ball pressure on the trunk $P=F_{a d} / \pi R_{b l}{ }^{2}=10^{7} \mathrm{~N} / \mathrm{m}^{2}=100 \mathrm{~atm}$. Ball lightning stuck to the trunk will move downward under the influence of the electric field of the atmosphere. In the core of real ball lightning, charge carriers move in closed orbits, as a result it is capable to emit radio waves. ${ }^{21-23}$ Upon close contact with water, it heated it to a boil, and the steam, expanding, tore the bark from the wood. We found above that the work done by ball lightning was no less than $A_{b l}=$ $7.78 \cdot 10^{5} \mathrm{~J}$. Let us assume that this work was performed due to the expenditure of part of the kinetic energy $W_{\mathrm{k}}$ of particles in the core of ball lightning and this energy was 2 times greater work $A_{b l}: W_{k}=2 A_{b l}$ $=1.6 \cdot 10^{6} \mathrm{~J}$. We find the kinetic energy density $\rho_{\mathrm{k}}$ by dividing $W_{k}$ by the volume occupied by the charges,

$$
\begin{equation*}
\rho_{k}=W_{k} /(4 / 3) \pi R_{i n}^{3}=3 \cdot 10^{9} \mathrm{~J} / \mathrm{m}^{3} \tag{8}
\end{equation*}
$$

The above analysis allows us to make the assumption that the existence of two types of ball lightning is possible: low-energy systems with a core of stationary ions and high-energy systems with a core of dynamic electric capacitors. ${ }^{25}$ The first of them appears, for example, during short circuits in household electrical appliances, and the second - during lightning discharges. For both types of ball lightning, the electric field strength on the surface reaches values sufficient to create a corona discharge. The ions that penetrate the shell are accelerated in this field to a speed at which they can ionize air molecules. This process takes on the character of an avalanche. A violet glow appears around ball lightning, which can be explained by the light emission of excited $\mathrm{NO}_{2}$ molecules. ${ }^{26}$ From this it follows that chemical reactions take place in the corona discharge plasma, leading to the formation of nitrogen dioxide and ozone. Sometimes
witnesses of ball lightning report the appearance of odors of these gases. The presence of such gases near ball lightning was directly proven by Dmitriev, who in 1967 collected gas from the trail of ball lightning into empty flasks. ${ }^{27-29} \mathrm{He}$ discovered that the content of $\mathrm{O}_{3}$ and $\mathrm{NO}_{2}$ in the flasks was noticeably higher than their presence in ordinary air, and the concentration ratio $\left[\mathrm{O}_{3}\right] /\left[\mathrm{NO}_{2}\right]$ was about 2.5 . Electronically excited $\mathrm{NO}_{2}$ molecules are formed in the reaction

$$
\begin{equation*}
\mathrm{NO}+\mathrm{O}+\mathrm{M} \rightarrow \mathrm{NO}_{2}+\mathrm{M} \tag{9}
\end{equation*}
$$

where the role of the third body $(\mathrm{M})$ is played by $\mathrm{N}_{2}$ and $\mathrm{O}_{2}$ molecules. At partial pressures of NO and O equal to one torr, the characteristic reaction time (9) is $\tau_{9}=2 \cdot 10^{-2} \mathrm{~s} .{ }^{26}$ Oxygen atoms are formed due to the dissociation of $\mathrm{O}_{2}$ molecules in collisions with electrons. The path to NO formation is more complex. First, during the dissociation of $\mathrm{N}_{2}$ in collisions with electrons, electronically excited nitrogen atoms $N^{*}(2 \mathrm{D})$ are formed:

$$
\begin{equation*}
\mathrm{N}_{2}+e \rightarrow \mathrm{~N}+\mathrm{N}^{*}\left({ }^{2} \mathrm{D}\right)+e \tag{10}
\end{equation*}
$$

and then the excited atoms react with oxygen molecules

$$
\begin{equation*}
\mathrm{N} *(2 \mathrm{D})+\mathrm{O}_{2} \rightarrow \mathrm{NO}+\mathrm{O} \tag{11}
\end{equation*}
$$

and oxygen atoms react with oxygen molecules to form ozone:

$$
\begin{equation*}
\mathrm{O}+\mathrm{O}_{2}+\mathrm{M} \rightarrow \mathrm{O}_{3}+\mathrm{M} \tag{12}
\end{equation*}
$$

At a partial pressure of oxygen atoms of about one torr, the characteristic time of ozone formation is about $\tau_{12}=4 \cdot 10^{-3} \mathrm{~s} .{ }^{26}$ Reaction (9), which competes with reaction (12) in consuming oxygen atoms, proceeds more slowly (with a characteristic time $\tau_{9}=2 \cdot 10^{-2} \mathrm{~s}$ ). The ratio of the rates of these reactions $k_{12} / k_{9}=\left(1 / \tau_{12}\right) /\left(1 / \tau_{9}\right)=\tau_{9} / \tau_{12}$ $=2 \cdot 10^{-2} \mathrm{~s} / 4 \cdot 10^{-3} \mathrm{~s}=5$ correlates with the maximum value of the ratio of gas concentrations in the flasks $\left[\mathrm{O}_{3}\right] /\left[\mathrm{NO}_{2}\right]=2.5$ found by Dmitriev. ${ }^{27-29}$

## Mass of ball lightning

Let us pay attention to another result of our calculations: we found that ball lightning should have a fairly noticeable mass. This conclusion contrasts with the widespread belief that ball lightning is similar to a balloon and the density of its substance is approximately equal to the density of air, $\rho_{a}=1.13 \mathrm{~kg} / \mathrm{m}^{3}$. Therefore, the mass of an "average" ball lightning (with a radius of 14 cm ) should be no more than $15-20 \mathrm{~g} .{ }^{30} \mathrm{In},{ }^{31}$ a case of a car colliding with ball lightning with a diameter 60 cm is described. At the moment of the collision, the driver (woman) felt "a strong blow (push), as if a car had hit an obstacle." Flying next to the car, ball lightning illuminated the inside of the cabin with a bright green light and then ended up behind the car. The car was moving at a speed of $70 \mathrm{~km} / \mathrm{h}(19.4 \mathrm{~m} / \mathrm{s})$. According to the witness, it was "a dull blow, like hitting a wall, shaking the car," that is, a blow with the transfer of mechanical and acoustic energy from ball lightning. Only a collision with an object weighing several kilograms can shake a car. Cases of aircraft collisions with ball lightning are described. These collisions are characterized by pilots as an impact from a solid body. ${ }^{6,26}$ Stakhanov ${ }^{4}$ spoke about a case when a hunter fired a shotgun at ball lightning with a diameter $20-25 \mathrm{~cm}$. The lightning swayed slightly, but remained intact. Let the mass of the pellets passing through the ball lightning be $m_{d}=10^{-2} \mathrm{~kg}$, and their speed $v_{d}=200 \mathrm{~m} / \mathrm{s}$. Let us assume that after the shot the ball lightning began to move at a speed $v_{b l}=10^{-1} \mathrm{~m} / \mathrm{s}$, that is, it acquired an impulse $v_{b l} \cdot m_{b l}=v_{d} \cdot m_{d}=2 \mathrm{~kg} \cdot \mathrm{~m} / \mathrm{s}$. Hence $m_{b l}=20 \mathrm{~kg}$. Thus, the mass of real ball lightning turns out to be no less than $0.1-20 \mathrm{~kg}$, that is, its density significantly exceeds the density of air.

According to the electrodynamic model, ${ }^{21-23}$ the bulk of ball lightning is concentrated in its shell. Let's consider a "typical" ball lightning with an internal radius $R=0.1 \mathrm{~m}$ and a shell thickness $a$ $=0.01 \mathrm{~m}$. Shell volume $V=(4 / 3) \pi\left[(R+a)^{3}-R^{3}\right]=1.39 \cdot 10^{-3} \mathrm{~m}^{3}$. Considering the density of the shell material to be equal to the density of water, we find the mass of the shell (mass of ball lightning) $m_{b l}=$ 1.39 kg . Such ball lightning is attracted to the ground with a gravity force $F_{g r}=m_{b l} \cdot g=13.6 \mathrm{~N}$. If the charge of ball lightning is $Q=10^{-3}$ C, its fall can be stopped by the electric field $E_{c l}=F_{g r} / Q=1.36 \cdot 10^{4}$ $\mathrm{V} / \mathrm{m}$.

## Why does ball lightning jump?

In the above descriptions, ball lightning appeared to observers as a solid, durable body, similar to a soccer ball. Here are typical examples of this behavior of ball lightning. In the summer of 1935, during a severe thunderstorm, a boy saw a fireball slightly smaller in size than a soccer ball jumping across the floor in the house, moving away to the corner of the entryway. With each hit on the floor, this ball seemed to be flattened, and then again took a round shape. With each blow, small balls bounced off him, like sparks of hot metal, which immediately went out. The ball became smaller and smaller with each blow and finally it disappeared in the corner of the entryway". ${ }^{3}$ A case is also described of how a ball that appeared on a wire after a lightning strike "fell on the pavement, scattering sparks around itself, and began to jump along the pavement like a ball, jumping up $10-15 \mathrm{~cm}$. After several jumps, it fell into pieces, which went out immediately. All this was happened during approximately $10-20$ seconds". ${ }^{4}$ Ball lightning can leave marks when it hits the ground. In August 1839, during a severe thunderstorm in Paris, "lightning struck the middle of the courtyard, turning into a ball. The ball hit the soil and knocked out a hole in it with a diameter 18 cm . After that, it began to rotate quickly, bounced off the ground and, having flown another 3 meters, fell to the ground again, forming a new hole with a diameter 9 cm . Jumping out of this hole, it flew up to wall, along which it rolled about another 30 meters". ${ }^{16}$ It turns out that ball lightning can bounce not only from a solid surface, but also from the surface of water. "Several people crossing the Vorona River on a ferry saw ball lightning moving over the water at a speed of about $0.5 \mathrm{~m} / \mathrm{s}$. It touched the water and bounced off it every 1-2 meters". ${ }^{3}$ In the summer of 1935, "after a discharge of linear lightning, a sparkling ball with a diameter of about 15 centimeters appeared over the middle of the river. Being jumping over the water, it exploded with a terrible squelching crack". ${ }^{3}$ One day, "after a linear lightning strike, ball lightning formed in the center of the pond. It flew about 100 meters at a height $3-5 \mathrm{~m}$ above the surface of water, then fell on the surface of water, jumped up and, having flown another 100 meters, hit the water again. After bouncing off the water, it was melted into the air". ${ }^{3}$

Thus, the interaction of ball lightning with a surface is similar to the behavior of an elastic body, for example, a ball. The air pressure inside the ball's shell is greater than atmospheric pressure. When hitting the ground, the volume of air inside the shell decreases, internal pressure increases, and a force is created that throws the ball away from the obstacle. The authors of some models of ball lightning believe that it should consist of a substance with surface tension. The nature of surface tension is the force of mutual attraction between molecules, which is non-zero at the phase boundary, for example, on the surface of a liquid. Since in models of "average" ball lightning it is assumed that the density of its substance is close to the density of air, the problem arises of explaining how the surface tension force arises in a substance with a gas density. A solution to this problem is to imagine
the structure of ball lightning in the form of a soap bubble. The value of surface tension in the bubble shell is close to its value for water $\sigma=$ $8 \cdot 10^{-2} \mathrm{~J} / \mathrm{m}^{2}$. The pressure inside a soap bubble with a radius $R=10 \mathrm{~cm}$ exceeds atmospheric pressure by the amount $\Delta P=\sigma / R=8 \cdot 10^{-1} \mathrm{~Pa}$. If the air pressure inside a soccer ball exceeds atmospheric pressure by $10 \%$, then for it $\Delta P=10^{4} \mathrm{~Pa}$. It is unlikely that a soap bubble bouncing off a surface will be as spectacular as a ball bouncing.

In the electrodynamic model of ball lightning, ${ }^{21-23}$ it is believed that pressure on the inner surface of the shell arises, in particular, due to Coulomb repulsion of charges. With a ball lightning charge of $Q=$ $10^{-3} \mathrm{C}$ and radius $R=0.1 \mathrm{~m}$, this force is equal to $F_{e m}=Q^{2} / 8 \pi \varepsilon_{0} R^{2}=$ $4.5 \cdot 10^{5} \mathrm{~N}$. The area of the inner surface of the shell is $S=4 \pi R^{2}=$ $0.126 \mathrm{~m}^{2}$, hence $P_{e}=F_{e m} / S=3.6 \cdot 10^{6} \mathrm{~Pa}$. If the additional pressure $P_{k}$, resulting from the movement of charge carriers inside the shell, is approximately equal to $P_{e}$, then the total pressure inside the shell will become $P_{\Sigma}=P_{e}+P_{k}=7.2 \cdot 10^{6} \mathrm{~Pa}=72 \mathrm{~atm}$. Therefore, such ball lightning will bounce when it hits the surface, like a ball. However, as follows from the above examples, the movement of ball lightning upon contact with an obstacle cannot be explained only by simple deformation of the shell upon impact. Indeed, it is not clear why ball lightning bounces off the surface of the water and why, after making several low jumps, it suddenly flew up onto the wall, and why, when jumping, it threw out sparks or made holes in the ground. The reason for this is the presence of a charge in ball lightning, part of which is discarded upon contact with an obstacle. Let us assume that ball lightning, having a charge $Q=10^{-3} \mathrm{C}$ and a mass $M=1 \mathrm{~kg}$, when hitting the ground transfers to it a charge $q=10^{-2} Q$ and a mass $m=10^{-2} \mathrm{M}$ . Let the radius of the ball lightning be $R=0.1 \mathrm{~m}$ remains the same. The separated charge $q$, moving towards the ground in the electric field of the charge $Q$, acquires energy $E_{q}=Q q / 4 \pi \varepsilon_{0} R=m v^{2} / 2$ and momentum $p=m v=\left(Q q m / 2 \pi \varepsilon_{0} R\right)^{1 / 2}$. This impulse is transmitted to the "large" ball lightning, and it acquires a speed in the direction from the earth's surface $V=m v / M=4.2 \mathrm{~m} / \mathrm{s}$. Having such an initial speed, ball lightning can jump to a height of $H=V^{2} / 2 g=0.9 \mathrm{~m}$. The energy of the detached fragment is $E_{q}=900 \mathrm{~J}$. Let us assume that this energy was spent on the formation of a hole $20 \mathrm{~cm} \times 20 \mathrm{~cm}$ and 20 cm deep. The volume of this hole is $V_{g}=8 \cdot 10^{-3} \mathrm{~m}^{3}$. Taking the soil density equal to $\rho_{g}=4 \cdot 10^{3} \mathrm{~kg} / \mathrm{m}^{3}$, we find the mass of discarded soil $m_{g}=\rho_{g} \cdot V_{g}$ $=30 \mathrm{~kg}$. This soil could be thrown to a height $H_{g}=E_{q} / m_{g} \cdot g=3 \mathrm{~m}$.

## Effect of ball lightning on glass: formation of holes

There are many reports of the appearance of round holes with a diameter $5-30 \mathrm{~cm}$ in window glass. Such holes usually appear during thunderstorms. ${ }^{32}$ Often, between the double panes of the frame, a disk is found that has fallen out of the hole. A large number of round holes in windows appeared in the summer and autumn of 1977 in Petrozavodsk. ${ }^{33}$ The fact that the appearance of such holes is associated with the action of ball lightning on glass is indicated by an incident that occurred in the summer of 1977 in the city Fryazino, Moscow region. ${ }^{34}$ In front of the teacher and a group of schoolchildren, it made a hole in the window glass. A ball lightning, in the form of a "red "furry" ball with a diameter of about 5 cm , approached the outer glass of the window. A small round hole with glowing red edges appeared in the glass. Then the diameter of the hole increased to $3-4 \mathrm{~cm}$, after which the ball lightning flashed brightly and disappeared with a loud sound." As a result of this event, which lasted 5 seconds, a circular hole with a diameter 5 cm was formed in the outer glass $(2.5 \mathrm{~mm}$ thick), while the inner glass remained intact (Figure 5).


Figure 5 A hole in glass made by ball lightning in the city Fryazino. ${ }^{34}$
The hole had a conical shape, its diameter on the outer side of the glass was approximately 1 mm larger than the diameter on the other side. The edges of the hole were not melted. According to Kolosovsky, ${ }^{34}$ the event occurred as follows. First, ball lightning melted a hole in the glass with a diameter of about 3 cm , and then, as the glass cooled, thermal stresses arose in it, which led to the formation of an annular crack with a diameter 5 cm . A similar incident occurred on April 13, 1994 in the city Shchelkovo. ${ }^{37}$ "The owner of the apartment saw a bright flash in the window with her peripheral vision, and after 1.5-2 seconds she heard the sound of falling glass. Approaching the window, she discovered a large almost round hole in the glass of the outer frame ( 3 mm thick), and a glass disk lay between the outer and inner frames. The inner glass of the frame remained intact. Figure 6 shows a glass with a hole and a fallen disk. ${ }^{33}$


Figure 6 A hole in the glass and a disk that fell out of it. ${ }^{33}$
The hole in the glass is an oval. Its major axis measures 82.0 mm and its minor axis measures 76.7 mm . The edge of the hole on the inside is rounded, which may indicate that this part of the glass was heated to the softening temperature (about $600^{\circ} \mathrm{C}$ ). However, the edge of the hole on the outside of the glass (on the street side) remained sharp. The dimensions of the oval axes on the street side were 80.5 and 74.7 mm . This means that the hole had the shape of a truncated cone with the base facing the inside of the room. It turned out that the disk could be perfectly inserted into the hole. It was a truncated cone with an extension from the inner surface of the glass. The rib had a smooth mirror surface. Adjacent to half the circumference of the inner surface of the disk was a sharp wedge-shaped edge about 50 microns thick and 2 to 6 mm high, torn from the inner surface of the frame glass. Analysis of the disk suggested that the circular crack in the glass could have appeared when a section of glass was rapidly heated to the softening temperature, followed by rapid cooling of the glass. It was estimated that the minimum energy required to heat glass until
it softened was about 1-7 kJ. The glass was heated primarily on the inside, most likely by high-frequency radiation from ball lightning. In the surface layer of an acutely fractured disk, a change in the ratio of silicon and oxygen content in the glass was found, which may be associated with the occurrence of a chemical reaction during the separation of the disk. ${ }^{36}$ The detachment of the disk occurred under the influence of a force applied perpendicular to the surface of the glass, most likely due to an explosion of ball lightning.

Kolosovsky ${ }^{34}$ conducted experiments to simulate the effect of ball lightning on glass. Using a 500-watt continuous-wave carbon dioxide laser, he melted a small hole in the glass and then turned off the laser. The glass cooled and a circular crack appeared around the melt zone. The edges of the hole had a conical shape with an expansion towards the laser. However, the disk that fell out of the hole was damaged. In our experiments, ${ }^{33}$ glass was heated using a flat nichrome spiral with a diameter 40 mm . When the glass surface was heated to a temperature $400^{\circ} \mathrm{C}$, the glass plate was destroyed with the formation of cracks. The central part of the glass plate, located under the spiral, remained intact. It was possible to obtain some similarity to the result of the action of ball lightning on glass (when not only the disk, but also the rest of the glass is intact) in only one case (Figure 7). When the glass was heated and subsequently cooled, two more cracks formed around the ring crack, running tangentially to it, as well as cracks in the circular disk. The edges of the hole and the disk had a conical shape, the cone was wider on the heating side, and its angle was $4^{0}-6^{0}$. During the heating process, more than 80 kJ of energy was "invested" into the glass. This led to a softening of the glass surface (the spiral turns fused into the glass).


Figure 7 The result of heating glass with a flat nichrome spiral. ${ }^{33}$
Thus, the formation of a hole in glass is not reduced to simple heating of the glass, but is a complex process. Something must "force" the ball lightning to approach the window, uniformly heat up a section of glass in a short period of time, sometimes on the wrong side where it is located, and create a force impulse that causes the disc to fall out until the glass remaining in the frame cracks.

The electrodynamic model ${ }^{21-23}$ has a chance to explain the sequence of these processes. Ball lightning is attracted to glass due to the polarization of its material in the non-uniform electric field created by its charge. Ball lightning is capable of generating radio waves $1-10 \mathrm{~cm}$ long, which are insignificantly absorbed by glass, but, however, can carry out its volumetric (rather than surface) heating. A ball lightning explosion can create a force that pushes the disk out of the window. Note that in the cases considered, ball lightning left the
inner glass untouched. It is possible that acoustic vibrations in the glass unit may play some role in the process of the hole formation.

## Passage of ball lightning through "intact" glass

The ability of ball lightning to "freely" pass through glass without leaving traces in it has become the main argument for substantiating the "field" hypothesis, according to which it is considered as a discharge in the air, powered by high-frequency radio emission. There is much evidence of this behavior of ball lightning. The book ${ }^{3}$ tells how "a bright blue ball lightning the size of an apple, in front of dozens of people, passed straight through the window glass without damaging it, and struck one of the witnesses with an electric charge." Here are other examples. "It was raining heavily with a thunderstorm... Suddenly, with a strong discharge, a ball flew through the window through the glass, looking like a brightly burning 100 W light bulb. The glass turned out to be intact, but on the outside there was a dry circle on it, although the rest of the glass was wet from heavy rain". ${ }^{3}$ "There was a thunderstorm outside. Suddenly, a clink of glass was heard at the top of the window, and immediately a fiery orange ball with a diameter 22 centimeters appeared there... When the ball entered through the window, the glass rattled violently, and it seemed to the witness that it had broken. However, it turned out to be completely intact, without damage" "During a very strong thunderstorm, a sparkling ball with a diameter 4-5 centimeters slowly passed into the room directly through the window glass. Passing through the glass, it did not change its shape and passed as if there was no glass at all... Having hit a metal ball on the bed, it bounced elastically towards the window and just as slowly moved away through the glass... All this lasted 5-7 seconds. There were no traces left in the glass through which the ball passed twice". ${ }^{3}$ In July 2004, in the city Pustoshka, Pskov region, "during a thunderstorm, a luminous ball appeared outside the window of a wooden house... It passed through the glass, as if there was no obstacle for it. The diameter of the ball was about $15-25 \mathrm{~cm}$. It glowed brightly, in the center the light was almost white, on the edges there was a red tint... The height of the ball above the floor was about one meter. Having entered the room, the ball began to move quickly between the right window and the left wall, each time returning after touching the window and wall. So it made about three "oscillations". This movement of the ball lasted about three seconds, the speed of the object was 1-2 m/s... Finally, the ball was pulled into an electrical outlet and disappeared. After this, the socket began to "spark"... A superficial survey of the window glass showed that it remained intact". ${ }^{37}$ As we can see, this is a typical description of observing the passage of ball lightning through glass and a typical conclusion about its result - the preservation of the integrity of the glass. However, in the hundred-year history of observing such events, glass has never been subjected to research. We asked the author of the observation in Pustoshka to give us glass for research. Our request was fulfilled, and we had at our disposal two sheets of glass measuring $530 \mathrm{~mm} \times 350 \mathrm{~mm} \times 2 \mathrm{~mm}$ - glass from the left window, through which ball lightning passed, and glass from the right window, which was touched by ball lightning.

The first impression from examining the glass was that it had not been damaged in any way. There were no cracks or defects on them on a scale comparable to the size of ball lightning. However, upon careful examination of the glass from the left window with a magnifying glass, at the place where ball lightning supposedly entered the room, located 15 cm from its edge, a defect resembling a streak on lowquality window glass was discovered. Figure 8 shows a photograph of the outer (street side) surface of the glass, taken using an optical microscope with a magnification $\times 200$. It turned out that ball lightning left a cylindrical cavity in the glass with a diameter 0.24 mm and a
depth 1 mm . This cavern was surrounded by a $0.43 \mathrm{~mm} \times 0.8 \mathrm{~mm}$ lentil-shaped zone of darkened glass. This zone was surrounded by a $1.2 \mathrm{~mm} \times 0.75 \mathrm{~mm}$ zone of slightly darkened glass. The glass area around the pit acquired the property of a collecting lens with a focal length 5 cm . The light transmission in the cavity region turned out to be 9.4 times less than the light transmission of intact glass, and the size of the area where a decrease in light transmission was observed was about $5 \mathrm{~mm} \times 5 \mathrm{~mm}$. An analysis of the path of rays through the resulting lens showed that the refractive index of its material was $4 \%$ greater than the refractive index of pure glass. This correlates with the discovery of spherical inclusions in the glass with a diameter of about 2 microns, which occupied approximately $4 \%$ of the glass volume. It is possible that these inclusions are bubbles that appeared due to the boiling of the glass.


Figure 8 View of the glass area from the street side. The length of the white stripe is 500 microns.

Thus, in the case studied, ball lightning was a material body consisting of small elements that passed through the glass. This process took a short time, so the observer had the impression that the ball lightning passed through the glass without changing its shape. Proponents of the "field" hypothesis of ball lightning explain this process by the free passage of a radio frequency electromagnetic field through the dielectric. However, no sources for the creation of such a field have been found in nature. Attempts to "construct" ball lightning in the form of a bubble filled with radiation ${ }^{38,39}$ also do not solve this problem: along with the electromagnetic field, the "material" wall of the bubble must somehow pass through the glass. In recent years, new results from solving Maxwell's equations have aroused some interest, according to which spherical configurations of electromagnetic fields with a zero radial component of the Poynting vector can exist. However, in these solutions there is no definition of boundary conditions: the electromagnetic configuration can exist only if it has an infinite size. ${ }^{40-42}$ It is clear that a ball of infinite size cannot pass through an ordinary window.

According to the electrodynamic model, ball lightning consists of a shell, inside of which there are dynamic capacitors - small charged objects. ${ }^{21-23}$ This is confirmed by a large number of observations. For example, for a witness who saw ball lightning close up, "the balls seemed to consist of a huge accumulation of small balls, almost points, with a diameter 1-1.5 millimeters, in chaotic motion, but not extending beyond the boundaries of the ball itself' ${ }^{3}$ Ball lightning is capable of generating high-frequency radiation, the intensity of which can vary over a wide range. Ball lightning has an uncompensated electrical charge. They usually travel along atmospheric electric field lines, which near the ground may tend to be condensed near the windows and doors of buildings. Upon close contact with glass in the electric field of ball lightning, the glass polarizes and an additional force of its attraction to the glass arises. The shape of the ball lightning changes: a
protrusion appears on it, directed towards the glass. The deformed ball lightning emits a powerful pulse of radio frequency radiation. Under the influence of this pulse, the temperature of a small area of glass increases to the melting point, and the viscosity of the glass decreases by several orders of magnitude. ${ }^{43}$ Under the influence of an external electric field, the elements of the core of ball lightning, together with the shell material, seem to flow through the formed channel. After ball lightning passes through it, the channel cools down and is drawn in by the surface tension of the glass. The scenario of this process is similar to that shown in Figure 9.


Figure 9 Modeling the process of ball lightning passing through a hole (calculation).

## Passage of ball lightning through cracks and small holes

The ability of ball lightning to find holes and penetrate through them is a property noted by many observers. In the overwhelming majority of cases, ball lightning passes through holes whose size is much smaller than its diameter. The book ${ }^{3}$ tells how "a yellow-orange ball with a diameter 15 centimeters crawled into the room through an open window. Having rolled along the wall, ... it crawled out onto the street, squeezing through a crack of cracked glass 1-2 millimeters wide." A ball with a diameter 50 cm flew into the cabin of a tower crane and passed through a 2 cm wide gap in a metal panel. ${ }^{4}$ Sometimes the ball seems to be looking for a hole: "it approached the window and began to push in the corner of the frame. At the same time, it stretched out and crawled along the glass, as if looking for a place to pass. Finally, it jerked and quickly went to the bathroom... On the way back, it passed through the same site without delay". ${ }^{4}$ Sometimes ball lightning passes through the gap quickly, as if without changing size, and sometimes this process takes some time. "The ball began to pass through the hole, taking the shape of a melon. It stretched out, became smaller in diameter and passed through the hole. When the ball passed through the hole and decreased in size, it seemed to tremble all the time, and it seemed that it was entirely made of jelly, and blue rays 1.5 cm long emanated from its surface and ended at the ends with flashes of sparks". ${ }^{4}$ Sometimes one can see that the ball, crawling through the hole, seems to "flow from one half to the other". ${ }^{4}$ Often, before passing through the gap, ball lightning changes shape: it is pulled out into a "sausage", enters it in the form of a "snake" or "yellow thread 1-1.5 cm thick". ${ }^{4}$ Ball lightning, passing through a hole with a diameter 1.5 cm , took the form of a "yellow-red fiery ribbon", and then took the shape of a ball the size of a football. ${ }^{3}$ Sometimes the transformation of the tape into a ball and back occurs several times. Thus, the book. ${ }^{3}$ tells how "after a strong thunder, a thin yellow-white lightning thread flew through the glass. It hit the stove and turned into a ball with a
diameter 10 centimeters... There was a cracking sound, and the ball again turned into a yellow thread." The book ${ }^{3}$ tells how, during a thunderstorm, a yellow-red ribbon with a diameter 2 cm and a length of one meter flew into the room through a small hole... This ribbon stopped and quickly spun in place, winding up into a ball the size of a football... Then the ball flew out into the street, where it exploded with a terrible roar, throwing tongues of flame in all directions." It is possible that the change in the shape of ball lightning occurs due to the action of nearby objects on it. For example, "a ball with a diameter 12 centimeters, which had previously been lying motionless, began to slowly stretch into a wide ribbon towards the furnace firebox. Finally, the entire tape had quickly slided into the oven"." "A shiny "silver" ball with a diameter 13 centimeters... slowly floated towards the hole for the shutter bolt. Suddenly the ball without a sound began to stretch out, turning into a "fat snake," and in this form it slid into the hole". ${ }^{3}$ Once, during a thunderstorm, a "red-brown ball with a diameter 40 cm" appeared in a room near a light bulb socket hanging on a 60 cm long cord... After 5 seconds, the ball began to slowly stretch out towards the open window. The ball stretched out into a long ribbon. When its end reached the window, the entire ribbon instantly went through the window into the street, shooting up". ${ }^{3}$

Based on the observations presented, we can draw the following conclusions: 1) There are some reasons that force ball lightning to "find" windows and strive to penetrate them. 2) The elements of ball lightning substance have a size of no more than 1 mm . 3) Upon close contact with a material in which there is a hole (glass, wood, metal), forces arise that lead to a change in the shape of ball lightning.

The issue of the passage of ball lightning through small holes was studied by Gaidukov. ${ }^{44}$ According to him, ball lightning passes through the hole, "shimmering like liquid." Due to the specific features of the shell of ball lightning (the absence of friction), this process is similar to the flow of a superfluid liquid. The force that makes ball lightning move is the difference in air pressure on different sides of the glass (gas flow). ${ }^{44}$

Let's try to explain the features of the behavior of ball lightning near holes based on the electrodynamic model. ${ }^{21-23}$ Ball lightning has an uncompensated electric charge, and its movement is primarily determined by the effect of atmospheric electric fields on this charge. Electric field lines between the cloud and the ground penetrate to grounded objects indoors through windows, doors and other openings. When ball lightning approaches glass (or another object), the glass polarizes in the electric field of its charge and a force arises that attracts it to the glass. The charge carriers of ball lightning are somehow distributed throughout its volume, so the action of a relatively short-range polarization force from the glass turns out to be different for different groups of charges inside the shell. The groups of charges closest to the glass are attracted to it more strongly than "distant" charges. Because of this, the shape of the ball lightning changes - it stretches in the direction of the glass and can turn into a cylinder. The passage of this cylinder (ribbon, snake) occurs due to the action of the electric field of the atmosphere (which "led" the ball lightning to the glass). Once at a certain distance from the glass (where the effect of the polarization force decreases), due to the action of Coulomb forces of repulsion of charges, the cylinder again turns into a sphere (Figure 9).

Figure 9 shows animation frames of ball lightning passing through an obstacle, obtained using computer simulation. The motion of a sphere consisting of ions was simulated, each of which was associated with a neighboring ion. The ions repelled from each other according to Coulomb's law, but at the same time they were attracted according to Hooke's law. A two-dimensional system in the form of
a ring consisting of 48 ions was considered. The total force acting on a specific ion was calculated, then, taking into account the mass of the ion, the acceleration, speed and displacement over a certain time interval were determined. To get closer to reality (to take into account energy losses), it was believed that the movement of the ion occurred with friction, the force of which was proportional to the speed of the ion. The Processing program (https://www.processing.org/) was used in the calculations. The process of ball lightning passing through a solid barrier was simulated. It was believed that ball lightning moves under the influence of an electric field from left to right. Away from the obstacle (metal wall), it has a spherical shape. As it approaches the wall, it changes shape (1st frame). This occurs due to the fact that in the electric field created by the ions, polarization of the wall material occurs and a force appears that attracts ball lightning. The force acting on ions near the wall is greater than the force acting on distant ions. As a result, the shape of the surface is distorted - a protrusion appears on it towards the wall. The deformed ball lightning emits a pulse of electromagnetic radiation, the energy of which burns a hole in the barrier (2nd frame). Under the influence of an external electric field, which is present both to the left and to the right of the obstacle, ball lightning passes through the hole, changing its shape (3rd and subsequent frames). Having passed through the hole, the ball lightning restores its spherical shape. If a hole is formed in the metal due to sublimation of the material, it remains in its original form. If ball lightning passes through a hole in the molten glass, it closes.

## Conclusion

The most unexpected result of observing ball lightning is the fact that after its disappearance, no "details" of its "framework" remain. A London resident could not find a cooled kernel in a barrel, and a student who poured boiling water out of a bucket found nothing in it except boiled fish. This calls into question the correctness of models of ball lightning, according to which it has a hard shell of silicon oxide. ${ }^{45,46}$ We have shown that a rigid elastic structure can be made from elastic materials and given strength by properly oriented forces. For example, the shell of a deflated ball is a shapeless soft structure. But if the ball is filled with air, it becomes an elastic solid object. The same can be said about ball lightning. The introduction of electric field energy into its shell makes it elastic and durable. Unlike a ball, in which the gas pressure on all parts of the surface is the same, in ball lightning the pressure force on the shell can be different in different parts of its surface. This occurs due to the fact that the pressure is created by the charged elements of its core, and their position inside the shell can change. This can occur under the influence of external influences. The appearance of local inhomogeneities in the volumetric charge distribution leads to a change in the shape of ball lightning. Let us note one more feature of ball lightning. Due to the reserve of internal energy and the presence of charge, ball lightning has an effect on the external environment, changing its properties. This explains the reason for the complex nature of its movement. ${ }^{24}$ External influence on ball lightning can initiate the generation of a pulse of electromagnetic radiation sufficient to burn through metal or melt glass. The presence of a charge makes ball lightning sensitive to the electric fields of the atmosphere. Moving along the lines of force of the field, it seeks to penetrate into rooms or pass through window panes. The presence of a charge gives ball lightning the ability to perform mechanical work and transport objects over long distances.

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## Conflicts of interest

The author declares there is no conflict of interest.

## References

1. Nikitin AI. The danger of ball lightning. Phys Astron Int $J$. 2023;7(2):91-97.
2. Nikitin AI. Rotatioinal dynamics of a ball lightning. Phys Astron Int $J$. 2023;7(3):185-187.
3. Grigoriev AI. Ball lightning. Yaroslavl: Publishing of YarGU; 2006.
4. Stakhanov IP. About the physical nature of ball lightning. Moscow: Nauchnyi Mir; 1996.
5. Egely G. Analysis of Hungarian ball lightning observations. In: Progress in ball lightning research. Keul AG, ed. Proc. VIZOTUM: Salzburg, Austria; 1993.
6. Stenhoff M. Ball lightning. An unsolved problem in atmospheric physics. London: Kluwer Acad; 1999.
7. Smirnov BM. A problem of ball lightning. Moscow: Nauka; 1988.
8. Goodlet BL. Lightning. J Inst Elect Eng. 1937;81:1.
9. Imianitov I, Tikhiy D. Beyond a boundary of laws of a science. Moscow: Atomizdat; 1980.
10. Nikitin AI, Bychkov VL, Nikitina TF, et al. High energy ball lightning observations. IEEE Trans Plasma Sci. 2014;42(12):3906-3911.
11. Covington AE. Ball lightning. Nature. 1970;226(5242):252.
12. Zimmerman PD. Energy content of Covington's lightning ball. Nature. 1970;228(5274):853.
13. Kozlov BN. Maximum energy liberated by ball lightning. Sov Phys Doklady. 1978;238(1):41-42.
14. Dmitriev MT, Bakhtin BI, Martynov VI. The theremal factor of ball lightning. Zh Tekh Fiz. 1981;51(12):2567-2572.
15. Teletov GS. About of ball lightning nature. In: Ball lightning in laboratory. Moscow: Khimia; 1994. 247-256 p.
16. Brand W. Der Kugelblitz. Hamburg: Verlag von H. Grand; 1923.
17. Pudovkin AK. Ball lightning in the Novosibirsk's campus. Uspekhi Fiz Nauk. 1996;166(11):1253-1254.
18. Ball lightning on the pine-tree. https://pikabu.ru/@yn4kwert
19. Hurricane in Gorny Altai; 2018. https://www.alt.kp.ru/ daily/26855.5/3897298/
20. Blakemore JS. Solid state physics. Cambridge: Cambridge University Press; 1985.
21. Nikitin AI. Electrodynamic model of ball lightning. Khimicheskaya Fizika. 2006;25(3):38-62.
22. Nikitin AI. Possible process of ball lightning training in nature. J Atm Solar-Terr Phys. 2019;190:54-61.
23. Nikitin AI. My ball lightning. Moscow: Nauka; 2022.
24. Nikitin AI. Reasons of ball lightning levitation. Phys Astron Int J. 2023;7(4):231-238.
25. Nikitin AI, Nikitin VA, Velichko AM, et al. Features of the mechanism of ball lightning electromagnetic radiation. J Atm Solar-Terr Phys. 2021;222:105711.
26. Bychkov VL, Nikitin AI. Ball lightning. A new step in understanding. In: The atmosphere and ionosphere. Elementary processes, monitoring and ball lightning. Bychkov VL, Golubkov GV, Nikitin AI, editors. Cham: Springer; 2014. 201-367 p.
27. Dmitriev MT. Nature of ball lightning. Priroda. 1967;(6):98-106.
28. Dmitriev MT. About a mechanism of ball lightning stability. J Techn Fiziki. 1969;39(2):387-394.
29. Singer S. The nature of ball lightning. New York: Plenum; 1971.
30. Smirnov BM. Physics of ball lightning. Uspekhi Fiz Nauk. 1990;160(4):1-45.
31. Keul AG. The Southern Bavaria ball lightning car collision. In: Proc. $5^{\text {th }}$ Int Symp on Ball Lightning (ISBL-97); 1997, 27-34; Tsugawa-Town, Niigata: Japan; 1997.
32. Turner DJ. The interaction of ball lightning with glass window panes. $J$ Meteorology. 1997;22(216):52-54.
33. Nikitin AI, Bychkov VL, Nikitina TF, et al. Modeling of ball lightning interaction with window panes. Khimicheskaya Fizika. 2006;25(4):98-105.
34. Kolosovskii OA. Observation of ball lightning track on the window glass. Zh Tekh Fiz. 1981;51(4):856-858.
35. Shchelkunov GP. Ball lightning: observation and analysis of tracks. Nauka i Zhizn. 2001;(10):52.
36. Nikitin AI, Bychkov VL, Velichko AM, et al. Analysis of results ball lightning action on window pane. Elektrichestvo. 2013;(9):12-22.
37. Bychkov VL, Nikitin AI, Ivanenko IP, et al. Ball lightning passage through a glass without breaking it. J Atmos Solar-Terr Phys. 2016;150:69-67.
38. Endean VG. Development of the radiation bubble model of ball lightning. Journ Meteorology. 1997;22(217):98-106.
39. Wu HC. Relativistic-microwave theory of ball lightning. Sci Rep. 2016;6:28263.
40. Arnhoff GH. On the spheric radiation. Proc. $6^{\text {th }}$ Int Symp on Ball Lightning (ISBL-99); 1999, 160-165; Antwerp: Belgium; 1999.
41. Cameron RP. Monochromatic knots and other unusual electromagnetic disturbances: light localized in 3D. J Phys Commun. 2018;2:015024.
42. Espinoza A, Chubykalo A. Mathematical foundation of Kapitsa's hypothesis about the origin and structure of ball lightning. Foundations of Physics. 2003;33(5):863-873.
43. Tareyev BM. Physics of dielectric materials. Moscow: Energia; 1975.
44. Gaidukov NI. Hydrodynamic model of the movement of a ball lightning jet through a narrow opening of a flat screen. J Techn Fiziki. 1991;61(11):49-56.
45. Abrahamson J, Dinnis J. Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil. Nature. 2000;403:519-521.
46. Bychkov VL. Natural and artificial ball lightning in the earth's atmosphere. Moscow: MAKS Press; 2021.
