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Laboratory demonstration of ball lightning

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Contents

Abstract. **A common laboratory facility for creating glowing flying plasmoids akin to a natural ball lightning, allowing a number of experiments to be performed to investigate the main properties of ball lightning, is described.**

1. Introduction

Ball lightning is a picturesque phenomenon accompanying an electric discharge in humid air. The bright rounded plasmoids floating up in a darkened room have an indelible effect on people, especially on those who have already witnessed the natural phenomenon. For experimental physicists, ball lightning is, first and foremost, the manifestation of a special, insufficiently explored state of matter known as hydrated plasma.

Hydrated plasma forms when a population of positive and negative ions enters the water vapor or humid air. When hydrated ions of opposite signs move closer to each other, clusters with a large dipole moment are produced [1, 2]. Due to plasma clusterization, ion recombination is slowed down substantially, and the accumulated energy gradually transforms into light. [1]

If a plasma jet is produced in humid air and then stopped by an electric field, a luminous plasmoid separates itself from the jet and begins to float in the air. Experiments have shown (see Ref. [3]) that the plasmoid is a blob of warm humid air containing many positive and negative ions. The excess of electrons, which is always present in a plasma jet, migrates to the plasmoid's surface, with the result that the cluster's core becomes polarized and a thin layer enriched with negative ions forms around it.

[1] One of the authors, G D Shabanov, has a different view on the theoretical model concerning the structure of the plasmoid studied.

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2. Description of experimental facility

Hydrated plasma can be produced in many ways, and the simplest one is to set up a pulsed discharge in a thin layer of water. Figure 1 shows the schematic of an experimental facility that makes it possible to introduce a massive population of ions of opposite signs into a blob of warm air saturated with water vapor. The facility is built around a capacitor bank which can be charged up to 5.5 kV. A capacitance of 600 – 800 μF is sufficient for demonstration: in this case the amount of electricity involved in the discharge is roughly one to two orders of magnitude smaller than in

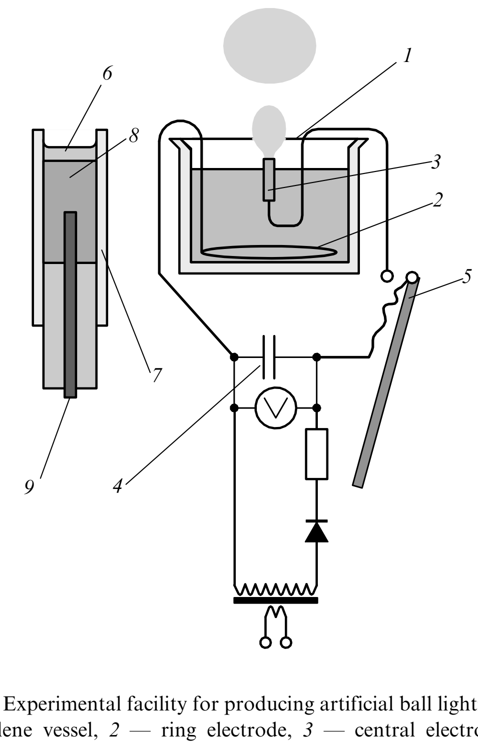

Figure 1. Experimental facility for producing artificial ball lightning: *1* — polyethylene vessel, *2* — ring electrode, *3* — central electrode, *4* — capacitor bank, *5* — discharger, *6* — drop of water or aqueous suspension, *7* — quartz tube, *8* — carbon electrode, and *9* — copper bus.

natural phenomena, but at the same time the consequences of random breakdowns are less disastrous.

A polyethylene cup 18 – 20 cm in diameter must be filled up to the 15-cm mark with poorly conducting water. This can be hard water from the tap with $CaHCO_3$ and $MgHCO_3$ content of 5 – 6 mM. A copper ring electrode connected by an insulated copper bus to the positive pole of the capacitor bank is placed at the bottom of the cup. The negative pole of the bank is connected to an electrode placed at the surface of the water at the center of the vessel and directed outwards in the air half-space. This second electrode is a cylinder 3 – 5 mm in diameter and can be fabricated from standard carbon used in arc spectral analysis. The quartz tubule tightly enclosing this electrode must rise above the end of the electrode and the water surface by 3 – 5 mm.

One or two drops of water are placed on the central electrode to produce artificial ball lightning. When the discharger is rapidly 'closed' and 'opened', a plasma jet flies out of the electrode with a light 'pop' sound, and then a luminous plasmoid separates itself from the jet and begins to float in the air surrounding the setup (Fig. 2).

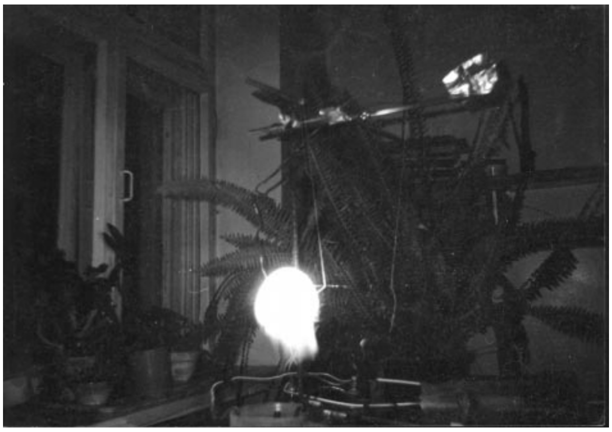

Figure 2. Formed ball lightning.

3. Experiments with ball lightning

Video recordings of a plasmoid make it possible to determine the ball lightning lifetime and dimensions. The sequence of frames shows the consecutive stages of nucleation, development, and decay of the plasmoid. The plasmoid acquires its orbicular shape only at a certain, not too high, potential difference between the electrodes. For the setup depicted in Fig. 1 the optimal breakdown voltage is in the 4.4 – 5.5-kV range. When selecting the optimal breakdown voltage, the production of plasmoids is first worked out at 4.8 kV, and then the entire range of voltages is tested to be certain that at higher breakdown voltages the rate of ion recombination increases and the plasmoid 'burns out'.

A reversal of the polarity of the electrodes changes the discharge pattern: a plasma jet is ejected from the positively charged central electrode and a small plasmoid in the shape of an irregular cloud separates itself from the jet. The lifetime of this small cloud is several times shorter than that of the orbed plasmoids ejected from the negatively charged electrode. This experiment illustrates the role that the excess of electrons plays in the formation of ball lightning and its outer shell.

On metal surfaces, the rate of ion recombination in a plasmoid increases and some portion of the metal gets sputtered. A small ring fabricated from copper or nichrome wire and suspended in the plasmoid's path loses some of its mass, which can be verified by weighing the ring before and after the experiment. There is the well-known case where high-power ball lightning disintegrated an entire wedding band without as much as burning the finger [4].

Video recordings of ball lightning against the background of a two-dimensional graticule make it possible to simultaneously determine the plasmoid diameter (12 – 18 cm) and the speed of the plasmoid's vertical displacement (0.6 – 0.8 m s^{-1}). These data can be used to calculate the average temperature of the blob of warm humid air containing the luminous hydrated plasma. According to our measurements, the average temperature of ball lightning is close to 330 K.

The color of ball lightning depends on the composition of the substance involved in the discharge. The color of the plasmoids ejected by moist metal electrodes is determined by the line spectrum of the electrode material. An iron electrode produces dazzling whitish plasmoids, a copper electrode gives rise to green plasmoids, and an aluminium electrode produces white plasmoids with a reddish tint. One or two drops of 0.001-molar solution of $NaHCO_3$ or 0.005-molar solution of $CaHCO_3$ gives the plasmoid a yellow or reddish color.

In addition to hydrated plasma, natural ball lightning may contain the aerosol of the substance dispersed in the electric discharge. Among such substances are soot, particles of soil, clay, sand, and various organic substances. The number of possible combinations is great, which explains the great variety of colors, shapes, and densities of ball lightning in nature.

To produce a plasmoid with a carbon aerosol, a suspension consisting of 3 g of colloidal graphite, 8 – 10 ml of acetone (wetting agent), and 90 ml of water can be used. If one or two drops of this suspension are deposited on the carbon electrode, the plasmoid ejected in the discharge gives a bright flamelike color.

Various mixtures of organic and inorganic substances, coal, and metallic powders can be directly deposited on a carbon electrode moistened with a drop of water. Video recordings of the ejected plasmoids show that some aerosols shorten the plasmoid lifetime, while other aerosols increase it. The search for the composition and amount of the dispersed phase that would substantially increase the plasmoid lifetime is still under way and there is a broad area for such a search [5]. The lifetime of water – dust plasmoids also depends on a number of factors: the potential difference between the electrodes, the length of the current pulse, the size and shape of the central electrode, the temperature and electrical conductivity of the base water volume, and the electric and magnetic fields in the plasmoid path.

Most plasmoids live for about 0.4 – 0.6 s, but some live as long as 1 s. The bright flash of the discharge causes the appearance of a bright afterimage of the plasmoid on the retina of the eyes of some observers. This afterimage exists for several seconds and moves in space as the observer wiggles his/her head (the Humphreys effect) [6, p. 34]. Each such case should be entered into the record, so that the fraction of long-lived 'physiological' phenomena among the observed natural phenomena can be estimated.

The shape of water – dust plasmoids varies substantially; usually the plasmoid consists of a bright core surrounded by a shell of a different color. Sometimes the plasmoid is shaped like a torus or crown, but by selecting the proper discharge parameters and electrode shape we can always make sure that the ejected plasmoids have an orbicular shape.

The experimental facility depicted in Fig. 1 has produced not only flying plasmoids but also various plasma jets and 'sitting' ball discharges. We believe that it is not too difficult to add to the demonstration experiments the measurements of the plasmoid charge by using a grid Faraday cup and the simplest probe measurements, which will reveal the presence of a thin negatively charged layer on the plasmoid surface.

4. Conclusions

The real image of ball lightning differs dramatically from the mythical image created by lovers of sensations. All the more important was the work of Stakhanov [6], who subjected the data from different observations to critical analysis and built the correct picture of this natural phenomenon. According to Stakhanov, ball lightning is a blob of cold hydrated plasma with a sharp boundary. The diameter of such a blob is 12–20 cm, and the lifetime amounts to several seconds; only in some rare cases does ball lightning last tens of seconds. The visible light emitted by ball lightning is generated due to progressive recombination of ions conserved in the hydrated clusters. Ball lightning can carry a small amount of uncompensated electric charge and in most cases disappears without producing any sound.

In conclusion, we would like to note that the mechanism of lightning formation in nature is a phenomenon that still awaits explanation. We do not know how streak lightning gathers its charge from an extended thundercloud, how a current channel is created, and why the glowing head of a streak lightning moves in the atmosphere with different speeds ranging from 10^7 m s^{-1} to several meters per second (this problem has partially been examined in Ref. [7]).

Plasma jets are a form of linear electric discharge in the atmosphere. They can be ejected by sharp objects that happened to acquire a high negative potential after streak lightning hit them. To initiate the ejection of an artificial plasma jet, a rocket whose tail is made of a thin wire or whose jet consists of conducting aerosol is launched into a thundercloud. The result is a current channel with a bright luminous head [8]. A natural plasma jet can pass through a narrow gap, a small hole in glass, enter a house along the electric cable or even through a chimney. In a closed room, the head of the jet can transform into an autonomous floating plasmoid which will exist only for several seconds thanks to the energy accumulated in the clusters.

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