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Rotational dynamics of a ball lightning

Abstract

In this paper we study rotational dynamics of a ball lightning. Cases of deceleration and acceleration of rotation are described, which suggests that the cause of rotation may be the internal movement of elements of the ball lightning core. A model for particles separation from the surface of a rotating ball lightning is presented. It is also shown a qualitative explanation of the interaction of rotational moments of the ball lightning core elements, causing a change in the rotation speed of the ball.

Keywords: Ball lightning; Rotation; Separation of the ring; Dynamic capacitor; Interaction of rotational moments.

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Cases of ball lightning rotation

Ball lightnings are self-contained luminous spheres that appear in the atmosphere during thunderstorms.[1-5] Often observers have reported that ball lightning rotated. Thus, in the Rayle's review, the rotation of ball lightning is mentioned in 20% of 98 observations.[6] According to Grigoriev's analysis, about 5% of 1743 observed ball lightning rotated.[5] Thus, the ability to rotate like a solid body can be considered one of the properties of ball lightning. The reason for the presence of rotation may be some internal movement in the core of ball lightning.

In the book[5] the behavior of ball lightning that appeared during a thunderstorm with a strong wind is described. First, the observer saw from the window of the power plant a ball 5 cm in size, which "rolled along the wind through the puddles, bouncing on the unevenness of the soil. Suddenly the ball broke up into several balls moving in the same direction. Then these balls began to burst like soap bubbles. Suddenly, a ball slightly larger than a tennis ball appeared inside the power plant. It moved, as if swaying, moving a few centimeters back and forth. The sphere radiated neither heat nor light. It had a shell 0.5-1 mm thickness, it was lighter than the rest of the mass. Then the ball froze motionless, and fire spray began to hiss from one side of it. It seemed that the ball had a jet turbine. It began to spin like a fireworks spinner, slowly at first, then faster. It spun at breakneck speed, spraying fireballs all over the place. Suddenly the rotation stopped as suddenly as it had begun. The color and size of the ball have not changed. It began to sway from side to side and, smoothly sliding down, went into a working electric generator. There was no explosion, only at that moment the light in the power plant room flashed very brightly".

"On March 18, 1988, at 21.35 local time, passengers of a TU-154 aircraft flying at a speed of 800 km/h at an altitude of 11,000 m saw a ball to the right of the aircraft emitting a beam of white light like a searchlight. Three minutes later, the ball turned left and began to move away from the aircraft. After a short time, it split into two parts: a smaller ball formed on top, and an elongated object formed on the bottom. The ball rotated at high speed and was surrounded by a green ring. Then both objects slowly merged into one, but the green ring remained. After that, the luminous object began to decrease and disappeared at 21.48."[7] There are no data on the size of the ball in the article. Usually, luminous objects observed at high altitudes are classified as unidentified flying objects (which are excluded from the class of ball lightning). At the same time, there are many reports of pilots observing luminous balls in the clouds, and they are called ball lightning (especially when they are inside the cockpit).[8]

On July 23, 1974, Alexander Mitrofanov, Doctor of Physical and Mathematical Sciences, and his friends saw ball lightning that appeared at night in clear weather on the bank of the Oka River. It was a dimly glowing white ball the size of a volley-ball with a clear border, inside which bright dots "jumped" like butterflies near a lantern. Suddenly, a white ring separated from the ball. It began to slowly and evenly spread symmetrically about the center of the ball (Figure 1). The ring increased in diameter up to 1-3 m and, having melted, disappeared. After that, a second ring, less bright than the first, separated from the ball. At the same time, ball lightning took on a pear shape and disappeared.[9]

Figure 1 View of ball lightning with a ring.[9]

Explanation of the reason for the separation of the ring from ball lightning

According to the electrodynamical model, ball lightning consists of a nucleus with a positive charge and a spherical shell of polarized water molecules.[10-14] Charge carriers Q placed inside the shell with an inner radius R_{in} stretch it with force

$$F_Q = Q^2/8\pi\varepsilon_0 R_{in}^2. \quad (1)$$

Here ε_0 is the dielectric constant. Let us imagine a water molecule as a ball with a diameter $d_w = 4\cdot10^{-10}$ m, having a dipole electric moment $p_w = 6.327\cdot10^{-30}$ C·m. A water molecule located at a distance R_{in} from the center of the ball lightning charge is attracted to it with a force

$$f_q = p_w\cdot\text{grad}\,(Q/4\pi\varepsilon_0R_{in}^2) = -2p_wQ/4\pi\varepsilon_0R_{in}^3. \quad (2)$$

The area occupied by one water molecule is equal to $s_w = d_w^2$. On the surface of a sphere with radius R_{in}, $n_w = 4\pi R_{in}^2/d_w^2$ water molecules can fit. The attraction force of a shell with a thickness of one water molecule to the center of the sphere is

$$f_w = f_q\cdot n_w = 2p_wQ/\varepsilon_0R_{in}d_w^2. \quad (3)$$

The ratio B of the force of repulsion of charges F_Q to the force of attraction of one layer of water molecules is equal to

$$B = F_Q/f_w = Qd_w^2/16\pi R_{in}p_w. \quad (4)$$

Let $Q = 10^{-3}$ C, and $R_{in} = 5\cdot10^{-2}$ m, then $B = 10^7$. To compensate for the force of repulsion of charge carriers $Q = 10^{-3}$ C by the compression force of the shell of water molecules, its thickness a must be increased by 10^7 times. From here we find $a = d_w\cdot10^7 = 4\cdot10^{-3}$ m. This means that the expansion of the region of immobile charges with a total value of $Q = 10^{-3}$ C can be stopped by a shell of water molecules 4 mm thick. If the charge carriers move, there will be an additional pressure force on the inner surface of the shell. This force can be compensated by increasing the thickness of the shell.

Suppose that in both cases considered above, the reason for the appearance of a ring around ball lightning was its rotation. Consider a small element of the shell at the equator of radius R. In the electric field E created by the charge Q of the core of ball lightning, this element will be polarized, and it will be attracted to the center of the ball with the force $F_{sh} = d\cdot\text{grad}\,E \sim Q/R^3$. Here d is the electric dipole moment of the shell element. In the direction opposite to F_{sh}, this element of the shell is affected by the centrifugal force $F_c = mv^2/R$, where m is the mass of this element, and v is the linear velocity at the equator. Since ball lightning continuously loses its charge, there may come a time when F_c becomes greater than F_{sh}. A shell element in the form of a spherical drop of mass m_d (with a cross-sectional area $S = \pi r^2$) will come off the ball and fly tangentially to the surface with a speed v_d. In this case, it will be decelerated in air by the force $F_f = C_x\cdot(\rho_a v_d^2/2)\cdot\pi r^2$.[15] (Here $C_x = 0.3$, and $\rho_a = 1.13$ kg/m^3 is the air density). The law of motion of a drop with mass m_d and radius r:

$$-dv_d/dt = F_f/m_d = A\cdot v_d^2, \text{ where } A \equiv C_x\rho_a\pi r^2/2m_d. \quad (5)$$

Solving this equation, we find $v_d = v_0 / (1 + Av_0t)$, where v_0 is the initial velocity of the drop. Replacing $v_d = dx/dt$, we find the law of change in the distance traveled by the drop as a function of time:

$$x = (1/A)\ln(1 + Av_0t). \quad (6)$$

Let us assume that the shell material has a density equal to that of water $\rho_w = 10^3$ kg/m^3. Let us estimate the radius r_d of a drop that, having an initial velocity $v_0 = 10$ m/s, will decelerate at a distance $x = 1$ m. The average drag force of the drop is $F_{fa} = C_x\cdot(\rho_a v_{av}^2/2)\cdot\pi r_d^2 = C_x\cdot(\rho_a v_0^2/8)\cdot\pi r_d^2$, where $v_{av} = v_0/2$ is assumed for the average velocity. Equating the work of the friction force on the length $x = 1$ m with the initial kinetic energy of the drop, we find $r_d = 3x\,C_x\,\rho_a / 16\,\rho_w = 6.3\cdot10^{-5}$ m. With this value r_d, $A = 2.117$, $1/A = 0.4724$. The law of drop motion at $v_0 = 10$ m/s: $x = 0.4724\cdot\ln(1 + 21.17\cdot t)$. Figure 2 shows a graph of the expansion of a ring consisting of drops with a radius of $r_d = 3\cdot10^{-5}$ m, which had an initial velocity $v_0 = 10$ m/s ($x = 0.236\ln(1+42.3\,t)$). The character of the movement of the ring is a rapid expansion to half the final size in the first second and then a slow increase in size.

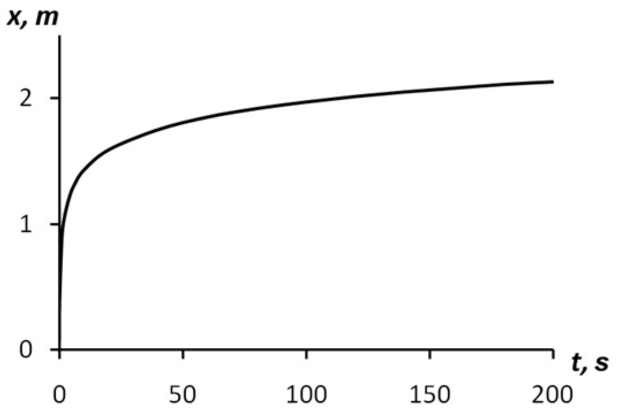

Figure 2 Graph of expansion of the ring according to the law $x = 0.236\ln(1 + 42.3t)$.

The reason for the rotation of ball lightning

It was suggested in the article[16] a possibility of existence of two types of ball lightning. The first of them is ball lightning with a core of motionless ions of the same sign. They are formed when a strong electric current flows through water. A typical representative of such objects is micro-sized ball lightning.[17] Ball lightnings of the second type are high-energy objects that are forming near the linear lightning channel. The core of such ball lightning consists of an ensemble of "dynamic electric capacitors".[10-14] Figure 3 shows the principle of such a capacitor. It consists of electrons and protons moving in closed orbits. In the central region of the capacitor there is a ring of moving electrons, and outside there is a ring of moving protons. Protons are held in orbit by attraction to the electron ring. Electrons move in orbit due to the action of mutually perpendicular fields: the magnetic field created by the movement of protons, and the electric field in the space between the orbits. The total charge of protons exceeds the total charge of electrons, so this system tends to expand. It can only exist inside a certain container that prevents it from expanding. In fact, the device of a dynamic electric capacitor is more complicated than shown in Figure 3. Only one fact is important for us: the system of charges, moving in closed orbits, has a mechanical torque. Thus, the complex nature of the behavior of ball lightning, which is capable of both starting and stopping rotation, can be explained by the fact that it includes elements that have their own moment of rotation. The coherent addition of these individual moments can create a macroscopic moment of rotation of the entire ball lightning. The orientation of the axis of rotation can be any.

To compare the values of the moments of rotation of the elements of the nucleus and the entire ball lightning, we consider an extremely simplified configuration with two dynamic capacitors located inside the shell with an outer radius $R_1 = 10$ cm and an inner radius $R_2 = 8$ cm. Let the radius of each capacitor (the radius of the proton orbit) be equal to $r = 4$ cm, and the total charge of the capacitor $q = 10^{-1}$ C. The number of protons is $n_p = q/e = 6.25\cdot10^{17}$, and their mass is $M_p = n_p\cdot m_p = 6.25\cdot10^{17}\times1.67\cdot10^{-27}$ kg $= 1.044\cdot10^{-9}$ kg. Let the velocity of the proton $v_p = 10^8$ m/s, then the moment of rotation of the proton ring with a radius $r = 4$ cm $M_{rp} = M_p\cdot v_p\cdot r = 4.176\cdot10^{-3}$ kg·m^2/s. If the directions of the vectors of the moment of rotation of the two capacitors are opposite (if the protons rotate in different directions), then the total moment will be equal to zero. In the opposite case (if the protons in both capacitors rotate in the same direction), the torques of the two capacitors will add up and the nucleus will acquire a torque $M_\Sigma = 2M_{rp} = 8.352\cdot10^{-3}$ kg·m²/s. This moment can be transferred to the shell, and the ball lightning will start to rotate.

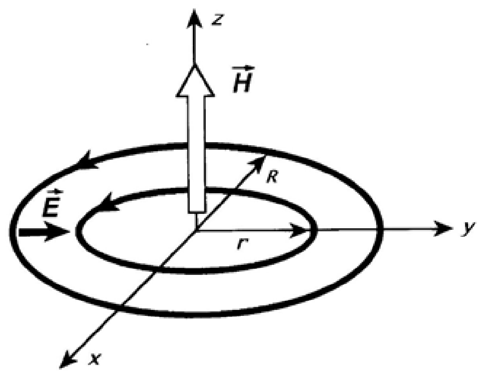

Figure 3 Scheme of charges movement in the dynamic electric capacitor. The inner ring is formed by electrons, and the outer one - by protons.[11-13]

The moment of inertia of a hollow sphere with outer radius R_1 and inner radius R_2 at material density ρ is equal to

$$I = (8/15)\cdot\pi\rho\,(R_1^5 - R_2^5). \quad (7)$$

At $R_1 = 10^{-1}$ m, $R_2 = 8\cdot10^{-2}$ m and $\rho = 10^3$ kg/m³ $I = 3.586\cdot10^{-2}$ kg·m². The same moment of inertia has a body of mass m_{eq}, rotating around a circle with a radius $R_1 = 10$ cm: $I = m_{eq}\cdot R_1^2$. Hence $m_{eq} = 3.586\cdot10^{-2}$ kg. Moment of rotation of a hollow sphere (ball lightning shell) $M_{en} = m_{eq}\cdot R_1\cdot v = 3.586\cdot10^{-3}\, v$. Equating M_{en} to the moment $M_\Sigma = 8.352\cdot10^{-3}$ kg·m²/s, we find the speed $v = 2.33$ m/s, at which ball lightning rotates with the frequency $\upsilon = v/2\pi R_1 = 3.7$ revolutions per second. Thus, the exchange of rotational moments between the core of ball lightning and its shell can cause its rotation.

Conclusion

There are two trends in the modern history of ball lightning study. One of them is a sharp increase in the amount of reliable information about its properties, which was the result of the widespread use of video recorders. The second is a stream of new hypotheses about its structure, which often appear "as if from nowhere". Unfortunately, both of these flows of information almost do not interact: the authors of new hypotheses, as a rule, do not set themselves the task of explaining all the fine details of ball lightning with the help of their model and limit themselves to explaining only individual properties of its behavior. If the requirement for completeness of explanation were to become the rule, then this would drastically reduce the number of poorly substantiated hypotheses and would make it possible to direct efforts towards the development of more adequate theories. The analysis of observations of rotating ball lightning, described in the article, directly indicates that ball lightning is a material solid body, and not discharges burning in the air, which were proposed at different times by Kapitsa,[18] Handel,[19] Rañada and Trueba,[20] Callebaut,[21] Ohtsuki and Ofuruton[22] and Lowke.[23]

An analysis of the cases of observation of rotating ball lightning, carried out on the basis of an electrodynamic model of its structure, allows a quantitative assessment of the processes occurring in this case. In this case, the assumption of the presence of relativistic electrons moving in closed orbits in the core of ball lightning is essential. The resulting synchrotron radiation can cause the emission of light by ball lightning in the form of a "searchlight" beam, mentioned in the report on the observation of ball lightning from a flying aircraft.[7]

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