CHARGE AND ENERGY OF THE BALL LIGHTNING

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ABSTRACT

If to assume that the ball lightning is positively charged vacuum bubble, its surface charge is 0.00134 C/m^2, and field strength at its surface is 151 MV/m. The energy of slow discharge of the ball lightning is 0.405 J/cm^3. The energy of explosive discharge is larger due to collapse of vacuum bubble.

INTRODUCTION

There is huge number of hypotheses on ball lightning (see Wikipedia, 2013a). The life is short, and it is better to consider the properties of this phenomenon. In accordance with collection of reports received from 1005 eye-witness, Stahanov (1985) gives the following estimates: lifetime (truly, duration of observation) broadly ranges from 1 to 200 s (97 % of cases), 10-20 s on average. It is spherical (90 % of cases), and its radius ranges from 1 to 50 cm (97 % of cases), with sharp maximum near 10 cm (radius 5-15 cm was reported for 55 % of cases). It drifts with velocity of walker (0.5-2 m/s; 48 % of cases), but may fly with velocity about 30 m/s and more, or stay motionless. As rule (in 75 % of cases), it is horizontal movement. In 20 % of cases, ball lightning goes down, and rarely (5 %) rises up. The brightness of ball lightning is comparable with 10-500 W lamp (100 W on average), so it can be seen clearly at the daylight. If the light emission is not too strong, the transparency of ball lightning is evident.

Based on reported details of explosions (mainly, on size of holes in metallic constructions), Stahanov (1985) have calculated the energy of discharge. It was obtained, that energy of discharge ranges from 1 to 100 kJ (0.24-24 grams in TNT equivalent), whereas the density of energy was estimated at 1-10 J/cm^3. Stahanov (1985) believe that the range 5-10 J/cm^3 is more realistic, because the ball lightning sometimes disappears in metallic construction even without visible traces. It should be also noted that if size of hole is overestimated by 2 times, the volume and thus energy may be overestimated by $2^3 = 8$ times. Similar errors in density of energy may be caused by error in size of ball lightning. However, if size of hole and size of ball lightning are both overestimated by several times (e.g. due to the fisher's effect) it gives true value for the density of energy.

The strangest property of ball lightning is almost complete absence of heat emission. Among eye-witness which have seen it at the distance 1 m and less, majority (91,5 %) report the absence of heat emission, and sensation of heat was observed solely in 8,5 % of cases. From the other hand, the color of ball lightning, ranging from red to blue (yellow in the most of cases), corresponds to spectral temperature about several thousands of degrees. Based on the absence of heat emission, Stahanov (1985) do not believe into so high temperature, and suspect some kind of luminescence.

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Because the ball lightning floats in air, Stahanov (1985) believe that the density of the ball lightning is not too far from that for ambient air. Similar conclusion on density was made by Barry (1980). However, the Earth has strong electrostatic field. Its strength varies between stationary ~ 100 V/m and about ~10000 V/m at thunderstorm events. Thus, as has been noted by Kunin (2000), the charged sphere, having low density, may float in air due to electrostatic attraction to the Earth.

The artificial ball lightnings (plasma balls, or electric fireballs, or plasmoids; the latter is however somewhat different phenomenon, see Wikipedia, 2013b) were first obtained, perhaps, by Arden and Constable in the end of 18 century (see Barry, 1980), and then were reproduced in numerous studies with use of highly variable equipment (beginning from Leyden jar). In general, the size of plasma balls ranges between few millimeters and up to 15 cm in diameter, their lifetime ranges from about one tenth to several seconds. Under reduced pressure, in presence of water vapor and small admixtures of flammable gases, generation of plasma ball is more effective.

It is likely, that the plasma ball has negative charge. Electron has low mass and it may be accelerated up to relativistic energy on a very short distance. Because of this, emission of free electrons from cathode at high voltage leads to electric breakdown of air. The electric breakdown of air occurs at field strength E ~ 3 MV/m and thus, the surface charge of negative plasma ball cannot exceed $\varepsilon_o\varepsilon E$, i.e., 2.7×10^{-5} C/m^2, whereas its density of electric energy is less than $1.5\varepsilon_o\varepsilon E^2$, i.e. 0.00012 J/cm^3 (almost zero; see definitions for variables below). Thus the energy of negative plasma ball is, in the main, heat energy of neutral gas. As soon as it cools down, it dies (with clap or without it).

HYPOTHESIS

Due to electrostatic repulsion, the charged ionic gas should be located near the surface of lightening ball. The density of charged ionic gas should decrease by exponent from interface to center of lightening ball. It likely, that the thickness of this diffuse layer is very small, whereas the interior of lightening ball is deep vacuum. If so, the lightening ball may be considered simply as charged vacuum bubble. Strength of the electric field near the surface of charged sphere is:

$$E = Q/4\pi r^2\varepsilon_o\varepsilon = \sigma/\varepsilon_o\varepsilon \quad (1)$$

Here E is field strength (V/m), Q is charge (Coulombs), σ (C/m^2) is surface charge, ε_o is dielectric constant of free space (8.8541878×10^{-12} C×V^{-1}×m^{-1}), ε is relative dielectric constant of air (almost unit), r is radius of sphere (meters).

The electric force applied to the element Δs of charged surface is

$$F_{el} = \Delta s\times\sigma\times(E + E_{inn})/2 = \Delta s\times\sigma\times E/2 = \Delta s\times\{\sigma^2/2\varepsilon_o\varepsilon\} \quad (2)$$

Here $E_{inn} = 0$ is field strength inside of ball lightning. The force of pressure, applied to the same element Δs of the surface, is

$$F_p = \Delta s\times(P_{atm} - P_{in}) \quad (3)$$

Here P_{atm} is atmospheric pressure, and P_{in} is pressure inside of the ball lightning.

In equilibrium, $F_{el} = F_p$, and thus, assuming $P_{in} \sim 0$,

$$\sigma,\ C/m^2 = \{2\varepsilon_o\varepsilon P_{atm}\}^{0.5} = 0.00134\times\{\varepsilon[P_{atm},\ Atm]\}^{0.5},\ \text{and} \quad (4)$$

$$E,\ V/m = \sigma/\varepsilon_o\varepsilon = \{2P_{atm}/\varepsilon_o\varepsilon\}^{0.5} = 1.51\times10^8\times\{[P_{atm},\ Atm]/\varepsilon\}^{0.5} \quad (5)$$

Here $[P_{atm}, Atm]$ is atmospheric pressure in atmospheres (1 Atm = 101325 Pa). As may be seen, field strength at the surface of ball lightning is 151 MV/m, independently of size. Since the emission of electrons from negatively charged electrode leads to electric breakdown at sufficiently smaller fields (~ 3 MV/m), it is likely that the plasma of the ball lightning has positive charge.

Let us estimate the thickness of plasma layer at the surface of ball lightning. In accordance with Boltzmann law, the density of potential atmosphere (at constant temperature) drops in accordance with:

$$n = n_o\exp(-u_p/kT) \quad (6)$$

Here n is number of positive ions (or protons) in the unit of volume, u_p is potential energy of ion (or proton), k is Boltzmann constant (1.38066×10^{-23} J/K). In the electric field ~ $\{E+E_{inn}\}/2 = E/2$ (see Eqs. 1, 2 and 5), the potential energy of ion (or proton) is defined by

$$u_p \sim e\times(E/2)\times h \quad (7)$$

Here e is elementary charge (1.602189×10^{-19} Coulombs), and h is distance from interface (toward the center of ball lightning). Applying $e\times(E/2)\times h = kT$, one may estimate the thickness of plasma layer:

$$h \sim 2kT/eE = 3.4\{T/298.15\},\ \text{Å} \quad (8)$$

Consequently, h ~ 3.4 Å at 25°C and 34 Å at 3000 K. As may be seen, plasma of ball lightning is not simply compressed within a very small layer. It looks like ideal two-dimensional gas.

In accordance with equipartition theorem, the heat energy is equally distributed among all degrees of freedom (in present case, between two tangential, x and y, and one orthogonal z direction of translation). However, there are many deviations from this rule. If the energy of excitation for some degree of freedom is very large, this degree of freedom does not participate in heat balance. This seems to be the case. If to assume that the degree of freedom "z" is frozen out, this may explain (at least, formally) low heat flux in "z" direction, in spite of high spectral temperature. However, this is just a formal definition for two-dimensional gas. It gives no explanation for the absence of collisions between ions (or protons) and molecules of air, as well as for highly effective repulsion of molecules at interface.

All other properties of ball lightning are much less mystical. The electrostatic energy of discharge of sphere with fixed radius r is:

$$U_e = \int\varphi dQ\ (\text{at } r = \text{const}) = 0.5\varphi Q = 0.5\times Er\times4\pi r^2\sigma = 3P_{atm}V \quad (9)$$

Here $\varphi = Er$ is potential, $Q = 4\pi r^2\sigma$ is total charge, and $V = (4/3)\pi r^3$ is volume of ball lightning; note that $\sigma E = 2P_{atm}$ (see Eqs 4, 5).

The mechanical energy of slow compression of vacuum bubble is:

$$U_m = \int F_p dr = \int P_{atm} \times 4\pi r^2 dr = P_{atm}V \qquad (10)$$

Thus, total energy of slow discharge is:

$$U_t = U_e + U_m = 4P_{atm}V \qquad (11)$$

At radius 0.1 m, it gives 1.7 kJ, or 0.406 grams in TNT equivalent. It is enough for melting of ~ 2 g of iron, and such hypothetical ball lightning is rather dangerous. The density of energy of ball lightning is:

$$w = U_t/V = 4P_{atm} = 0.405 \text{ J/cm}^3 \qquad (12)$$

This value is realistic, but 2.5-25 times smaller than expected. However, at explosive discharge, the "electric pressure" ($F_{el}/\Delta s$, see Eq. 2) drops very fast, and this causes collapse of vacuum bubble, followed by air hammer on interface. Peak pressure at air hammer may exceed several atmospheres. Consequently, peak potential at the interface and thus energy of discharge also may increase. Note that this additional energy of discharge is heat energy of air (which cools upon explosion).

The electric conductivity of subsurface air Λ is about $1 \div 3 \times 10^{-14}$ $Om^{-1} \times m^{-1}$ (see Kamsali et al, 2009; Moore and Vonnegut, 1988; Mani and Huddar, 1972). Thus, the electrical emission from the surface of stable ball lightning is

$$J, \text{C} \times \text{s}^{-1} \times \text{m}^{-2} \text{ or A/m}^2 = \Lambda E = 1.51 \div 4.54 \times 10^{-6} \times \{[\text{Patm, Atm}]/\varepsilon\}^{0.5} \qquad (13)$$

Consequently, ball lightning looses $100 \times (1.51 \div 4.54) \times 10^{-6}/0.00134 = 0.113 \div 0.34$ % of total charge per second, or 6.8÷20 % per minute. So on, "lifetime" of the ball lightning is about 5÷15 minutes (note, however, that the total charge decreases simply by exponent). Constant emission of ions leads to charging of all surfaces around, and slowly drifting ball lightning repulses from everything, except grounded conducting bodies.

From total energy and life time, the emission of energy is:

$$U_t/\{60 \times [5 \div 15 \text{ min}]\}, \text{W} = 1900 \div 5600 \times [r, \text{m}]^3 \qquad (14)$$

For the ball lightning with radius 0.1 m, it is 1.9-5.6 W. This is comparable with light emission from 100 W incandescent lump, i.e., about 2.6 W (Wikipedia, 2013c). However, in case of the ball lightning, the efficiency of energy conversion into visible light should be also smaller than 100 %, and thus, these values cannot be compared directly.

Because the ball lightning floats in air, the lifting force should be equilibrated by electric force, which is $F_E = QE_E$ (Q is total charge of ball lightning, and E_E is field strength of the Earth). The lifting force is $F_A = (\rho_{air} - \rho_{ball})gV$, where ρ_{air} is density of air, 1.184 kg/m^3 at 25^oC and 1 Atm, ρ_{ball} is density of ball lightning, g is acceleration, 9.80665 N/kg, V is volume of vacuum bubble. In equilibrium, $F_E = F_A$, and thus, assuming $\rho_{ball} = 0$, the electric field of the Earth may be estimated from:

$$E_E, \text{V/m} = \rho_{air}gV/Q = \{\rho_{air}g/3\sigma\} \times r = 2920 \times [r, \text{m}] \qquad (15)$$

Consequently, the ball lightning with radius 0.1 m floats in air at field strength of the Earth 292 V/m (note that the Earth has negative charge, and thus, the ball lightning should be charged positively). At the same conditions, larger ball lightning should rise up, and smaller one should sink down. The ball lightning slowly discharges, and it may float in air about 1 minute. And then, as it loses about 10 % of initial charge, it becomes smaller, moves down and discharges into the ground.

CONCLUDING REMARKS

It appears to be that the ball lightning is rather dull phenomenon. There is no neutrino, antimatter, black holes, and star gates. However, may be, there are the gates to something new.

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