Observation and Analysis of Ball Lightning Group Flights
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There are many evidences in literature and Internet about observation in atmosphere of spherical luminous objects, which form combined structures – dumbbells, triangles, squares and so on [1-5].

![Figure 1](a) ![Figure 1](b)

**FIGURE 1.** Photos of groups of ball lightning.

Fig. 1a is a photo of three light sources, flowing in the sky as a triangle [6]. Fig 1b is a frame from the film, where a pair of ball lightning (BL) was flowing over a corn field [7]. These balls move as if they are connected by an invisible thread, a ratio of a distance between the balls to their diameter is about 15. According to the electrodynamical model of ball lightning, it has a non-compensated positive electric charge [8-10]. This charge slowly leaks to atmosphere. A loss of the charge, which supports a stability of BL, in the end results its dead. Let us explain the existence of BL groups, basing on the sole assumption: of the presence in it of electric charge. The charge of the same sign pushes BLs away by the Coulomb force. However the forces preventing pushing away of BL may act in a group of these objects. These forces are a "gradient" force, arising due to polarization of BL substance, and forces, connected with gradual leaking of BL charge to atmosphere. Our purpose is to estimate the contribution of these forces into interaction of BL groups and to try to find conditions of existence of steady configurations from the charged objects.
For modeling of interaction between BLs we performed experiments for measurement of force, pushing away two the same charged balls for table tennis. Balls in radius \(a = 2\) cm and mass \(m = 2.72\) g were suspended on a thin copper wire of length \(L = 57\) cm, and a positive potential \(U\) from 0 to 30 kV was supplied to them. Measuring a ball deviation angle from a starting position, we found a force, acting on it from the other ball. A charge of the ball is \(Q = \frac{4\pi\varepsilon_0 a U}{R^2}\), and a Coulomb force is:

\[
F_c = 4\pi\varepsilon_0 a^2 U^2 / R^2, \tag{1}
\]

where \(R\) is a distance between the balls centres.

![Graph showing force vs. voltage](image_url)

**FIGURE 2.** Dependence on voltage of a force, pushing away two plastic balls of diameter 4 cm.

Fig. 2 shows a dependence \(F_c\) from \(U\), constructed under the formula (1) (the top curve). A middle curve is an experimentally found dependence of force of pushing apart of balls \(F_{exp}\) on potential \(U\). One can see that this force is approximately in 1.5 times less than Coulomb force \(F_c\). The bottom curve is a dependence of this additional force \(F_{gr} = (F_c - F_{exp})\), decreasing action of the Coulomb force, on potential \(U\). Force \(F_{gr}\) can appear because of polarization of substance of a ball in the non-uniform electric field \(E\), created by other ball.

\[
F_{gr} = D \cdot \nabla E = 2DQ/4\pi\varepsilon_0 R^3. \tag{2}
\]
Here $D$ is a dipole moment of the ball, $\varepsilon_0$ is an electric constant, $R^3 = 4\pi\varepsilon_0 a^2 U^2 L/mg$ is a cube of a distance between centres of balls, and $g$ is an acceleration of free falling. Substituting in (2) expressions for $R^3$ and $Q$, we have:

$$F_{gr} = \frac{D \cdot mg}{4\pi\varepsilon_0 a UL}.$$  \hspace{1cm} (3)

According to Fig. 2, $F_{gr} \sim U$, and according to formula (3) $F_{gr} \sim U^{-1}$. It can be provided if $D \sim U^2$. However the gradient force $F_{gr}$ cannot be a unique reason of full indemnification for the Coulomb force, pushing away the charges. First, it is less than the Coulomb force, and, secondly, it falls down with distance $R$ faster, than the Coulomb force. Therefore we should address to search other force which pulls charges together. This force can appear because leakage of charges from balls. In Fig. 3 a dependence of the force, acting on a ball, which has some needles thrust in it with spikes outside, at increasing of its potential, is shown. It is seen that at change of ball potential in 2 times (from 14 kV to 28 kV) a force, acting on it, increases in 8 times (from 0.1 mN to 0.8 mN). The reason of this force arising is pushing away of the charged ball from a cloud of the charges, which have left a ball. In a group of charged spheres these clouds will be located outside of group, and forces, pushing away the spheres from these clouds, will be directed opposite the Coulomb forces, pushing them apart. Let us assume that a positive ion with a charge $e$, which "has filtered" through a BL cover, will stick to a cluster, consisting of 1000 water molecules. A drift velocity $v_{dr}$ of such cluster in electric field of intensity $E$ is [11]:

![FIGURE 2b. Dependence of the force, acting on a ball with five needles, on its potential.](image-url)
\[ v_{dr} = (eE/m_cN_a \sigma)^{1/2}. \] (4)

Here \( e = 1.6 \cdot 10^{-19} \text{ C} \), \( m_c \) is a cluster mass, \( \sigma \) is a cluster cross-section, and \( N_a \) is air density. For a cluster of 1000 water molecules \( m_c = 3 \cdot 10^{-23} \text{ kg} \), \( \sigma = 1.17 \cdot 10^{-17} \text{ m}^2 \). At \( N_a = 2.687 \cdot 10^{25} \text{ m}^{-3} \) \( v_{dr} = 0.1412 \cdot 10^{-2} (E)^{1/2} \). At BL charge \( Q = 10^{-3} \text{ C} \) a cluster drift velocity at various distances \( R_{cl} \) from the BL centre is \( v_{dr} = 12.35/R_{cl} \text{ (m/s)} \). Thus, drift velocity decreases with growth \( R_{cl} \), and charges density \( n \) in the "cloud", on the contrary, increases with growth \( R_{cl} \). Breaking a space near to BL on cells of thickness \( \Delta R_{cl} \) and considering, that charges are located in a column of radius \( a_b \), we find quantity of charges in cell \( N = n \cdot \Delta V_{cl} = n \cdot \pi a_b^2 \Delta R_{cl} = \pi a_b^2 \Delta R_{cl} R_{cl} \). A force of a cell charge with BL charge \( Q \) interaction is:

\[ F_{cl}(R_{cl}) = eNQ/4\pi\varepsilon_0R_{cl}^2 = eab^2Q \cdot \Delta R_{cl} / 4\pi\varepsilon_0R_{cl} \equiv A \cdot \Delta R_{cl}/R_{cl}. \] (5)

Directing \( \Delta R_{cl} \) to zero and integrating (5) from \( R_{min} \) to \( R_{max} \), we have:

\[ F_{cl} = A \cdot \ln R_{cl}^{R_{max}}. \] (6)

Force \( F_{cl} \), pushing away BL charge from a cluster cloud, does not depend directly on distance \( R_{cl} \) and there can be any. Fig. 3 shows, how the forces balance in a group of two BLs with identical charges \( Q = 10^{-3} \text{ C} \), which are surrounded by a cloud of charges, varies with a distance \( R \). To the left of minimum \( F_{cl}^2 \) at \( R = 2 \text{ m} \) a force of BL Coulomb pushing away prevails, and to the right of minimum a force of BL pushing away from a cloud of charged clusters prevails. Position of balance (2 m) is comparable with a distance between two BLs in Fig. 1b.
FIGURE 3. Dependence of a square of the forces sum $F_s^2 = (F_c - F_g - F_{cl})^2$ on a distance $R$ between two BLs with a charge of everyone $Q = 10^{-3}$ C. Function $F_{cl}(R_{cl})$ is considered a constant.

Thus, the configurations, consisting of several luminous objects, repeatedly observed in atmosphere, can be groups of BLs. A Coulomb pushing away of the BL charges of the same name is compensated by force of their pushing away from clouds of charged clusters. The groups, consisting of two, three, four etc. BLs, can be formed by the specified principle. At a great number of BL a group of objects can be perceived by the observer as a round object with windows.

8. A.I. Nikitin, An Electrical Capacitor as the Element of the Power Core of Ball Lightning. Electrical Technology Russia, 1998, No 4, pp. 70-85.