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Features of ball lightning stability

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Abstract. An electrostriction optical effect, effect of separation of a gas mixture in a field of an intense light and effect of a violation of homogeneity of plasma by an intense light are considered. It is shown that the first effect shows itself after penetration of Ball Lightning through glass panes and the last two ones are the most favorable for appearance Ball Lightning. The density of the energy and conditions of Ball Lightning stability are analyzed.

PACS. 42.65.Jx Beam trapping, self-focusing and defocusing; self-phase modulation

1 Introduction

A phenomenon of Ball Lightning (BL) is a shame of up to date physics. Physicists studies the phenomenon over two centuries, above 200 various theories are proposed, above 2000 paper and reports are published but simple questions can not be answered. Why directions of a wind and BL may be different, how BL penetrates in a room through window panes, chimneys, small splits and holes, why BL radiates white light which spectrum corresponds to the temperature of several thousands degrees and is relatively cold in the same time? How BL catches up a flying airplane and penetrates within its salon? How BL can store extremely great amount of the energy? The list of the questions may be continued easily. There is an understanding that a majority of the theories ought to be withdrawn and efforts ought to be concentrated on the hypothesizes which satisfy certain requirements. One of such attempts is undertaken in [1] where a possibility to store the energy about 1 MJ within BL is the main criteria of the validities of a theory.

In 2002 we put forward a hypothesis [2] where BL is considered as a perfectly unusual at first glance object in a form of a light bubble (LB). Unlike a conventional soap bubble where a thin-film-soap-shell confines the air compressed in the volume of the soap bubble due to the surface tension of the shell, a shell of the LB is a compressed air where an intense light circulates in all possible directions. The refraction index n of the compressed air is greater than that of the surrounding air. In fact, the thin film of the compressed air is a thin-film-planar-lightguide which curvature is different from zero. Planar lightguides of such type are a basis of up-to-date integrated optics [3]. They confine a light propagating within them from radiation in free space. In turn, an intense light produces the electrostriction pressure in any optical medium, in particular in the air where it propagates. The electrostriction pressure is proportional to the light intensity and tends to near the air molecules close together. Thus, the LB shell is a system of the compressed air and intense light. The compressed air provides a confinement of the intense light and the intense light provides a confinement of the compressed air. The air pressures within the volume of LB and outside the LB shell are the same and are equal to the normal atmosphere pressure. Such LBs have been studied neither theoretically nor experimentally. Indeed it is very hard to imagine that a light can propagate in a homogeneous optical medium along curve close lightguides which have been produced by the light itself. Nevertheless the hypothesis enables to answer all listed above questions [4–10]. In particular, it has been shown that an increase in n by 0.1% is sufficient for safe confinement of a light within a sphere of several centimeters radius [6]. Such n corresponds to the air pressure about 4 atmospheres. Besides, it was shown in the same paper that the radiation losses which are inevitable for waves propagating in any curve dielectric waveguide can be neglected as compared with the losses because of light scattering in this case.

Analyzing possible means suitable for storage of a great amount of the energy, a storage of the energy in a form of intense light circulating along closed trajectories has been rejected in [1] with arguments that the circulating light exerts the pressure at walls providing its circulation. Since the walls are subject to the pressure that tends to expand them and the means that can prevent the walls from expansion are not seen, such circulation in opinion of author [1] is instable. We are going to show that such means exist. This is the electrostriction pressure produced by the intense light. It turns out that nobody from BL investigators used this effect as a means that provides BL stability. Besides, analysis of available

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encyclopedias, handbooks and physical dictionaries shows that the effect is still not clearly understood and widely known. Moreover, it is supposed by many investigators that the electrostriction pressure appears only in a region where an inhomogeneity of the light intensity takes place [11] and, therefore, the electrostriction pressure is equal to zero in the region where the light intensity is constant. We would like to present our understanding this problem.

2 Electrostriction effect

It is commonly supposed that the electrostriction pressure exerted by a light in fluids or gases is determined as follows [12–14]

$$P_L = \varepsilon_0 \rho \frac{d\varepsilon}{d\rho} \frac{E^2}{2} \quad (1)$$

where $\varepsilon_0 = 8.85 \times 10^{-12}$ F m^{-1} is the permittivity of vacuum,

$$\varepsilon = n^2, \quad (2)$$

ρ is the density of the medium, E is the electrical field strength of the light. Since the density W_L of the light energy is expressed as

$$W_L = \varepsilon_0 \varepsilon \frac{E^2}{2} \quad (3)$$

then

$$P_L = \frac{\rho}{\varepsilon} \frac{d\varepsilon}{d\rho} W_L. \quad (4)$$

For gases the value $(\varepsilon - 1)$ is proportional to ρ and therefore

$$\frac{\varepsilon - 1}{\varepsilon_n - 1} = \frac{\rho}{\rho_n}, \quad (5)$$

where ε_n and ρ_n are the gas permittivity and density, respectively, at normal conditions. Taking into account that $(\varepsilon - 1) \ll 1$ for gases we have from (4), (5)

$$P_L = \frac{\rho}{\varepsilon} \frac{\varepsilon_n - 1}{\rho_n} W_L = \frac{\varepsilon - 1}{\varepsilon} \cong (\varepsilon - 1) W_L. \quad (6)$$

Designating $\Delta n = n - 1$, and $\Delta\varepsilon = \varepsilon - 1$, from (2), (6) we have

$$P_L \cong 2\Delta n W_L. \quad (7)$$

Seemingly in accordance with (2), (3) W_L increases with an increase in ε or n. It is true if E^2 is constant and does not depend on n. In actuality results may be various depending on environmental. For example, the energy of a plane capacitor of capacitance $C = \varepsilon_0 \varepsilon S/w$ where S, w and ε are the area of plates, distance between them and permittivity of the dielectric between the plates, respectively, is equal to $E = Q^2/2C$ where Q is the charge of the capacitor. In this case the force of attraction between the plates

$$F = -\frac{dE}{dw} = -\frac{Q^2}{2\varepsilon_0 \varepsilon S} = -\frac{E_0}{w_0} \quad (8)$$

where E_0 is the energy of the capacitor for which the distance between the plates is equal to w_0.

On the other hand, if the capacitor is connected with a battery of voltage $U = Q/C$, situation is different although both charge Q and voltage U at the capacitor are the same as in the first situation. But unlike the first situation, the voltage U is constant in this case at a change in the distance w between the plates. In this case the force of attraction between the plates is equal to

$$F = -\frac{dE}{dw} = -\frac{d(CU^2/2)}{dw} = -\frac{U^2}{2}\frac{d}{dw}(\varepsilon_0 \varepsilon S/w) = \frac{E_0}{w_0}. \quad (9)$$

Comparing (8) and (9), one can see that the there are quite discrepant results. The forces that act between the plates are equal by value but are opposite by signs. The plates are attracted one to another in the first case and are repelled in the second one. The permittivity ε of the dielectric located between plates and its refraction index increase in the first case and decrease in the second one. What is happened with n in a field of light wave within LB? Unfortunately, we were not able to find out the reference where the answer this question has been given directly. Since the answer is of great importance for explanation of the BL phenomenon, it is worthwhile to analyze this problem in detail. Consider firstly the following intermediate problem [15]. Let we have a LC circuit where oscillations of the charge at the capacitance C take place. In this case the equation describing the oscillations is the following

$$\frac{d^2Q}{dt^2} + \omega_0^2 Q = 0 \quad (10)$$

where

$$\omega_0^2 = \frac{1}{LC}. \quad (11)$$

Let the capacitance C is changed slowly in time so that

$$\frac{1}{C}\frac{dC}{dt} \ll \omega_0. \quad (12)$$

Then (10) is transformed in the following equation

$$\frac{d^2Q}{dt^2} + \kappa^2(t) Q = 0 \quad (13)$$

where

$$\kappa^2(t) = \frac{1}{LC(t)}. \quad (14)$$

Solutions of (13) may be presented in a form

$$q(t) = A(t) \exp[j\omega(t)t] \quad (15)$$

where functions $A(t)$ and $\omega(t)$ describe changes in the amplitude and frequency of oscillations, respectively. These functions changes in time relatively slowly so that

$$\frac{1}{A}\frac{dA}{dt} \ll \omega_0 \quad \text{and} \quad \frac{1}{\omega}\frac{d\omega}{dt} \ll \omega_0.$$

Substituting (15) in (13), we obtain

$$-\omega^2 A + \kappa^2 A = 0 \quad (16)$$

$$2\omega \frac{dA}{dt} + A\frac{d\omega}{dt} = 0 \quad (17)$$

and therefore

$$\omega^2(t) = \frac{1}{LC(t)} \quad (18)$$

$$A(t) \sim \frac{1}{\sqrt{\omega(t)}} \sim C^{1/4}. \quad (19)$$

Then the average energy of the capacitance

$$E(t) = \frac{A^2(t)}{2C(t)} \sim C^{-1/2}. \quad (20)$$

Comparing (18), (20), we have

$$E(t) \sim \omega(t). \quad (21)$$

Since $C(t) \sim \varepsilon(t)$, then from (20)

$$E(t) \sim \varepsilon^{-1/2}. \quad (22)$$

Taking into account (2), we have from (22)

$$E(t) \sim n^{-1}. \quad (23)$$

Thus, the energy and frequency of oscillations decrease with an increase in n so that

$$\omega n = \text{Const} \quad (24)$$

and

$$En = \text{Const}. \quad (25)$$

Going from the LC circuit to an optical medium where a plane light wave propagates and taking into account that its wavelength is expressed as

$$\lambda = \frac{2\pi c}{\omega n} \quad (26)$$

and (24), we obtain that $\lambda = \text{Const}$ at a change in n in time. It may be explained easily because any as small as wished change in λ of the plane wave $\exp[j\omega t - (2\pi/\lambda)z]$ caused by a change in n along the z-axis entails significant changes in phase at great enough z. It is impossible physically because a small change in n causes great changes of light wave field in space [16].

An experiment has been undertaken to obtain a light wavelength conversion by means of a change in n of the glass where light wave propagates [17]. It turns out that the main factor that limits the maximal shift of the wavelength is the lifetime of the light wave that is equal in the experiment to tens nanoseconds at the best. The lifetime of the light within LB is greater by a factor of 7–8 orders of magnitude. That is why great wavelength shifts within LB are possible and BLs of various colors are observed.

As follows from presented analysis, the electrostriction pressure within LB ought to determine from perfectly different considerations taking into account (24). Let determine the electrostriction pressure within LB from condition of thermodynamic equilibrium between the circulating light and compressed air. Choosing the refraction index n as an independent variable which value needs to determine at the equilibrium, we can write

$$\frac{dE_G}{dn} + \frac{dE_L}{dn} = 0. \quad (27)$$

Comparing Clapeyron's equation $P_G V = NkT$ and the expression for the inner energy of an ideal gas $E_G = \gamma NkT$ where N is Avogadro number, k is the Boltzmann constant, T is the gas temperature, $\gamma = 5/2$ for two-atoms gases, we have $E_G = \gamma P_G V$ or

$$W_G = E_G/V = \gamma P_G \quad (28)$$

where W_G is the density of gas energy.

An increase in the gas energy density ΔE_G due to appearance of the additional excess gas pressure P_G exerted by an intense light is equal to $\Delta E_G = \gamma P_G$. Since $d\Delta E_G/dn = (d\Delta E_G/dV)(dV/dn)$, $d\Delta E_G/dV = \gamma P_G$, $(\varepsilon - 1)V = \text{Const}$, $(n^2-1)V = \text{Const}$, we have $dV/dn = 2nV/(n^2-1)$ and $d\Delta E_G/dn = \gamma P_G 2nV/(n^2-1)$. Designating the density of the light energy $W_L = E_L/V$ and taking into account that from $W_L dn + n dW_L = 0$, we have $dE_L/dn = VW_L/n$. In this case and condition (27) may be rewritten as follows $\gamma P_G 2n/(n^2-1) = W_L/n$ or

$$P_G = \frac{n^2-1}{2\gamma n^2} W_L. \quad (29)$$

For gases $n = 1 + \Delta n$ where $\Delta n \ll 1$. Then from (29) we have

$$P_G \cong (n-1)W_L/\gamma. \quad (30)$$

In the steady state the excess gas pressure P_G is equal to the electrostriction pressure P_L produced by the light. Comparing (7) and (30) we can see that P_L in (7) is greater by a factor of 2γ than that in (30).

3 Effect of an increase in the refraction index owning separation of gas mixture

Using the same approach, consider now a condition of thermodynamic equilibrium of a gas mixture where an intense light propagates. For the sake of simplicity consider a mixture comprising of two components only which refraction indexes are respectively n_a and n_b ($n_b > n_a$) and their initial relative concentrations are equal z_a and z_b respectively ($z_a + z_b = 1$). As is known, certain energy is required to separate components of gas mixture. The energy W_m is determined by the following expression

$$W_m = T\Delta S, \quad (31)$$

where T is the temperature of the mixture, ΔS is an increase in the entropy of gas mixture [18]. But $\Delta S = 0$ at adiabatic process where no heat is added to the system. We are considering namely such situation. This means that a change in the energy of gas mixture at conditions closed to adiabatic ones is closed to zero. In this case a small light density can force full separation of gas mixture. On the other hand, at the full separation where only molecules with n_b are located in the region where an intense light exists an increase in the refraction index is the following

$$\Delta n = n_b - (z_b n_b + (1 - z_b)n_a) = (1 - z_b)(n_b - n_a). \quad (32)$$

Usually in experiments $z_b \ll 1$ and $(n_b - n_a) \cong (n_0 - 1)$. In this case $\Delta n \cong n_0 - 1$. This means that at relatively small intensity we can obtain a change Δn which is comparable with that at the electrostriction pressure $P_L \cong P_0$. As follows from (6) electrostriction pressure $P_L = P_0$ is achieved at the density of light energy $W_L = 2.22 \times 10^8$ J/m^3. This corresponds to the light intensity $I_L = W_L c = 8.46 \times 10^{12}$ W/cm^2. The light intensity I_M required to separate gas mixture and increase the refraction index in accordance with (31) depends on a degree of "adiabaticness" of separation process. As follows from experiments, the light intensity in gas discharge is sufficient for separation. In this case I_M is smaller than I_L by several orders of magnitude and therefore degree of nonlinearity of gas mixture may be extremely great.

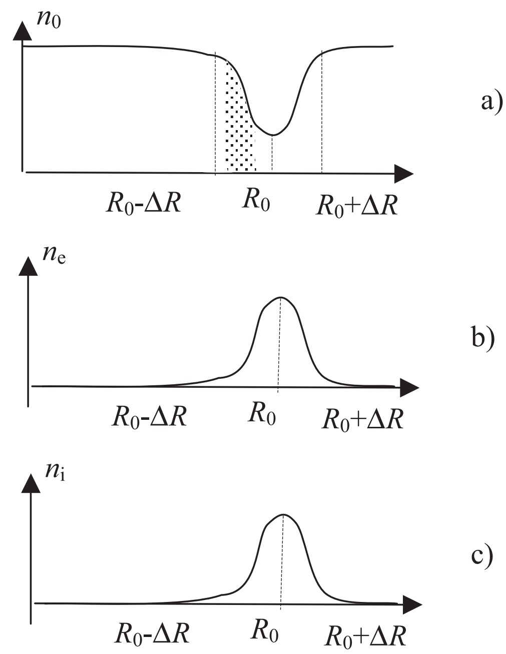

Fig. 1. Dependences of the refraction index n (a), electron concentration n_e, (b) and ion concentration n_i (c) on the distance from the LB center in neutral plasma.

4 Effect of an increase in the refraction index owning separation of plasma concentration

As is known, the permittivity of plasma depends on the concentration n_e of electrons within it and is determined as follows [19]

$$\varepsilon = 1 - \frac{4\pi e^2 n_e}{m\omega^2} \quad (33)$$

where e and m are the electron charge and mass, respectively, $\omega = 2\pi/\lambda$, λ is the wavelength of light for which ε is determined. As is seen ε depends on the electron concentration n_e and does not depend on the ion concentration n_i. Ought to distinguish plasma in time of a gas discharge and in time when the gas discharge is completed. In the first case there is a steady-state process where a recombination of plasma is compensated by an ionization of air atoms due to the gas discharge. In the second case plasma disappears gradually. As was shown, the lifetime of plasma is about several milliseconds only [20]. That is why all theories where plasma is used for explanation of the BL phenomenon are concern about plasma lifetime. In our opinion this anxiety is unjustified because there is usually no plasma within BL after its generation. There is certain no plasma after penetrating BL through window panes because plasma can not penetrate through glass. On the contrary, there are no doubts that plasma exists in time of BL appearance and it may play essential role in the process of BL generation.

Under assumption that all atoms of a gas are ionized and a number of free electrons is equal to a number of atoms in the gas and equal to $n_e = 5 \times 10^{19}$ cm^{-1} we obtain from (33) that at normal conditions and $\lambda = 0.6$ μm the refraction index of such completely ionized plasma is smaller than 1 by 1.6%. For example, if we have neutral plasma which n is smaller by 0.8% than that of conventional air, concentrations n_i and n_e within the shell may be equal to zero and $n \cong 1$. On the contrary, outside the shell we may have a neutral completely ionized plasma which $n = 0.984$. A change in the refraction index is greater by about 50 times than that obtained at a separation of gas mixture.

As was shown above, a light beam propagating in a gas mixture tends to increase the refraction index in the region where it propagates. As applied to plasma, it tends to decrease n_e within itself, that is, to push out electrons outside. In this case a homogeneity and neutrality of plasma are violated. As for neutrality that positive charged ions are attracted to electrons and are pushed out too. They are substituted in the region within the beam by neutral atoms. As a result, n in the layer adjacent to the LB outside decreases. Dependencies of the refraction index n as well as concentrations n_e and n_i on the distance r from the LB center are shown in Figure 1. A spherical layer where an intense light propagates is dotted.

The energy required for such separation of plasma concentration is minimal because plasma remains neutral. It is not required to overcome forces of attraction or repulsion between electrons or ions. This situation reminds separation of molecules of gas mixture where molecules of the component with minimal n are pushed out LB. The region $R_0 - \Delta R < r < R_0 + \Delta R$ in Figure 1 is a tunnel [21] which confines the light circulating within LB and prevent

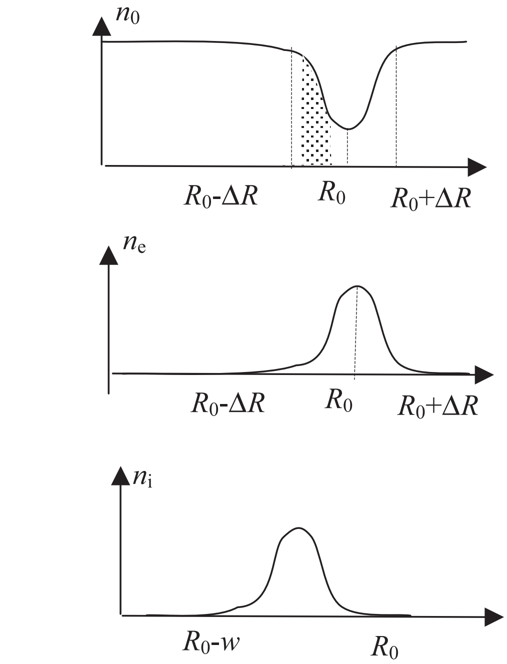

Fig. 2. Dependences of the refraction index n (a), electron concentration n_e, (b) and ion concentration n_i (c) on the distance from the LB center in a double layer.

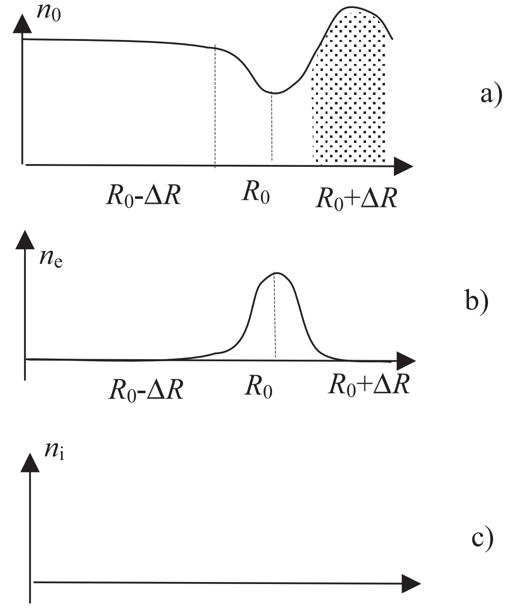

Fig. 3. Dependences of the refraction index n (a), electron concentration n_e, (b) and ion concentration n_i (c) on the distance from the LB center in a negatively charged LB.

it from radiation in free space. The light is concentrated in the region near R_0.

Unfortunately, such situation can not last for a long time after a cease of gas discharge because of recombination of plasma. But situation shown in Figure 2 may be imagined. As is seen concentration of electrons is shifted to the LB periphery. There is a double layer in a form of two charged layers. In fact, it is a capacitor where annihilation of charges is prevented due to an intense light circulating in the positive charged layer. The light tends to force out free electrons outside and increase in such a way n within itself. This is once more reason that provides existence of long-lived positive and negative charges.

This conclusion is confirmed by results of experimental investigations of autonomous objects (AO) obtained at gas discharges [22]. AOs are considered by many scientists as artificial Ball Lightnings produced on demand in a laboratory. Double layer shown in Figure 2 has been measured and presented in Figures 4 and 5 in [22]. Ought to note that, like results of our considerations, the inner layer is positive and outer one is negative.

Let estimate the energy of this double layer. Assume that positive and negative charges of completely ionized plasma with $n_e = n_i = 5 \times 10^{25}$ m^{-3} are separated by a layer of width $w = 10^{-5}$ m and the radius of the LB is $R = 0.1$ m. In this case we have a capacitor which capacitance is determined as follows $C = \varepsilon_0 \varepsilon S/w$ where $S = 4\pi R^2$. For given parameters $C = 0.11$ μF. The charge of the capacitor is equal to $Q = en_i V$ where $V = 4\pi R^2 w = 1.26 \times 10^{-6}$ m^{-3}. In this case $Q \cong 10$ coulombs. The energy stored in the capacitor $E = Q^2/2C = 5 \times 10^8$ J. The density of the energy is $W_C = E/V = 3.6 \times 10^{13}$ J/m^3.

Determine now the energy required to obtain $\Delta n = n_0 - 1 = 0.00027$. Such Δn appears at increase in the air pressure by 1 atmosphere and it is smaller by $K = 59$ times as compared with $\Delta n = 1.6\%$ which corresponds to completely ionized plasma. In this case Q decreases by K times, W_C decreases by K^2 times and $W_C = 10^{11}$ J/m^3. Comparing W_C with $W_G = \gamma P_L$, we may conclude that compression of the air to obtain given Δn is more favorable by a factor of 5 orders of magnitude than separation of charges. This means that an increase in n within an intense light due to separation of charges is negligible as compared with other processes providing existence of LB.

Nevertheless, the following situation shown in Figure 3 may be imagined. Here a thin spherical layer of compressed air provides confinement of an intense light circulating within it. The light can provide confinement of a layer of electrons located within the spherical layer of compressed air from expansion as is shown in Figure 3. Since electrons within LB decrease its n, they are forced out LB. Thus, LB can confine negative charges from dispersion due to mutual repulsion and negative charged BLs may exist. Such BLs as any charged things can be attracted to metal objects until other factors come into force.

5 The density of the energy stored within LB and its stability

As usual, there is a minimum of total energy of a system in any local stable state. In the LB the total energy consists of the energy of light and compressed gas. Since the gas pressure and, therefore, the gas energy density W_G increases with increase in the gas density and, therefore, in the gas refraction index n, the light energy density W_L must decrease with an increase in n. Seemingly, the last requirement contradicts to up to date notions about dependence of the density W_L of the light energy on n. In accordance with (2), (3) W_L increases with an increase in n. In this case both W_G and W_L increase in an increase in n and, therefore, a minimum of the summary energy is absent. This entails instability of LB. Such instability corresponds to intuitive notions that the light tends to propagate along a straight line and can not confine itself within LB. Possibly these circumstances retarded consideration of the presented approach.

What actually happens is that the light energy decreases with an increase in n in accordance with (25). In this case condition of thermodynamic equilibrium (27) is valid if $P_G = P_L$ where P_L is determined by (30). From (28), (30) we have $W_G = (n-1)W_L$. This means that the density of the gas energy is smaller by a factor $(n-1)$ than the density of the light energy. If the air may be considered as an ideal gas where dependence between the gas pressure and volume is expressed by Clayperron equation, $W_G/W_L \cong 2.77 \times 10^{-4} P$ where P (atmospheres) is the excess gas pressure within LB. Van der Vaals equation or more exact one ought to use instead of the Clayperron equation because the gas pressure within LB is extremely great. In this case expression $P_G = -dE_G/\mathrm{d}V$ ought to use instead of (28). In any case W_G is significantly smaller than W_L. Ought to underline that a condition of LB stability has been derived from energetic considerations. This enables to eliminate any inner forces, in particular centripetal forces mentioned in [1] that are exerted by the circulating light and act on the compressed air

If BL is negatively charged as is shown in Figure 3, electrons resided inside LB shell tend to expand and exert the pressure ΔP_E on the inner surface of the shell. The pressure ΔP_E decreases the electrostriction pressure exerted by the circulating light. Determine a relation between ΔP_E and charge Q in LB. The energy E of the spherical capacitor of R radius and the pressure ΔP_E exerted by charges are equal to respectively [1]

$$E = \frac{Q^2}{8\pi\varepsilon_0 R} \tag{34}$$

$$\Delta P_E = \frac{Q^2}{16\pi^2\varepsilon_0 R^4}. \tag{35}$$

From (34), (35) we have

$$\Delta P_E = \frac{E}{2\pi R^3} = W_E \frac{2w}{R} \tag{36}$$

where W_E is the density of the electric field as if the field is located within BL shell of thickness w. Comparing (28) and (36) one can see that the electric energy of the density W_E decreases the electrostriction pressure by $2\gamma w/R$ times smaller than the gas energy of the same density. In the same time a relation of pressures exerted by the light and electric field which densities of the energy are the same is equal to $\Delta P_E/\Delta P_L = 2\gamma w/((n-1)R)$. If a tunnel in the LB shell appears occasionally, compressed electrons passes through the tunnel and are ejected in free space. An explosion may take place in this case.

Since there is a steady-state volume of BL where a minimum of total energy takes place and certain stable thickness of the LB shell determined by the intensity of the light circulating within LB shell after disappearance of exciting light produced by a gas discharge, we have constant LB surface at constant volume and thickness. This is a reason why LB tends to preserve its entity.

LB tends to preserve its spherical shape too. But this tendency is not so clearly expressed. As is known a formless closed uniform shell of constant area S with a gas compressed within it takes form of the body, which volume is maximal for given area S. This is a ball. An example is a shell of a football ball. It becomes spherical after pumping. A situation with BL shell is a little more complex than that with the football shell. Unlike the football shell where the air pressure is in whole volume of the ball, the pressure in LB layer takes place within a thin closed uniform layer of thickness w. In this case the compressed air does not penetrate to the sphere center owning the electrostriction pressure formed by an intense light, which provides a definite thickness of the layer. Being pumped, the body takes a form of spherical layer but the stiffness of the layer is smaller than that of a whole ball.

6 Conclusion

Thus, a great diversity of BL and AO compositions is possible. This is a compressed air. This is any compressed vapors which n is greater than n of the air at normal conditions. This is a double layer as is shown in Figure 2. This is a negative charged light bubble as is shown in Figure 3. At last, this may be any combination of these alternatives. A necessary condition for existence of BL is an availability of an intense light which circulates in the LB shell and provides confinement of these materials. The relatively small lifetime of artificial LBs is explained by small lifetime of the light circulating within them. It is necessary to increase the light intensity to increase the lifetime. In this case the light scattering may be decreased noticeable owning the self-compression and Ball Lightning lifetime may be increased accordingly.

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