Eur. Phys. J. D **36**, 319–327 (2005)
DOI: 10.1140/epjd/e2005-00240-4

THE EUROPEAN PHYSICAL JOURNAL D

Physical nature of Ball lightning

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Received 20 May 2004 / Received in final form 28 February 2005
Published online 30 August 2005 –

Abstract. Physical effects responsible for existence of Ball lightning are considered. It is shown that Ball lightning can be a pure optical phenomenon where only an intense light and compressed air interact. An anomalous great light intensity and light lifetime within Ball lightning are analyzed.

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

1 Introduction

Ball lightning (BL) is a natural phenomenon occurring during regular thunderstorms but also under less extreme conditions. It is a phenomenon which is sufficiently rare that most people have never seen it but sufficiently common that its main characteristics are well-known. These characteristics include several properties which, taken together, appear inconsistent with the accepted laws of physics. As a consequence, a number of eminent physicists, including Kelvin, have refused to accept that it is anything more than an optical illusion. Faraday treated the evidence more objectively but still refused to believe that it is an electrical phenomenon (we are going to show below that he was right).

At present there is an abundance of reports and publications on BL observations and proposed explanations, linking BL to a variety of physical and chemical processes, but none of these theories seems to have gained general acceptance because they fail to explain all observed characteristics of the phenomenon. Recent theories are no exception also. For example, the Turner theory [1] of BL is based on features of chemical thermodynamics of ions in saturated water vapor. But such BL can not penetrate through window panes. This BL property rejects a lot of theories where some ions, electrons, clusters, plasma and other material particles are considered. This fact is taken into account in the Tore Wessel-Berg theory where an attempt is undertaken to explain once more BL nature on the base of electromagnetic phenomena [2]. But it is hard to agree that intriguing and puzzling motions of BL within rooms and flying aircrafts are explained by random changes of electrical field near the ground in thunderstorm. First, BLs are observed in sun days also. Second, there is some regularity in BL motion. For example, entering a room through a window, BL drops and moves near a floor rather than ceiling. Moreover, BL bypasses obstacles in process of its motion. As show numerous experiments with artificial BLs carried out in last two hundreds years, autonomous objects (artificial BLs in opinion of experimentalists) appeared usually at gas discharges exist for a long time upon competition of the discharge and disappearance of the electrical field connected with it. A radically new approach to the explanation of the BL phenomenon is required.

One of such approach was presented in [3]. We tried to construct a physical object which behavior in the conventional air atmosphere resembles BL behavior. As is known, there are so-called self-action nonlinear effects at propagation of an intense light in a nonlinear optical medium. One of the most known self-action effects is a self-focusing of an intense light beam [4]. In this case the intense light beam increases the refractive index n of the optical medium where it propagates. As a result, the cross-section of the light beam decreases gradually. This effect is responsible for appearance of so-called optical space solitons [5]. Such soliton is a plane light beam. It turns out that its width is stable and is determined by its intensity. A space soliton may be considered as a planar waveguide which guides the intense light wave [6]. The waveguide is formed by the wave and disappears with disappearance of the wave. The same result takes place if there are many plane light beams of the same summary intensity that propagate in all possible directions in the planar waveguide. Now suppose that the curvature of the planar waveguide is different from zero. In this case the waveguide is transformed in a spherical shell where light waves circulate in all possible directions. If the nonlinear optical medium is the conventional atmosphere air, such system is BL.

In fact, BL is a light bubble (LB) which shell is a thin film where the refractive index n is increased as compared with that of the surrounding space. The shell confines an intense light circulating within it in all possible directions. In turn, the intense light provides an increase in n within the shell. Mechanisms responsible for the increase in n are

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considered in [7]. One of them is the optical electrostriction effect that provides the increase in n due to compression of the air within the shell.

Under assumption that LBs do exist their behavior in the air atmosphere have been studied theoretically. A quite reasonable LB property to move along the gradient of n of the surrounding atmosphere air has been used. Indeed, LB is motionless in a homogeneous optical medium because of a central symmetry of the system where all directions are interchangeable. As is known, a conventional light beam bends in an inhomogeneous optical medium in the direction of the gradient of the refractive index n. The same is valid for a light beam circulating along a closed trajectory. Because the air refractive index increases linearly with increasing the air density, LB moves in the direction where the air density is maximal. The air density is in inverse proportion with the air temperature at constant pressure and LB moves in the direction where the air is cooler. The situation is complicated if an inhomogeneity of the medium is such that directions of the gradient n are different in various points of the space where LB is located. In this case various parts of LB surface tend to move in various directions and forces appear that tend to deform LB.

Such puzzling BL properties as features of BL motion near the earth surface, bypassing obstacles, penetration in rooms through window panes, small splits and chimneys have been explained [8,9]. Besides, it was explained how BL can catch up a flying airplane and penetrate in its salon or cabin [10]. Explanation of all these facts is unthinkable for other known approaches.

But the assertion that there are light bubbles in the nature is such objectionable that many scientists are skeptical. Indeed, such bubbles have not been investigated before either theoretically or experimentally and nobody even has spoken about a possibility of their existence. A certain time is required for scientific community to perceive and accept this fact. On the other hand, it is possible to initiate explanations of a pool of experimental data accumulated for many centuries as a result of observations of natural BLs and attempts to obtain artificial BLs in a laboratory. All facts of such kind are called usually abnormal because they are contradicted to conventional notions. In our opinion positive results in these explanations can decrease the mentioned time. First steps in this direction have been made already.

There are numerous evidences collected in last two hundreds years about production of luminous spherical autonomous objects (AOs) on a demand in a laboratory [11–13]. AOs exhibit many properties of BLs and are considered often as artificial BLs. Analysis of AO properties offers decisive advantages because of an availability of AO parameters and conditions at which AOs were produced and investigated. We succeeded to explain the following anomalous AO properties. First, a paradoxical phenomenon laid in the fact that the spectrum of AOs obtained at gas discharges in an atmosphere of nitrogen or oxygen does not contain lines related with these gases but contains lines of admixtures [12]. It turns out that the refractive index n of the admixtures is greater than that of the gas where AOs were produced. This enables us to consider a new mechanism of optical quadratic nonlinearity in gas admixtures and show that n within an intense light can increase because molecules of the mixture component which refractive index n is maximal are drawn in the region where the intense light propagates. It was shown that this mechanism of optical nonlinearity is characterized by the index of nonlinearity n_2 which surpasses significantly n_2 for other known nonlinear mechanisms.

Second, applying the same approach which has been used for an explanation of LB motion in an inhomogeneous earth atmosphere, we seceded to explain an anomalous behavior of AOs at their interaction with obstacles in a form of a paper sheet or metal foil. As is known, AOs are repulsed from a paper sheet but burned out a metal foil [13]. Third, we have explained an anomalous splitting of a beam of AOs at the instant they leave a plasmotron where they are produced and meet a stream of gas. A part of the beam is entrained by the gas stream but another part moves in the opposite direction. Forth, we have explained a positive role of so-called erosive gas discharge in production of AOs. Fifth, we have explained a mechanism of penetration of AOs through transparent walls of a hermetic glass tube where a gas charge takes place. These works enable us to draw a conclusion that, indeed, AOs and BLs are based on one and the same physical phenomenon.

Recognition of the fact that LBs exist enables us to obtain progress in theoretical notions about nonlinear optical phenomena, in particular, about properties of optical incoherent space solitons. Only recently an existence of such solitons has been demonstrated experimentally. Like classical optical coherent space solitons, the incoherent solitons are plane. It turns out that the nature demonstrates for a long time an existence of optical incoherent solitons of more general character. An example of such soliton is LB which may be considered as a generalization of known plane optical space solitons. Unlike these solitons which curvature is equal to zero, a curvature of LB is different from zero. A progress was obtained in studying of the molecular scattering of an intense light in gases. It was shown that the light scattering may be decreased by several orders of magnitude at extremely great light intensity and duration. Analysis of conditions favorable for AO production has enabled us to conclude that an intense light radiated by excited atoms at gas discharge is instable. The instability shows itself in a form of appearance of AOs. Thus, recognition of the fact that LBs exist have enabled us to consider a body of new optical effects and phenomena which can show themselves in their own rights without a frame of LBs.

Having more comprehensive ideas of physical processes within LBs, the next iteration may be undertaken to bring the former simple LB model closer to the reality. In doing so it is worthwhile to concentrate attention on problems which are most open to questions. The initial attempt in this direction has been undertaken in [7], where the nature of the electrostriction pressure responsible for an increase in the refractive index within LB has been considered as well as mechanisms providing LB stability have been analyzed. The next step is undertaken in the present paper where an optical effect of self-confinement of the light circulating within LB in all possible directions is considered in the first section. In the next section a phenomenon of a significant increase in the lifetime of the light within LB is analyzed. It is shown that there are at least 2 mechanisms responsible for the increase in the lifetime. One of them shows itself in natural LBs and is related with a decrease in fluctuations of the gas density that are responsible for the light scattering. This mechanism comes into force at great enough light intensity which is not achieved within AOs. The second mechanism is related with a specificity of the light scattering within the LB shell. It is shown that a major part of the light that is scattered by LB inhomogeneity remains in the LB shell but propagates in other directions. Such light scattering does not result in a noticeable decrease in the intensity of the light circulating within LB. This mechanism shows itself within both BLs and AOs. In the last section processes of accumulation of the light within LB are considered. It is shown that these processes provide an accumulation of the light intensity that is sufficient for an increase in the refractive index within LB and for safe confinement of the light within LB.

2 Self-confinement of light radiation

The most controversial problem for an uninitiated reader is a possibility of existence of self-confined light radiation in the conventional air atmosphere. Indeed, it is hard to imagine that conventional white light which propagates along a straight line in the air atmosphere can circulate in the same atmosphere along closed circle trajectories of several centimeters in diameter. This problem has its prehistory. Initially we have studied an ordinary applied problem which has no bearing on the BL problem. We have studied optical glass resonators of whispering gallery (WG) waves that are characterized by the extremely high quality factor $Q > 10^{10}$. Usually a glass ball of several tens micrometers in diameter has been used as the resonator. A WG wave may be imagined as a light wave which propagates within the ball along its equator near its surface. The WG wave can not leave the ball because of the phenomenon of total inner reflection on the boundary between the glass surface of the ball and surrounding space. The quality factor Q of such resonator depends on the quality of its surface. In the first minutes after fabrication $Q > 10^{10}$ but Q decreases in time by a factor of two orders of magnitude because of degradation of the resonator surface connected with a negative influence of air moisture. In this case losses of light connected with its scattering increase significantly. A solution of this problem is known. Like a fiber core is protected by a glass coating, the surface of the ball ought to be protected by a glass shell. The refractive index of the shell should be smaller than that of the glass ball as is shown in Figure 1 to provide the effect of total inner reflection. But in this case losses of light connected with its radiation in free space

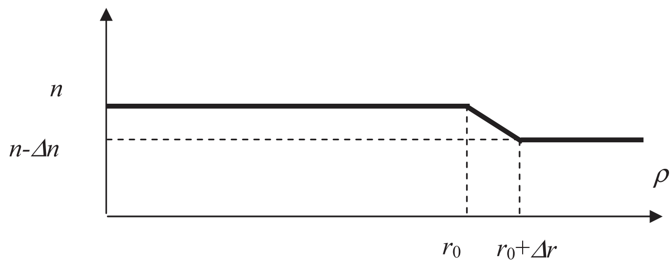

Fig. 1. Dependence of the refractive index n on the distance ρ in a glass cylinder with glass coating at $\rho = r_0$.

Table 1. Dependence of the index of attenuation γ of light field outside a glass cylindrical resonator on parameters $\Delta n/n$, $\Delta r/r_0$ and r_0.

$r_0 = 500$ μm	$\Delta r/r_0 = 0.001$	$\Delta r/r_0 = 0.002$	$\Delta r/r_0 = 0.005$
$\Delta n/n = 0.005$	$\gamma = 1.16$	$\gamma = 1.02$	
$\Delta n/n = 0.010$	$\gamma = 14$	$\gamma = 11$	$\gamma = 4.5$
$\Delta n/n = 0.015$	$\gamma = 800$	$\gamma = 590$	$\gamma = 229$
$r_0 = 4000$ μm	$\Delta r/r_0 = 0.001$	$\Delta r/r_0 = 0.002$	$\Delta r/r_0 = 0.004$
$\Delta n/n = 0.0025$	$\gamma = 6.55$	$\gamma = 1.8$	
$\Delta n/n = 0.0050$	$\gamma = 43800$	$\gamma = 7750$	$\gamma = 71$
$\Delta n/n = 0.0100$	$\gamma = 8.9 \times 10^{16}$	$\gamma = 6.8 \times 10^{15}$	$\gamma = 3.4 \times 10^{13}$

may be significant if the difference Δn between n of the ball and shell is small. Studying dependence of the necessary difference Δn on the ball diameter, we obtained to our great surprise that the difference $\Delta n/n$ about 1% is sufficient for balls of several centimeters in diameter.

The following tables illustrate this fact for WG light wave rotating in a glass cylinder. Here γ is index of attenuation equaled to the relation of amplitude of the light wave circulating within the cylinder to the amplitude of the light wave radiated in a free space, Δr is the distance along the cylinder radius where n decreases by Δn as is shown in Figure 1.

Results obtained are in Table 1. It was supposed that the dependence of the amplitude u of a cylindrical electromagnetic wave rotating around the z-axis of a dielectric cylinder of radius ρ is described by the following equation [14]

$$d^2u/d\rho^2 + (du/d\rho)/\rho + (k^2 - k_\varphi^2 - k_z^2)u = 0, \quad (1)$$

where $k = 2\pi n/\lambda$ is the module of the wave vector, k_z is the axial component of the wave vector (parallel to the cylinder axis). Azimuth component of the wave vector $k_\varphi(\rho) = k_\varphi(\rho_0)\rho_0/\rho$ decreases with an increase in ρ. Under assumption that the refractive index of the glass begins to decrease at $\rho = r_0$ and decreases by Δn at the distance Δr (Fig. 1) the dependence of square of radial component of the wave vector $k_r^2 = (k^2 - k_\varphi^2 - k_z^2)$ on ρ is shown in Figure 2a. There is a maximum at $\rho = r_0$ if the following condition is valid $\Delta n/n > \Delta r/r_0$. An existence of the maximum is a necessary condition for concentration of light wave near the cylindrical surface of radius r_0. But this condition is not sufficient. In accordance with WKB approach the following additional condition should

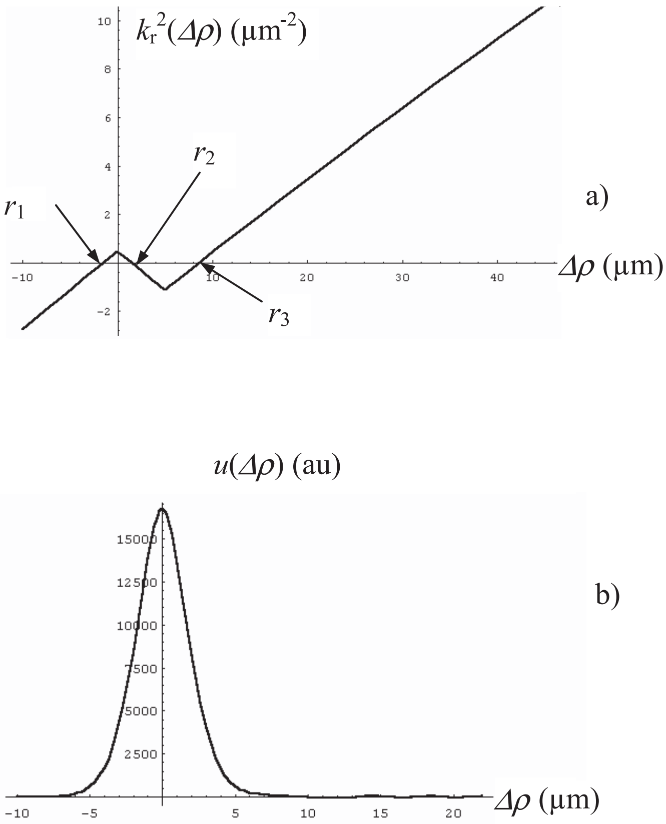

Fig. 2. (a) Dependence of the square of the radial propagation constant on the distance $\Delta\rho$ in the cylinder in the region where a step of the refractive index takes place at $\Delta\rho = 0$. (b) Dependence of the amplitude of light wave on the distance $\Delta\rho$.

be valid [15]

$$\int k_r(\rho)d\rho = \pi/2 + m\pi \tag{2}$$

where m is any integer, r_1 and r_2 are return points in which $k_r(r_1) = 0$ and $k_r(r_2) = 0$ as is shown in Figure 2a.

Dependence of the amplitude of the light wave on the radius $u(\Delta\rho)$ in the case where (2) is valid for $m = 1$ is shown in Figure 2b. The dependence was obtained by means of numerical solution of (1). As is seen, the amplitude decreases abruptly at $r \to 0$. At $r \gg r_0$ there are oscillations which amplitude is smaller by a factor $\gamma \cong 100$ than the maximal amplitude at $\rho = r_0$. Appearance of the oscillations is connected with penetration of light through a tunnel from $\rho = r_2$ till $\rho = r_3$, where $k_r^2 < 0$ and light wave can not propagate. The wave attenuates exponentially in the tunnel with an increase in ρ. Penetrating through the tunnel, a small field of light wave excites small light wave which propagates in glass. The energy of this wave is proportional to the radiation losses of the resonator. As is seen in the table at $r_0 = 4$ mm, $\Delta n/n = 0.01$ and $\Delta r/r = 0.001$ the amplitude of the wave decreases by 10^{15} times and its intensity is smaller by 10^{30} times as compared with the light wave circulating within the resonator. In this case radiation losses may be neglected as compared with other types of losses.

The following rough estimations based on laws of geometrical optics can confirm this conclusion. As follows from the eikonal equation the radius of curvature R of the light beam propagating in an inhomogeneous optical medium perpendicular to the gradient of the refractive index n is the following

$$R = [\text{grad}(n)]^{-1}. \tag{3}$$

Taking for example $\Delta n/n = 0.01$, $\Delta r/r_0 = 0.01$, $n_0 = 1.45$, $r_0 = 4\times10^{-3}$ m, we have $\Delta n = 1.45\times10^{-2}$, $\Delta r = 4\times10^{-5}$ m and $\text{grad}(n) = \Delta n/\Delta r = 360$ m^{-1}. In this case in accordance with (3) $R = 2.76\times10^{-3}$ m and therefore $R < r_0$ and the light beam remains within the glass cylinder.

Thus, studying propagation of WG light waves in an inhomogeneous glass, we draw a conclusion that a relatively small increase in the refractive index is sufficient to guide WG light waves. This conclusion was valuable for us because our available technology of production of inhomogeneous glass allowed variations of the inhomogeneity about of 1% only. We have no thoughts about Ball lightnings at that time

Later, bringing to mind nonlinear optical effects which increase the refractive index in the region where an intense light propagates, we have taken an abstract interest in a possibility to obtain a necessary inhomogeneous optical medium by means of an intense light which circulates in a homogeneous glass in the region where the refractive index should be increased. In principle, there are no reasons to reject such possibility. There is an unsolved problem to provide necessary initial conditions for circulating light. The other problems connect with a consistency between the inhomogeneity of glass and the light intensity which provides this inhomogeneity as well as a stability of the circulating light.

It is hard to imagine that the first problem can be solved in a homogeneous glass. But it is reasonable to assume that similar problems were solved repeatedly in thunderstorms in the conventional atmosphere air which certain to be of a nonlinear optical medium. There are both the intense light and the inhomogeneous optical medium in a form of the conventional air with the inhomogeneous temperature and pressure at any lightning strike [16]. We put forward a hypothesis that BLs appearing at lightning strikes are LBs.

3 Increase in lifetime of intense light propagating in gases

A problem with theoretical justification of LB lifetime is the main test for the optical nature of BL. Indeed, the lifetime of BL can exceed tens seconds. The LB lifetime is seemingly determined by the lifetime of white light in the air atmosphere. A main reason responsible for a decrease in the intensity of the light propagating in transparent optical mediums such as high quality glass fibers or pure atmosphere air is the molecular light scattering [17]. The index of light scattering α in the earth atmosphere is equal to $\alpha = 2.7\times10^{-7}$ cm^{-1} [17]. In this case the light intensity decrease by 15 times at the distance 100 Km or in the time 0.3 ms. Thus the BL lifetime is greater by 4 order of magnitude than that of LB and the hypothesis that BL and LB are the same fails.

But the similarity in behavior of BL and LB is so amazingly that we were sure that there are some explanations of this distinction. Actually, we have succeeded to find out initially one mechanism providing a decrease in the light scattering within BL and then another one. Initially the first mechanism has been considered in [8]. Analyzing dependence of the molecular light scattering index α on the pressure for real gases, we found out that α decreases at very great pressure where gas molecules are packed close together. In this case fluctuations of the air density and, therefore, fluctuations of the air refractive index n can not appear because of small gas compressibility. Analyzing the lifetime of AOs we understood that there should be the second mechanism responsible for an increase of the light lifetime within AOs. The mechanism is connected with a specificity of the molecular light scattering within AO shell. Below we undertake the next step in analyzing joint actions of these mechanisms in more detail. This enables us to correct estimations of BL parameters obtained in [8] where only the first mechanism has been taken into account.

The index of the light scattering in gases α is described by the following expression [17]

$$\alpha = \frac{\pi V}{2\lambda^4 L^2}\left(\rho\frac{d\varepsilon_0\varepsilon}{d\rho}\right)_T^2 \beta_T kT(1+\cos^2\Theta) \quad (4)$$

where V is the volume of the gas; λ is the light wavelength; L is the distance from the volume V to the point where the intensity of scattered light is measured; $\beta_T = -V^{-1}(dV/dP)_T$ is the isothermal compressibility of the gas; ρ, P , T, and ε are the density, pressure, temperature and relative permittivity of the gas, respectively; ε_0 is the permittivity of vacuum; k is Boltzmann's constant; and θ is the scattering angle of light. The expression had been derived by Einstein in 1910 and is consistent with experiments very well. For example, the Avogadro number may be calculated from it with great precision.

As is seen from (4) only two multipliers $(\rho d\varepsilon_0\varepsilon/d\rho)_T^2$ and β_T depend on the gas pressure. From van der Vaals equation for real gases and, in particular, for an air we have

$$(P + a/V^2)(V - b) = RT \quad (5)$$

where $a = 1.3247$ N m^4/mole, $b = 114.09\times10^{-6}$ m^3/mole, $R = 8.314$ J mole^{-1} K^{-1} is the universal gas constant [18]. Then from (5) we have

$$\beta_T = 1\Big/\left(\frac{RTV}{(V-b)^2} - \frac{2a}{V^2}\right). \quad (6)$$

The electrostriction pressure P_L induced by a light in an optical medium is determined as follows [7]:

$$P_L \cong \sigma(n_0 - 1)W_L/\gamma, \quad (7)$$

where W_L is the density of the light energy, $n_0 = \varepsilon_n^{1/2}$, $\gamma = 5/2$, index $\sigma = V_n/V$ is a degree of gas compression,

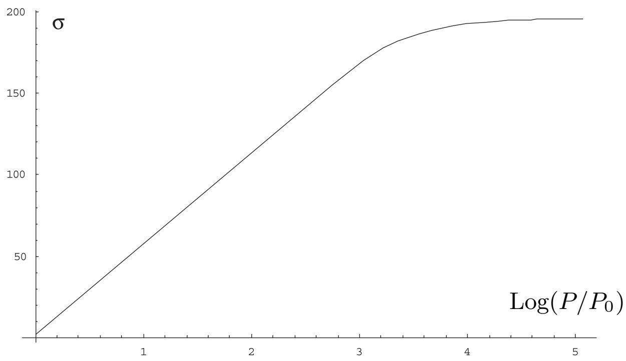

Fig. 3. Dependence of the index of compression σ on the gas pressure P.

V_n is the gas volume at normal condition, V is the gas volume at compression owning the electrostriction pressure, ε_n is the air permittivity an normal conditions. Dependence of the index compression $\sigma(P)$ on the gas pressure P can be determined from (5) and is shown in Figure 3 for the air heated from normal conditions at the temperature $T = 1000$ K. As is seen in Figure 3 and follows from the van der Vaals equation there is a limiting value $\sigma_{lim} = V_n/b$ and $\sigma(P) \to \sigma_{lim}$ as $P \to \infty$. Taking into account that $P = P_0 + P_L$, where $P_0 \approx 3\times10^5$ Pa is the air pressure at $T = 1000$ K, we can obtain dependence $P_L(W_L)$ which is shown in Figure 4a. As is seen P_L achieves P_0 at $W_L \approx 80P_0 \approx 240\times10^5$ J/m^3. Dependence $\sigma(P_0 + P_L(W_L))$ is shown in Figure 4b. Unlike smooth curve $\sigma(P)$, there is a great slope at $W_L \approx 10^9$ J/m^3 for curve $\sigma(W_L)$. Knowing dependence $\sigma(W_L)$ and taking into account (4) and (6), one can obtain dependence of index of light scattering $\alpha(W_L)$ which is shown in Figure 4c. A is seen there is a maximum of the index at $W_L \approx 10^9$ J/m^3 where light scattering is grater by a factor above 100 than that at $W_L = 0$. Indeed, the gas density increases with increase with the gas pressure and in accordance with (4) the light scattering increases proportional to the square of the gas density. But as seen in Figure 3 the gas density which is proportional to the index of compression $\sigma(P)$ increases slowly with an increase in the gas pressure at $P \gg 10^3P_0$. In the same time the isothermal compressibility β_T of the air in (4) as is seen in Figure 5 decreases abruptly as $\sigma \to \sigma_{lim}$. As a result, the light scattering decreases at $W_L > W_{th}$ and achieves the initial value at $W_L = W_0 \approx 10^{10}$ J/m^3. As is seen in Figure 4c, the light scattering at $W_L > W_0$ may be smaller by several orders of magnitude than that at $W_L = 0$. This approach has been used in [8] to determine the electrostriction pressure within BL. Actually, knowing an increase in light lifetime within LB, we can determine W_L from Figure 4c and the electrostriction pressure P_L from (7). It turned out that an increase in the light lifetime by 4 orders of magnitude takes place at $P_L \approx 30$ GPa.

This result is valid if the considered effect is the single one responsible for an increase in the light lifetime. Later we understood that this is not the case. Indeed, there is the second mechanism responsible for increase in

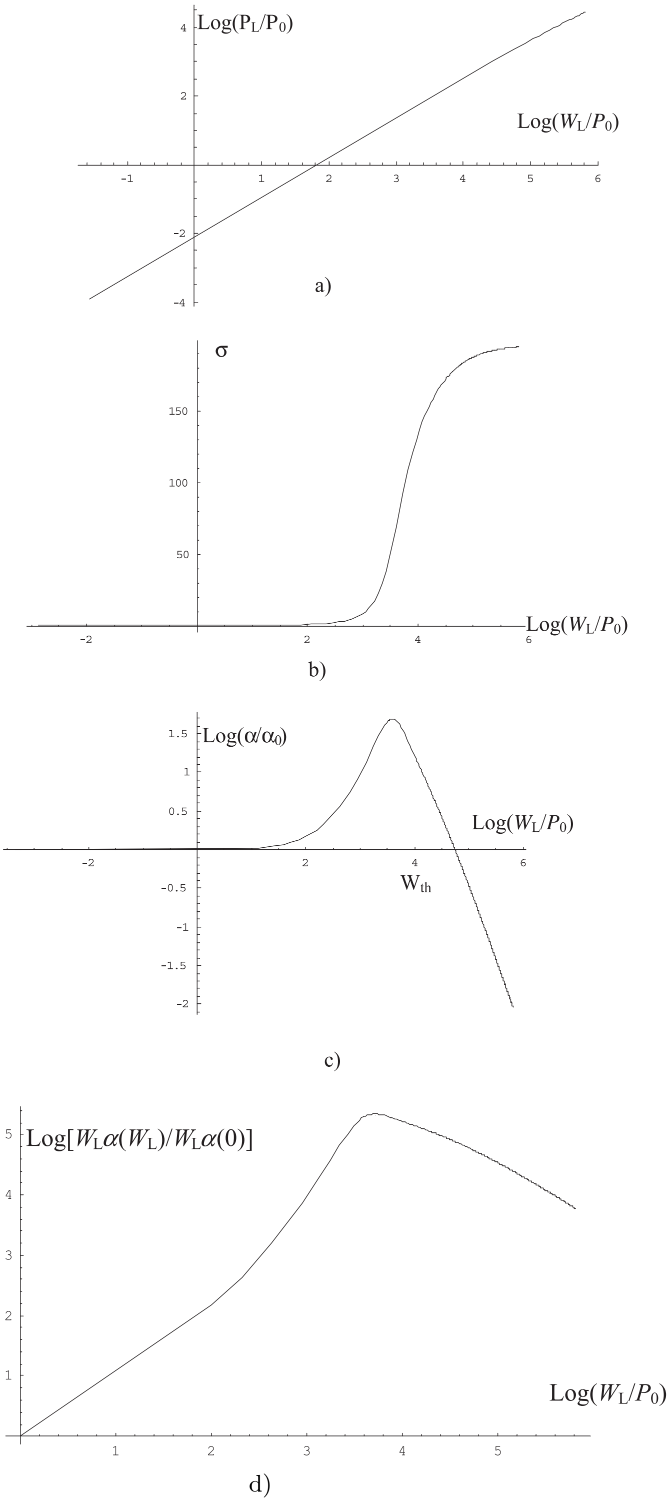

Fig. 4. Dependences of the electrostriction pressure P_L (a), index of air compression σ (b), index of light scattering α (c), and absolute losses proportional to the production of αW_L (d) on the density of the light energy W_L.

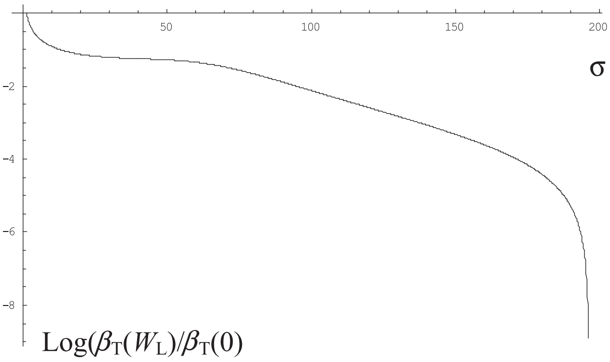

Fig. 5. Dependences of the isothermal compressibility β_T of the air on the index of air compression σ.

light lifetime within LB. It turns out that the light scattering within a thin film that is in essence a planar lightguide differs radically from the light scattering in 3D free space for which (4) has been derived. We should not consider the light scattering by an inhomogeneity in the film as a scattering light if it continues to propagate within the same film but in another direction. As is known, planar lightguides are a base of the contemporary integrated optics. A wealth of experience in a practical usage of "inhomogeneities" in a form of various devices of integrated optics such as channel lightguides, resonators, couplers, splitters, filters, gratings and so on shows that the light which was "scattered" by these inhomogeneities does not leave the film mainly.

As is known the lifetime of AOs is a fraction of second usually. It is greater by 2–3 orders of magnitude than that for white light in the conventional air atmosphere. Since the energy stored within AO is insufficient to compress the air up to the pressure of tens gigapascals, we can assume that AO lifetime is determined by the second effect only and is connected with feature of light scattering within planar waveguides. The second effect does not depend on the light intensity. Thus, we may conclude that the second effect is responsible for an increase in the light lifetime by 2–3 orders of magnitude.

Note that the electrostriction pressure within AOs can be insignificant and a necessary increase in the refractive index within AO can take place owning separation of gas mixture in such a way that molecules of the mixture component with maximal n are drawn in the AO shell and increase n within it [19,20]. Thus, only the second effect shows itself in AOs but both effects show themselves in long-lived BLs. In this case the estimates [8] of the electrostriction pressure within LB which lifetime is greater by 4 orders of magnitude than that of the conventional light in the earth atmosphere ought to be decreased by 2–3 orders of magnitude.

4 Process of accumulation of the light energy within a thin spherical layer

The density of the light energy W_L within a gas discharge may be estimated as follows. In accordance with the Stefan-Boltzmann law the total volume density of radiation is the following $W_L = aT^4$, where $a = 7.56 \times 10^{-16}$ J m^{-3} K^{-4}. At $T = 3 \times 10^4$ K^0 we have $W_L = 612$ J/m^3. It is essentially smaller than that required to increase $\Delta n = n_0 - 1$ by several times to provide a confinement of the light within LB, where $n_0 = 1.000277$ is the refractive index of the air at normal conditions. There should be some other mechanisms that provide an increase in the density of the light energy. One of such mechanism has been considered in [21] where was shown that about 10% of the light energy E radiated by an excited atom located within LB shell is preserved in the shell. Thus, the light energy stored within LB increases linearly by $0.1E$ for each period of rotation $\tau \approx 10^{-10}$ s. Since an accumulation of the energy lasts several milliseconds, the light energy within LB can be increased by a factor of 6 orders of magnitude. This conclusion is confirmed by optimal conditions for production of LBs. Optimal duration must be as long as possible. Increase in the temperature within the discharge space entails an increase in the air pressure. As a result, molecules of the air leave the space and the air density decreases. Moving in the direction where the air density is maximal, LBs leave the space too and process of accumulation of the light energy within them ceases. Additional measures ought to be undertaken to retain LB in the discharge space. For example, experimentalists have discovered that so-called erosive gas discharge is favorable for AO production [13]. In this case evaporation of electrodes or walls of a discharge camera provides a delivery of new portions of gas in the discharge space and an increase in n in such a way.

It turns out that there is once more mechanism which provides an accumulation of the light energy within LB. An accumulation is connected with properties of a space soliton to draw in light beams propagating parallel to the soliton at some small distance from it. The same mechanism provides a conversion of a plain light beam propagating in a Kerr-like nonlinear optical medium in a stable space soliton [5,6]. Consider initially this property in the case of known classical plane space soliton. It has been shown that a light beam which sizes of the cross-section are equal to w along the x-axis and infinity along the y-axis propagating along the z-axis acquires a stable profile which intensity is described by function

$$I(x, y, z) = I_0 \operatorname{ch}^{-2}(x/w). \tag{8}$$

Such beam is called a space soliton. The width w is determined from the condition

$$J(w) = 2\pi \tag{9}$$

where

$$J = \sqrt{\kappa/2} \int_{-\infty}^{\infty} u_0 \operatorname{ch}^{-1}(x/w) dx, \tag{10}$$

$\kappa = 2k_0^2 n_2/n_0$, $k_0 = 2\pi/\lambda_0, \lambda_0$ is the light wavelength in vacuum, n_0 is the refractive index of the medium for a light wave of small amplitude, n_2 is the index of nonlinearity determined by the relation $\Delta n = n_2 I$, Δn is an increase in n under action of the light wave of I intensity, $u_0^2 = I_0$, I_0 is the maximal intensity at $x = 0$.

One can see from (10) that

$$J \sim I_0^{1/2} w. \tag{11}$$

And, therefore, the greater I_0 the smaller the width w of the soliton. There is a very important property of beams from which soliton is formed [6]. If J in (10) for any light beam at some $z = z_0$ is in the range $\pi < J < 3\pi$, the parameters w and I_0 of the beam are changed as the beam propagates at $z > z_0$ in such a way that the beam becomes a space soliton and, therefore, its J becomes equal to 2π. For example, let $2\pi < J < 3\pi$. Show that I_0 increases and w decreases in this case. Since the power of the beam is constant and does not depend on z, then

$$I_0 w = \text{const}. \tag{12}$$

Substituting w from (12) in (11), we have $J \sim I_0^{-1/2}$ and J decreases with an increase in I_0. If $J > 2\pi$, I_0 increases until J becomes equal to 2π.

If there is a background in a form of an additional light wave propagating along the z-axis in the region $-h < x < h$, $-\infty < y < \infty$, where $h \approx w$, then in accordance with the above consideration this background wave will be drawn in space soliton determined by (10) and width w of this result soliton decreases. If the energy of the background wave is restored repeatedly due to radiation of light by atoms excited at the gas discharge, we have a gradual increase in the light intensity within the space soliton.

Ought to underline that this situation differs radically from the situation at which the same background light wave propagates in a inhomogeneous linear optical medium where distribution of the refractive index is determined by the expression $n(x, y, z) = n_0 + n_2 I_0 \operatorname{ch}^{-2}(x/w)$, i.e. coincides completely with distribution $n(x, y, z)$ produced in an homogeneous nonlinear medium by the space soliton. By way of illustration, trajectories of light beams in the first case are shown in Figure 6a. As is seen maximal deflections of light beams from the plane $x = 0$ are constant as light beams propagate along the z-axis. The picture is invariant under a shift along the z-axis. Trajectories of light beams in the second case are shown in Figure 6b. As is seen maximal deflections of light beams from the plane $x = 0$ decreases as light beams propagate along the z-axis. But the deflections tend to a constant as $z \to \infty$. Unlike the first case where distribution of the refractive index $n(x, y, z)$ in space is constant and does not depend on the light waves, in the second case distribution of the refractive index $n(x, y, z)$ in space is variable and depends on the trajectories both the space soliton and background light beams. In other words, the background light beams increases the refractive index in regions where they propagates. As a result, they are concentrated around the region where n is maximal. If background waves are generated at all times along the space soliton, they are drawn in the soliton in the same manner and light intensity within the soliton increases progressively.

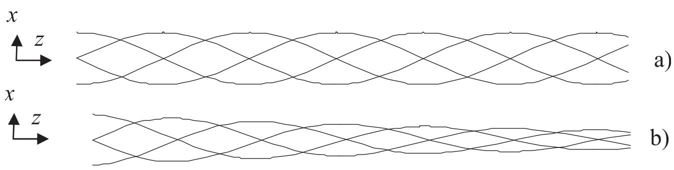

Fig. 6. Trajectories of background light beams propagating in an inhomogeneous linear medium (a) and in homogeneous nonlinear medium (b) where a space soliton propagates and forms an inhomogeneity that is identical to that of the linear medium.

Now let show that the same effect is possible for a LB which is a generalization of a plane optical incoherent space soliton. For this purpose we will try to convert the considered above situation with plane space soliton and plane background wave which both propagates along the z-axis into a situation where spherical space soliton is surrounded by plane background waves. Both light waves within the spherical soliton and background waves propagate in all possible directions. The conversion can be carried out in two steps. At the first step we convert the plane space soliton (8) propagating along the z-axis into N plane waves of intensity $(I_0/N)\mathrm{ch}^{-2}(x/w)$ where ith wave $(i = 1, 2, ...N)$ propagates in parallel to the plane $x = 0$ in the direction which makes an angle $\alpha_i = (2\pi/N)i$ with the z-axis. It is easy to check that the summary intensity of these waves in any point of the space is equal to the intensity produced by the initial plane space soliton. As a result, these N waves form the same distribution of n in the space and therefore the same plane lightguide where they propagate. Analogical conversion may be performed for the background wave. In a like manner, these N waves can draw in itself background light waves propagating in parallel to the plane $x = 0$ in all possible directions.

At the second step let increase the curvature of the plane lightguide from zero to some definite value. In this case the plane lightguide is transformed in LB and the background waves are transformed in a majority of light waves propagating in parallel with planes tangent to the LB surface. Such situation takes place at gas discharges where a majority of light waves produced by excited atoms are propagating in all possible directions and, in particular, in parallel with planes tangent to the LB surface. In this case the intense light circulating within LB takes up a part of the energy from these waves.

Thus, appearing in gas discharge as a result of instability of an intense light propagating in a gas mixture [20], AO draws in its shell not only molecules of the gas component with maximal n but also both the light energy radiated by excited atoms within its shell and the light energy of background light waves propagating near its shell in parallel with the shell surface. Like an intense light provides an existence of LB shell with increased n and LB shell confines the intense light in the shell, the intense light circulating in the shell draws in the shell molecules of the gas mixture component with maximal n and the shell in turn draws in the background light surrounding the shell.

Let estimate the distance that is required to drawn in an adjacent beam within the plane space soliton. In accordance with the eikonal equation the additional shift of light beam in presence of a gradient of the refractive index is determined by the following expression

$$d^2\Delta x/dz^2 = g_n \tag{13}$$

where Δx is the deflection of the light beam from a rectilinear line, g_n is the gradient component perpendicular to the light beam. In our case $g_n \approx \Delta n/(w/2)$ where Δn is the maximal increase in the refractive index at $x = 0$. Integrating (13) at initial conditions $\Delta x(0) = w/2$, $d\Delta x/dt = 0$ at $t = 0$, we have $\Delta x = w/2 - g_n z^2/2$ and, therefore, $\Delta x = 0$ at $z = (w/g_n)^{1/2}$. For example if $w = 10\mu\mathrm{m}$, $\Delta n = 10^{-3}$ then $z \approx 450$ μm. This distance ought to be increased for LB because (13) is transformed as follows

$$d^2\Delta x/dz^2 = g_n - R^{-1} \tag{14}$$

where R is LB radius. In the above example $g_n = 2000$ m^{-1}. If $R = 0.5$ cm, $R^{-1} = 200$ m^{-1} and influence of the curvature is insignificant.

One can see that a LB is a very good accumulator of light energy. Process of accumulation of the light energy terminates if the energy sucked into LB per one period of light rotation is equal to the losses in the same time. If conditions for suction are preserving for a long time, the density of the light energy within LB may be significantly greater than that in the space surrounding LB. Ought to note that the losses within LB (both irradiative and because of molecular light scattering) decrease with an increase in the light intensity within LB. In this case a situation is possible where the light energy introduced into LB per one period of circulation is greater than the total energy dissipated at the same time and a gradual increase in the light energy can take place. Possibly, this effect takes place for natural BLs too. In this case a usual sunlight is used as background light waves that are drawn in the BL. There are many evidences that BLs are observed in a sun day when no thunderstorms are observed. A storage of the light energy is an extremely difficult and in the same time extremely important problem. The light energy can be stored in optical resonators. But time of the storage is about several microseconds in the best case. As follows from observations of BLs, the time of the storage within BLs can be several minutes at least.

5 Conclusion

We can answer the question about the nature of Ball lightning as follows. It is a thin spherical layer of any gases which refractive index is greater than that of surrounding air. The gases are compressed in a thin spherical layer by an intense light circulating within it in all possible directions. The intense light is that binding means which prevents the gases from expansion. In the same time the thin spherical layer of gases is that means which confines the circulating light. As a special case the conventional air can substitute gases. By the way, a process of penetration of Ball lightning through a window glass clears Ball lightning from extraneous gases because no gases can penetrate through glass but the conventional air at the opposite side of the glass is available for compression by an intense light.

Comparing natures of BLs and AOs, we can conclude that, indeed, AOs are BLs but mechanisms responsible for existence of AOs and BLs may be different. Unlike the optical electrostriction effect responsible for an increase in n within BL shell, the new mechanism of optical quadratic nonlinearity in a gas mixture is responsible for an increase in n within AOs. Unlike extremely high air pressure responsible for the great light lifetime within BLs, the considered above specificity of light scattering within thin films provides an increase in the light lifetime within AOs. At last, mechanisms of appearance of BLs and AOs can be different. Certainly, mechanisms within AOs can show themselves within BLs too.

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