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How Ball Lightning penetrates in room through small holes and splits

V.P. Torchigin*, A.V. Torchigin

Institute of Informatics Problems, Federal Research Center "Computer Science and Control" of the Russian Academy of Sciences, Nakhimovsky Prospect, 36/1, Moscow, 119278, Russia

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ABSTRACT

We show in a frame of optical model of Ball Lightning how it finds out holes and splits to penetrate through them and analyze forces responsible for deformation of Ball Lightning. There is no plasma responsible for the natural Ball Lightning existence.

1. Introduction

There are numerous evidence that natural Ball Lightnings (BL) penetrate indoor through various small holes slots, splits, and keyholes as well as through chimneys [1–4]. BLs change their cross-section if it is required in this time. Even living creatures do not have similar properties. None of the known theories does not even try to explain these properties. Of course, BL has no sight, touch and other senses to find the hole. Of course, BL has no means to assess the size of the hole and change its shape so as to freely penetrate through the opening. If the theory could explain these features in a natural way, with a high degree of confidence it can be argued that this theory correctly describes the BL physical nature.

Below we will show that the self-confined light (SCL) has all necessary properties to satisfy the presented requirements. Unfortunately, nobody investigated the SCL till 2002 when we put forward a hypothesis that the SCL exists in the nature and BLs are a confirmation of its existence. The SCL can be imagined as a thin spherical layer of strongly compressed air where the intensive white light is circulating in all possible directions. The refractive index of the layer of the compressed air is greater than that of the surrounding space and the layer is a planar waveguide, the curvature of which is different from zero. Similar planar waveguides are a basis of the contemporary integrated optics where the optical processes take place in a transparent film, refractive index of which is greater than that of the surrounding space. The planar waveguide, the curvature of which is different from zero is also possible. Thus, the layer of the compressed air prevents radiation of light in free space.

In turn, the circulating light compresses the air due to the electrostriction pressure in the regions where it is circulating. The combination of the layer with the increasing refractive index due to compressed air and the intense light that provides the compression is called by the optical incoherent space soliton. Typically, such solitons are studied in the situation where their curvature is equal to zero because it is unknown how the spherical soliton can be formed. The fact that the BL is a rare natural phenomenon testifies that the production of the spherical solitons is not trivial problem. We can conclude that at present the scientific knowledge is sufficient to study the SCL. No new terms and notions are required for this purpose.

* Corresponding author.
E-mail address: v_torchigin@mail.ru (V.P. Torchigin).

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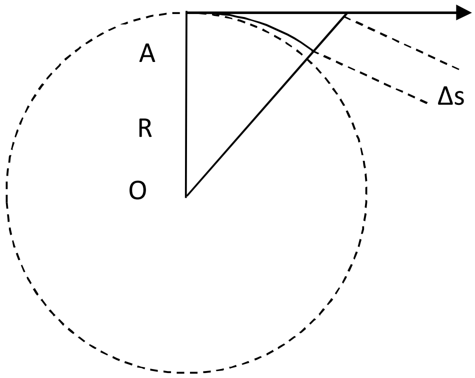

Fig. 1. Propagation of a light beam in the optical medium, where grad(n) depends on R and is directed to the center O. Dotted lines are perpendicular to the surfaces. They show directions of the gradient of the refractive index.

The energy of light in the SCL is significantly greater than the energy of the compressed air. That is why the behavior of the SCL is determined mainly by laws of optics rather than laws of mechanics. Optically induced forces (OIF) arising at an interaction between the light and matter (surrounding air in our case) were known since time of Maxwell. Having taken into account this kind of force, we have explained numerous puzzles and intriguing BL behavior [5–15] as well have presented a theory of the SCL [16–19].

Unfortunately, the contemporary notions about OIF are erroneous. The Lorentz force is taken as a foundation of OIF in last 40 years. We have shown that this approach gives incorrect results in the simplest situations [20]. It is not surprising that our SCL theory is not met in a proper understanding of the scientific community. In last five years we have developed on the basis of the unambiguous thought experiments the theory of OIF and have shown that notions of Maxwell and Helmholtz remains in force at the present time [21–38]. In particular, the century-old dilemma of the theoretical physics about a magnitude of the momentum in matter has been resolved.

The most essential property of the SCL for considered situation is its great deformability. Unlike a child balloon where the pressures inside and outside the balloon are different and the air cannot penetrate through the shell of the balloon, the pressures inside and outside the SCL are identical and the air can penetrate through the shell of the compressed air.

OIF applied to the SCL surface is proportional to the gradient of the refractive index of the surrounding air. If the surrounding air is homogeneous, then the gradient is equal to zero and the SCL is motionless. If the surrounding air is inhomogeneous (for example, different air pressure due to wind or flying aircraft, different temperature, different proportion of various gas components) the SCL is moving in the direction of the gradient of the refractive index (along the gradient of the pressure at the homogeneous temperature, against the gradient of the temperature at the homogeneous pressure). Thus, if the gradient of the refractive index is homogeneous in the space where the SCL is located, it moves along the gradient without deformation of its shape. If the gradient is inhomogeneous in the space where the SCL is located, its shape is deformed.

These information is sufficient to explain a majority of BL puzzles.

2. BL motion in a terrestrial atmosphere

SCL is an extremely sensitive device to the inhomogeneity of the refractive index of the surrounding air. SCL can react on the smallest changes in the refractive index. Let us consider a motion of light in an inhomogeneous optical medium, the refractive index of which is changed in space. A trajectory of the light beam is determined by the following eikonal equation

$$grad(n) = \frac{d}{dl}(n\boldsymbol{e}_S) \tag{1}$$

where n is the refractive index that is changed in space, l is the distance along the light beam, $\boldsymbol{e}_s$ is the unit vector directed along the propagation of the beam. Let grad(n) be dependent on R only where R is the distance between center O and the beam. Let the beam propagate along the tangent to circumference of R as is shown in Fig. 1. At this case, $\mathrm{d}n/\mathrm{d}l = 0$ and $\mathrm{d}\boldsymbol{e}_s/\mathrm{d}l$ determines the curvature of the trajectory at point A. Then the radius of the curvature R_0 at point A in accordance with Eq. (1) is equal to $n/\mathrm{grad}(n)$. Let us calculate a displacement of SCL of 0.1 m diameter at the time of one rotation of light within SCL when the light propagates at distance about s = 0.3 m. Let us assume that the same displacement by order of magnitude has the beam propagating from point A at distance 0.3m. The displacement of the beam from a straight line Δs in Fig. 1 is equal to $\Delta s = R_0/Cos(\frac{s}{2\pi R_0}) - R_0 = R_0(\frac{s}{2\pi R_0})^2/2 = \frac{s^2}{(2\pi)^2 R_0}/2 = \frac{s^2 grad(n)}{(2\pi)^2 n}/2$.

For example, if grad(n) = 10^{-6} m^{-1}, we have $\Delta s = 10^{-9}$ m. However, the light makes $N = c/s$ rps in the SCL. Since $s = 0.3$ m, we have $N = 10^9$ and SCL is displaced by 1 m per second.

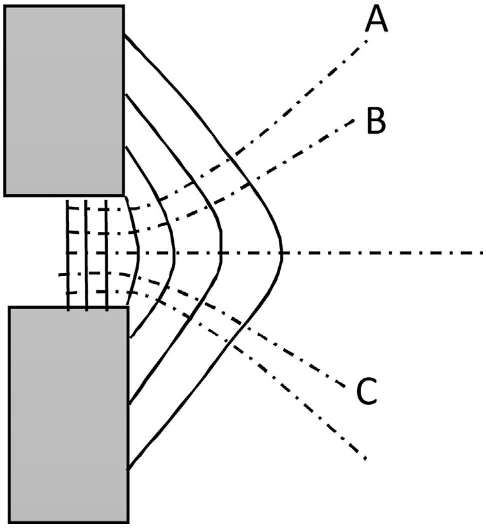

Fig. 2. Surfaces of equal temperatures and refractive indexes near the split in a wall are shown by solids.

Let us estimate conditions when $\text{grad}(n) = 10^{-6}$. The refractive index of the air at normal condition is equal to $1 + \Delta n$ where $\Delta n = 2.7 \times 10^{-4}$. If the temperature of the air is changed by $1\,^\circ$ Celsius at distance 1 m, we have that Δn is changed by $\Delta n/(278 + 20) = 10^{-6}$. Thus, at this case we have $\text{grad}(n) = 10^{-6}\,\text{m}^{-1}$.

3. How BL bypasses obstacles

Bypassing obstacles is explained as follow. When the SCL approaches an obstacle, the air becomes inhomogeneous. The SCL heat up the obstacle due to the light radiation. The obstacle heats up the nearest air due to the heat conductivity. The gradient of the refractive index arises that is directed outside the obstacle. As a result, OIF arises directed from the obstacle. The near the SCL the obstacle the greater the gradient. As a result, the obstacle repulses the SCL.

If ground or floor are considered as an obstacle and the weight of the SCL is greater than the Archimedes force (the weight of the compressed air should be taken into account), the bouncing of the BL is understood.

The motion of the SCL near the earth's surface is explained as follows. The density of air decreases with increasing altitude and, therefore, the gradient of the refractive index is directed down to the earth's surface. However, there is a correction near the surface connected with a change of the temperature in this region. The surface is heated up due to the sun radiation and the surface heats up the air near the surface due to the heat conductivity. In this case, the air density near the surface increases and the gradient of the refractive index is directed upward. There is a certain height where the vertical component of the gradient is equal to zero. In the regions above this height, the gradient is directed downward. In the regions below this height, the gradient is directed upward. The SCL is located in the region below the height where the OIF directed upward compensates the weight of the SCL. This height is about several meters.

The fact that the BL is relatively cold although the spectrum of its radiation corresponds to the radiation of a body heated by several thousand degree centigrade is explained quite naturally. Mechanism of radiation of the SCL is different from the mechanism of radiation of a hot body. The SCL radiates a part of the circulating light due to the phenomenon of the molecular light scattering. The hot body radiates due to exited atoms in accordance with the Stefan–Boltzmann law.

Thus, on the basis of simple physical laws studied in secondary school, puzzles of the BL behavior can be explained in a natural way on one page on assumption that the BL is the SCL.

4. Explanation how the Ball Lightning finds out splits, holes, and chimneys to penetrate through them

Before considering the mechanisms that ensure the penetration of BL through small cracks and openings, let us answer a simple question—how BL finds out similar objects. Actually, why is BL not indifferent to the cracks and holes. It is clear that the BL has no organs of sight, smell, touch, that are in living beings. However, BL can "feel" the slightest change of the refractive index of the environment and move along the gradient of the refractive index. Let us show that the splits and holes are sources of such changes

Consider the motion of BL near the tunnel between a room and outside space. Suppose that the room temperature is lower than outside, and the air pressures inside and outside are the same. In this case, the density of the air in the room is greater than that outside, and the gradient of the refractive index on the axis of the tunnel is directed into the room. Since the density of the air when moving along the tunnel varies gradually and continuously, the surfaces of equal density have the form shown in Fig. 2 by solid lines. Dashed lines in the figure are perpendicular to these surfaces. The direction of the tangent to any such line at any point coincides with the direction of the gradient of the refractive index at that point. It

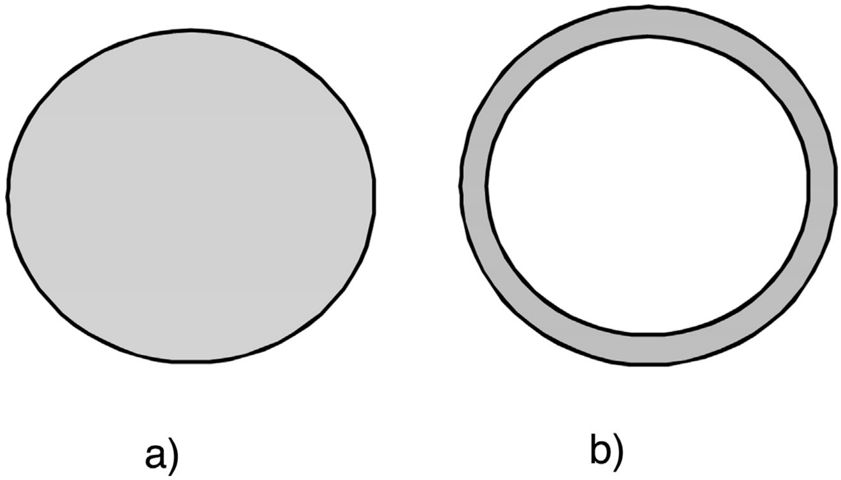

Fig. 3. Difference between compressed air (dotted area) in a football ball (a) and Ball Light shell (b).

is easy to verify that the BL, moving along any of the dashed lines from various points A–C, moves toward the tunnel. An original funnel is created near the tunnel. Caught in this funnel, BL falls into the tunnel.

Similarly, BL finds out roof chimneys to penetrate through them into the room. There is a funnel around each tube. Falling from a height, BL falls into one of these funnels and begins its movement along the gradient of the refractive index. If necessary, BL can change its shape as will be described now.

5. Explanation of penetration in rooms through small splits and holes

BL can penetrate into the room through the door cracks, windows, chimneys, may leave the premises. There are numerous reports that BLs move along the walls of the room at a certain height, avoiding the emerging obstacles in their way, come to slots and penetrate through them into the room. The dimensions of the slots or openings can be considerably smaller than the diameter of the BL.

There is a huge amount of evidence that BL can penetrate through small slits. Let us present a few of them, taken from the book of Stakhanov [3].

During a severe thunderstorm, BL of 20–30 cm of diameter entered through a hole in the wall for grounding.

During thunderstorms, BL 10 cm of diameter penetrated in the hole 2 cm wide. BL deformed in “stretched sausage.ẅhile penetration.

BL 10–20 cm diameter went through a cleft in the window glass.

BL diameter of 30–50 cm entered through a small hole in the window (glass chipped corner) 1–1.5 cm in width as the ‘yellow thread’. Having done a few laps around the room, BL exploded after 20–30 s.

BL 5–10 cm of diameter entered as a “snake” during a thunderstorm through the open window and then forming a bead. After going around the room a distance of 5–10 m, BL disappeared without an explosion near the switch.

During a severe thunderstorm, BL entered the house in the gap between the boards around the pipe. The board was smoked. The fire began.

BL 10–20 cm of diameter passed through a hole diameter of 8 cm.

BL of «the size of a tennis ball” has gone through a closed window, in which the glass had a crack.

BL «flowed” in the hole between the logs in the forge room. The slit width was much smaller than the BL diameter. BL was a ball of 12–13 cm diameter, orange, brightness of the lamp 50–100 W.

The yellow ball is the size of a large orange creeping through the crack in the wall. Most likely, it does not creep, but poured from one half to the other.

BL walked into the room through a hole in the glass, was flattened, as its size was larger than the hole. Eyewitnesses clarify: “the ball was in the 10–15 cm from our faces, and we have seen well as he began to pass through the hole, taking the form of a melon. He stretched out, was less in diameter and passed through the hole. When the ball passed through the hole and decreased in size, it was shaking all the time, and it seems that it consists of jelly”.

Consider the reasons for which BL can change its shape to penetrate into the room through a small slit or hole. In the beginning, we must note that BL deformability is extremely great. Unlike a child balloon or a soap bubble, the pressurized air in which is confined in a volume limited by their shells, the pressurized air in BL is confined in a thin layer of the shell itself. As is known, the shapeless closed homogeneous shell having a surface of S area, being pumped up by gas, gets the form of a body which volume is maximal. It is a sphere for given surface of the shell. A shell of a child balloon can serve as an example. The situation with a shell of a light bubble is a little bit more complex, than that with the child balloon. Unlike it, where pressure of air takes place in all volume limited by the shell (Fig. 3a), the air pressure in BL shell takes place only in a thin closed spherical layer of thickness ΔR (Fig. 3b).

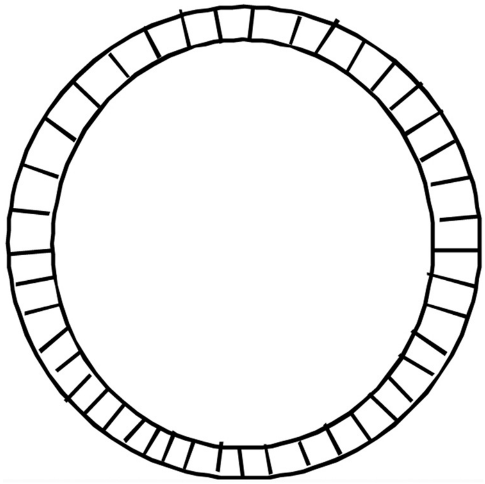

Fig. 4. Two shapeless film are connected to one another by means of strips of equal length. The film acquires a spherical shape after pumping up the space between the films.

In this case the compressed air is concentrated only in a thin superficial spherical layer. Such layer can be produced in the object, formed by two shapeless impenetrable for air films which are connected among themselves by set of threads of identical length ΔR, as is shown in Fig. 4. Being pumped up, such object gets also the form of a sphere. The deformability of such sphere is essentially smaller, than the deformability of a child balloon. Really, if we consider a site of the layer limited by a spatial angle α and shift this site in a direction to the center, we make the mechanical work equal $\delta w = \delta Rp(\Delta S_{out} - \Delta S_{in})$, where δR is the shift of the site, p is the air pressure, ΔS_{out} and ΔS_{in} are areas of outer and inner sites, respectively. Since $\Delta S_{in} = \pi(R-h)^2\alpha^2$ and $\Delta S_{out} = \pi R^2\alpha^2$ then, taking into account that $\Delta R << R$, obtain

$$\delta w = \delta Rp\pi R^2\alpha^2(\Delta R/R)^2. \tag{2}$$

Comparing this expression with the expression where $\Delta S_{in} = 0$, we obtain

$$\delta w = \delta Rp\Delta S_{out} = \delta Rp\pi\alpha^2 R^2 \tag{3}$$

Thus the deformability of the child balloon is smaller $(\Delta R/R)^2$ times than that of BL shell. For example, if $\Delta R = 10\,\mu m$ and $R = 10$ cm then $(\Delta R/R)^2 = 10^{-8}$. That is why the light bubble is easily deformed under action of the weak external forces arising at its penetration through small holes. If BL is located in the a space with inhomogeneous refractive index but this heterogeneity is characterized in all space by an identical gradient of the refractive index, BL moves along this gradient without deformation. If the gradient of the refractive index in the considered area is different in different points of the space, various sites of BL surface are subjected to action of various forces and BL movement is accompanied by its deformation. This property of LB allows to get it through cracks, which thickness is smaller than LB diameter.

When the BL is approaching the opening in the wall, wherein the gradient of refractive index of air is directed to the wall, a distribution of the gradient of the refractive index shown in Fig. 1 is changed due to the appearance of the next effect of self-action. When BL approaching to the opening, the inhomogeneity of air increases because BL heats the wall, which in turn heats the layer of the air between the BL and the opening. Thus, BL indirectly heats the air. BL cannot heat the air directly because the air is transparent. Solid objects, that absorb radiation radiated by BL, must first be heated. The regions surrounding the opening are used as these objects. These regions heat adjacent air layers due to the phenomenon of heat conduction.

The closer the air layer to the opaque surface of the wall, the higher its temperature. When heated, the density and the refractive index of the air decreases. Forces arise that repels BL regions, which are closer to the wall, from the wall surface. At the same time, according to our original assumption the gradient of the refractive index directed into the room continues to exist. As a result, there is optically induced forces of different directions applied to a different region of the BL shell. The action of these forces leads to a deformation of BL since the reducing properties of the BL shell are extremely weak. BL takes the form shown in Fig. 5c.

As BL penetrates into the hole, as shown in Fig. 5d, the following feedback takes place. The shorter the distance between the BL shell and an adjacent lateral internal region of the hole, the more the region is heated and the greater the force of repulsion of the BL shell from the side internal surface of the hole. As a result, the deformed BL is located in the middle of the hole as shown in Fig. 5e. Subsequent phases of penetration BL into the room through the hole are shown in Fig. 5f–h.

Thus, the forces associated with the initial gradient of the refractive index of air, “drag” BL through a hole in the wall. BL recovers its original spherical shape after it has passed the hole and came in the homogeneous air. It is easy to see that the same physical effects are responsible both for BL penetration through a hole and for BL horizontal movement at a certain

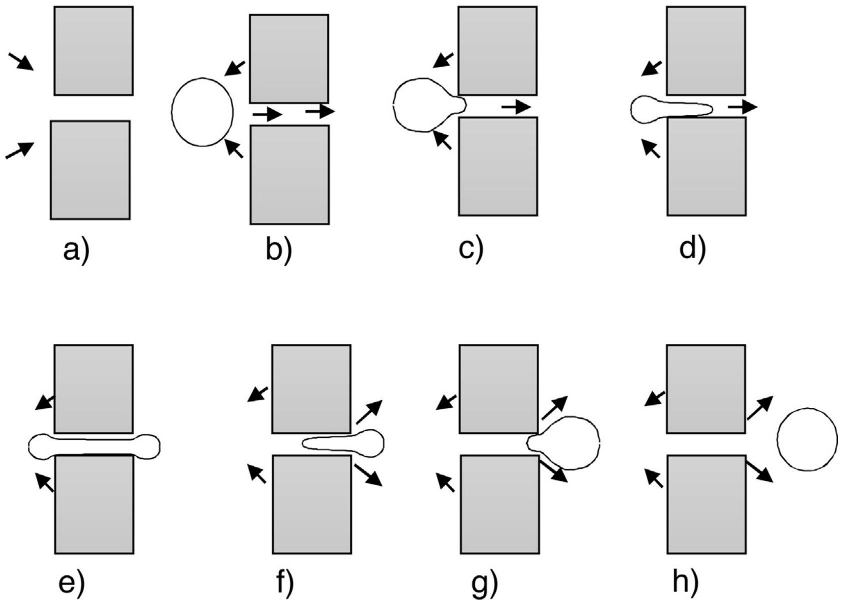

Fig. 5. Sequential steps of penetration of the self-confined light through the opening in a wall.

distance from the earth's surface. Since the thickness of the shell BL can be extremely thin, BL can penetrate through a very narrow gap of the tens of micrometer width.

Similar processes take place at BL penetration in a cabin of an aircraft. As is known, the air pressure is small at the high altitude where aircrafts fly. To provide the normal air pressure within the saloon, outdoor air is pumped continuously. At the same time, the indoor air penetrates outdoor through any holes and slots. These are excellent places for BL to penetrate indoor. The air pressure in these places is greater than the air pressure in the vicinity and therefore the gradient of the air pressure and the gradient of the air refractive index are directed inwards.

The following incident that occurred in the Vologda region in February 1946 is rather indicative. Copilot saw that the bright white ball appeared on the right wing of the aircraft near the running green lamp. He thought that it was a short-circuit bulb, but the flash was not disappeared, as usually happens. The ball slowly crawled along the front edge of the wing, and disappeared under the nose of the airplane. There was a loud crack, and the black smoke threw in the pilot, the connection was lost.

The commander asked the navigator, "Nicholas, maybe you noticed how the ball rolled out? After all, he appeared right at your feet". The navigator replied, "I took the pistol to check the color in her charge. But I do not have time to open it. At the same moment, a blinding white ball flashed. He, like the eyes of the devil, peered at me and then swam to you".

Here we note two things. The ball was moving along the front edge of the wing where the air pressure is maximal. The ball entered the cabin through the hole into which a rocket launcher is inserted. This hole extends outwardly, as this hole is intended for missile launch outdoors. The pressure in the cabin is higher than outside, because at the high altitude where planes fly, the air pressure is small, and the pressure that is close to normal one is maintained in the cabin. Therefore, the ball, moving in the direction of the gradient of the air density, penetrated into the cabin through the hole into which the rocket launcher was inserted.

Note that in any confined space such as a pipe, BL is moving in the direction opposite to the direction of the airflow. Indeed, in this case, the air flows from the high pressure to the lower pressure, i.e. in a direction opposite to the pressure gradient. Since the refractive index is proportional to the pressure and BL travels along the gradient of the refractive index, the BL travels along the pressure gradient, and thus in a direction opposite to the direction of air movement. Nearly any gap, through which the air escapes from the interior, there is a region where the refractive index gradient is directed towards this gap. Appearing in this area, BL penetrates through a slot in the cabin, where the refractive index of the air is greater than that outside. The mechanisms that lead to a change of the shape when BL is passing through the gap were discussed above. Simple recommendations can be given to aircraft designers to avoid BL penetration into an aircraft. There should be no gaps in the regions of the outer surface where the outdoor excess air pressure is maximal when the aircraft is flying.

In our opinion, the main reason that prevents a general recognition of an existence of the SCL in the nature is the belief that the SCL is impossible although at present the scientific knowledge and notions are sufficient to be persuaded in its existence. Unfortunately, up-to-date notions about optically induced forces are incomplete and erroneous. Above forty years, the erroneous approach based on the Lorentz force are used for calculation of optically induced forces. More than a century there is a dispute about a magnitude of the momentum of light in matter. It is obvious that it is difficult to expect a generally accepted recognition of the optical theory of Ball Lightning at this case. That is why we have devoted the last years to the development of the theory of optically induced forces that is a basis of the optical Ball Lightning theory. The following results have been obtained and published in the international physical journals.

The momentum of light in matter has been determined and the century-old debates about a magnitude of the momentum of light in matter have been resolved. The known contradictory thought experiments about a magnitude of the momentum in an optical medium have been matched. Properties and features of the optical electrostriction pressure have been elaborated. An erroneousness of the Lorentz force approach has been shown. About two dozens of papers have been published [21–38].

6. Conclusion

We can conclude that behaviors of the self-confined light derived from known laws of physics and natural Ball Lightning based on numerous evidence of eyewitnesses are identical.

References

[1] J.D. Barry, Ball Lightning and Bead Lightning, Plenum Press, NY, 1980.
[2] S. Singer, The Nature of Ball Lightning, Plenum Press, NY, 1971.
[3] I.P. Stakhanov, The physical nature of Ball Lightning (Atomizdat, Moscow 1979 CEGB trans CE 8244).
[4] P. Sagan, Ball Lightning: Paradox of Physics, Lincoln, NJ, 2004.
[5] V.P. Torchigin, A.V. Torchigin, Ball Lightning as an optical incoherent space spherical soliton, in: S.P. Lang, H. Salim (Eds.), Handbook of Solitons: Research, Technology and Applications, Nova Publishers, 2009.
[6] V.P. Torchigin, A.V. Torchigin, Propagation of self-confined light radiation in inhomogeneous air, Phys. Scr. 68 (2003) 388–393.
[7] V.P. Torchigin, On the nature of ball lightning, Dokl. Phys. 48 (3) (2003) 108–111.
[8] V.P. Torchigin, A.V. Torchigin, Behavior of self-confined layer of light radiation in the air atmosphere, Phys. Lett. A 328 (2–3) (2004) 189–195.
[9] V.P. Torchigin, Manifestation of optical quadratic nonlinearity in gas mixtures, Physics 49 (10) (2004) 553–555.
[10] V.P. Torchigin, A.V. Torchigin, Space soliton in gas mixtures, Opt. Commun. 240 (4–6) (2004) 449–455.
[11] V.P. Torchigin, A.V. Torchigin, Mechanism of the appearance of ball lightning from usual lightning, Dokl. Phys. 49 (9) (2004) 494–495.
[12] V.P. Torchigin, A.V. Torchigin, Physical nature of ball lightning, Eur. Phys. J. D 36 (2005) 319–327.
[13] V.P. Torchigin, A.V. Torchigin, Features of ball lightning stability, Eur. Phys. J. D 32 (2005) 383–389.
[14] V.P. Torchigin, A.V. Torchigin, Phenomenon of ball lightning and its outgrowth, Phys. Lett. A 337 (2005) 112–120.
[15] V.P. Torchigin, A.V. Torchigin, Self-organization of intense light within erosive gas discharge, Phys. Lett. A 361 (2007) 167–172.
[16] V.P. Torchigin, A.V. Torchigin, Ball lightning as a self-confined light, Opt. Int. J. Light Electron Optics 127 (2016) 2202.
[17] V.P. Torchigin, A.V. Torchigin, Nonlinear properties of gaseous optical mediums in a context of ball lightning explanation, Opt. Int. J. Light Electron Optics 127 (2016) 2319.
[18] V.P. Torchigin, A.V. Torchigin, Stability of the self-confined light, Opt. Int. J. Light Electron Optics 127 (4) (2016) 2298–2300.
[19] V.P. Torchigin, A.V. Torchigin, Interrelation between ball lightning and optically induced forces, Phys. Scr. 88 (3) (2013) 035402.
[20] V.P. Torchigin, A.V. Torchigin, Comment on theoretical analysis of the force on the end face of a nanofilament exerted by an outgoing light pulse, Phys. Rev. A 89 (2014) 057801.
[21] V.P. Torchigin, A.V. Torchigin, Comparison of various approaches to the calculation of optically induced forces, Ann. Phys. 327 (2012) 2288.
[22] V.P. Torchigin, A.V. Torchigin, Comment on transverse radiation force in a tailored optical fiber, Phys. Rev. A 88 (2013) 027801.
[23] V.P. Torchigin, A.V. Torchigin, Interrelation between various types of optically induced forces, Opt. Commun. 301 (2013) 147–151.
[24] V.P. Torchigin, A.V. Torchigin, Compensation of the optically induced Lorentz force in a homogeneous optical medium, Optik 124 (2013) 5492–5495.
[25] V.P. Torchigin, A.V. Torchigin, Optically induced force in a curve lightguide, EPJ AP Eur. Phys. J. Appl. Phys. 63 (2013) 10501.
[26] V.P. Torchigin, A.V. Torchigin, Interrelation between ball lightning and optically induced forces, Phys. Scr. 88 (3) (2013) 035402.
[27] V.P. Torchigin, A.V. Torchigin, On phenomenon of light radiation from miniature balls immersed in water, Phys. Lett. A 374 (2010) 588–591.
[28] V.P. Torchigin, A.V. Torchigin, Interrelation between striction forces in dielectrics and optically induced forces in transparent media, Phys. Scr. 86 (2012) 025402.
[29] V.P. Torchigin, A.V. Torchigin, Ball Lightning as an Optical Incoherent Space Spherical.
[30] V.P. Torchigin, A.V. Torchigin, Chapter 6 Ball Lightning as an Optical Incoherent Space Spherical Soliton, in: Matthew D. Wood (Ed.), Book Lightning: Properties, Formation and Types, Nova Publishers, 2011, pp. 133–184, Chapter 6.
[31] V.P. Torchigin, A.V. Torchigin, Magnitude of the photon momentum in matter, Am. J. Sci. Technol. 1 (4) (2014) 151–156.
[32] V.P. Torchigin, A.V. Torchigin, Pressure exerted on a semi-Infinite lossles dispersionless dielectric by a plane electromagnetic wave, Open J. Modern Phys. 2372 (2014) 6288.
[33] V.P. Torchigin, A.V. Torchigin, The momentum of an electromagnetic wave inside a dielectric derived from the Snell refraction law, Ann. Phys. 351 (2014) 444–446.
[34] V.P. Torchigin, A.V. Torchigin, Propagation of a light pulse inside matter in a context of the Abraham-Minkowski dilemma, Optik 125 (2014) 2687.
[35] V.P. Torchigin, A.V. Torchigin, Resolution of the age-old dilemma about a magnitude of the momentum of light in matter, Phys. Res. Int. (2014) (2014), Article ID 126436.
[36] V.P. Torchigin, A.V. Torchigin, Radiation pressure on plane dielectric surface, Optik 126 (2015) 1767.
[37] V.P. Torchigin, A.V. Torchigin, Kinds of optically induced force derived from laws of conservation of the momentum and energy, Optik 126 (2015) 1878–1883.
[38] V.P. Torchigin, A.V. Torchigin, Comment on deducing radiation pressure on a submerged mirror from the Doppler shift, Phys. Rev. A 92 (2015) 01794.