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Explanation of anomalous bouncing luminous droplets of liquid silicon in a framework of the optical model of ball lightning

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ABSTRACT

We analyze the results of experimental study of the anomalous properties of luminous droplets of liquid silicon that can perform numerous jumps on a thermal paper. Analyzing the traces left by the droplets on the paper, we show that the anomalous properties of the droplets can be explained by introducing into consideration optically induced forces that are the basis of the optical model of ball lightning.

1. Introduction

There are numerous attempts to produce a laboratory ball lightning [1]. Luminous objects having life time a fraction of second are generated in many laboratories. These objects have anomalous properties resembling the properties of natural ball lightning [2]. Various researchers called these objects differently. We will call them simply anomalous objects (AO). It should be borne in mind that all of them emit light and are luminous. Because of the short time of life, it is not possible to study the AO behavior in the earth's atmosphere and their bouncing. Situation is changed when a new method of AO production has been invented [3].

It turned out that a drop of molten silicon has properties reminiscent of the properties of natural ball lightning. Firstly, the lifetime of such a drop is a few seconds. Secondly, the drop bounces when it falls on the horizontal surface of the table or floor. Many drops gradually decrease in size and completely disappear. This indicates that the hot drop reacts with the surrounding air. Apparently, this is an exothermic reaction of silicon oxidation. As a result, a film of silicon dioxide (SiO_2) is formed on the surface of the drop, which is an excellent transparent glass, where the molecular scattering of light is very small. As a result, a spherical glass film can accumulate light emitted by a hot white drop. Light accumulates in the form of whispering gallery waves that circulate in the glass film in all possible directions.

Apparently, there is another chemical reaction, since the motion of the drop is accompanied by the appearance of smoke, which the drop leaves behind it. The smoke consists of fine solid particles. Most likely, this is silicon nitride (Si_3N_4), because, as follows from the catalogs, it is a powder. This reaction heats the drop additionally

Thus, the nature suggested another way, in which the prolonged existence of light in a spherical shell is provided by exothermic reactions. The heat generated by these reactions prevents the ball from quickly cooling down. This cooling can be observed in iron balls, which appear as a spray in the casting of steel. There is evidence that chemical reactions are also taking place in some natural ball lightning. Stakhanov points out that after the disappearance of ball lightning, a hot mass remained that was cooled down for 10 min [4].

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On the basis of the optical model of ball lightning we showed that the prolonged existence of ball lightning was attributed to the small losses of light circulating in the shell of ball lightning, because of the decrease in losses in highly compressed air, when the fluctuations in air density causing molecular light scattering significantly decrease [5]. The mechanism for obtaining natural ball lightning from linear lightning is considered in [6]. Luminous droplets of liquid silicon show another way both for production and prolonged existence of luminous objects with anomalous properties. These objects unite the fact that optically induced forces are responsible for their anomalous behavior.

2. Explanation of anomalous bouncing of ball lightning in a framework of the optical model of ball lightning

As is well-known, any light propagating in an optical medium produces forces on the medium. The force density of these forces is given by [7]

$$f = -\varepsilon_0 grad(\varepsilon)\frac{E^2}{4} - \mu_0 grad(\mu)\frac{H^2}{4} = -\frac{grad(\varepsilon)}{\varepsilon}W_E - \frac{grad(\mu)}{\mu}W_H \tag{1}$$

Here ε and μ are the permittivity and permeability of the optical medium, respectively; E and H are amplitudes of the electric field and magnetic fields, respectively; W_E and W_H are energy density of the electrical and magnetic fields, respectively. We will consider the conventional terrestrial air as the optical medium. In this case μ is constant and $\mu = 1$. Then the second term is Eq. (1) is neglected. These forces are applied to the optical medium.

In accordance with the third Newton law there should be other forces applied to the object that is a reason of arising of forces applied to the optical medium. This object is the light circulating around the surface of the drop. Since the light can not leave the surface, the force from the optical medium is applied to the drop

Integrating force density in Eq. (1) over the volume near the surface of the drop on assumption that grad(ε) in the volume is constant, we obtain that the total force F applied to the drop is given by

$$F = grad(\varepsilon)\Sigma/2 \tag{2}$$

where Σ is the total energy of light stored in the drop.

A change of the permittivity in space around the drop can be caused by various means, in particular various temperatures. The dependence of grad(ε) on the temperature can be obtained from the following consideration. Dependence of the air permittivity on the air density ρ can be presented as follow. Permittivity of the air ε at $\rho = 0$ is equal to 1. An increase of the permittivity is proportional to the density and therefore $\Delta\varepsilon/\rho = \text{const}$. At normal conditions we have $\Delta\varepsilon_N = 0.00054$, $\rho_N = 1400\ \text{kg/m}^3$. Then $\Delta\varepsilon/\rho = \Delta\varepsilon_N/\rho_N$ or

$$\Delta\varepsilon = \Delta\varepsilon_N\frac{\rho}{\rho_N} \tag{3}$$

As is known the air density decreases with increasing the temperature at constant pressure. That is why balloons with gas burners to heat the air inside the balloon can come off the ground. The density is in inverse proportion with the temperature. Then Eq. (3) can be rewritten as follows

$$\Delta\varepsilon = \Delta\varepsilon_N\frac{T_N}{T} \tag{4}$$

where T_N and T are the temperature at normal conditions $T_N = 300°$ K and the temperature of heated air, respectively.

Taking into account Eq. (4), we can wtite Eq. (2) and as follows

$$F = grad(1+\Delta\varepsilon)\Sigma/2 = grad(\Delta\varepsilon)\Sigma/2 = grad(\Delta\varepsilon_N\frac{T_N}{T})\Sigma/2 = -\Delta\varepsilon_N\frac{T_N}{T^2}grad(T)\Sigma/2 \tag{5}$$

We can conclude from Eq. (5) that the force applied to the drop is directed opposite to the grad(T) that is to the side where the temperature is the lowest. Eq. (5) is valid under the assumption that grad(T) is constant in whole region where the drop is located. If bouncing of the drop is considered, the grad(T) is different from zero in the region between the drop and the obstacle from which the drop bounces off. Thus, the force applied to the drop is produced in the region between the drop and obstacle at the moment when the drop can heat the air in the region.

We need to note that the drop cannot heat up the air surrounding the drop directly. The drop heats the surface of the obstacle due to the radiation of light. In turn, the obstacle heats up the layers of air near the obstacle due to the phenomenon of heat conductivity. The closer the layer is to the obstacle, the stronger it will be heated. Thus, the grad(T) is directed to the obstacle perpendicular to its surface, and the force acting on the drop is directed in the opposite direction.

It should be borne in mind that the heating of the layers is not an instantaneous process. It is determined by the laws of heat propagation in time, in particular, by the differential equation of the Fourier heat conductivity. In addition, the propagation of heat in time is accompanied by a change in the volume between the droplet and the obstacle due to the motion of a droplet with variable speed at the same time as the heat spreads.

Let us estimate an order of magnitude of the force applied to the drop. Let, for the sake of simplicity $\Sigma = 0.1$ J and $\Delta T = 100$ °C at distance $\Delta s = 0.1$ mm. In this case $grad(T) = \Delta T/\Delta s = 10^4\ \Delta T\ \text{m}^{-1}$. In accordance with Eq. (5) we have $F = 0.09$ N. This magnitude is obtained on assumption that grad(T) exist around whole surface of the drop. On assumption that the gradient exist on 1% of the