Physics – Uspekhi **53** (2) 209 – 213 (2010)

METHODOLOGICAL NOTES PACS numbers: 52.80.Mg, 92.60.Pw

Energy density calculations for ball-lightning-like luminous silicon balls

G S Paiva, J V Ferreira, C C Bastos, M V P dos Santos, A C Pavão

DOI: 10.3367/UFNe.0180.201002g.0218

Contents

Abstract. The energy density of a luminous silicon ball [*Phys. Rev. Lett.* 98 048501 (2007)] is calculated for a model with a metal core surrounded by an atmosphere of silicon oxides. Experimental data combined with the molecular orbital calculations of the oxidation enthalpy lead to a mean energy density of 3.9 MJ m^{-3}, which is within the range of estimates from other ball lightning models. This result provides good evidence to support the silicon-based model.

1. Introduction

Ball lightning (BL) is a luminous phenomenon sometimes associated with thunderstorms. It takes the form of a long-lived glowing sphere, as opposed to the short-lived arcing between two points, commonly associated with lightning. According to reports collected from thousands of witnesses in the past two centuries, BL is a luminous globe observed in nature, most often after ordinary lightning, either near the impact or at some distance from it. Its diameter varies from a few centimeters to several meters. It sometimes hovers at a height of a few to tens meters, but it can also bounce or roll on the ground. Various colors of BL have been seen: sometimes its colors change, and occasionally it has internal structure such as glowing layers or moving sparks. Sometimes it disappears silently, at other times it explodes with extreme violence. Various mechanisms underlying the generation of luminous balls with a similar appearance can be imagined, and this has given rise to a variety of theories for the origin of ball lightning [1 – 19].

David Turner [4] has suggested that BL is a plasma surrounded by water molecules, hydrated ions, and aerosols of nitric and sulfuric acid. All the apparent anomalies in BL behavior seem to result from electro-chemical processes which arise at the surface of a wet air plasma. The structure and stability of BL are maintained by these processes and the ball operates as a thermochemical heat pump powered by the electric field of a thunderstorm. BL can sometimes develop from the rare spherical form of St. Elmo's fire. Over the last few years the author of Ref. [4] has occasionally attempted to prepare St. Elmo's fire in a spherical form within a large humidity-controlled chamber, the hope being that ball lightning could then be detached from the conductor. However, he has never been able to control more than a few of the variables whose regulation seems to be essential. Probably for this reason, he has not even succeeded in making the large spherical kinds of corona discharge to which he believes this phenomenon is related.

According to Bychkov [2] BL appears as the result of the aggregation of natural polymers, such as lignin and cellulose, soot, polymeric silica, and other natural dust particles produced when linear lightning hits trees. Its ability to glow is explained by the appearance over its perimeter of gas discharges near the highly charged BL surface and the electrical breakdown of some regions on the surface, consisting of polymerized and aggregated threads. A number of experiments [12] have been conducted to verify the conclusions of this theory. Glowing spheres have also been obtained by wood breakdown in a discharge [13].

Kapitza [14] suggested that ball lightning should appear at the antinodes of electromagnetic waves in the radio-frequency band between the earth and thunderclouds. Ohtsuki and Ofuruton [15] and Ofuruton et al. [16] obtained fireballs by microwaves in an air-filled cavity, which exhibited motions similar to those observed in nature (also through ceramic plates and against wind).

According to Meshcheryakov [17], the processes of electrochemical oxidation within separate aerosol particles are the basis for this phenomenon, and BL is a cloud of composite nano- or submicron particles, where each particle is a spontaneously formed nanobattery which is short-circuited by the surface discharge because it is of such a small size. As free discharge-shorted current loops, aerosol nanobatteries are exposed to a powerful mutual magnetic

G S Paiva, J V Ferreira, C C Bastos, M V P dos Santos, A C Pavão
Departamento de Qu'mica Fundamental,
Universidade Federal de Pernambuco,
50740-540, Recife, Pernambuco, Brazil.
E-mail: pavao@ufpe.br

Received 10 April 2009, revised 27 November 2009
Uspekhi Fizicheskikh Nauk **180** (2) 218 – 222 (2010)
DOI: 10.3367/UFNr.0180.201002g.0218
Translated by E N Ragozin; edited by A Radzig

dipole–dipole attraction. The gaseous products and thermal energy produced by each nanobattery as a result of the intraparticle self-sustaining electrochemical reactions cause a mutual repulsion of these particles over short distances and prevent their aggregation, while a collectivization of the current loops of separate particles, due to the electric arc overlapping between adjacent particles, weakens their mutual magnetic attraction over short distances. Discharge currents in the range of several amperes to several thousand amperes, as well as pre-explosive megaampere currents generated in reduction–oxidation reactions and distributed between all the aerosol particles, explain both the magnetic attraction between the elements of the ball lightning substance and the impressive electromagnetic effects of ball lightning.

Abrahamson and Dinniss [5] proposed that BL is due to the oxidation of silicon nanoparticles in the atmosphere. At the high temperatures created by a lightning strike, the carbon in the soil chemically reduces the Si oxides to the vaporized, metallic form of Si: $SiO_2 + 2C \rightarrow Si + 2CO$. The passage of a lightning strike through sand is discussed in the study by Andrianov and Sinitsyn [20], which presents a picture of the obtained fulgurites. As the hot vapor cools in the atmosphere, the Si condenses into an aerosol of nanometer-sized Si particles in the air. Electrical charges created on heating gather around the surface of the aerosol, binding it together, and the resulting ball begins to glow with the heat of the Si oxidation in the atmosphere: $Si + O_2 \rightarrow SiO_2$. This model has been extended by Abrahamson to include a broad range of starting materials, from soil, or soil and wood, and to also include metal and plastic or metal and wood.

Recently, Fußmann has produced plasmoids above a water surface that have lifetimes of about 0.3 second and diameters of 10 to 20 centimeters [18]. This involves igniting a short high-voltage discharge (5 kV, 60 A) in a water tank. Fußmann analyzed the light in the plasma balls with a spectrograph at short intervals. In their tests, the researcher established the characteristic emission lines of calcium hydroxide and other molecules, as well as those of atoms and ions. From these, the physicist deduced that the initial temperature in the balls was on the order of 5,000 degrees, and that it fell by about half within the first tenth of a second, which is quite hot plasma containing electrons and positive ions of, for instance, sodium, calcium, and copper. While the first two are present in tap water in the form of salts, the copper ions come from the electrode.

Previously, we performed experiments with electric arc discharges in pure silicon to generate luminous balls with a lifetime on the order of seconds and with several properties usually reported for natural ball lightning [19]. We used pieces of 2-inch diameter, (111) or (100), 0.02 to 1 Ω cm resistivity, p-type doped, 350 ± 50 μm thick Si wafers placed on a 5 mm thick 1000×1000 mm flat steel plate as the base electrode and a tungsten (or graphite) top electrode, as shown in Fig. 1a. The top electrode is 4 mm in diameter and 30 cm long. The voltage at the secondary winding is in the range from 20 to 25 V and the current varies from 100 to 140 A. The top electrode is movable and is hand operated. The operator gently touches the Si piece with the top electrode and closes the circuit, as shown in Fig. 1b. Then, the top electrode is raised to a distance of approximately 1 to 2 mm. An electrical arc is formed during the upraising movement, as shown in Fig. 1c. During the upward movement of the top electrode, glowing hot fragments and, eventually, ball-lightning-like luminous balls fly away in all directions.

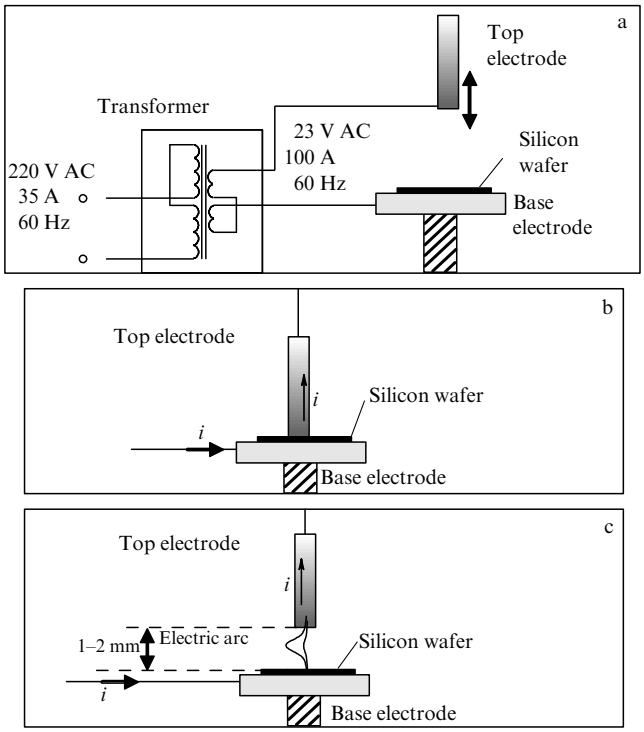

Figure 1. Experimental arrangement showing the power supply, electrode geometry, and Si wafer.

Many small, glowing hot fragments fly away in all directions during the discharge. It is clear that the luminous balls resembling the ball-lightning phenomenon have a very distinct behavior. Their apparent diameter is in the range from 1 to 4 cm, much bigger than that of a typical fragment. Also, their lifetime may be up to 8 s, whereas the fragments cool very quickly: in approximately 1 s. The balls leave smoke trails behind themselves. The balls seem to be spinning because the smoke trails tend to form spirals. Also, the inclination angle changes in this rotational axis (from vertical to horizontal, for instance) may be responsible for the sudden increase in speed and changes in direction observed in BL movement, as can be seen in a video widely available to the public [21]. The luminous balls behave like a jumping, elastic ball with glowing jets off its turbulent surface that apparently thrust it forward or sideways. These balls are hot (they burned polystyrene Styrofoam upon contact and ignited ethanol-saturated cotton) and decay leaving no trace.

There have been many claims that BL represents a significant hazard and that it has caused death, injury, and severe damage. However, it can be inferred from several publications that BL cannot contain high energy [5, 9, 10]. For example, Stenhoff [9] states that all strong effects associated with BL are in reality connected with the action of linear lightning, and that BL creates some sort of a route for atmospheric currents. Stakhanov (1979) [11], who supposed that the energy density (ED) of average BL is about 20 – 30 MJ m^{-3}, expresses the opinion that BL can take up charges that are induced on the surfaces of different objects under thunderstorm conditions, and then carry them, producing high-energy effects. In this article we have calculated the mean ED of silicon luminous balls (SLBs) produced in our previous experiments to be 3.9 MJ m^{-3},

which is in the same range of ED calculated by several other authors. The present finding is an additional evidence in considering the SLB as similar to the natural phenomenon.

2. The silicon luminous ball model

Let us consider the SLB model (Fig. 2) in which a metallic silicon core is surrounded by an atmosphere of oxidizing silicon atoms:

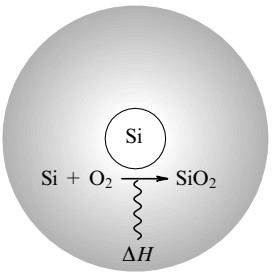

Figure 2. The SLB model showing a hot condensed core surrounded by an oxidizing silicon atmosphere.

This SLB model is in agreement with the recently reported sightings of ball lightning [3] and with the theory developed by Abrahamson and Dinniss [5]. According to this theory, at the high temperatures created by a lightning strike, the silicon dioxide in the soil is reduced to the metallic form of silicon. The fast-cooling hot vapor condenses the silicon into an aerosol of nanometer-sized particles. Balls appear once silicon starts to oxidize with the oxygen from the air. The oxidation rate, however, is limited by the need of oxygen to diffuse through the developing silicon-oxide layer at the surface of the ball. Here, we consider that the most important source of energy in the SLB is the silicon-oxidation exothermic reaction going on in the sphere. Details of calculations are presented in the next section.

3. Results and discussions

Let us calculate the temperature of an SLB. As shown in the video images (Fig. 3), the SBL orange-white color is invariant during ball lifetime, indicating a constant, or almost constant, temperature of the ball.

The SLB spectrum obtained by using a portable photospectrometer (Ocean Optics, USB 2000 model) is presented in Fig. 4.

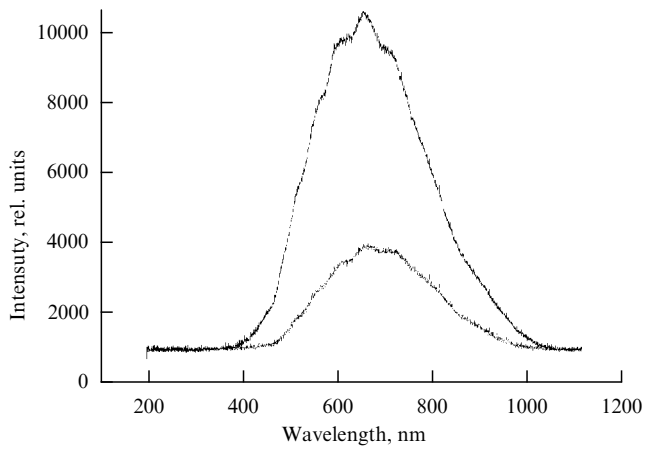

Figure 4. Optical spectra of two distinct SLBs.

The color temperature of the SLB can be calculated by using the Wien law [22]:

$$T = \frac{2.9 \times 10^{-3}}{\lambda_{\max}} , \quad (1)$$

where $\lambda_{\max}$ is the wavelength at which a Planck peak occurs. According to Fig. 4, $\lambda_{\max} = 675$ nm, which gives $T = 4296$ K. Recently, Stephan and Massey [23] made a rough estimate of the temperature of the sphere. In spite of the fact that they found $\lambda_{\max} = 700$ nm, which corresponds to $T = 4142$ K, their corrected experimental relative intensity data from the spheres give a temperature of 3140 K. However, they match the actual spectrum of liquid silicon, while we are considering gaseous silicon.

We have observed that in our experiments the SLB leaves a white powder trail [19]. Our Fourier Transform Infrared (FT-IR) system operating in transmission mode showed that the spectrum of these particles has strong absorption bands at 1463 cm^{-1} and 2924 cm^{-1}, thus confirming SiO_2 formation (Fig. 5).

The mean mass of the white powder collected in the trail left by selected luminous balls was measured as 7×10^{-3} g for each SLB. The energy released in the formation of this powder can be calculated by using the SiO_2 heat of reaction (ΔH) in the gas phase. Since the SiO_2 heat of reaction of gaseous silicon at that temperature is not available experimentally, we have performed molecular orbital calculations, using different levels of theory, in order to estimate its value at a temperature of 4296 K.

According to Helgaker et al. [24], the *ab initio* coupled cluster calculations, including simple, double, and triple excitations with the correlation-consistent polarized basis

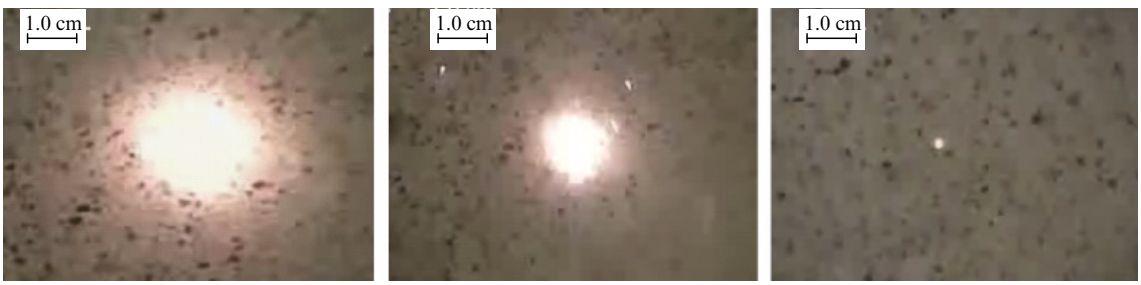

Figure 3. Successive video frames showing the decay of a luminous ball. Time interval between frames is 80 ms.

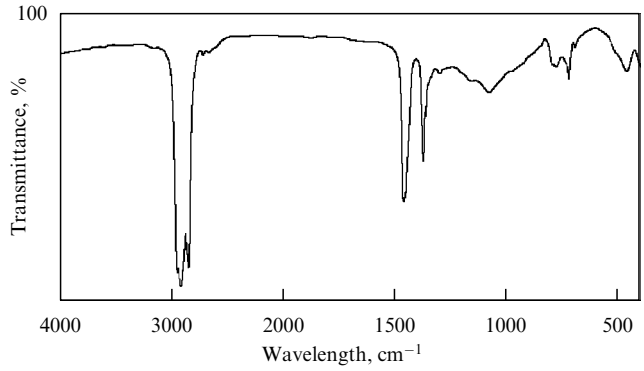

Figure 5. FT-IR spectrum of the white powder produced by SLB.

sets of Dunning and coworkers, denoted as CCSD(T)/cc-pVTZ, give accurate reaction enthalpies [25]. The coupled-cluster (CC) method, which accounts well for dynamical electron correlation, treats excitations between pairwise correlated electrons (pair clusters) in a nonlinear way via a cluster operator acting on a single-determinantal reference state. The cluster operator is partitioned into classes of all single (S), double (D), or triple (T) excitations. The SiO_2 heat of reaction is determined as the difference in electronic energies between product and reactants in the ground state, in accordance with the expression

$$\Delta H = E(\mathrm{SiO_2}) - \left[E(\mathrm{Si}) + E(\mathrm{O_2})\right] ,$$

where $E(\mathrm{SiO_2})$, $E(\mathrm{Si})$, and $E(\mathrm{O_2})$ are the electronic energies (including the zero-point energy correction) plus thermal enthalpy contributions for SiO_2 (−439.3166897 a.u.), Si (−288.9000116 a.u.), and O_2 (−150.1254283 a.u.), respectively. Thus, we found $\Delta H = -755$ kJ mol^{-1}. Including entropic effects, which are relevant to the energetic content of SLBs, we found $\Delta H = -273.4$ kJ mol^{-1}, resulting in $H = 31.9$ J as the released energy during the SLB oxidation process. All calculations are performed by using the Gaussian03 program.

The energy density of the SLB is given by

$$\mathrm{ED} = \frac{W_\mathrm{t}}{(4/3)\pi R^3} . \qquad (2)$$

Taking the mean radius of the SLB as $R = 1.25$ cm^{-1}, one finds ED = 3.9 MJ m^{-3}. Table 1 shows the energy densities estimated for BLs by several authors based on the damage caused by this phenomenon.

We can see in Table 1 that our calculated energy density of SLBs is in the same range as those for BL (with a diameter of the same order of magnitude as the SLB) estimated by Stakhanov [11], Imyanitov and Tikhii [26], and Barry [10]. Therefore, the SLB can be included in the BL category. It is important to observe that our SBL has a relatively small diameter, maybe due to the experimental conditions in which it was produced. For instance, we used 20 – 25 V and 100 – 140 A in the electric discharges, but natural conditions are quite different. We pointed out that the use of pure Si wafers probably optimized the evaporation of Si, so that ball-lightning-like luminous balls could appear to be associated with discharges involving currents much lower than expected in normal lightning strikes [1]. One discrepancy that should be addressed is the difference between eyewitness accounts of the apparent diameter of these spheres and their true diameter. As pointed out by Stephan and Massey [23], in the case of silicon spheres, the difference can be explained by the cloud of particulates that surrounds the sphere in motion. Even photographs of silicon experiments give the impression that the spheres are at least 1 cm in diameter. If we implicate this ball radius in our calculations, the ED will be about sixteen times higher.

Table 1. Mean diameter of various BLs, associated with their energy density.

Observation case / author	D, m	ED, MJ m^{-3}
Stakhanov [11]	0.08	25.85
Stakhanov [11]	0.055	1.99×10^2
Imyanitov, Tikhii [26]	0.07	6.25
Stenhoff [9] (the 1981 case, p. 65)	0.0175	2.4×10^2
Stenhoff [9] (the Smethwick event)	0.099	6
Barry [10]	0.098	0.8
This work	0.025	3.9

4. Conclusions

The energy content of the SLB has been estimated by using experimental data and the thermochemistry-calculated silicon oxidation heat. For an SLB with a radius of 1.25 cm, the calculated total energy released by the ball is 31.9 J, leading to an energy density of 3.9 MJ m^{-3}, in fairly good agreement with the estimates of many authors for natural BL. It seems quite plausible that BL could contain within its small volume sufficient thermal energy to explain several high-energy events of the natural phenomenon.

We stress that our SLB experiment does not rely on energy sources and excitation mechanisms that are improbable in the natural phenomenon and clearly demonstrates the role of vaporization and oxidation of Si, as proposed by the Abrahamson–Dinniss theory for ball-lightning formation [5]. It results in generation of luminous balls with long lifetimes and several properties observed in the natural phenomenon (to move over an extended, erratic path, sometimes with varying speeds; to subdivide into smaller balls; a vibrating surface, sparks; to have a fluffy cotton appearance; to roll; to bounce off the ground or solid objects; to squeeze into confined spaces; to spin; to burn objects upon contact; to have a bright orange-white color; to be spherical in shape without well-defined boundaries, and to have a lifetime of 2 to 5 seconds). However, this work adds new evidence in favor of the silicon BL theory.

Acknowledgments. The authors are grateful to Elder A de Vasconcelos, Eronides F da Silva, Jr., and Lucio Acioli from the Physics Department of the Federal University of Pernambuco for support in developing the present work. This work is sponsored by the Brazilian research agencies CAPES and CNPq.

References

1. Barry J D *Ball Lightning and Bead Lightning: Extreme Forms of Atmospheric Electricity* (New York: Plenum Press, 1980) [Translated into Russian (Moscow: Mir, 1983)]
2. Bychkov V L *Phil. Trans. R. Soc. Lond. A* **360** 37 (2002)
3. Singer S *Phil. Trans. R. Soc. Lond. A* **360** 5 (2002)
4. Turner D J *Phil. Trans. R. Soc. Lond. A* **360** 107 (2002)

5. Abrahamson J, Dinniss J *Nature* **403** 519 (2000)
6. Matthews R *New Scientist* (2233) 23 (2000)
7. Abrahamson J, Bychkov A V, Bychkov V L *Phil. Trans. R. Soc. Lond. A* **360** 11 (2002)
8. Uman M A *Lightning* (New York: McGraw-Hill, 1969) p. 230
9. Stenhoff M *Ball Lightning*: *An Unsolved Problem in Atmospheric Physics* (New York: Kluwer Acad., 1999) p. 24
10. Barry J D *J. Geophys. Res.* **85** (C7) 4111 (1980)
11. Stakhanov I P *Fizicheskaya Priroda Sharovoi Molnii* (On the Physical Nature of Ball Lightning) (Moscow: Atomizdat, 1979)
12. Emelin S E et al. *Zh. Tekh. Fiz.* **67** (3) 19 (1997) [*Tech. Phys.* **42** 269 (1997)]
13. Slyusarev N M "Sharovaya molniya i drevesina" ("Ball lightning and wood"), in *Sharovaya Molniya* (Ball Lightning) (Ed. B M Smirnov) (Moscow: IVTAN, 1990) pp. 18 – 29
14. Kapitza P L *Zh. Eksp. Teor. Fiz.* **57** 1801 (1969) [*Sov. Phys. JETP* **30** 973 (1970)]
15. Ohtsuki Y H, Ofuruton H *Nature* **350** 139 (1991)
16. Ofuruton H et al. *J. Geophys. Res.* **106** (D12) 12367 (2001)
17. Meshcheryakov O *Nanoscale Res. Lett.* **2** 319 (2007)
18. Fußmann G *Phys. unserer Zeit* **39** 246 (2008)
19. Paiva G S et al. *Phys. Rev. Lett.* **98** 048501 (2007)
20. Andrianov A M, Sinitsyn V I *Zh. Tekh. Fiz.* **47** 2318 (1977) [*Sov. Phys. Tech. Phys.* **22** 1342 (1977)]
21. Real Ball Lightning Created in the Lab, http://www.youtube.com/watch?v = KVDU-6opEqA&feature = fvw
22. Lang K R *Astrophysical Formulae*: *A Compendium for the Physicist and Astrophysicist* 3rd ed. (New York: Springer, 1999)
23. Stephan K D, Massey N *J. Atm. Sol. Terr. Phys.* **70** 1589 (2008)
24. Helgaker T, Jørgensen P, Olsen J *Molecular Electronic-Structure Theory* (Chichester: Wiley, 2000)
25. Kendall R A, Dunning T H (Jr.), Harrison R J *J. Chem. Phys.* **96** 6796 (1992)
26. Imyanitov I M, Tikhii D Ya *Za Gran'yu Zakonov Nauki* (Beyond the Edge of Scientific Laws) (Moscow: Atomizdat, 1980)