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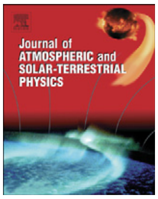

Burning molten metallic spheres: One class of ball lightning?

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ABSTRACT

Abrahamson and Dinniss [2000. Ball lightning caused by oxidation of nanoparticle networks from normal lightning strikes on soil. Nature 403, 519–521] proposed a theory of ball lighting in which silicon nanoparticles undergo slow oxidation and emit light. Paiva et al. [2007. Production of ball-lightning-like luminous balls by electrical discharges in silicon. Physical Review Letters 98, 048501] reported that an electric arc to silicon produced long-lasting luminous white spheres showing many characteristics of ball lightning. We show experimentally that these consist of burning molten silicon spheres with diameters in the 0.1–1 mm range. The evidence of our experiments leads us to propose that a subset of ball lightning events may consist of macro-scale molten spheres of burning metallic materials likely to be ejected from a conventional lightning strike to earth.

1. Introduction

1.1. Abrahamson–Dinniss theory

Ball lightning is a hitherto unsolved problem in atmospheric physics. As summarized by Stenhoff (1999), literally dozens of different theories have been proposed to account for its unusual characteristics. According to numerous eyewitness reports, ball lightning typically emits visible light over a period of 1–5 s or longer from an approximately spherical region 5–30 cm in diameter, which can float in the air near ground level in a way that is often non-ballistic. By non-ballistic, we mean that ball lightning is often observed to behave either like an object with near-neutral atmospheric buoyancy, or as though it is propelled by invisible forces in arbitrary directions.

Theories of ball lightning may be divided into two broad classes: external-energy theories and internal-energy ones. External-energy theories suppose that the luminous emissions come from energy that is supplied from a field or structure outside the visible boundaries of the ball itself. Kapitza (1955) proposed the first well-known external-energy theory, positing that a concentrated naturally occurring microwave electromagnetic field gave rise to ball lightning. Internal-energy theories, on the other hand, assume that sufficient energy is stored within the ball itself to account for its visible-light emission and other energetic phenomena (setting fires, explosions, etc.), which are occasionally attributed to ball lightning.

One of the most detailed internal-energy theories was developed by Abrahamson and Dinniss (2000). When conventional linear lightning strikes the ground, the high temperatures produced can form long glassy fused-mineral formations known as fulgurites, as Rakov and Uman (2003) describe. Abrahamson and Dinniss theorized that if lightning struck a region of soil containing sufficient quantities of both carbon-bearing material and silica, temperatures could rise high enough to reduce the silica to elemental silicon, as the carbon removed the silica's oxygen to form CO or CO_2. This process would presumably occur primarily in the liquid phase. As the temperature fell after the strike, silicon droplets would form a cloud of airborne nanoparticles, which would then

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oxidize at a rate dependent on their size and other factors. Due to the increased ratio of surface area to volume for small particles, powdered materials generally burn much faster than the same substance in bulk form. But Abrahamson and Dinniss pointed out that hot silicon in air quickly forms a native oxide. The rate of oxidation even for small silicon nanoparticles is thus limited by diffusion of oxygen through the oxide layer to the elemental silicon beneath. It is therefore possible for the combustion energy of burning silicon nanoparticles to be released relatively slowly over a period of many seconds—a time period which is consistent with most ball lightning observations. Abrahamson and Dinniss attempted to produce ball lightning in the laboratory by electrical discharges to soil samples containing both carbon and silica or silicates. Although the residue contained chains of nanoparticles, no effects similar to ball lightning were observed. In a later paper, Abrahamson (2002) expanded the range of possible materials that could participate in a nanoparticle-forming reaction to include metals such as copper and aluminum, and speculated that oxidation of metals and formation of nanoparticle chains may also be involved in some ball lightning processes. Abrahamson's ideas along these lines are some of the most recent of a series of proposals involving oxidation of metals that includes the experimental production by Golka (1994) of objects resembling ball lightning by using an arc-welding type of process with iron, aluminum, and copper.

1.2. *Paiva experiments*

Paiva et al. (2007) reported the production of luminous white balls upon striking an electric arc to pure silicon wafers. Their yield was relatively low: about 1 in every 30 attempts produced a luminous sphere. When spheres were produced, however, they reportedly exhibited up to 10 characteristics in common with ball lightning, including moving "over an extended, erratic path, sometimes with varying speeds," subdividing into smaller balls, rolling and bouncing off the floor, having a bright bluish-white or orange-white color, and lasting two to five seconds or longer. The balls gave off white trails of smoke, sometimes appeared to be spinning, and presented a fuzzy, ill-defined boundary to the eye and in video recordings published online.

All these characteristics are strongly suggestive of certain eyewitness ball lightning reports as recorded in sources such as Stenhoff (1999) and Barry (1980). Paiva et al. did not propose a specific hypothesis to explain their observations, other than to suggest that their experiments supported the Abrahamson–Dinniss theory of silicon-nanoparticle oxidation.

In this paper, we report experiments designed to duplicate those of Paiva et al. We believe that we have successfully duplicated their experiments in most essentials, with only minor differences. Based on our experiments and observations to be described below, we are proposing a modified theory to account for some types of events described as ball lightning. In common with the Abrahamson–Dinniss theory, our hypothesis involves diffusion-limited oxidation of elemental silicon (or other materials), but does not involve nanoparticles as the energy source of ball lightning. Instead, we propose that a subset of events described as ball lightning may be explained as the combustion of macro-scale liquid droplets of aluminum, copper, silicon, or other materials and mixtures with similar chemistries. While nanoparticles may be produced in the process we propose, they arise naturally as a type of smoke or vapor, and form a combustion product rather than the energy source.

We should note at this point that there is an extensive literature on the behavior of molten metal in welding arcs, including detailed physical models used to analyze and improve the performance of certain advanced welding technologies. For example, Hu and Tsai (2006) showed it is possible to model the complex behavior of a pulsed-DC arc that produces one molten droplet per pulse from the welding electrode under the proper conditions. While neither Paiva's nor our experiments were well controlled enough to permit such detailed modeling, this approach could be used in the future to elucidate further details of the process that forms these objects from silicon wafers.

2. Experiments

2.1. *Experimental setup*

The experimental setup is shown in Fig. 1. A commercial arc welder producing 48 V (rms) open circuit with a maximum short-circuit current of approximately 40 A was connected to two pure-tungsten rod electrodes, one fixed and one movable. In order to heat the wafers with a propane torch, the fixed electrode was placed on a ceramic support (a firebrick) and contacted one end of a slice of silicon wafer 0.5 mm thick, about 1 cm wide, and about 2–4 cm long. The silicon had $(\bar{1}\,\bar{0}\,\bar{0})$ orientation and was p-doped to have resistivity in the range of 10–15 Ω-cm. These slices were in continuous contact with the fixed electrode and were intermittently contacted with the movable handheld tungsten electrode. Our setup differs

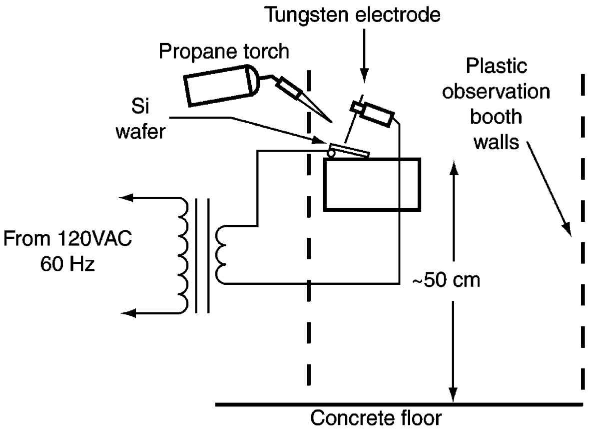

Fig. 1. Experimental setup used in silicon sphere experiments. Transformer provided approximately 49 V rms at 40 A through tungsten electrodes.

from the one described by Paiva et al. (2007) in that they directed current perpendicular to the plane of the silicon wafer, while our setup sends current lengthwise parallel to the long dimension of the slice. The estimated resistance of the wafer at 300 K in our configuration exceeds 100 Ω, leading to insufficient current in any case to fuse the silicon without heating the slice. But if the resistivity of the silicon falls to an estimated 0.05 Ω-cm at 1000 K, the slice's resistance goes down to about 1 Ω, which permits sufficient arc current to flow.

We then directed the flame of a propane torch at the silicon before attempting to draw an arc. Since the heated silicon glowed dark red to orange, we estimate its temperature was 1000–1400 K before the arcing electrode was applied. The movable tungsten electrode was hand-held in a welding-electrode holder and used to touch the heated surface of the silicon mometarily to produce an arc. The setup was enclosed in a polycarbonate plastic observation booth 60 cm wide, 30 cm deep, and 50 cm high, which confined the motion of the resulting objects to a definite volume above the concrete laboratory floor.

2.2. Experiments and observations

We easily obtained multiple arcs from each sample of hot silicon. About one in every six arc attempts produced one or more glowing white spheres, which strongly resembled those reported by Paiva et al. In common with Paiva's report, we observed the following characteristics of these spheres:

1. *Emission of bright white light*. Spectral analysis of the light emitted by these spheres shows that it roughly matches the emission curve of a blackbody at a temperature in the range of 2800–3400 K. An Ocean Optics QE65000 spectrometer with a 1 mm diameter fiber-optic input cable operating with an exposure time of 100 ms was used to obtain spectra from the spheres. Since the spheres have an active lifetime of less than 5 s and are highly mobile during that time, it was not possible to situate a single sphere at the focus of a light-collimation system leading to the spectrometer. Instead, we simply pointed the bare end of the 1 mm fiber-optic cable at the floor where the spheres were likely to collect after production, at a distance of a few centimeters away. When several spheres at once were active, the fiber's acceptance angle of 24.5° permitted enough light to enter the system and produce a usable spectrum.

The raw spectrum of light emitted from one such exposure is shown in Fig. 2, uncorrected for the wavelength response function of the spectrometer and fiber-optic cable used to couple the spectrometer to the light source. The spectrum was taken a few seconds after a considerable number of luminous spheres were produced, and represents an average of the radiant intensity from several spheres at different stages of their active lifetimes. We calibrated the spectrometer-cable system with a tungsten-filament quartz-halogen source in order to obtain the system's relative (not absolute) wavelength response to a source of known spectral shape. This allowed us to correct the raw spectrum of Fig. 2 for the spectrometer system's non-uniform response over the 400–700 nm range.

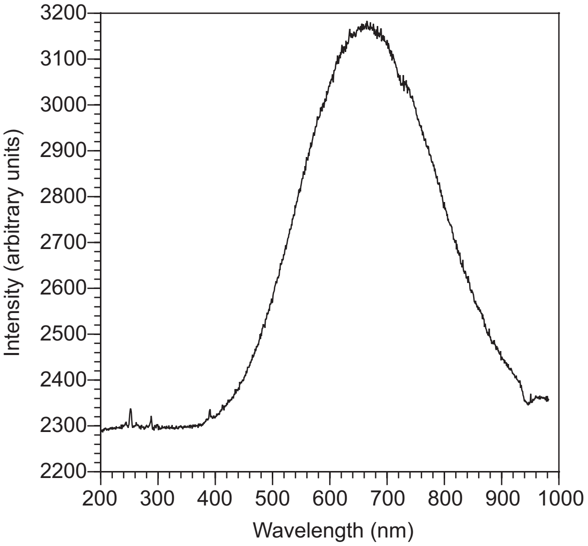

Fig. 2. Raw spectrum (uncompensated for spectrometer and fiber-cable response) produced by silicon spheres formed in setup of Fig. 1. 100 ms exposure time used.

A rough estimate of the spheres' temperature can be made as follows with an extension of the well-known "two-color pyrometer" algorithm, in which the ratio of intensities at two different wavelengths is used to calculate an object's temperature. Assuming the thermal radiation from an object is modeled by Planck's radiation law except for a constant emissivity factor over a given wavelength range, the shape of the object's spectral irradiance curve versus wavelength is uniquely determined by its temperature. The line in Fig. 3 labeled "Sphere" shows the relative radiant intensity from the spheres over the range 400–700 nm, corrected for the non-uniform response of the spectrometer and cable. In order to make comparisons easier, we have normalized all functions in Fig. 3 so that their value is unity at $\lambda = 700$ nm. Along with the corrected experimental relative intensity data from the spheres, we have plotted the theoretical relative intensities of ideal blackbody radiation at temperatures of 2800, 3100, and 3400 K. Although none of the ideal Planck curves matches the actual spectrum particularly well, a temperature of 3140 K matches the actual spectrum best in a least-squares sense over the wavelength range shown. While it is possible to model the emissivity versus wavelength of liquid silicon using estimates of its dielectric properties in order to obtain a better theoretical fit to the experimentally measured spectrum, such analysis was beyond the scope of this study. Since the intensity and color of emitted light from the spheres is observed to be nearly constant during their active lifetimes, we conclude that an exothermic reaction sufficiently intense to maintain a small sphere at a temperature in excess of 2800 K proceeds during the 1–5 s that the spheres emit light. When the reaction ceases, the fireball's light emission is seen to decline rapidly over a period of less than a second as it cools

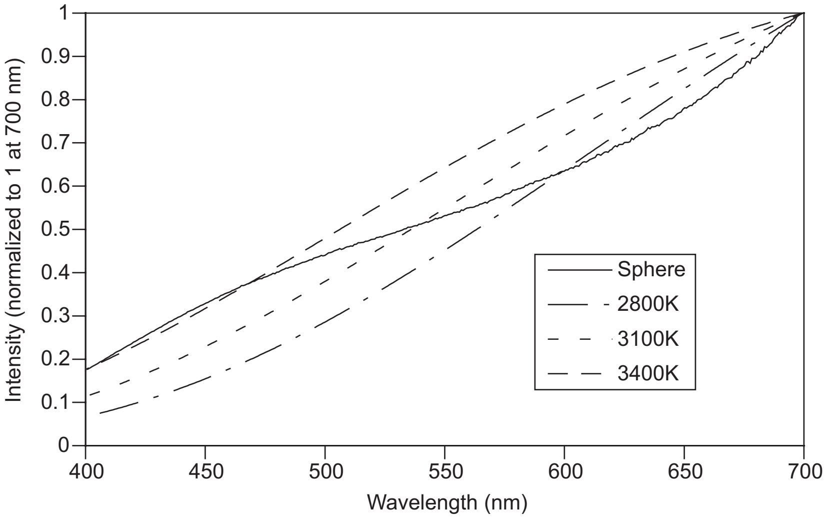

Fig. 3. Silicon luminous sphere emission spectrum corrected for spectrometer and cable response (normalized to 1 at 700 nm), compared with ideal blackbody Planck-law emission spectra for 2800, 3100 and 3400 K.

through the usual processes of radiation, convection, and conduction. The value of about 3100 K is in the same range as the simulated temperatures of molten metal in welding arcs as calculated by Hu and Tsai (2006).

2. *Active motion during lifetime*. The luminous spheres we created behaved in a non-ballistic way to the following limited extent. The electric arc imparts considerable momentum to a sphere immediately after its creation. This momentum is enough to move the sphere through the air at a velocity of a few m/s, in a trajectory that appears to be ballistic. However, upon colliding with a concrete floor, many spheres either break up into two or more smaller ones, or bounce multiple times at heights that do not decrease monotonically with time. For example, one sphere was observed to break up into several smaller ones upon its initial impact with the concrete laboratory floor (see Fig. 4). After certain impacts with the floor, some spheres would appear to gain translational kinetic energy, because they would bounce higher after an impact than they bounced before the impact. In other words, the sphere's translational kinetic energy did not appear to be limited only to that energy, which it received from its initial flight from the arc, plus whatever gravitational potential energy was converted into kinetic energy during its fall to the floor. When a small bounce is followed by a bigger one, some energy source must be available to provide the additional kinetic energy for the higher subsequent bounce. We believe we have identified the source of this energy, which we will describe below.

3. *Fuzzy ill-defined boundaries*. During the active phase of the sphere's existence, it is surrounded by a hazy white cloud. This cloud can turn into a trail of smoke, which the sphere leaves behind as it moves. Paiva et al. (2007) described the apparent diameter of their objects as "in the range from 1–4 cm." Although our objects have a similar appearance, we believe that most of the apparent diameter is accounted for by silicon monoxide vapor that continuously sublimes into a white cloud of small solid particles, all brightly illuminated by an ~1 mm diameter central liquid core. We have recovered such cores once they solidify and they appear to be solid silicon surrounded by a thin oxide coating.

Fig. 4. Video frame taken immediately after impact of sphere with concrete floor. Note that paths of smaller outward-moving spheres radiate from initial sphere's point of impact.

4. *Subdivision into smaller balls*. As described above and shown in Fig. 4, we have also observed our fireballs to divide into smaller ones. This effect is also easily accounted for by the hypothesis to be described.

The only characteristic claimed by Paiva et al. for their fireballs that we did not observe for ours was that the Paiva fireballs were alleged to "leave no trace." Although the fireballs we observed may have decreased in size during their active lifetime, we have always been able to find remnants of them after they cool. Such remnants are typically small (0.1–1 mm diameter) and might easily be overlooked in a large-scale experiment. Our analysis of these remnants has led us to a considerable modification of the Abrahamson–Dinniss hypothesis, and we will now describe our modification of that theory.

3. Oxidation of macro-scale molten spheres

3.1. Silicon case

Here is our hypothesis of the process described by both Paiva et al. and ourselves, as described sequentially in four steps.

1. An intense electric arc to solid elemental silicon will raise the solid's temperature high enough to fuse and ignite the silicon. The relative ease with which we generated fireballs compared with that of Paiva et al. can be attributed to our preheating the silicon. Besides the intended effect of increasing the conductivity of silicon, preheating means that less additional thermal energy must be imparted to the silicon by the arc to raise it to its ignition temperature. The ignition temperature of a material is not a fundamental property, but depends on a number of factors such as surface condition, particle size, and so on. However, since we have observed spectroscopic emissions from the luminous spheres consistent with a temperature in the range of 2800–3400 K, we conclude that the ignition temperature of silicon under the conditions of this experiment must be at least 2800 K, well above the melting temperature of 1688 K, but below the vaporization temperature of 3538 K.

2. The impartation of high temperature via an electric arc, with the additional factor of possible magnetohydrodynamic interactions between the liquefied silicon and the arc current, leads to the ejection of one or more burning liquefied droplets of silicon from the solid substrate. Liquid silicon has a high surface tension of about 800 mN/m according to Ratto et al. (2000). This high surface tension quickly draws all available molten material into a single sphere of limited size, which is then ejected from the arc. Under the conditions of this experiment, this limiting size seems to be on the order of 1 mm diameter.

As mentioned previously, a hot silicon surface exposed to air immediately forms a coating of SiO_2. Under static conditions for the liquid–gas interface such as those which prevail in a Czochralski furnace where single-crystal silicon ingots are produced, a complex but fairly well-understood equilibrium between dissolved oxygen, oxygen gas, SiO_2, and SiO occurs. (Silicon monoxide vaporizes or sublimes at or below a temperature of 2153 K, and thus can be considered as a gas for most of the processes under discussion herein.) The formation of an SiO_2 layer drastically slows the further oxidation of elemental silicon, although some oxidation still occurs through diffusion of O_2 through the SiO_2 layer, which is typically thin (a few microns or less). Wagner (1958) first showed that the partial pressure of oxygen determines whether an oxidation-inhibiting oxide layer will form on the surface of silicon. The partial pressure of oxygen under normal atmospheric conditions well exceeds this threshold. Hibiya et al. (2006) studied surface oxidation of a levitated drop of molten silicon at partial pressures of oxygen well below atmospheric, and showed experimentally that even at an oxygen partial pressure at the chamber inlet of only 750 Pa, a substantial oxide coating can form. Ratto et al. (2000) derived a complex dynamic-equilibrium model for the process and verified it with a well-controlled experiment operating under quasi-steady-state conditions. Exact modeling of the very non-equilibrium situation that creates the luminous silicon spheres described here would be difficult, but enough is now understood about the process to draw some reasonably certain qualitative conclusions.

We believe the main reactions at the liquid surface of the spheres are

$$\mathrm{Si(l)} + \mathrm{O_2(g)} \rightarrow \mathrm{SiO_2(l)} \tag{1}$$

$$\mathrm{Si(l)} + \tfrac{1}{2}\mathrm{O_2(g)} \rightarrow \mathrm{SiO(g)} \tag{2}$$

Reaction (1) has a standard enthalpy $\Delta_f H^\circ_{\mathrm{solid}} = -910.7\,\mathrm{kJ/mol}$ according to the US National Institute of Standards and Technology (2008), and provides the heat, which maintains the sphere at its combustion temperature for the duration of its active lifetime. Since we assume these reactions occur in the 2800–3400 K range, any SiO_2 formed will produce a liquid coating at these temperatures, not a solid one. Liquid SiO_2 can be displaced by mechanical perturbations, a point that will become important below.

Competing with reaction (1) is reaction (2) forming volatile silicon monoxide. Although the standard enthalpy of reaction (2) is also exothermic ($\Delta_f H^\circ_{\mathrm{gas}} = -100.42\,\mathrm{kJ/mol}$), according to Hibiya et al. (2006) the evaporation of SiO removes more heat from the object than its formation provides, so the overall effect of SiO formation is to cool the sphere. At the temperatures under consideration, SiO is a volatile gas and is also unstable, converting to SiO_2 at elevated temperatures. The whitish cloud that surrounds the fireballs is probably SiO vapor condensing and forming small particles of SiO_2.

While detailed mass measurements of the silicon before and after its alleged ignition would confirm these speculations about the chemistry of the process, the arc produces broken pieces of solid silicon, liquid silicon that immediately refreezes, silicon dioxide, and vapor as it erodes the silicon wafer, not all of which contribute to the glowing spheres. Generally, an area a few millimeter square was eroded away from a wafer during each successful generation of one or more luminous spheres. The opacity of the smoke generated around the spheres is also difficult to determine because of the transient nature of the phenomenon. The smoke appears nearly as bright as the sphere itself and is difficult to distinguish independently for optical measurements.

3. The trajectory of the spheres in air appears to be ballistic—that is, the only translational kinetic energy the spheres possess while in flight appears to be imparted to them by the initial arc. However, we have noted that when a fireball hits a cement floor, it can bounce several times, and the bounce heights do not always decrease monotonically, as they would when a passive elastic object such as a rubber ball bounces. For instance, an actively burning sphere can make a 2 cm high bounce off the floor, strike the floor again, and then bounce 4 cm high, a situation that clearly cannot occur without the addition of kinetic energy.

We believe this additional kinetic energy comes from a momentary increase in the rate of silicon oxidation that occurs when the sphere collides with the concrete surface. As the silicon oxidizes and produces SiO vapor, the vapor effuses away from the sphere. This effusion will normally be isotropic in the sense that there is no preferred direction of more intense effusion of vapor. However, when a sphere collides with the floor, the collision disrupts the liquid SiO_2 coating, exposing more elemental silicon at that point. The oxidation reaction is no longer inhibited by the SiO_2 coating in the region of disruption, which is at the bottom of the sphere. This leads to an increased reaction rate beneath the sphere, producing a burst of SiO vapor and a rocket type of reaction that propels the sphere higher into the air than normal ballistic dynamics would predict. Similar processes propel small particles of sodium metal around on the surface of liquid water in a well-known demonstration experiment in elementary chemistry, as the sodium reacts with water to release hydrogen, which burns and furnishes the motive power for the effect.

The spheres bounce in this way only when they strike a refractory material such as concrete that does not fuse easily at a temperature below 3400 K. Attempts to repeat the bouncing behavior by allowing the silicon spheres to fall on other materials such as aluminum or glass resulted in the material's melting and capturing the sphere, and no bounces were observed.

The motion of these spheres has important implications for the classification of ball lightning observations. Naturally occurring ball lightning exhibits both vertical and horizontal motions, but rather surprisingly, in one survey by Rayle (1966), 54% of ball lightning reports noted mainly horizontal motion while only 19% reported vertical motion (upward and downward motions were not distinguished in the survey). There is no systematic survey data to indicate what percentage of observations classified as ball lightning involve buoyant or non-ballistic behavior, although it is clear that many do. Stenhoff (1999, pp. 168–173) discussed seven independent ball lightning reports from trained scientists. Of these unusually specific and detailed reports, six described motions of the object that are either horizontal, stationary, or involve an upward component not arising from a bounce. The seventh described a ball as descending from a telephone pole and bouncing along the ground in a manner similar to the objects in this study.

4. All effects (light emission, smoke, etc.) resulting from the self-propagating oxidation of the molten silicon sphere appear to cease at a time that varies from less than 1 s to about 5 s after the initial arc that created the sphere. The reasons for this self-limiting behavior are not yet positively established. But our examination of sphere remnants strongly suggests that the reaction is a victim of its own success. Combustion of elemental silicon produces a layer of liquid SiO_2, which eventually becomes too thick for oxygen to diffuse through to the silicon fast enough to maintain the reaction. When this happens, the normal avenues of heat loss through radiation, conduction, and convection, plus evaporation of SiO, all overcome the decreasing heat generation due to the falling oxidation rate. Self-propagating combustion ceases and the sphere cools with a time constant of less than 1 s, leaving a spherical remnant.

A photograph of one such remnant is shown in Fig. 5, which shows a sphere that embedded itself in a piece of borosilicate glass, melting a part of the glass in the process. Most of the sphere's surface is covered by a brittle grayish-black coating, which is probably the solidified form of the thin liquid SiO_2 coating presumably present during combustion. Since silicon expands about 9% upon freezing and the cooling sphere's surface temperature is lower than its interior temperature, the sphere freezes from the outside in. As the liquid inside the sphere freezes, it expands and creates high pressure inside the sphere. In many spheres, this pressure causes the outer skin to rupture, and liquid silicon erupts through the opening, only to freeze upon emerging. Fig. 5 shows clear evidence of just such a process, and numerous remnants we recovered have such "satellite" extrusions on them. A smoke ring observed from one cooling ball probably resulted when some gas was expelled from the shell along with liquid during the cooling phase.

3.2. *Other materials*

Many other metals and some semimetals form native oxide coatings at elevated temperatures. Perhaps the most well-known example is aluminum, whose oxide coating accounts for its relative freedom from corrosion despite the highly active chemical nature of the metal. After numerous attempts, we successfully produced a burning droplet of aluminum from a molten sample (fused initially with the propane torch) with the same setup used for the silicon experiments (see Fig. 6). A smoke trail can be seen to the upper left of the glowing sphere, which subsequently bounced off the laboratory floor and moved in a manner similar to the silicon spheres for approximately 1 s before cooling.

Copper also forms a surface oxide at elevated temperatures. Several reports in the ball lightning literature suggest that relatively ordinary conditions can give rise to such an event. Jones (1910) gives an eyewitness account of such an incident in a Purdue University undergraduate electrical instructional laboratory. The account is brief enough to quote in its essentials:

> With a copper wire a student accidentally short-circuited the terminals of an ordinary 110-volt circuit….

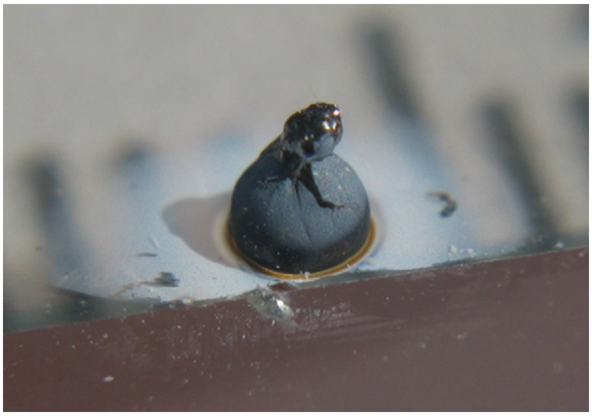

Fig. 5. Remnant of a luminous ball after it embedded itself in a borosilicate-glass sheet. Lines in background are spaced 1 mm apart.

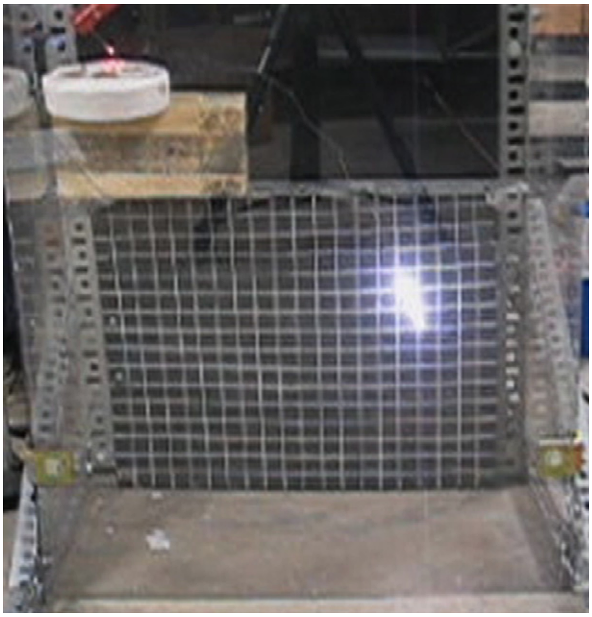

Fig. 6. Burning droplet of aluminum produced with setup used for generation of silicon fireballs.

> At the instant of the short circuit I saw an incandescent ball which appeared to roll rather slowly from the terminals across the laboratory table and then disappeared.... [T]he ball may have appeared to be about three centimeters in diameter. On the table where the ball had rolled we found a line of scorched spots, as if the ball had bounced along the table and had scorched the wood wherever it touched.... In the top of the table was a crack perhaps a millimeter or two wide, and at this crack the scorched line ended. In a drawer immediately under this crack we found a tiny copper ball, perhaps a millimeter in diameter.

By 1903 (the approximate year of the incident reported), the electric utility at Purdue was probably 60 Hz AC, which means that the electrical conditions under which the event occurred closely resemble those of the Paiva experiments and ours. This incident shares with these experiments the following commonalities: (1) initiation of the fireball from an electric arc, (2) production of a whitish glowing fireball lasting several seconds, (3) apparent visual diameter estimated to be several centimeters, (4) evidence of the fireball's high temperature (the scorched table), (5) limited non-ballistic behavior (bouncing along the table), and (6) the discovery of a small spherical remnant about 1 mm in diameter.

When we connected a 60 mm length of 0.4 mm diameter copper wire between screw terminals, heated the center with a propane torch to red heat, and applied 40–50 A AC, the wire fused and emitted numerous drops of molten incandenscent copper. Several of these balls emitted yellow–white light at an approximately constant intensity for about 1 s, as observed on video recordings. Some of them bounced on sheets of paper placed underneath the setup and left periodically spaced burn marks similar to those described by Jones. Some of the spherical remnants recovered from these experiments appeared to be pure (unoxidized) copper, while others had a smooth, shiny gray coating, presumably a form of copper oxide. Although further studies will be needed to determine whether the heat from these objects originates from combustion or is simply left-over heat from the applied current, the similarities between this experiment and the incident reported by Jones suggest the conclusion that the two phenomena are basically the same.

One of the more well-known artificially induced events that is believed by some to resemble ball lightning is the phenomenon that can occur when abnormally high currents in a submarine's switchgear are interrupted by a circuit breaker. Silberg (1962, 1977) noted that at currents exceeding 100 kA, a pair of contacts consisting of silver and copper occasionally gave rise to a "green fireball", which "floats off the contacts into the engine room." The present author has interviewed an eyewitness to a similar phenomenon witnessed several years ago on the USS *Sea Poacher* (Brinkman, 2008), who claimed that the object glowed white, not green, and moved rapidly around the room during its lifetime of a few seconds.

Silberg's (1962, 1977) reports were cited by Golka (1994), who claimed to have produced a type of ball lightning in the laboratory by shorting copper, aluminum, or iron electrodes together under water while they carried currents ranging from 1.2 to 10 kA (the paper is not clear on the minimum current required). Golka's experiments produced brightly glowing spheres that moved around on the water's surface for several seconds. Like the objects described in the present paper, these molten metallic spheres emitted smoke trails, glowed white or yellow, and lasted several seconds, leaving behind a small metallic remnant. Golka mentions that some accounts of ball lightning inside aircraft may be explained if aluminum fragments ignited by a lightning strike to the aircraft skin fly-off inside the cabin.

According to Vettori (1998), all metals except gold, silver, and platinum will burn "in the proper environment." The proper environment for ignition and continued combustion of aluminum, copper and other oxide-forming metals may consist of extremely high temperatures such as those which can occur in an electric arc or lightning strike, together with other conditions involving discharge duration, physical surroundings, the presence of certain impurities, and other factors. Numerous accounts in the ball lightning literature of ground-based rolling balls (as opposed to balls that float in the air) should be re-examined in the light of this research to determine whether the phenomenon in question could be accounted for by the hypothesis of burning liquid metal, semimetals, or a combination thereof.

One discrepancy that should be addressed is the difference between eyewitness accounts of the apparent diameter of these spheres and their true diameter. In the case of the silicon spheres, the difference can be explained by the cloud of particulates that surrounds the sphere in motion. Even photographs of our silicon experiments give the impression that the spheres are at least 1 cm in diameter, as Fig. 4 appears to show. When we interposed a

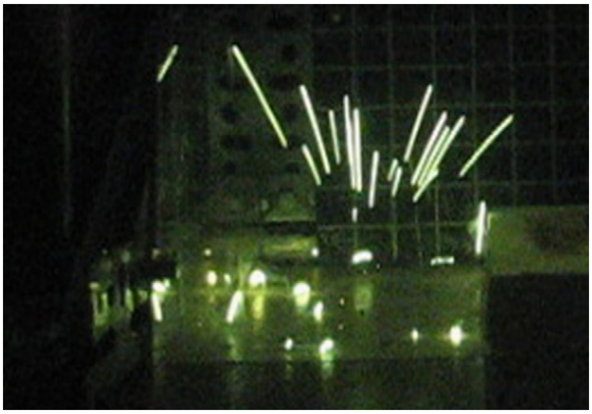

Fig. 7. Same scene of silicon spheres shown in Fig. 4, but viewed through No. 5 welding filter to show actual size of spheres.

No. 5 welding filter between the experiment and the camera lens, the light reflected from the cloud of vapor surrounding the sphere was insufficient to register, but the direct visible radiation from the sphere itself remained. Fig. 7 shows the same scene as in Fig. 4, except for the interposition of the welding filter in front of a separate video camera. The tracks in Fig. 7 show that the central core of the visible phenomenon is the burning sphere itself, less than 1 mm in diameter. But the psychological impression left in the observer's mind is that of a much bigger object.

4. Conclusions

We have shown that the phenomenon described by Paiva et al. appears to consist of burning molten silicon droplets whose combustion is initiated by the high temperature of an electric arc. To the extent that the oxidation of the molten silicon is inhibited by the presence of a native layer of liquid SiO_2, the experiments of Paiva and our own experiments confirm the hypothesis of Abrahamson and Dinniss that oxidation of silicon at high temperatures can produce a luminous ball during a reaction that lasts several seconds. However, the details of the process differ considerably from the Abrahamson–Dinniss hypothesis, in that macro-size (0.1–1 mm) liquid silicon spheres are involved, not a cloud of silicon nanoparticles. Although we have not analyzed the smoke produced by this reaction, its size may lie in the range of nanometers. If this is the case, nanoparticles are involved in the phenomenon, but not in the way Abrahamson and Dinniss proposed.

Our demonstration of the same basic process with aluminum and copper, together with reports such as Jones (1910) and Golka (1994), shows that electric arcs or lightning strikes on metals such as aluminum and copper, as well as elemental silicon, may on occasion create burning liquid droplets that behave in ways consistent with a certain class of ball lightning observations. Where sufficient observational data are available, a distinction should be made between events on the one hand in which the ball is observed to behave ballistically while in flight, with possibly some non-ballistic behavior during collisions (as in these experiments), and events on the other hand in which the object in question appears to float or move in a non-ballistic way that "defies gravity" over a time span of several seconds or more. We believe that our hypothesis may explain a number of ball lightning observations in the former category, but not those in the latter one.

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