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Microwave generation of stable atmospheric-pressure fireballs in air

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The generation of stable buoyant fireballs in a microwave cavity in air at atmospheric pressure without the use of vaporized solids is described. These fireballs have some of the characteristics of ball lightning and resemble those reported by Dikhtyar and Jerby [Phys. Rev. Lett. **96**, 045002 (2006)], although of a different color, and do not require the presence of molten or vaporized material. Mechanisms of microwave plasma formation and fluid dynamics can account for the observed behavior of the fireballs, which do not appear to meet the accepted definition of dusty plasmas in this case. Relevance to models of ball lightning and industrial applications are discussed.

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The exact nature of ball lightning remains unknown, despite centuries of recorded observations [1] and numerous attempts to reproduce the phenomenon in the laboratory. After Kapitza made ball-lightninglike phenomena with a high-power rf discharge [2], Ofuruton *et al.* demonstrated fireballs both in a microwave cavity [3] and in an air-gap in free space [4] illuminated by high-power microwaves. However, no microwave or rf fields of sufficient power to produce such fireballs have been observed to occur naturally. More recently, Abrahamson and Dinniss [5] have proposed an energy source for ball lightning in the form of chemical reactions involving silicates ejected from the ground by a lightning strike to form a network of nanoparticles.

Dikhtyar and Jerby recently reported the observation of stable glowing fireballs produced from vaporized solid material in a setup originally designed for microwave drilling [6]. The fireballs glowed brightly and maintained their shape for the duration of the applied 2.45-GHz microwave power, although they showed some instability in the form of elastic quivering. The fireballs showed colors ranging from yellow through orange to red, and lasted about 30 ms after the microwave power was turned off. Dikhtyar and Jerby [6] hypothesized that a mechanism similar to the silicate-ejection process proposed by Abrahamson and Dinniss [5] for the production of ball lightning might be involved in their fireballs. They also mentioned possible similarities between the phenomenon they observed and dusty plasmas studied by Shukla and others [7,8].

This communication reports the experimental production by microwaves of fireballs similar to those observed by Dikhtyar and Jerby [6], without the need to melt or vaporize materials that are solid at room temperature (i.e., similar to the spherical gaseous microwave breakdown phenomena reported by Kirichenko *et al.* [9] and Lebedev *et al.* [10]). The experimental setup is shown in Fig. 1. A 2.45-GHz microwave power source with a variable output power of 1.5 kW maximum was connected through two cascaded water-cooled isolators and a dual directional coupler for power monitoring to an aluminum sample chamber whose transverse dimensions of 7.2 cm × 3.4 cm matched the dimensions of the rectangular waveguide used for the rest of the setup. The chamber was 11.4 cm long. It was terminated at one end by a teflon window facing the microwave generator. The other end of the chamber faced a viewport similar to the one used by Dikhtyar and Jerby [6], made of vanes spaced to create cutoff waveguides that allow direct visual observation of the chamber. Two 2.4-mm diameter pure tungsten rods were sharpened at the ends and used as electrodes in the chamber. The upper electrode slides through a close-fitting hole in the aluminum ceiling of the chamber, similar to the configuration of Ref. [6]. The lower electrode was affixed to a sliding coaxial short in a 2.5-cm-diameter tube extending downward from the floor of the chamber. Network-analyzer measurements show that the coaxial short reflects 99% of incident 2.45-GHz power in a 50-Ω system. For most of the experiments, the lower electrode extended about 3 to 5 mm above the floor level of the chamber.

To form a fireball, a power level of 400 to 600 W is applied. With no fireball in the chamber, about 90% of the incident power is reflected. When the upper electrode is extended downward to contact the lower electrode and then withdrawn slightly, the high electric field between the tips causes breakdown of the intervening air and produces a blue glow. As the upper electrode is withdrawn more, a microwave arc forms between the tips, and the fraction of power

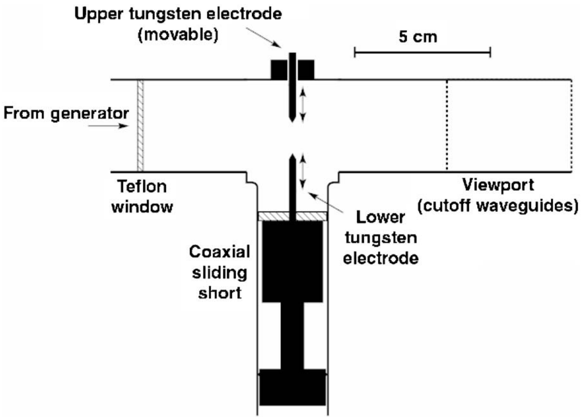

FIG. 1. Cross-section diagram of microwave chamber and electrodes used to produce fireballs.

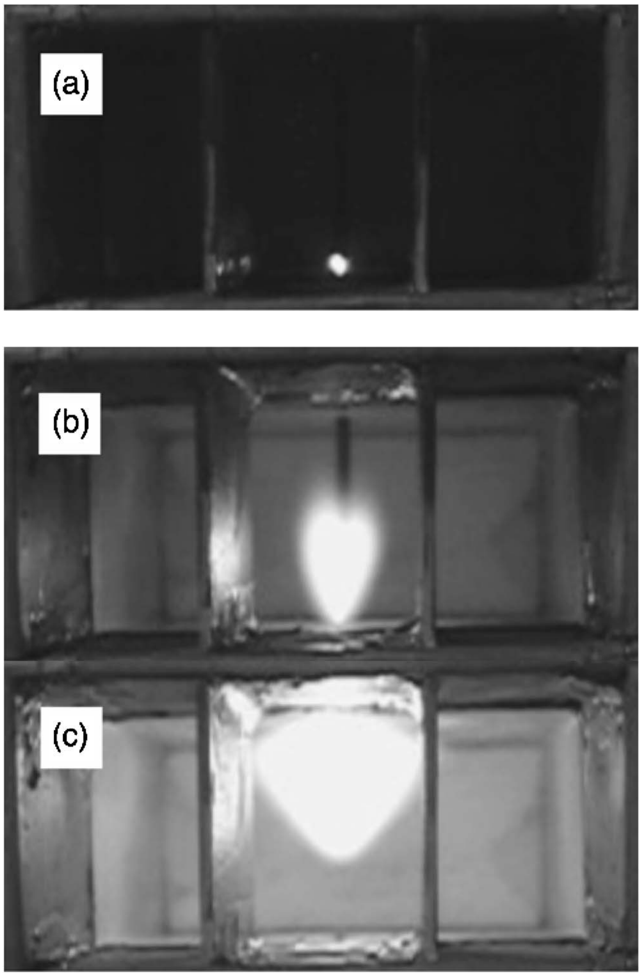

FIG. 2. Sequence of photographs showing (a) initial arc formation following contact between tungsten electrode tips, (b) microwave arc growth as upper electrode is withdrawn into chamber ceiling, (c) formation of stable fireball 67 ms after (b).

reflected falls to about 20%. As long as the applied power level is less than about 600 W, the arc detaches from the lower electrode as the upper electrode is withdrawn completely into the ceiling. The arc then transforms to a free-floating fireball that hovers on the ceiling. The sequence of photos in Fig. 2 depicts the fireball formation process. These figures closely resemble Figs. 3(a)–3(c) in Ref. [6] except for the difference in color.

Once the fireball is formed, it shows essentially all the characteristics of the ones described in Ref. [6], including a quivering instability, a volume of between 15 and 25 cm^3, and persistence under most conditions as long as power is applied. The lifetime of the fireball after microwave power is turned off was not measured, but does not appear to be substantially longer than the 30 ms reported in Ref. [6]. Although I have not been able to produce multiple fireballs simultaneously, the chamber used here is shorter than the one described in Ref. [6], and may contain only one longitudinal location favorable to the fireball's formation and persistence. The fireballs in my experiments show a bluish-white color, as opposed to the orange or yellow color of Ref. [6]. If a small quantity of powdered alumina is held in a teflon support near the bottom tip of the fireball, the alumina becomes incandescent and the fireball color changes to orange-yellow. This experiment, along with formation of the fireball, is shown in Ref. [11]. We were unable to reproduce the experiment with a molten hot spot in a refractory solid as reported in Ref. [6], possibly because of the differences between the electromagnetic configurations in our smaller chamber compared to their larger one. However, our experiment with alumina shows that the presence of a refractory material can produce a yellow-orange fireball as reported in Ref. [6].

The fireball appears to be a special type of microwave flame, similar to those produced in the well-known microwave plasma torches used for spectroscopy, sterilization, and other plasma-based industrial processes [12–14]. With an applied power of 1.5 kW and a large standing-wave ratio, the peak electric field in the empty waveguide is about 700 V/cm, much less than the atmospheric-pressure microwave breakdown field in air of about 20 kV/cm [15,16]. When the electrodes are mechanically contacted and then separated slightly, the electric field between the tips increases to exceed the breakdown potential of air. In Diktyar and Jerby's experiment [6], the plasma was initiated when hot vaporized material was ejected from a local molten area where thermal runaway was occurring. In my experiments, by contrast, the presence of molten material is unnecessary, similar to the situations in Refs. [3,4,9,10]. While at least 400 to 500 W is required to initiate the phenomenon reliably, it persists once initiated when the applied power is reduced to as little as 200 W. In terms of average power density (applied power divided by waveguide cross-sectional area), 400 W in our waveguide produces an average power density of 16.3 W/cm^2, which is the same power density achieved with the larger chamber in Ref. [6] at a power of 600 W. Reduction of applied power does not affect the plasma's brightness appreciably. Instead, the plasma's volume decreases until the minimum power needed to sustain the plasma is reached, when it disappears abruptly. This behavior is consistent with the findings of Green *et al.* [12], whose atmospheric-pressure microwave plasma torch flame's volume decreased with decreased applied power.

Convection is an important process in the fireball's formation and stability. As in Dikhtyar and Jerby's experiment [6], my forward and reflected power measurements show that most of the applied microwave power is absorbed in the fireball. The dissipation of several hundred watts in a volume of only about 20 cm^3 causes considerable heating of the entrained air, which rises to the chamber ceiling and spreads out laterally around a stagnation point. Landau and Lifshitz [17] show to a first approximation that the streamlines of flow at a stagnation point are cubic hyperbolas following the equation $r^2 z=$const., where r and z are cylindrical coordinates with the z axis corresponding to the axis of symmetry of the flow, as shown in the upper part of Fig. 3. This airflow pattern may explain why the fireball has "skirts" of exiting heated air that taper outward where the fireball boundary meets the chamber ceiling. According to this hypothesis, air enters the fireball primarily at the bottom surface, where

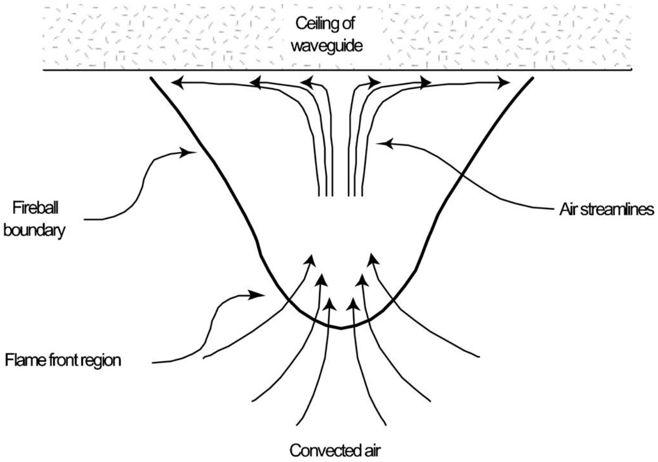

FIG. 3. A proposed mechanism of fireball airflow showing microwave flame front at lower boundary of fireball, and probable streamlines resulting from convection of heated air.

a boundary layer similar to a combustion flame front is coincident with the plasma sheath region. As neutral air molecules enter the plasma from below, some are ionized by free electrons energized by the microwave field. Further ionization may be provided by electrons emitted from a small area of the metallic chamber ceiling, which shows a localized intense glow similar to the "negative glow" seen in glow discharges [18]. The ceiling does not need to be metallic, however. I have successfully formed fireballs with a borosilicate glass plate between the fireball and the aluminum chamber ceiling, although operation for more than a few seconds cracked the plate.

Conservation of energy requires that the net absorbed microwave power (about 480 W when the total applied power is 600 W) equal the power dissipated in heat or other mechanisms. Taking the boundary of the plasmoid to be the solid black line in Fig. 3 and the waveguide ceiling, energy can leave this boundary through direct radiation, convection, or conduction through the aluminum waveguide ceiling (assuming energy absorbed in chemical reactions is negligible). All these mechanisms are sensitive to the plasmoid temperature. Timofeev [19], as cited in Green [12], implies that atmospheric-pressure spherically symmetric microwave discharges cannot produce enough electron density to be self-sustaining below a temperature of about 1740 K. Assuming a uniform fireball temperature of 1800 K enables us to estimate the contribution of each mechanism to the power balance. Since symmetric diatomic molecules N_2 and O_2 do not radiate appreciably at wavelengths longer than visible, an upper bound on radiation loss can be set by assuming the plasmoid is a black body below 0.7 μm and transparent otherwise [20]. At 1800 K, such radiative emission from a 2-cm-radius hemisphere is only about 15 W. With regard to convection, observations of glowing particulates and other behavior of the fireballs produced in my experiments indicate that air passes upward through them at an average rate of about 20 cm/s. If this uniform velocity of air is assumed to move through a cross-sectional area of 1.8 cm^2, and if we assume that room-temperature (300 K) entering air exits the fireball at an upper limit of 1800 K, the resulting power loss due to convection is about 80 W [21]. This leaves at least 385 W to be accounted for by conduction. The waveguide ceiling (thickness ~1 cm) can be approximated as a semi-infinite slab for thermal calculations during a 1-min experiment. Heat-transfer calculations [21] show that a uniform temperature rise of only 60 K over the 1.6-cm-diameter disc of aluminum in contact with the plasmoid can transfer 385 W of power, accounting for the remaining heat loss. Therefore, cooling by means of conduction through the ceiling is probably the most important power-loss mechanism in this system.

The quivering instability noted both in Ref. [6] and these experiments is similar to the fluid-dynamic instability that occurs in other types of flames, including candle flames. The fireballs can be blown out by a puff of air, as when one blows out a candle.

The fireballs produced in these experiments do not appear to contain significant amounts of dust or other solid particulates. These fireballs can be formed without significant oxidation of either the tungsten electrodes or the aluminum waveguide walls. Shukla and Mamun [7] show that for interesting dusty-plasma effects such as dust crystals or liquids to occur, comparatively high densities of dust must be present in a plasma. Since there is virtually no dust in the fireballs produced in my experiments, dusty-plasma effects cannot account for their structure or behavior. While dust particles can be introduced into the fireball, as demonstrated in my experiment with the alumina powder and possibly in Ref. [6], they are not essential to its formation or persistence. Once a source of ions such as the alumina is withdrawn, the fireball color gradually reverts from orange to blue-white in about 3–6 s. This observation is consistent with gradual diffusion of ions out of the plasma.

Ball lightning and the fireballs produced in these experiments share the characteristics of a bright glow and a roughly spherical shape. But it is unlikely that a process such as the one reported herein, which heats entrained air (and nothing else) to more than a few °C above ambient temperature, is responsible for the phenomenon of ball lightning. As these experiments make clear, a free-floating fireball produced by microwaves tends to rise with the convected air contained within it. Rakov and Uman [22] require a successful ball-lightning theory to account for the fact that "ball lightning motion is inconsistent with the convective behavior of a hot gas," namely, it often moves horizontally or downward. The only way the fireballs in these experiments can be restrained from rising is if some other physical structure (in this experiment, electrodes or the chamber ceiling) intervenes. This fact still allows for the Abrahamson-Dinniss hypothesis of a chemical process (possibly with some electrical features) to take place in association with a physical structure that is heavy enough for gravity to oppose the convection forces that are set up when atmospheric-pressure air is heated during ionization or other energetic phenomena that release visible light.

The simplicity and ease with which these microwave fireballs can be formed in a standard waveguide at moderate microwave power levels may lead to applications in heat treatment, chemical processing, and other plasma-related industrial processes. In addition, studies such as this one which elucidate the conditions under which stable energetic ionizing processes can occur in atmospheric-pressure air may clarify the mechanisms giving rise to ball lightning.

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[11] See EPAPS Document No. E-PLEEE8-74-R02612 for a video clip showing fireball formation and color change due to introduction of alumina powder. For more information on EPAPS, see http://www.aip.org/pubservs/epaps.html.

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