



Seeking to solve the mystery of ball lightning

Scientists have struggled for centuries to explain the balls of fire that are sometimes seen to occur during thunderstorms. But as **Edwin Cartlidge** reports, recent attempts to reproduce ball lightning in the laboratory might reveal once and for all the nature of this strange phenomenon

Former electronic engineer Eddie Sines will never forget what he saw one stormy summer's day while staying at his grandparents' house in Maryland, US, in the early 1960s. As he watched a lightning bolt strike a transformer on a telephone pole near the house, Sines suddenly noticed a light-green luminous sphere, about the size of a tennis ball, appear on top of the transformer. Bouncing off the transformer, the ball skirted along the underside of the cable that connected the pole to the house, came off at a dip in the cable and passed straight through the window that Sines was looking through. It then hit the back wall of the room, where it made a small crackling sound and left bright trails of static electricity dancing all over the wall.

Sines had witnessed what is known as ball lightning, a phenomenon in which a fiery sphere floats through the air near the surface of the Earth, usually during a thunderstorm. Eyewitnesses usually describe the ball as being flame coloured but some have reported seeing

white, red, blue or green objects. The diameter of ball lightning can range from a centimetre to a metre or more, while its motion also varies dramatically. It can drop out of the sky, move upwards from the ground, travel quickly in a straight horizontal line, and at other times meander slowly – sometimes entering or leaving buildings by way of chimneys, doors or, like that seen by Sines, windows. Balls of lightning have even been seen passing down the aisles of aircraft in mid-flight.

Such is the bewildering variety of characteristics of ball lightning that it has kept scientists, professional and amateur alike, baffled for centuries. The Roman philosopher Seneca, the 18th-century scientist and politician Benjamin Franklin, the inventor Nikola Tesla and the quantum physicist Niels Bohr, among many others, have all tried and failed to either reproduce ball lightning or come up with a convincing explanation for it. As Stanley Singer, president of the International Committee on Ball Lightning, points out, almost any

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Caught in the act Very few photographs of natural ball lightning have ever been taken, but Werner Burger managed to record this event in Austria in 1978. This object has a luminous tail protruding from a central core.

physicist would, at first glance, find ball lightning “accessible to ready explanation” but would then quickly get into difficulty when trying to account for its full range of properties. One feature of ball lightning that causes a particular headache is its longevity, with some eyewitnesses reporting fireballs that have lasted for 10 s or even longer.

According to Singer, who is an atmospheric scientist at the company Athenex Research in California, researchers have so far put forward at least 100 theories but none of these has yet gained general acceptance by others working in the field. The most popular of these theories describes ball lightning as either a plasma of some kind, as a moving electrical discharge, or alternatively as hydrocarbon fuels that ignite in the air. Somewhat more improbably, researchers have also suggested that ball lightning could involve antimatter or perhaps nuclear reactions. Physicist Pace VanDevender of Sandia National Laboratories in New Mexico has even recently speculated that a red glowing sphere observed moving down an Irish hillside in 1868 was in fact powered by a mini black hole created in the Big Bang.

What is needed to discriminate between these many proposals are better data. Although ball lightning is a very rare phenomenon, researchers have collected

thousands of eyewitness observations from around the world. The problem is that all of these recollections have been of events that have come completely out of the blue, and any attempt to record ball lightning systematically has so far come to nothing. But what scientists have so far failed to observe in the great outdoors they hope to reproduce in the laboratory. A number of groups have managed to produce artificial luminous objects with a number of the characteristics common to the fireballs seen in nature, and they hope that within a few years someone may be able to recreate actual ball lightning.

Problems with plasma

According to plasma-based explanations of ball lightning, the huge amount of energy deposited by a lightning strike vaporizes and then ionizes material on the ground or in the air, creating a gas of positively charged ions and negatively charged electrons. The highly energetic electrons collide with both ions and neutral atoms and molecules in the gas, exciting these particles so that they then emit radiation as they drop back down to a stable energy level.

It sounds simple enough, but there are a number of problems with this type of theory; the most significant being the inability to explain how the plasma can last for so long. The ions and electrons within a plasma usually recombine within microseconds of the external energy supply being switched off, and yet eyewitnesses claim to have seen ball lightning that can last for many seconds after the initial lightning strike. It is also unclear how ball lightning manages to remain a discrete object – the plasma generated inside fusion reactors, for example, needs to be confined using enormous magnets. Furthermore, the fact that ball lightning remains close to the ground is puzzling because the plasma would be much hotter than the surrounding air and would therefore be expected to rise very rapidly.

To try and shed light on some of these questions, last year Gerd Fussmann and colleagues at the Max Planck Institute for Plasma Physics near Munich and Humboldt University in Berlin simulated the effect of a lightning strike on a small pool of water. They inserted two electrodes into a large beaker filled with water, with one of the electrodes surrounded by a ceramic tube. Using a powerful capacitor bank they then sent a current of some 60 A through the water, which caused the water within the tube to evaporate and ionize. The result was a blob of plasma that hovered over the water for about 0.3 s after the current was switched off (see image on page opposite).

Fussmann believes that were his group to multiply the 8 kJ of energy released in the electrical discharge by a factor of about 1000 – thereby bringing it in line with the energy of a typical lightning strike – then it might be able to create fireballs that last as long as those seen in nature. He admits that he has little idea of why the group’s luminous ball lasts for as long as it does, but he believes that the energy stored in chemical bonds between atoms in the plasma must be at least partly responsible for sustaining the effect. “Whether or not this demonstration bears any relation to ball lightning remains to be seen,” he says. “But it is an interesting phenomenon.”

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One unusual characteristic of Fussmann's plasma is that a piece of paper placed above it does not burn. Fussmann concludes that the plasma is enclosed in a "cold skin", which would tally with a theory put forward by David Turner, a retired physical chemist living in Maryland. Building on the work of the Russian physicist Igor Stakhanov, Turner has developed a model in which one type of chemical process supplies energy to the plasma while another cools its surface. The first chemical process, Turner says, can explain the reported longevity of ball lightning, while the second can account for its ability to remain close to the ground – the cold surface allows ions within the plasma to bind with airborne water molecules and so weigh down the sphere (2002 *Phil. Trans. R. Soc. A* **360** 3–152). Indeed, Turner claims that his theory can account for all of the common characteristics of ball lightning, pointing out, for example, that the temperature gradient between the hot plasma and its outer, cold surface would be large enough to crack glass. He admits that his theory will be difficult to prove because it provides little clue as to the initial conditions needed for the production of ball lightning, but he hopes to carry out experiments soon.

Nanoparticle networks

One theory that has, however, been investigated in the lab is that of Vladimir Bychkov of the Institute for High Temperatures in Moscow. According to Bychkov, a lightning strike can convert a variety of organic materials present in vegetation and soil into long polymer molecules that link up with each other to form a ball. Such balls, he says, could build up huge amounts of electrical energy on their surface that then ionizes the surrounding air, producing orange or blue coronas (2002 *Phil. Trans. R. Soc. A* **360** 37). In the lab, Bychkov has produced fireballs 10–20 cm in diameter and with lifetimes of up to half a second by sending electric discharges through samples of wax and resin. He has recently generalized his theory to incorporate both organic and inorganic material within ball lightning, and proposed that the energy for the phenomenon is generated mainly through combustion, rather than electric charges.

A similar theory was put forward in 2000 by John Abrahamson, a chemical engineer from the University of Canterbury in New Zealand. Abrahamson thinks that ball lightning forms when a lightning strike heats up a solid material to the point of vaporizing it. If the lightning strikes soil, some of the carbon and silicon oxides present within the soil will be vaporized, allowing the carbon to chemically reduce the silicon into its elemental form. As the silicon atoms cool, they condense and group together into nanoparticles, releasing energy as they oxidize in the surrounding air and emitting black-body radiation (2002 *Phil. Trans. R. Soc. A* **360** 61).

Abrahamson believes that his theory can explain a number of the properties of ball lightning. In particular, he thinks the fireballs last as long as they do because the layer of oxide that he claims forms on the silicon nanoparticles limits the rate at which further oxygen molecules can reach the silicon and so prevents chemical energy being dissipated. To account for the coherence of ball lightning, Abrahamson proposes that the silicon nanoparticles link up into chains via elec-



Fire and water Gerd Fussmann and colleagues in Germany have produced this glowing, hovering blob of plasma by simulating the effect of a lightning strike on water. The plasma persisted for about 0.3 s.

tric charges that accumulate on their surface and that these chains form ball shapes owing to the creation of a vortex when the vapour is expelled from the ground by the lightning strike.

Abrahamson has himself tried to reproduce ball lightning in the lab by discharging some 20 kV into samples of dirt, but so far he has been unsuccessful. Others, however, have had more luck. Last year electrical engineer Eli Jerby and his colleague Vladimir Dikhtyar of Tel Aviv University in Israel reported having generated fireballs by exposing silicon and other solid materials, such as glass and alumina, to concentrated microwaves (*Phys. Rev. Lett.* **96** 045002). By melting and vaporizing the material, the researchers were able to form a column and then a ball of fire (see image on page 35). The fireball did not last for long – it only glowed for about 30–40 ms after the microwave source was turned off – but Jerby and Dikhtyar hope that by using longer-wavelength radiation they can produce larger fireballs that have proportionally longer lifetimes.

Longer-lived fireballs have in fact since been produced using a slightly different method by Antonio Pavão and Gerson Paiva at the Federal University of Pernambuco in Brazil. Pavão and Paiva sandwiched a piece of silicon 0.3 mm thick between two electrodes, and applied a voltage of 20–25 V. They then raised the top electrode, thereby creating an electric arc from which luminous spheres the size of table-tennis balls flew in all directions (*Phys. Rev. Lett.* **98** 048501). The group's fireballs show many of the characteristics of natural ball lightning, principally that they last for up to 8 s. However, these fireballs are not a perfect match with the ball lightning observed in nature since they are not as large, or as hot, and do not float freely (although they do bounce around, sometimes reaching heights of 20 cm). Pavão and Paiva hope to make more realistic fireballs by using higher voltages and larger samples of silicon.

However, one significant challenge facing Abraham-



Gerson Paiva

Long-lasting imitations

Antonio Pavão and Gerson Paiva at the Federal University of Pernambuco in Brazil have created these fireballs the size of table-tennis balls by sending an electric discharge through silicon. The balls last for about 8 s.



Bright sparks Eli Jerby and Vladimir Dikhtyar of Tel Aviv University in Israel have produced fireballs that bear some resemblance to natural ball lightning by placing a silicon substrate in a microwave cavity and then lowering a metal tip – which they call a “microwave drill bit” – onto the substrate. This drill bit concentrates the microwave power and creates a molten hot spot in the silicon after about 1 s. When the researchers then pull the drill bit away from the substrate, the bit drags vaporized material with it and creates a column of fire. When this column detaches itself from the substrate it forms a buoyant, quivering, orange, red and yellow fireball that sticks to the metallic ceiling of the chamber (as pictured on page 35).

son or any other group testing his theory is how to create fireballs that can penetrate glass as Eddie Sines and a number of others have observed. Abrahamson admits that this is a problem for his theory but believes he has an explanation. He thinks that because the lightning ball is electrically charged its presence near a pane of glass creates a high field across the pane (with condensation on the inside serving to earth the back of the glass). This field breaks down the domains that make up the glass and leads to micrometre-sized pinholes through which the nanoparticle chains can pass.

Learning from the farmer

For some scientists, however, the fact that ball lightning can pass through windows demonstrates that it is not a self-contained material entity but rather the result of a propagating electrical effect. John Lowke, a physicist at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) in Sydney, believes that the phenomenon is caused by the charges that disperse just below the surface of the Earth following a lightning strike. Lowke claims that the increased electric field above the charges is enough to ionize the air – causing it to glow – and that as the charges move through the ground so too does the region of air that glows. This, he adds, accounts for another strange aspect of ball lightning – its ability to move against a prevailing wind.

Another physicist who believes that ball lightning is a fundamentally electrical phenomenon is Peter Handel of the University of Missouri in St Louis, US. Handel’s “maser-soliton” theory builds on the work of Russian physicist Pjotr Kapitsa, who shared the 1978 Nobel Prize for Physics for his work on low-temperature physics. In 1955 Kapitsa proposed that microwave radiation emitted from a lightning strike would generate a standing wave, and that air near an antinode in this wave would be ionized and result in a small, glowing ball of plasma.

In Handel’s theory, which he has been working on since the 1970s, the electric field pulse from a lightning strike generates a population inversion in the rotational energy levels of water molecules. This in effect creates a maser – the microwave equivalent of a laser – in a certain volume of humid air. At an antinode of the standing wave generated within this maser the electric field breaks down and creates a soliton – a particle-like state of a solitary wave – which glows as ball lightning (1994 *J. Geophys. Res.* **99** 10689).

According to Handel, ball lightning can be observed inside buildings, aeroplanes or submarines, to name three examples, because these structures act as maser cavities. But he thinks his theory can also explain why ball lightning is observed outdoors, as long as there is a large enough area of open, flat ground. In such places, he maintains, the volume of water molecules energized by a lightning bolt is large enough that new photons generated through stimulated emission more than make up for escaping photons. This, he adds, explains why scientists have so far failed to make systematic observations of ball lightning. Whereas someone on open ground may observe ball lightning, a scientist scaling mountain peaks or climbing to the top of tall buildings (where conventional lightning strikes predominate) will not. This, he says, is because the electric field pulse generated at a peak is restricted to a narrow cone. “Ball lightning thus keeps its secrets,” he says. “It visits the farmer and avoids the scientist.”

Handel’s theory has been verified by Yoshi-Hiko Ohtsuki of Waseda University in Japan, who passed window panes and ceramic tiles through a simulated ball-lightning discharge without extinguishing the discharge. However, some researchers, like Karl Stephan of Texas State University, are sceptical of Handel’s theory. Stephan, who last year reported that, like Jerby, he had produced luminous fireballs in a microwave cavity, believes that microwaves of the power needed for Handel’s maser-soliton mechanism have never been observed in nature.

Whether the theory of either Handel or Abrahamson, or indeed any of the other theories of ball lightning that have so far been put forward, is ultimately vindicated remains to be seen. Such has been the difficulty of studying ball lightning in controlled conditions, and the multitude of different events reported by eye witnesses, that some have dismissed the phenomenon as merely some sort of optical illusion. Turner, however, thinks that there are enough similarities between observations to imply that ball lightning is a real phenomenon, or at least a family of related phenomena. He is in no doubt that much remains to be done to understand ball lightning, and that understanding it will require the co-operation of researchers within many subfields of physics and chemistry. But he, like others, believes that solving the problem could bring potentially huge practical benefits. For example, understanding the way in which plasma is confined inside a ball might one day lead to a cheap and easy alternative to the magnetic confinement of plasmas inside fusion reactors.

For Jerby, patient investigation will resolve the mystery. “Each group contributes to the solution of another part of the puzzle,” he says. “Eventually, we will reveal the whole picture.” ■

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