Ball Lightning from a Water Beaker

The very existence of these balls of light is the subject of controversy. People who have seen them say they can move along power lines and even go through windowpanes. Until recently, there was no way to get closer to ball lightning by scientific means. But now, **Gerd Fussmann** *from the* **Max Planck Institute for Plasma Physics** *and* **Berlin's Humboldt University** *has managed to create blazing balls of plasma in his lab – and they may just help explain the phenomenon.*

Ball lightning is a curious thing. Many people claim to have seen it, including some very credible witnesses, such as the famous physicists Benjamin Franklin, Nikola Tesla, Niels Bohr and Pyotr Kapitza. There's even a Russian society that keeps a list detailing around 5,000 sightings of the phenomenon. However, a closer look at the evidence often causes confidence to dwindle fairly rapidly. "At the institute where Bohr used to work, we couldn't get any confirmation that he had seen ball lightning," says Gerd Fußmann, a scientist at the Max Planck Institute for Plasma Physics (IPP) and Berlin's Humboldt University. Nevertheless, there are so many reports from credible people that the IPP researcher is convinced of the existence of the balls of light. "They're just very rare," he says.

Photos of ball lightning are few and far between, and those that do exist are not very convincing. Taking all of the descriptions of ball lightning together, the following picture emerges: ball lightning almost always happens during storms, has a diameter of a few dozen centimeters and glows in various colors, predominantly described as reddish. In most cases, they last between two and eight seconds. The phenomenon sometimes ends with a loud bang. The list of around a hundred theories and hypotheses incorporates all sorts of weird and wonderful ideas, including the appearance of antimatter and miniature black holes.

Until four years ago, Gerd Fußmann wasn't particularly interested in ball lightning. Back then, he was head of the plasma physics research group run by the IPP and Humboldt University, studying the flow behavior of the plasmas involved in fusion reactors, like the Stellarator in Greifswald and the ITER that was under construction. He was Director of the IPP's Berlin branch until 2004, and was also a professor of experimental plasma physics at the university "on the side," as he notes with irony.

Light Bubbles from the Water Bath

But then, in 2003, he attended a seminar where he heard a speech by a Russian scientist who told of astonishing experiments at the Institute for Nuclear Physics in St. Petersburg. The researchers there were trying to develop a method of disinfecting water with high-voltage discharge. In the process, they had stumbled upon spherical light emissions rising out of the water. "It seemed very interesting, but I didn't believe it," recalls Fußmann. There were a few photos, but no measurements.

However, now he was struck with ball lightning fever. He was keen to look into the phenomenon and set up his own experiment in Berlin with his colleague Burkhardt Jüttner. It is actually quite simple: a container measuring about 25 centimeters in diameter is filled with regular tap water, and a ring-shaped electrode is attached to the base. The second electrode, a copper wire, is placed inside a one-centimeter-wide ceramic tube. The space between the tube and the wire is almost completely filled with an insulator, with only the end of the copper wire uncovered. The scientists bring the wire and the ceramic tube from the bottom of the container up to the water's surface such that they stick out of the water slightly – just enough to position a droplet of water around the uncovered piece of copper wire.

A condenser bench then generates 5,000 volts, which is discharged abruptly above the two electrodes. At that moment, the water droplet on the uppermost electrode vaporizes and becomes a ball of light, measuring about 20 centimeters in diameter, that rises half a meter into the air. It's no more than half a second before the ball of light disappears. "Even though it's very brief, you can clearly see the ball of plasma," says Fußmann.

During the first few experiments, Fußmann and his colleagues placed pieces of paper in the path of the rising balls. As the paper did not burn on contact, the scientists suspected that the balls of light were relatively cool. This turned out to be wrong. In the past two years, the two professors and two degree candidates have been getting down to the bones of the phenomenon using all the rules

Photo: Norbert Michalke

It's not magic, but electrical discharge that Gerd Fußmann (left) and Burkhardt Jüttner use to create a blazing ball of plasma from a droplet of water.

Plasma Balls in the Lab

There have been many other attempts to explain ball lightning. Two physicists at the Universidade Federal de Pernambuco in Brazil vaporized silicon in a low-voltage arc discharge. The result was glowing balls of plasma the size of tennis balls that rolled over tables and across the floor. They last up to eight seconds, but are unable to float in the air.

Building on Pyotr Kapitza's theory, Japanese scientists created, in (standing) microwaves, plasma balls that were even able to travel through glass. Here, however, these glowing balls are essentially being constantly created anew in the microwaves' power cavities. Since microwaves can penetrate glass, the plasma balls appeared able to do this as well. In reality, they disintegrated in front of the glass and were recreated behind it. But they definitely do not have anything to do with ball lightning, because microwave fields of this kind and intensity do not occur in nature.

Tension-filled: This condenser bench generates 5,000 volts. Gerd Fußmann attaches the electrodes that will vaporize and ionize a water droplet.

Photo: Norbert Michalke

of physics – and have discovered all sorts of amazing things.

High-speed cameras show a spidery, glowing net spreading over the surface of the water around the uppermost electrode shortly after the voltage discharge – within a few thousandths of a second. This is caused by the high voltage between the lower electrode and the water's surface, which collects electric charge carriers. It also creates a raised field between the surface and the upper electrode, which attracts the charge carriers from all sides. This current heats the water droplet on the uppermost electrode to such a high temperature that it vaporizes and partially transforms into a plasma – that is, an ionized gas.

Thin Wires Made of Different Metals

The diameter of the ball of light rising at about 1 meter per second grows from about 8 to 20 centimeters. Then the ball morphs into a tire-shaped form and disappears. The plasma bubble contains just one- to three-tenths of a gram of gas.

Experiments with thermoelements yielded the first temperature findings. The thermoelements in this case are two extremely thin wires made of different metals, welded together at both ends. When a difference in temperature occurs between the two ends, a current flows that can easily be measured. The strength of the current provides a measurement of the temperature at the end of the thermoelement in contact with the object. In these experiments, the physicists held the thermoelement in the balls of plasma. They recorded temperatures of around 1,300 degrees Celsius – and then the wire melted. Only non-contact measurements could help them now.

The method of choice in such cases is always spectroscopy. Degree candidates Alex Versteegh from Eindhoven Technical University and Stefan Noack from Leipzig University undertook the experiments. The two had heard about Fußmann's experiments and were eager to get involved in the research. They had to analyze the light in the plasma balls with a spectrograph at short intervals. In their tests, the researchers established the characteristic emission lines of calcium hydroxide and other molecules, as well as those of atoms and ions. From these, the physicists 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. That's pretty hot plasma, containing electrons and positive ions from, for instance, sodium, calcium and copper. While the first two are present in tap water in the form of salts, the copper comes from the electrode.

Energy – Stored in Molecules

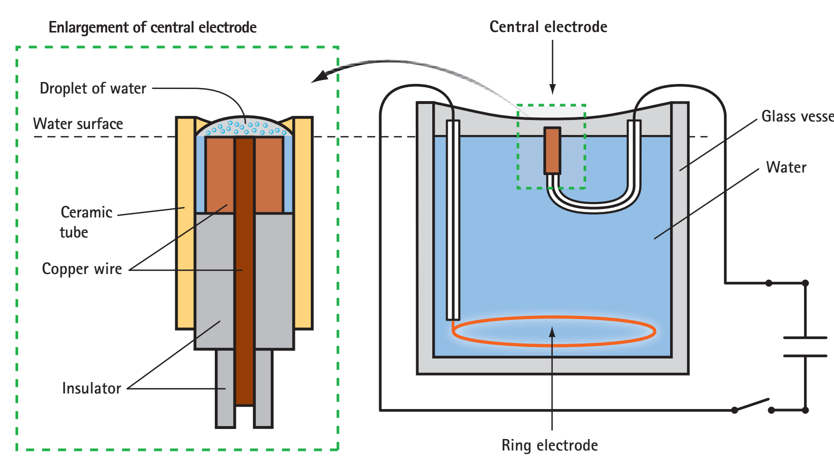
Many chemical reactions, however, also take place in the plasma ball. The scientists' latest discoveries show that it is these that are responsible for most of the glow. At these high temperatures, the water gives rise to hydroxide radicals, which in turn react with calcium to form calcium hydroxide. This reaction also occurs in flames and causes a light emission known as chemoluminescence.

Although Gerd Fußmann and his team have largely solved the riddle of the glowing plasma, one big issue remains unresolved: the sodium and calcium atoms also emit light in characteristic colors: sodium glows yellow; calcium, reddish-orange. But they can do this only when continuously bombarded by hot and fast electrons. By rights, the electrons should quickly cool down in a plasma, and thus the light from the plasma ball should quickly extinguish, too. More quickly than the Berlin scientists have been seeing, at any rate. That means that the electrons must continue being heated for as long as the ball is aglow. The researchers suspect that the energy needed to do this is stored in the molecules and released to the electrons in an as yet unknown manner – a baffling procedure, and one that the scientists are still looking into.

Salts Bring Color into Play

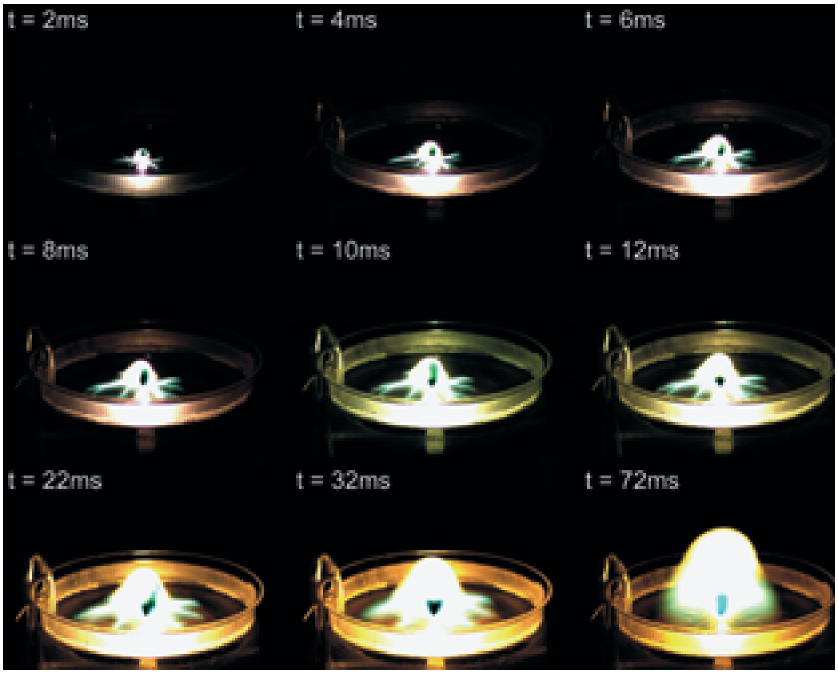
The yellow of the sodium and the reddish-orange of the calcium are not the only colors with which the plasma balls can glow. They can take on other colors, depending on which salts the researchers dissolve in the water. Copper salts, for instance, make them glow a shade of green. Salts also enhance the brightness of the balls. This increases the electrical conductivity of the water, resulting in more electric energy being converted into light. A total of some eight kilojoules of energy flow from the high voltage into the discharge, with about three kilojoules going directly into the water droplet. The vaporization of the liquid and the heating of the water vapor consume around half of this. Approximately 30 percent of the remaining 50 percent goes into dissociating the molecules and ionizing the atoms, and

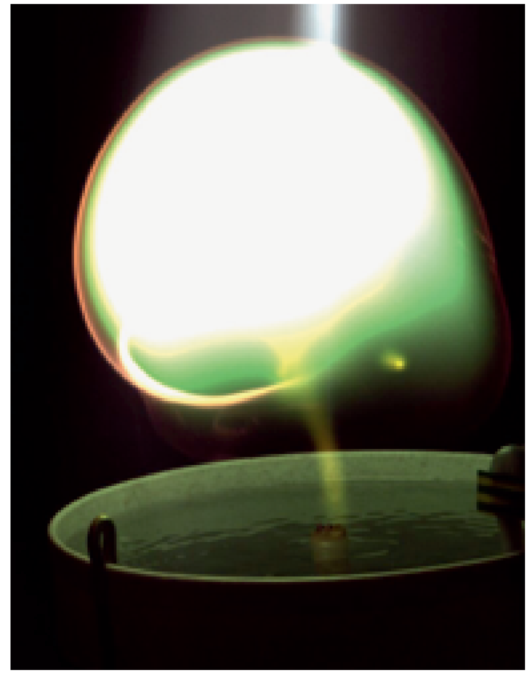
Ball lightning under observation: The Berlin-based scientists analyze their measurements and the images from a high-speed camera.



It's clever design that creates a ball of plasma from a high-voltage discharge between two electrodes. The lower electrode forms a ring. The central electrode is surrounded by an insulator and a ceramic tube and protrudes a few millimeters out of the water, carrying a droplet of water.

Illustration: Christoph Schneider, based on a model from the MPI for Plasma Physics / photo: Norbert Michalke





Photos: MPI for Plasma Physics – Gerd Fussmann

Ball lightning development: In increments of a few milliseconds, the researchers record the plasma ball's growth. Salts in the water give it a greenish glow.

about 20 percent goes into the light emission.

So the bottom line is that only a few percent of the total electric energy is converted into light. The percentage can be increased by using a material with low electrical resistance as a conductor, which would therefore consume less energy. Completely different, dielectric materials also have this effect, in addition to a higher salt content in the water. "Right now, we are considering what we can use to take our experiments further," says Fußmann.

In the meantime, the researchers have discovered why they were convinced right from the start that the balls were relatively cool: they discovered that they have a thin, relatively cool outer layer. This was indicated in the photos from the high-speed camera. However, it can be seen more clearly with laser beams. One of the students arranged 20 laser pointers so that their light illuminated the rising bubbles in intervals of five-hundredths of a second and then hit a wall five meters away on the other side.

From Berlin-Made Balls to Ball Lightning

When these laser lights cross through the outer layers and turbulent interiors, they are strongly deflected as a result of the changing refraction index. This makes the points of light dance several centimeters back and forth on the rear wall. "The movement was easy to measure," says Fußmann. "The difficult thing was analyzing and correctly translating the measurements into an interior model of the balls." The preliminary, still fairly rough finding is that the outer, relatively cool shell is only 40 percent as dense as air. A second, much thinner shell with a temperature of 2,000 degrees Celsius or more attaches to it on the inside. So the external shell envelops the hot plasma in the interior and gives the ball of gas its stability.

However, the decisive question is, of course: Does this explain ball lightning – assuming it really exists? The duration of the phenomenon differs substantially between the experiments and the observations in nature. The balls created in Berlin are very short-lived – but this need not be the case in nature. A flash of lightning contains around a thousand times more energy than the high-voltage discharge. This should mean that plasma balls measuring up to a meter across could be generated. But whether they would be much longer-lived as a result is entirely uncertain. This is a question that can be answered only through experiments in a lightning lab, like the one at the Deutsches Museum.

One thing is clear, however: when lightning strikes a pond, for example, no balls of plasma will be formed, as the energy dissipates in the vast quantity of water. It would have to be a small vessel, like a glass of water or a small puddle, that the lightning struck. However, the occurrence of such conditions is rather improbable. But then again, ball lightning is also a very rare event.

Thomas Bührke