EXTRACTING LIGHT FROM WATER:

SONOLUMINESCENCE

BY RYAN GUTENKUNST

WATER IS ONE OF THE MOST ABUNDANT compounds on Earth. No known form of life can survive without it, and for a human, a day without water is a day of suffering. Water is such a familiar element in everyday life that one might assume that it is completely understood. Unfortunately, that is not true. Our ignorance is well illustrated by sonoluminescence, the astounding ability of water to concentrate energy from sound waves into flashes of light. After over a decade of intense study, the scientific community is still unable to provide a complete explanation for this phenomenon, but its work has pushed the frontiers of fluid mechanics and expanded our understanding of physics at high pressures and temperatures.

A LONG FORGOTTEN PHENOMENON

In 1934, two German scientists, Frenzel and Schultes, were surprised to discover that a photographic plate submerged in an acoustically driven water bath became dark, indicating exposure to light. Only 40 years earlier, Henri Becquerel had discovered that uranium salts would darken a photographic plate. His observation led to the discovery of radioactivity that took decades to understand, but led to fundamental advances in our understanding of

atomic and nuclear physics. Frenzel and Schultes' observation led to the discovery of sonoluminescence, which is still not understood, and may lead to great advances in our understanding of fluid mechanics.

Frenzel and Schultes initially attributed the light produced in their bath to the sound field itself. It took them time to realize that the sound was not directly exposing the plate. Instead, the sound was creating bubbles in the fluid, and when these bubbles collapsed they generated the observed light. Researchers subsequently studied this light emission, but made little progress as the random nature of multiple bubble formation and collapse limited them to measuring only the time-averaged properties of the phenomenon, which revealed few details about the underlying physics. It took over fifty years for researchers to develop the tools necessary to study sonoluminescence deeply.

D. Felipe Gaitan, a graduate student at the University of Mississippi working under Lawrence A. Crum, made the breakthrough in 1988. Crum had developed a simple, inexpensive apparatus from off-the-shelf parts to acoustically levitate bubbles in water. Gaitan found that by adjusting the parameters of the apparatus he was able to reliably create single, stable, light-emitting bubbles. Gaitan's basic apparatus to produce single-bubble sonoluminescence is simple. It costs only a few hundred dollars and fits easily on a tabletop, a far cry from the multi-million dollar and several-mile-long particle accelerators used in modern high-energy physics.

A sealed quartz cell is filled with water. An attached speaker sends sound waves into the cavity at a level of 110 decibels. This is comparable to the intensity of a smoke alarm from a few centimeters away, but the frequency of the sound used is generally just above the range of human hearing. If the frequency is chosen carefully, a standing wave forms inside the container. To generate bubbles, some of the water is boiled by inserting a heated wire.

The bubbles migrate toward the center of the container where the pressure fluctuations are greatest. There they are trapped by sound waves and coalesce into a single bubble approximately 100 microns across, which pulsates at the frequency of the sound field. Above some critical value for the amplitude of the driving field, the bubble emits dim flashes of blue light during each compression cycle. Under ideal water conditions and in a perfectly dark room, this light is bright enough to see with the naked eye (see Figure 1).

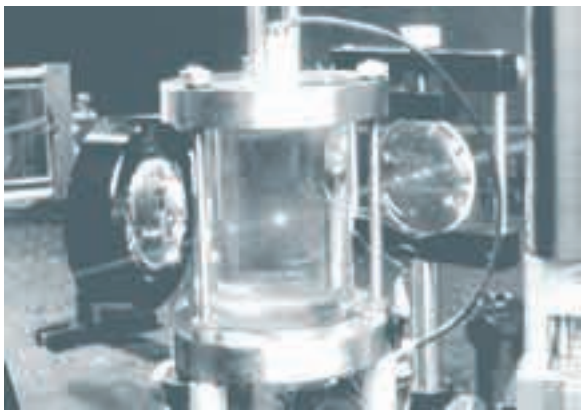


FIGURE 1. A laser beam illuminates a bubble trapped in the center of the containment vessel. Measuring the laser light scattered from the bubble is the easiest way to determine its radius. *Source: S. J. Putterman, Scientific American 272, 46 (1995).* © *Ed Kashi*

A SIMPLE SYSTEM WITH COMPLEX BEHAVIOR

Although the basic apparatus for producing sonoluminescence is simple and inexpensive by modern standards, there was little further interest in the phenomenon for several years after Gaitan's work. Then Bradley P. Barber and Seth J. Putterman of UCLA attempted to measure the duration of the light flash emitted during each compression. They were surprised to discover that their photomultiplier tubes were not fast enough to resolve the flash, and were even more surprised to find that the flash was quicker than one of the world's fastest pulsed lasers. Currently, the best measurements can only tell us that the sono-

luminescence flash is shorter than 50 trillionths of a second; the actual time is too short for modern equipment to gauge. This simple mechanical system concentrates the energy of the acoustical wave into an emission that is shorter than a millionth of the period of the wave itself, resulting in flashes shorter than those seen in high-energy particle physics.

Barber and Putterman were more successful at measuring the period between the flashes, which typically varies by less than 40 trillionths of a second. This extraordinarily consistent period is remarkable because the variation in the time between the flashes is about one one-hundredth of the variation of the output from the precision device generating the driving sound. That is, the flashes occur with greater regularity than the period of the sound that generates it. Barber and Putterman's measurements of the period and duration of the light flashes brought sonoluminescence to the attention of a wider scientific community and inspired almost all subsequent research. No one expected such precise behavior from a crude macroscopic system, and to this day no one can explain it.

The best information about the interior of the bubble collapse comes from the spectrum of emitted light. In general, sonoluminescence spectra are featureless. One might expect to see spectral lines from the gases inside the bubble, but the pressure and temperature inside the collapsing bubble distort the lines to the point where they are unrecognizable. A typical spectrum is shown in Figure 2. There is a peak near 230 nanometers, just outside the blue end of the visible range. This peak appears since more energetic photons are absorbed by the water in which the bubbles are produced, so the radiation is probably emitted at much higher energies. From the spectrum of the emitted light, one can estimate the temperature of the interior of the bubble. In room temperature water, the temperature at the center of the collapsing bubble is 16,000 kelvins—roughly three times as hot as the surface of the sun. Lowering the water temperature reduces the presence of water vapor inside a bubble and allows for the creation of more photons with even higher-energy spectra. Consequently, temperatures inside the bubble reach as high as 30,000 kelvins. However, since surrounding water absorbs the highest energy photons, the calculated values are most likely underestimates. Theoreticians have speculated that the temperature at the very center of the bubble may rise to millions of kelvins, hot enough to initiate fusion. However, whether one can rigorously speak of "temperature" in processes that last for such short times and in such small volumes is debatable. Explaining how water vapor can interfere with such light emission is a major test for any model of sonoluminescence.

The intensity of sonoluminescence depends critically on the driving pressure. Light emission begins at a pressure of 1.1 atmospheres. Here, the mean radius of the bubble decreases dramatically, which has yet to be explained, but at higher pressures the bubble size increases again. As the driving wave pressure increases, so does the intensity of the light that is emitted, simply because the higher-pressure wave carries more energy for the bubble to convert into light. However, at 1.5 atmospheres the pressure becomes too high, thus destroying the bubble.

The radius of a bubble can be easily determined by measuring the amount of light that it scatters from a laser beam. A typical profile of the radius versus time is shown in Figure 3. The bubble slowly expands when the driving pressure is negative, then rapidly shrinks as the pressure becomes positive. The light emission happens at the extreme of the first collapse, after which the bubble rebounds many times, but these smaller oscillations do not produce observable light. The slow expansion and subsequent violent collapse is repeated with each cycle of the driving wave.

Unfortunately, it is difficult to determine the absolute minimum radius, since the bubbles do not persist long enough to make measurements. Knowledge of the minimum radius would allow calculation of the ultimate interior pressure, an important parameter in almost all models of sonoluminescence.

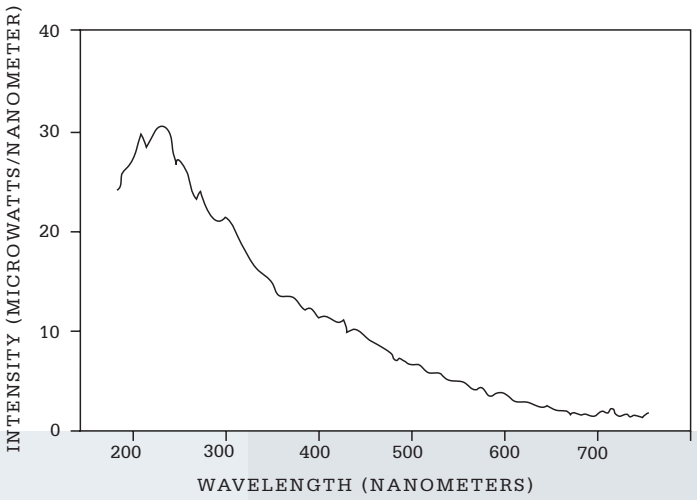


FIGURE 2. The spectrum of a sonoluminescence bubble. The only significant feature is the peak at 230 nanometers, but this peak exists because the water surrounding the bubble absorbs higher energy photons.
Adapted from: L. A. Crum, Physics Today 47, 28 (1994).

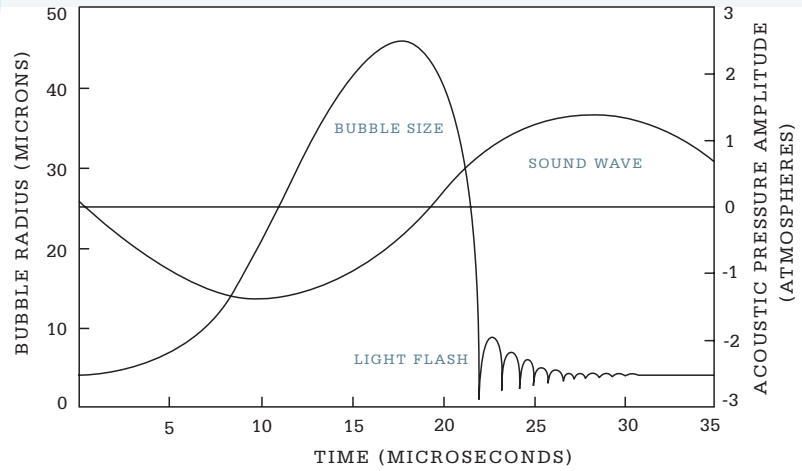


FIGURE 3. The radius of a sonoluminescence bubble and the pressure amplitude of the driving sound wave plotted against time. After the first dramatic collapse during a cycle, the bubble rebounds several times, but these small collapses are not violent enough to emit detectable light.
Source: S. J. Putterman, Scientific American 272, 46 (1995).

The intensity of the sonoluminescence flash also depends greatly upon the amounts and types of gases dissolved in the fluid. The interior of a bubble contains vapors from both the fluid itself and from any gases that may have been dissolved in it. Attempts are being made to induce sonoluminescence in fluids other than water, but this has proven to be very difficult. Only very faint bursts of light have been observed, and those were in fluids that are very similar to water. No one understands what properties of water make it so uniquely amenable to sonoluminescence.

Based on measurements with various dissolved gases, Putterman's group demonstrated that the presence of a noble gas is vital to sonoluminescence. The brightest flashes are seen at noble gas concentrations of about 1 percent. A higher concentration lowers the brightness. It is not understood why a small concentration of a chemically inert gas is so vital to sonoluminescence or why too much suppresses it.

The extremely short duration and consistent period of the flashes that first excited scientists about sonoluminescence only hint at other, even more interesting conclusions that can be drawn from the observations. The production of highly focused energy from such a crude mechanical system is remarkable. The unique properties of sonoluminescence have prompted many models coming from a diverse cross section of physics, fluid mechanics, and chemistry, though a complete explanation has only recently started to emerge.

A MULTITUDE OF EXPLANATORY MODELS

The simplest model that might explain sonoluminescence involves adiabatic compression. Such compression is the reason why, for example, a recently used can of compressed air will be very cold. The rapid expansion of the gas in the can cools it dramatically, and the process happens so fast that no energy is exchanged with the environment. Conversely, compressing a gas raises its temperature. Therefore, when a bubble is squeezed by a sound wave, its interior heats up. Although scientists have not yet determined the mini-

mum size of the bubble, they have estimated that its collapse to one-hundredth of its initial radius could create temperatures as high as 10,000 kelvins at the center. However, this predicted temperature is not quite high enough to explain the emitted light, so researchers look to more complex models to explain the missing energy.

According to fluid dynamics, a collapsing spherical bubble is very unstable, and one way a bubble can break down is through the ejection of a jet of water from one side of the bubble to the other. Traveling perhaps as fast as 4,000 miles per hour, the jet may "fracture" the bubble wall as it impacts the other side, releasing the energy necessary to create the observed light. Proponents of this theory speculate that the atoms of noble gas introduce defects into the bubble wall that serve as starting points for the fractures. However, since the fluid dynamics of the bubble interior are vaguely understood, scientists have modeled the formation of these defects as random processes. Unfortunately, this only makes the jet theory less credible as it is difficult to imagine that something random could produce such an amazingly consistent period of sonoluminescence emissions.

Another model is based on the electric properties of water molecules. In regions of large pressure changes over small distances, such as at the collapsing bubble wall, water can become polarized so that the negative and positive charges may separate slightly. Known as the flexoelectric effect, it creates a strong electric field that can ionize molecules outside the imploding surface of the bubble. Freed electrons may interact with the trapped noble gas atoms and emit radiation. The high temperatures suggested by spectral analysis would correspond to the energy of the free electrons, not the gas atoms inside the bubble, so the bubble's interior would not need to reach such astonishingly high temperatures to create the observed emissions. Most scientists are uncomfortable with the extreme temperatures claimed by some models, so the fact that this model only requires the electrons to be at

these temperatures is an advantage. Unfortunately, the interaction between free electrons and noble gas atoms is poorly understood, and how that interaction could generate light is unclear. The chemistry and physics involved in the model are too subtle to be well understood at this time.

Perhaps the most exotic model was Nobel laureate Julian Schwinger's proposal that sonoluminescence was a quantum mechanical effect. In quantum theory there is an uncertainty relation between energy and time. That is, the more accurately you measure a particle's energy, the less accurately you can measure exactly when the particle was at that energy. One of its implications is that even empty space is filled with energy, the so-called "zero-point" energy. At the very high pressures predicted at the center of a sonoluminescence bubble, Schwinger thought that the zero-point energy might be converted into the observed light—the bubble squeezes space so much that out pop real photons. Detailed quantum field theory calculations showed that this was possible, but experiments have ruled out Schwinger's proposal. Conservation of momentum requires that the photons be produced in pairs traveling in opposite directions, and this correlation was never observed. If Schwinger's model had been correct, it would have been the most significant example of energy extraction from quantum zero-point energy.

The most popular of the current attempts to explain sonoluminescence is an extension of the adiabatic model based on shock waves. A model by Sacha Hilgenfeldt, Siegfried Grossman, and Detlef Lohse incorporates many of the ideas of the previous models. Rather than relying on the unstable bubble wall to compress the interior, their model predicts that the collapsing wall launches a shock wave into the core. This shock wave surges ahead, compressing the interior gas much more than a primitive adiabatic compression and creating higher temperatures and pressures. Under these extreme temperatures, noble gas atoms trapped inside the bubble ionize, changing into plasma. Electrons freed in this process would undergo extreme acceleration, causing them to radiate the observed light. As the model proposed by Hilgenfeld *et al*. does not require any fundamentally new physics or chemistry, it may seem less exciting than previous speculations. However, by making detailed considerations of the optical properties of the plasma and by incorporating a quantum description of the electronic states of the noble gases, they produced the first quantitatively correct prediction of the sonoluminescent spectrum and duration of the light flashes.

STAR IN A JAR

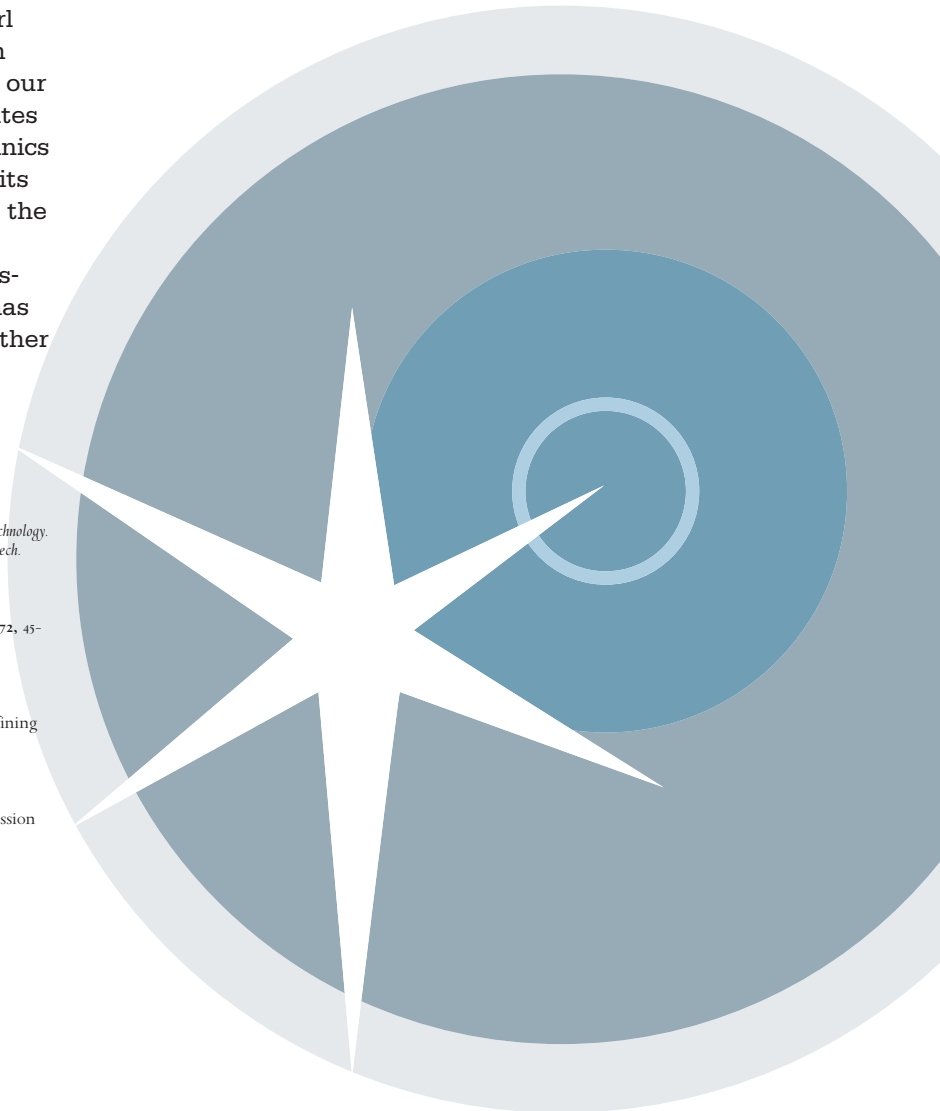
Practical applications of sonoluminescence research tend to be indirect, although the enhanced understanding of fluids at very high pressures is important in many engineering applications. Although a long shot, sonoluminescence could even enable cold fusion, which if possible, has the potential to revolutionize society.

It is speculated that the pressures and temperatures produced during the collapse of a sonoluminescence bubble might be high enough to ignite small bursts of fusion in heavy water. As mentioned previously, the temperature at the core of a hundred-micron diameter bubble is in the tens of thousands of kelvins. In terms of pressure and temperature, this environment might be similar to the core of our sun. If these conditions were present in heavy water, nuclei would fuse, releasing significant energy. Fusion has been the Holy Grail of energy research for decades, and sonoluminescence may make fusion possible on a tabletop.

Admittedly, the prospect of fusion from sonoluminescence is remote. It is unclear whether or not the extreme temperatures and pressures necessary for fusion are achieved in the bubble collapse. A millimeter-sized bubble may also be too large for the

necessary chemical transport processes to operate. Finally, even after nuclei fuse and energy is released, extracting it from the water without disturbing other fusion events may prove impossible.

Even given the uncertainties that swirl around the concept of cold fusion, research into sonoluminescence has already refined our understanding of the physical world. It unites physics, chemistry, optics, and fluid mechanics into one beautiful and simple system, and its study has sharpened our understanding of the wonderful subtleties in all four fields. Sonoluminescence raises fundamental questions concerning water. Answering them has pushed the limits of our understanding further than we once thought possible.



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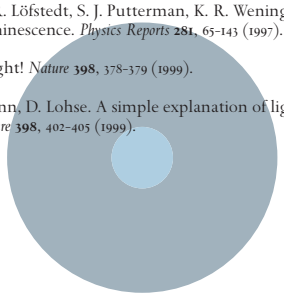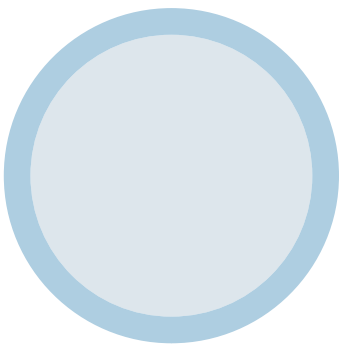
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