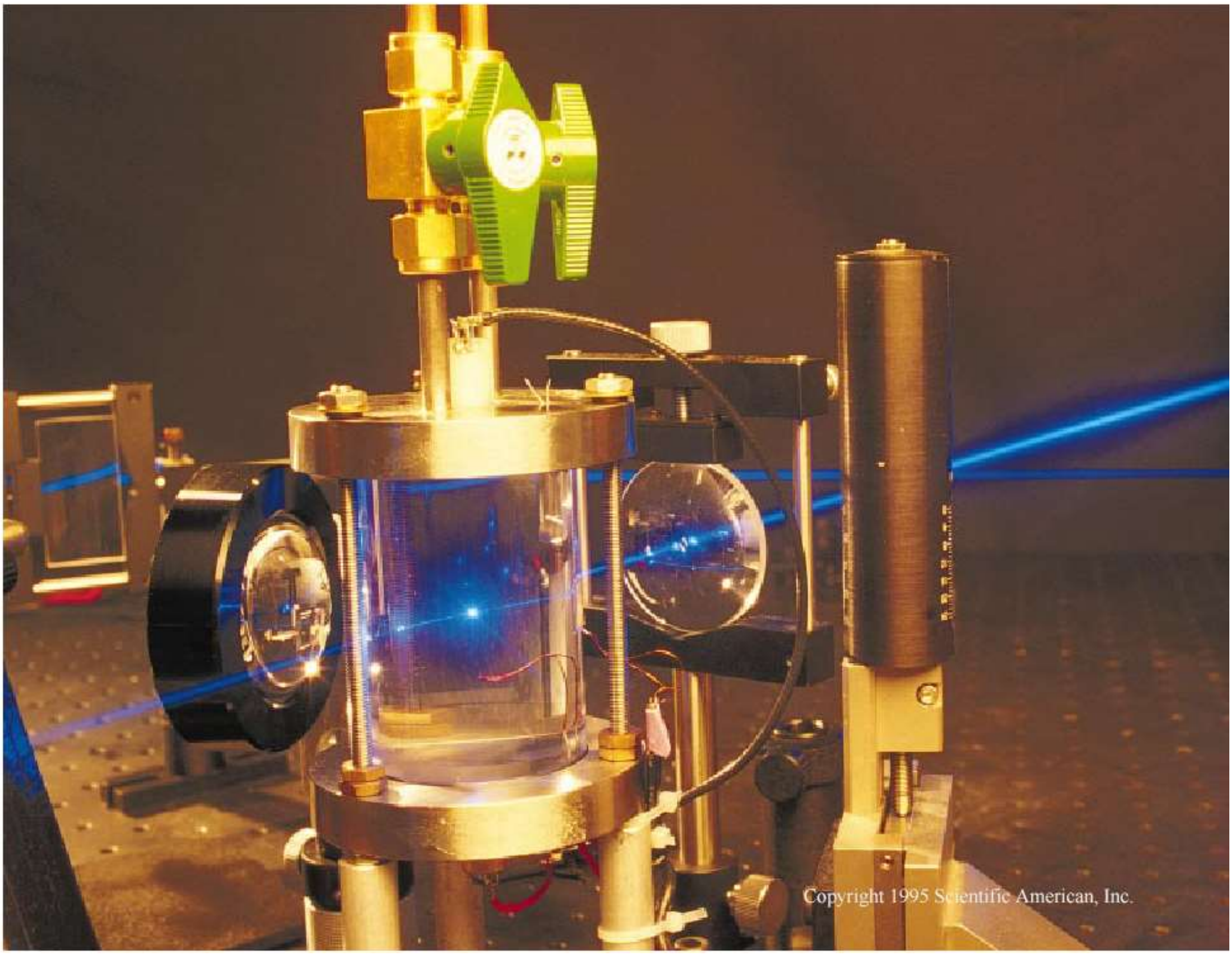
Sonoluminescence: Sound into Light

A bubble of air can focus acoustic energy a trillionfold to produce picosecond flashes of light. The mechanism eludes complete explanation

by Seth J. Putterman

Imagine you are riding a roller coaster. First, you chug up a long incline slowly. When you get to the top, your car free-falls, speeding up until it reaches the bottom of the drop, where the deceleration crams you into your seat. That sensation is what you would feel if you were riding a pulsating bubble of air trapped in water—except that the drop would reach supersonic speeds and at the bottom you would be crushed into your seat with a force equal to 1,000 billion times your weight.

Obviously, more than your stomach would react to such a ride. As for the bubble, it responds to the extraordinary force by creating a flash of light only a tiny fraction of a second long. The light



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is mostly ultraviolet, which indicates that when the bubble's free fall stops, its interior becomes much hotter than the surface of the sun. A sound wave can make the bubble repeat this wild ride more than 30,000 times a second, so that the flashes burst out with clocklike regularity.

In sonoluminescence—as the process of converting sound into light is called—the bubble is concentrating the energy of the acoustic vibrations by a factor of one trillion. That is, the sound wave that drives the bubble is centimeters long, but the light is emitted from a region of atomic dimensions.

A detailed accounting of this inexpensive yet unusual illumination source remains elusive. The flashes are so brief that to measure the properties of light, we must use photodetectors that respond more quickly than those employed by high-energy physicists. (In fact, sonoluminescence is the only means of generating picosecond flashes of light that does not require expensive lasers.) The physical process by which sonoluminescence achieves such a huge focusing of energy may serve as a useful model for researchers seeking to develop controlled nuclear fusion. Current attempts to fathom the mysteries of sonoluminescence in my laboratory at the University of California at Los Angeles and in other institutions are generating new paradoxes faster than the existing questions can be answered.

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Skeptical Inquirer

I was actually quite incredulous of sonoluminescence when I first heard about it in the mid-1980s from my scholarly colleague Thomas Erber of the Illinois Institute of Technology. One day at the U.C.L.A. coffeehouse, he taunted me about my long-standing interest in fluid mechanics, focusing on the Navier-Stokes equations, which describe the flow of fluids. He asked, "If you think the Navier-Stokes equations are so great, then please explain to me how sound can be made into light." Based on my intuition, I replied that I did not believe sonoluminescence was possible. But he insisted that this effect had been documented some time ago. So along with Ritva Löfstedt, who was then a U.C.L.A. undergraduate, I went back through the old papers to see if sonoluminescence was for real.

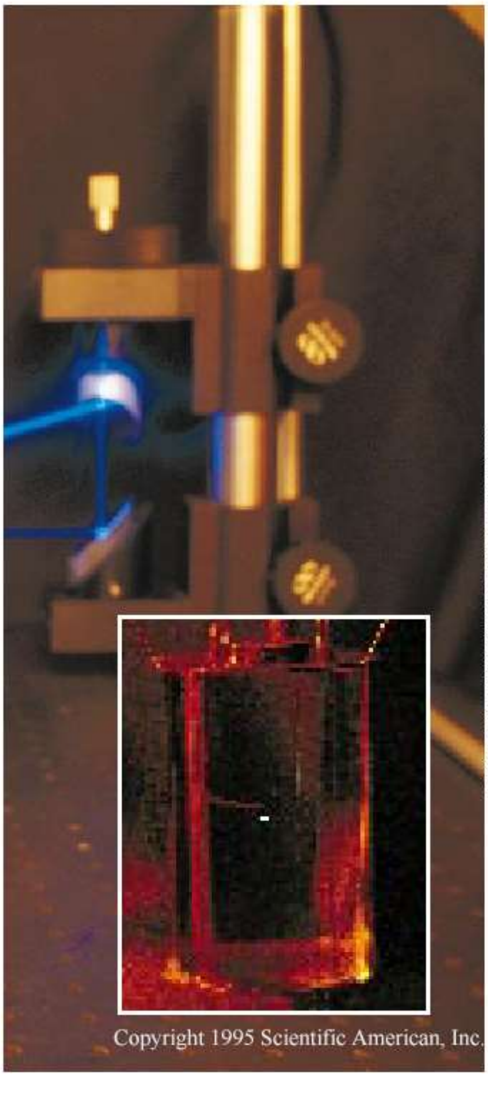
In the 1920s and 1930s, we learned, chemists working with loudspeakers developed for sonar systems during World War I came across an interesting phenomenon: a strong sound field could catalyze reactions that take place in an aqueous solution. A German scientist, Reinhard Mecke of the University of Heidelberg, then commented to his coworkers that the amount of energy needed for a chemical reaction is the same as that needed to excite the emission of light from an atom. So he suggested a search for such a signal. Soon afterward, in 1934, H. Frenzel and H. Schultes of the University of Cologne discovered sonoluminescence in a bath of water excited by acoustic waves.

Perhaps it was the common observation that one can generate a spark of light by touching a doorknob after walking on a carpet. Whatever their inspiration, Frenzel and Schultes explained the light emission in terms of *Reibungselektrizität,* or "frictional electricity." In their experiment the sound wave initiated the process of cavitation—the growth and collapse of bubbles in water. They pictured the bubbles' motion through the liquid as analogous to that of shoes shuffling on a carpet. The abrasion causes electrical charges to separate in the originally neutral media. A spark releases the built-up charge. Then they concluded their paper by saying they had more important matters to attend to.

Other researchers, seeking clues to the mechanism, proceeded to carry out spectral measurements of this new light source. These studies were inconclusive because of the transient nature of the phenomenon. The strong sound fields they used created clouds of bubbles that grew, collapsed and gave off light in an unpredictable and unsynchronized manner.

At U.C.L.A., Bradley P. Barber, a graduate student, and I became enthusiastic about characterizing and understanding the mechanism responsible for sonoluminescence. I learned that other investigators had just succeeded in trapping a single, light-emitting bubble in water that was partially degassed. They were D. Felipe Gaitan, now at the Naval Postgraduate School, and Lawrence A. Crum, now at the University of Washington. It seems that my enthusiasm for their advance far exceeded theirs. They had dismantled the experiment and abandoned this avenue of research. But they did show us how to adjust our apparatus to find single-bubble sonoluminescence.

So with a boiling flask from the chemistry laboratory, an oscilloscope from the undergraduate lab, my home stereo and a photomultiplier tube (light sensor) purchased with my credit card, we were off and running [see "The Ama-



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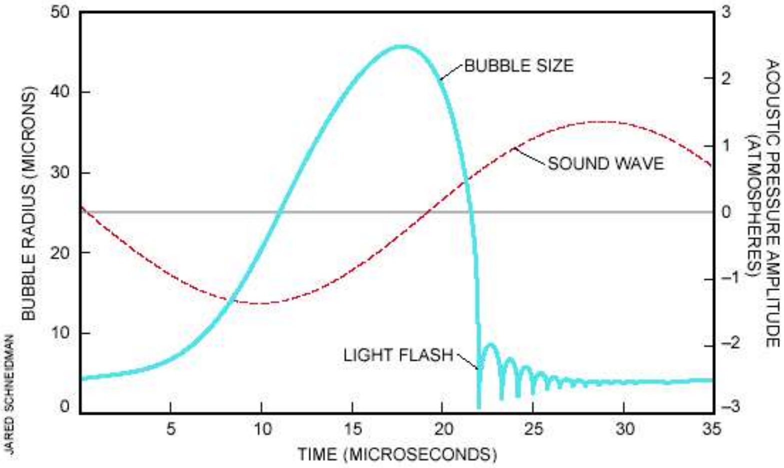
ED KASHI; SETH J. PUTTERMAN AND ROBERT A. HILLER (INSET)

MAKING LIGHT OF SOUND is accomplished by a bubble of air trapped in a cylindrical flask of degassed water. Sound from speakers above and below the flask trap the bubble. A flash of light 50 picoseconds long emerges during the compression part of the acoustic wave. A laser measures the bubble size as it pulses in time with the sound. The light emission itself is rather faint (*inset*).



ROLLER-COASTER RIDE of a pulsating bubble lags slightly behind the expansion and compression of sound waves. The bubble expands to its maximum radius just after the acoustic pressure becomes negative. During compression, the bubble rapidly shrinks to less than one micron in radius and emits a flash of light. The bubble continues to swell and contract briefly before settling down.

teur Scientist," page 96]. For some of our initial work, we injected an air bubble into water with a syringe. Over the years we have refined our setup. Our current apparatus consists of a piezoelectric transducer on the top of a cylindrical flask filled with water. The transducer is a ceramic material that turns an oscillating voltage into a mechanical vibration and thereby sets up sound waves—alternating fields of compression and expansion—in the water. Submerged in the water is a small piece of toaster wire. When current flows through it, the wire heats up, boiling the water nearby. As a result, a bubble filled with water vapor forms. Before the vapor recondenses, air dissolved in the water flows into the pocket to create an air bubble.

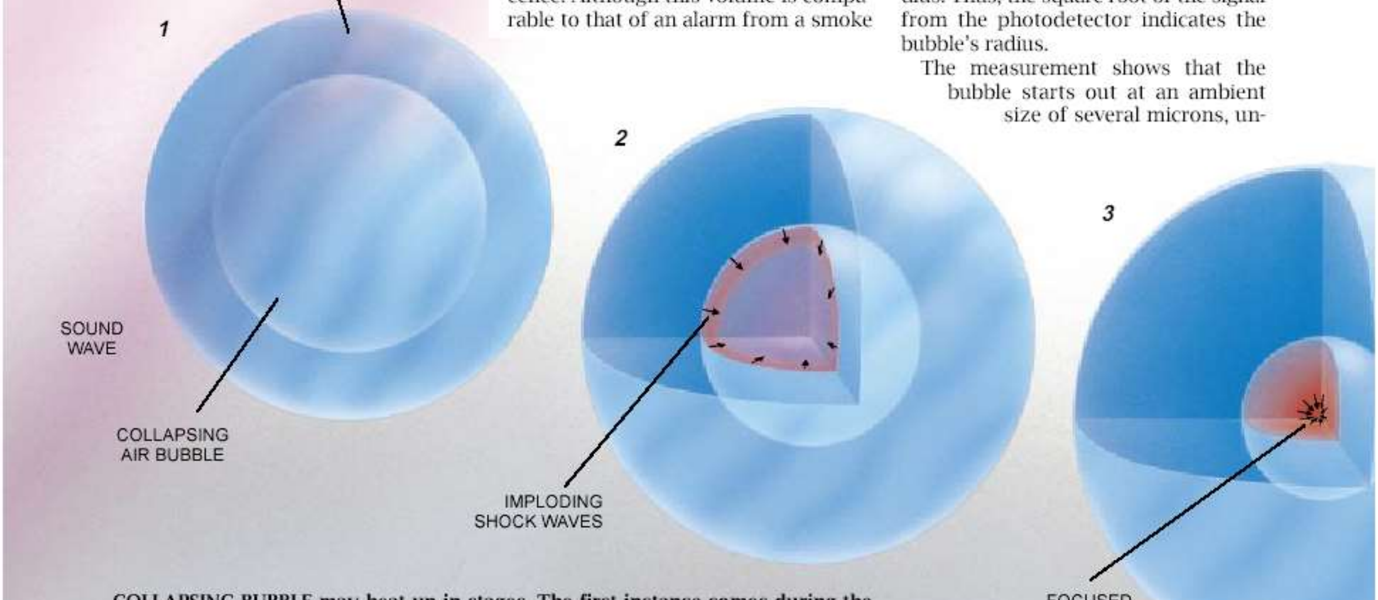
This bubble is then trapped at the center of the cylindrical flask, where the buoyancy force that would make the bubble rise to the top is balanced by the force of the sound waves. Acoustic waves equivalent to about 110 decibels are required to generate the characteristic bubble motion of sonoluminescence. Although this volume is comparable to that of an alarm from a smoke detector a few centimeters away, the frequency of the sound lies just beyond the range of human hearing.

Probing the Bouncing Bubble

As physicists attempting to characterize sonoluminescence, our first goal was to identify the time scales involved in the process—specifically, the duration of the flash. We were amazed to find that such a measurement would require the use of the fastest known light sensors. Our analysis yielded an upper bound of about 50 picoseconds. We also found that the flashes came out with an incredible regularity. The timing between consecutive flashes, typically about 35 microseconds, varies by no more than 40 picoseconds.

To determine the radius of the sonoluminescing bubble, Barber shone a laser on it and measured the light scattered from the beam. The intensity of light scattered by a spherical object depends on the square of the object's radius. Thus, the square root of the signal from the photodetector indicates the bubble's radius.

The measurement shows that the bubble starts out at an ambient size of several microns, un-



COLLAPSING BUBBLE may heat up in stages. The first instance comes during the increase in pressure as a sound wave causes the bubble to shrink (*1*). The second occurs as the walls collapse at supersonic speeds, which in turn launches shock waves toward the bubble center (*2*). The shock further heats the interior. Even more heat is generated as the shock waves focus (*3*) and then explode out (*4*).

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