# The Spell of Sonoluminescence

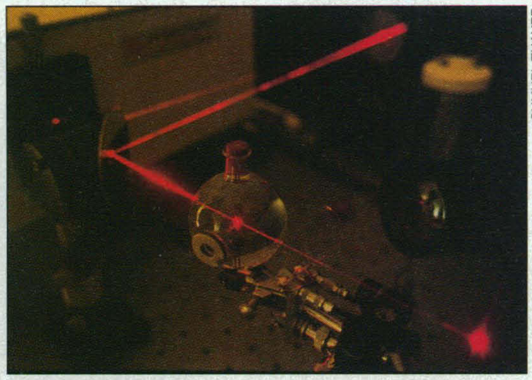
To explain these bubbles pulsing with mysterious light, physicists are invoking everything from miniature implosions to tiny lightning storms to photons stolen from empty space

It's easy to accept that fields like cosmology and particle physics, with their inconceivable scales of size and energy, are full of unsolved mysteries. But it may come as a shock to learn that a system as simple and accessible as a flask of water containing a hot toaster wire and pervaded by ultrasound should hold an equally stubborn enigma. Called sonoluminescence, it consists of brief bursts of visible and ultraviolet light, produced as the bubbles of vapor that drift away from the toaster wire are periodically squeezed and expanded by the pressure of the sound waves. Somehow, the ultrasound is leveraged into photons of light, with energy densities a trillion times higher, at the centers of the bubbles. Faced with this decades-old puzzle, says William Moss of Lawrence Livermore National Laboratory, "the theorists are going wild."

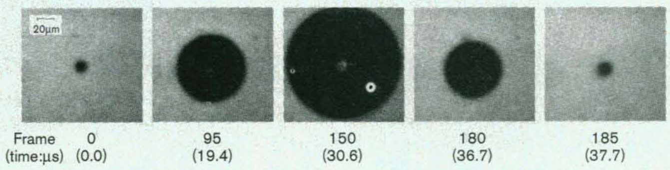
In recent months, ideas about what could be producing the light have proliferated, and the list now includes imploding shock waves, jets of liquid crashing into the bubble wall, tiny electric sparks, and radiation torn from the background fluctuations of empty space. But Moss—himself a theorist—and others hope that this free-for-all is about to be cut short by another growing list: measurements of both light and sound emitted from the bubbles, along with their response to powerful magnetic fields and other changes in conditions. "You've got experimentalists who are dealing with the nitty-gritty problems," says Seth Putterman, a physicist at the University of California, Los Angeles (UCLA). In the process, he adds, they are laying out the criteria for a winning theory, which he and others hope will lay bare a new world of physics sandwiched between microscopic quantum mechanics and the familiar laws of macroscopic phenomena.

This process of natural selection may soon be on fast forward thanks to a challenge issued in September by Robert Apfel, an experimentalist at Yale University who complains that there are "just about as many theories as theorists." During a joint meeting of the Acoustical Societies of America and Japan in Honolulu on 2–6 December, Apfel will chair sessions on "implosion acoustics" and sonoluminescence, and he has challenged each theorist to come prepared to define a make-or-break experiment that would test his ideas. The challenge, says Michael Brenner of the Massachusetts Institute of Technology (MIT), "was a stroke of genius on Apfel's part," and has theorists like himself scratching on napkins and piling up computer time in anticipation of the meeting.

Most of the theoretical effort focuses on the most spectacular version of the phenomenon, in which the light comes from a single bubble, trapped for hours or days when its buoyancy balances the downward pressure of the ultrasound field. The bubble expands to 50 or 100 microns in diameter during the low-pressure part of the ultrasound wave, then collapses to a fraction of a micron. It's the bubble's shrunken phase that emits the light, from a region that may be an order of magnitude smaller still. The flashes come with clocklike regularity once per sonic cycle, each flash lasting less than 50 picoseconds (trillionths of a second). Adding to the mystery, the flashes brighten dramatically as the water temperature drops towards freezing. And for any light to be produced at all, the gas dissolved in the water must include at least a trace of a noble gas like xenon or argon—as ordinary air does.




**Bubbling mystery.** Laser passes through sonoluminescence flask at UCLA. Bubble, seen in another lab, emits light when ultrasound swells and collapses it (*below*).




For the last several years, physicists have had a standard scenario for the light generation: The bubble walls, snapping back at near-supersonic speeds during the bubble's collapse, generate a shock wave that implodes to create a hot, glowing plasma, or ionized gas. But the daunting mathematics of imploding shock waves has left the idea with "no predictive value," says Putterman.

That could change, thanks to supercomputers running codes originally written for analyzing laser fusion experiments, in which converging laser beams implode hydrogen pellets. In results to be presented in Honolulu, Livermore's Moss has done simulations of imploding shocks within collapsing bubbles in water, and he has been able to reproduce at least some features of sonoluminescence. "The calculations are horrendous," he says. They have to balance the heating and compression generated by the shock with the effect of hot electrons from the ionized gas inside it, which collide frenetically, conducting heat away from the very center of the plasma. Even so, the computer simulations indicate that the temperature at the very center of the shocked bubble rises to 100,000 K, while a slightly cooler halo puts out the sonoluminescent flash.

The smooth spectrum Moss's calculations predict for the flash, he says, generally matches the spectrum that UCLA's Robert Hiller and colleagues recorded from actual bubbles (see *Science*, 14 October 1994, p. 248)—"a minimum requirement," says Moss. More encouraging are other resemblances to the real thing: In the computer, the shocks generated flashes of around the same brightness and duration—about 15 picoseconds—as seen in experiments. And the computations seem to explain why warmer water dims the light: As the concentration of water vapor in the bubbles rises, so does the speed of the sound waves within them, making it harder for the collapsing walls to reach the near-supersonic speeds needed to create a shock. "He's done some nice calculations," says Lawrence Crum of the University of Washington, Seattle. "They show [the shock wave model] is a very robust concept."

The sensitivity of the light emission to traces of noble gases may be "a little bit difficult to explain" using shock waves, says Kyuichi Yasui of Waseda University in Tokyo, who does related calculations. But the overall theory may have received a boost by fresh laboratory results to be announced in Honolulu by Washington's Thomas Matula and colleagues. By placing a sensitive hydrophone near a bubble, Matula may actually have heard the shock wave, after it rebounded from the implosion and passed back through the bubble wall. He has detected what Crum calls an "enormously sharp" sonic pop.

### Lopsided light

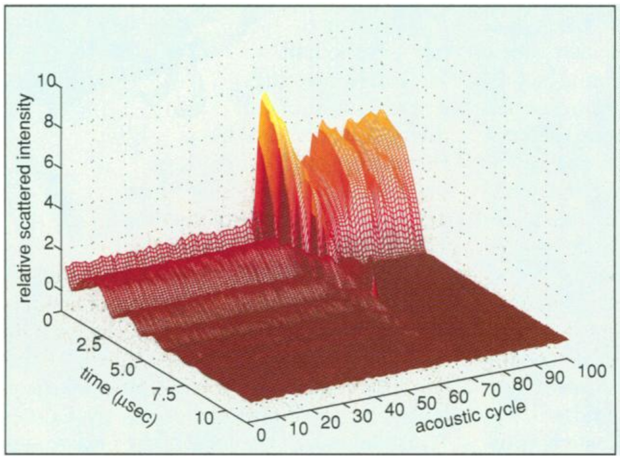
That pop should be music to the ears of shock-wave proponents. But they may have also just heard some less welcome news, which Livermore's Michael Moran calls "a bombshell": the demonstration by Keith Weninger and Putterman at UCLA and Bradley Barber, now at Lucent Technologies in Murray Hill, New Jersey, that the sonoluminescence is not strictly uniform in all directions but has a slight "dipole" component. The measurement, published in the September issue of *Physical Review E*, could simply mean that "the bubble wall has some elliptical shape" at the instant of light emission, says Weninger.

On the other hand, it could also mean that something about the gas inside the bubble itself is lopsided. If so, then the emission is unlikely to be the product of a uniformly imploding shock wave. That reasoning has prompted Brenner and his collaborators at MIT and the University of Marburg in Germany to put forth a major variation on the shock-wave theme in a paper in the 14 October *Physical Review Letters* (*PRL*). In their model, light emission is powered by acoustic resonances inside the bubble, analogous to the harmonics of a violin string.

Instead of being driven by a bow, however, these resonances are fed by the bubble's regular expansion and contraction, with successive cycles piling up energy inside. The kicker: "Some of the easiest modes in which to store energy are not spherically symmetric," says Brenner. When a weak shock focuses some of this stored energy, he suggests, the emitted light wouldn't be symmetrical either. The proposal has been attacked on several grounds—for example, because coherent oscillations might not survive the shock implosions. But Brenner says he will mount a defense in Honolulu and present new predictions, including one on how trace gases can affect a bubble's ability to contain the resonances and generate light.

Andrea Prosperetti, a theorist at Johns Hopkins University, takes an even more lopsided view of sonoluminescence. He points out that a trapped bubble actually jitters up and down in time with the ultrasound waves—and a collapsing bubble moving through a fluid will not remain spherical. That could mean that any imploding shock driven by the bubble wall wouldn't concentrate energy nearly well enough to spark the light. Instead, his computations show, the bubble wall develops a narrow, ingoing spike or jet as it implodes. The jet hits the opposite wall at roughly a kilometer per second, and at its tip "you get tremendous compression," he says.

What happens next, according to Prosperetti, is familiar to any child who has produced flickers of light by chomping on mint Lifesaver candy in the dark. (Smashing glass can produce the same effect.) On these brief time scales, water may behave like the solid Lifesaver and undergo the same poorly understood phenomenon, called fractoluminescence. Prosperetti admits that he hasn't worked out all the details. But this mechanism "will account for the extreme brevity of the light pulse," he says. It might also explain the effect of dissolved noble gases, which would affect the bonds between water molecules, and therefore how they fracture and spit out light. Still, says Crum, "I just think it's a little bit fantastical." Prosperetti's reply: "It is indeed strange, but you can do it with a piece of candy."




**Turn on the light.** A graph shows how the radius of a bubble changes over successive cycles of ultrasound. Around cycle 60, the intensity was stepped up, generating light.

Jets also figure in a model that has been taken up by a group of researchers including Thierry Lepoint at the Institut Meurice in Brussels, Belgium. Instead of a single jet, though, Lepoint envisions many of them, stabbing toward the center of the bubble. The jets would grow from instabilities in the bubble walls, similar to the ones that develop in laser-fusion pellets in spite of researchers' best efforts to compress them uniformly. As all these jets jostle within the bubble, they would generate static electricity by processes similar to those that may go on in a thundercloud. Tiny electrical discharges would result—and Lepoint says they would produce a spectrum of light that nicely matches the emitted light spectrum.

The idea has had a mixed reception. "I don't believe in them," says Brenner of the jets. "In my opinion, the answer is either the [standard] shock-wave theory or our theory." But Crum notes that other groups have put forward variants of the multijet model.

The skepticism that greeted Lepoint's model is nothing compared with the reaction to a still more exotic model, published in *PRL* last May by Claudia Eberlein of the University of Cambridge. Eberlein builds on ideas first put forth by the late physicist Julian Schwinger to propose that the accelerating bubble interface scoops photons out of the normally undetectable fluctuations of energy that, according to quantum mechanics, seethe within empty space. The mechanism would produce light at all different energies, matching the smooth spectrum Hiller and his colleagues observed.

But a flurry of negative commentaries has greeted the paper, and several have been accepted for publication at *PRL* or are "in the pipeline," with responses by Eberlein, says Jerome Malenfant, a *PRL* editor. A common theme of the objections is that for the mechanism to generate enough light, the bubble walls would have to undergo implausibly fast acceleration changes. Eberlein responds that uncertainties in the physics of interfaces at atomic dimensions mean that such changes cannot be ruled out.

A wave of new experiments may indicate just what can be ruled out. At the University of Chicago, Woowon Kang and collaborators have shown that imposing a powerful magnetic field on the bubbles raises the ultrasound intensity needed to trigger light emission—suggesting that electronic processes, which would be affected by such fields, are at work. That could spell trouble for theories, like Prosperetti's, that don't invoke ionized gases. Meanwhile, Hiller at UCLA and Kenneth Suslick, at the University of Illinois at Urbana-Champaign, are cranking up for improved optical measurements, in hopes of finding bumps and dips in the spectrum that will unambiguously pin down the temperature in the bubbles.

In place of water, Suslick intends to generate single-bubble sonoluminescence in alcohols and other solvents, where he will dissolve compounds whose spectra develop distinctive peaks at very high temperatures. These chemical thermometers should reveal whether the bubbles do reach the hundreds of thousands of degrees predicted, for example, by the shock-wave theory. Suslick isn't naming all the compounds, but he hints darkly that they are extremely toxic—"things that chemists are comfortable with but that send shudders down the spines of physicists." But at this point, physicists would welcome any experimental stratagem that could kill off some of the theories and allow others to flourish.

**–James Glanz**