Sonoluminescence in from the dark

The idea that a sufficiently intense sound wave might make a liquid glow with light is almost an exercise in magic; but the facts are verifiable, the understanding lags behind.

NOT everything is yet understood, but that unexceptional statement surely applies with as much force to the shadowy phenomenon of sonoluminescence as to the other great puzzles of our times — where are the missing neutrinos from the Sun, for example, or for what phenomenon is the Big Bang a metaphor?

One puzzle with sonoluminescence is that it seems to be a means of making energy run uphill. A coherent beam of sound waves is made to travel through a liquid whereupon, when the conditions are right, flashes of light can be observed; phonons seem to have been converted into more energetic photons, some of them with ultraviolet energy. Another puzzle is that the duration of sonoluminescent flashes of light, which are at the present limits of fast measurement, seems to be faster than typical electronic transitions in atoms and molecules. What on Earth can be going on?

When reports of phenomena excite disbelief, it is comforting to announce that, far from being unexpected, the phenomena were predicted. That seems to be the spirit in which those working in the field delight in referring to a paper by Lord Rayleigh published in 1917 (*Phil. Mag.* **34**, 94; 1917).

Prolific Rayleigh, with his habit of treating every problem in physics as a candidate question for the Cambridge Tripos examinations, set out to calculate the pressure within an incompressible fluid after a "spherical portion of the fluid is suddenly annihilated". He pointed out the connection with the hissing sound from steam bubbles condensing in a nearly boiling kettle and the way in which the efficiency of ships' propellers is reduced by cavitation. His conclusion was that, at some stage during the collapse of a spherical void in which fluid has been annihilated, almost arbitrarily high pressures may be generated near the boundary, but within the fluid. Sonoluminescence as such is not mentioned, but has been inferred.

Now, mercifully, sonoluminescence is well on the way to being a part of physics, and of experimental physics at that. The mechanism remains that sketched by Rayleigh. Bubbles in a liquid that happen to be at a pressure anti-node (which is, by definition, a stagnation-point of the velocity field and thus a place at which bubbles will hang about) of a sound wave will first be driven to expand and then to collapse catastrophically. Flashes of light appear towards the end of the collapse phase, and can be measured with photomultiplier tubes. Bradley P. Barber and Seth J. Putterman, from the University of California at Los Angeles, seem now to have gone a long way towards the goal of making sonoluminescent bubbles reproducible (*Phys. Rev. Lett.* **69**, 3839; 1992).

The latest development is the direct measurement of the radii of sonoluminescent bubbles oscillating at the centre of a spherical vessel filled with water, within which a pattern of ultrasonic pressure waves is driven by a pair of piezoelectric elements cemented to the outer walls. (In the measurements described, the period of the sound waves is 37.7 μs, corresponding to a frequency of 26.5 Hz.) The trick then is to use a fast photomultiplier to record the time course of the light output from a bubble when it is illuminated by a laser beam.

The signal consists mostly of light scattered from an oscillating bubble, expected to depend directly on the radius (or the square thereof). But the system is sensitive enough to record a brief peak of extra light emission just before light scattering reaches its minimum, taken as a mark of when the collapse is complete. When all this is going on, the walls of the cavity are calculated to be travelling inwards at supersonic speed. Imploding is the word for them.

The flash of light appears soon afterwards, and no more than 10 nanoseconds before the bubble has shrunk to its minimum dimensions. The experiments described suggest that the duration of the flashes is no more than 50 picoseconds. A remarkable feature of their appearance is their constancy in phase — the jitter from one sound-wave cycle to the next is also reckoned to be no greater than 50 picoseconds, meaning that the flashes of light can be used as triggers for the recording equipment. And after they have flashed, bubbles appear to oscillate more narrowly in radius, as do bubbles that do not meet the conditions for light emission. Sonoluminescent bubbles are also smaller than Barber and Putterman had expected — bubbles of 4 m are efficient sources of flashlight.

The virtue of this development is that it puts the investigation of the sonoluminescent bubble on a solid and reproducible foundation. More than that, Barber and Putterman have shown that the behaviour of their bubbles can be accounted for by the hydrodynamic equations of motion, at least outside the region in which supersonic implosion takes over. By way of fine tuning, they speculate about the way in which energy may be dissipated from the bubble system by shock waves during the supersonic implosion and by the radiation of sound energy during the post-collapse bouncing phase.

Unfortunately, none of this does much to show what is really going on in sonoluminescence. Nor, for that matter, does the same authors' observation last year (with Robert Hiller) that the spectrum of the light flashed out once every acoustic cycle from their bubbles spans the whole visible spectrum, from red to blue, and then extends into the ultraviolet as far as the frequency at which water becomes an efficient absorber of radiation. In short, the argument then was, the spectrum could well be the tail of a Planck distribution, in which case the corresponding black-body temperature might be 50,000 K or even 100,000 K.

So does this mean that the concentration of acoustic energy during the collapse of a bubble turns its contents into a plasma for a 50 picosecond instant? That is certainly one possibility.

Another, canvassed in 1991 (*Nature* **352**, 318; 1991) when the same authors described their first observations that sonoluminescent flashes keep step with the acoustic fluctuations, is that the mechanism of the flashes may involve some kind of collective emission, as in a laser. All of us will be glad to know how this tale comes out.

Meanwhile, it is as well to keep in mind that sonoluminescence may take different forms. Somehow, collapsing cavities concentrate mechanical energy on a few molecules or atoms in such a way as to evoke unexpected happenings. Everybody seems to agree that the first observation of sonoluminescence was that of the formation of hydrogen peroxide molecules in water nearly 60 years ago. More recently, other groups working with non-aqueous materials have found that the most probable source of light from acoustically assaulted materials is the storage of energy in particular chemical reactions, followed by their luminescent reversal (Suslick, K.S. & Flint, E. B. *Nature* **330**, 553; 1987). Other mechanisms than these are no doubt waiting to be found.

Meanwhile, the rest of us may usefully contemplate a few incidental features of this interesting work. First, Barber and Putterman have repeated on several occasions that they can see the flashes they have recorded with the naked eye. Second, on this occasion the measurements have outstripped the hydrodynamics. This territory is unknown.

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