SONOLUMINESCENCE

Sound basis for light emission

Tiny collapsing bubbles can focus acoustic energy into bursts of visible light. Careful measurements of the emitted light reveal extraordinary conditions at the centre of the implosion of a single bubble, but not so extraordinary as to support fantastical claims.

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Sonoluminescence is the astounding phenomenon that converts sound energy into visible light. The debate over its mechanism has stirred controversy several times in recent years, but it is known to occur only in tiny gas bubbles collapsing at high velocity. In a recent issue of *Physical Review Letters*, Flannigan *et al.* present data gathered directly from the light spectrum emitted by the collapsing bubble[1]. Applying molecular collision theory, they related the measured widths of lines in the sonoluminescence spectrum to the pressure and density in the light-emitting bubble. They found pressures of thousands of bar, consistent with previous measurements inferring temperatures of tens of thousands of kelvin. Their findings add to a growing body of evidence for the microscopic physical conditions behind sonoluminescence — astonishing for a table-top experiment, but not sufficiently extreme to fuel ongoing speculations of nuclear fusion reactions.

How can micrometre-sized gas bubbles become so hot and dense that they emit a bluish glow visible to the naked eye? It's all in the symmetry: for bubbles just a few micrometres in diameter, surface tension is strong enough to maintain their spherical shape. When exposed to an ultrasound field of sufficient amplitude, the bubble expands during the decompression (rarefaction) part of the acoustic wave and then, as the pressure increases towards the compression part, undergoes an extremely rapid collapse (Fig. 1a). If undisturbed, the bubble behaves as a spherical piston compressing the gas volume by a factor of up to one million. If many bubbles are present, however, mutual perturbations prevent a spherical collapse and result in only a very faint glow, first noticed in the 1930s (ref. 2). Only when Gaitan and Crum[3], in 1990, isolated a single bubble in a standing-wave ultrasound field did we recognize the extent of violence of the collapse and the full

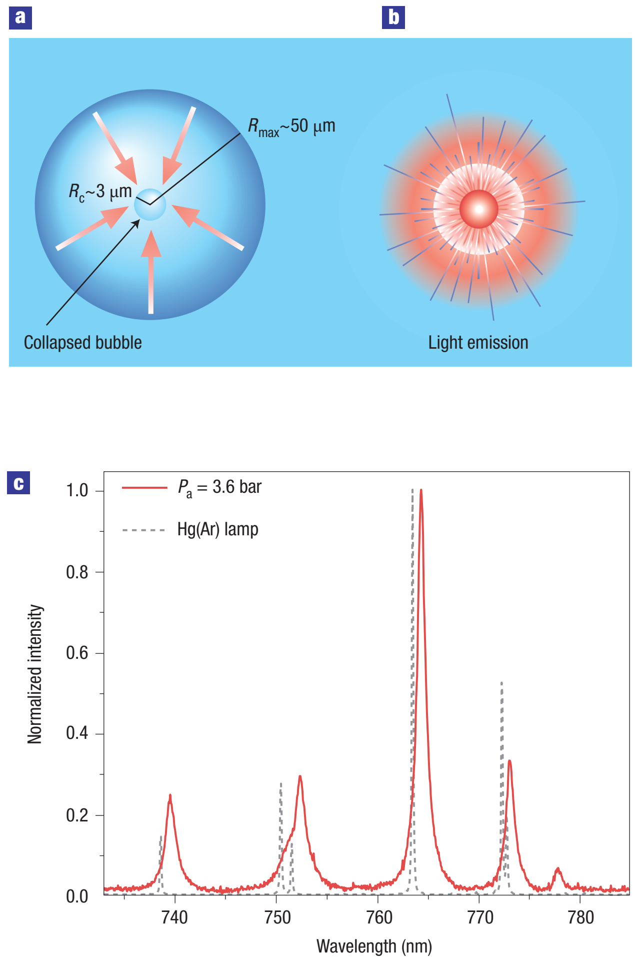

Figure 1 Sonoluminescence. An argon bubble in sulphuric acid is exposed to an ultrasound field. **a**, When the pressure induced by the acoustic wave is lowest, the bubble expands to a maximum size of about 50 μm. As the acoustic pressure increases, the bubble collapses very rapidly, compressing to a collapse radius of about 3 μm. **b**, For roughly 200 ps, the compressed bubble is hot enough to emit light from a variety of atomic excitation processes. **c**, The spectrum of the emitted SBSL light (red line) for an ultrasound amplitude of 3.6 bar. Comparison with the Hg(Ar) calibration spectrum (grey) shows a pronounced shift and broadening of the SBSL lines, attributed to a pressure of 1,500 bar in this example. Reprinted with permission from ref. 1. Copyright (2006) by the American Physical Society.

brightness of this single-bubble sonoluminescence (SBSL) phenomenon (Fig. 1b).

Speculation about the light-emission mechanism was rampant directly after the discovery of SBSL. Models based on converging shock waves inside the bubble (and sometimes much more outlandish effects) argued that there was no limit to the temperatures and pressures that could be achieved near the bubble centre. The burning questions were whether the light emission was sufficiently explained by the image of the bubble as a piston heating up in an essentially adiabatic compression, or whether the above more-exotic processes might allow for temperatures of millions of kelvin and thus make the bubble a potential nuclear reactor.

The profusion of competing theories made it clear that we needed more experimental data about the light emission. A first decisive result came when Gompf and co-workers[4] found that the duration of the light pulse emitted on collapse was typically 100–300 ps — very short indeed, but longer than previously thought and, most importantly, compatible with the timescales of bubble collapse inferred from the venerable theory of bubble dynamics introduced by Lord Rayleigh. In other words, the duration of the light pulse was consistent with the 'rebound time' of a spherical piston as pointed out in ref. 5.

A nagging uncertainty remained concerning the actual temperatures and pressures inside the bubble: were they, too, compatible with those expected from Rayleigh's bubble dynamics — namely, of the order of 10,000 K and a few 1,000 bar, respectively? Suslick's group established earlier that the perturbed collapses in multiple-bubble fields yielded only about 5,000 K, which they found from measurements of relative intensities of molecular emission lines[6]. SBSL, however, proved too hot to handle with this method at first: line emissions were absent from the spectrum as they would be drowned out by continuum emissions under the more extreme conditions. Through patience and careful experimentation, Suslick and co-workers found a combination of gases, liquids and driving conditions that would yield lines even in SBSL — in the case of their most current publication[1], argon dissolved in sulphuric acid. The most prominent lines are from the excited states of neutral argon atoms. Whereas their intensity reveals temperatures of typically 15,000 K in SBSL bubbles[7], the shift and broadening of the lines as compared with a calibration spectrum (see Fig. 1c) yields enough information to deduce maximum pressures of a few 1,000 bar, and maximum densities that fall short of those in condensed matter by an order of magnitude. These results are in excellent quantitative agreement with those deduced from the oscillation of the bubble by Rayleigh's equations. In fact, for SBSL bubbles without clear lines in the spectrum, the spherical-piston formalism can still be used to quantify the pressure.

Although it is still possible that a few atoms at the very centre of the bubble might experience a more extreme environment, it is clear that the argon atoms emit light under conditions expected in dense gases after adiabatic compression. This is not only a reminder of the power of classical bubble dynamics, but a further indictment of recent prominent claims of 'bubble fusion'[8]. Many of these claims have been retracted or discredited[9,10], and the new data from the careful experiments by Flannigan *et al.* suggest that, although SBSL bubbles can transfer high excitation energies to argon atoms, they are a long way from fusing their nuclei. We may be sure that Lord Rayleigh, who received his Nobel Prize partly for his discovery of argon, would approve of both the experiments and the outcome.

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