SONOLUMINESCENCE

A simple mechanical system can produce light from sound. In the process energy densities can increase by a factor of 1012, and 50-picosecond light pulses are synchronized to a few parts in 1011.

Lawrence A. Crum

And the four winds, that had long blown as one,
Shone in my ears the light of sound
Called in my eyes the sound of light.

--Dylan Thomas, "From Love's First Fever to Her Plague

In 1896 Henri Becquerel discovered that a uranium salt could darken a photographic plate, and from this effect he went on to discover radioactivity. In 1934 H. Frenzel and H. Schultes[1] exposed a photographic plate to acoustic waves generated in a water bath and also observed a darkening of the plate. They attributed that result to luminescence from the sound field--an effect that has come to be known as sonoluminescence. The luminescence they observed did not result from the sound field directly but arose through a process called cavitation, in which voids filled with gas and vapor are generated within the liquid during the tensile portion of the pressure variation. The subsequent collapse of these voids during the compression portion of the acoustic cycle can be extremely violent and represents a remarkable degree of energy concentration-as high as 12 orders of magnitude.[2] This energy concentration results principally from the fact that cavitation-bubble collapse obeys spherical symmetry, at least until the final stages, when instabilities in the interface may develop. This spherical symmetry is apparently preserved to submicron-size dimensions in single-bubble sonoluminescence,[3] resulting in another remarkable phenomenon: Extremely short bursts of light are emitted from the bubble with clock-like precision.

Multiple-bubble sonoluminescence

When the local acoustic pressure in the bulk of a liquid exceeds the threshold for cavitation, a zone develops in which many cavitation bubbles are activated. In a lab this cavitation is typically produced within an acoustic resonator or cell in which geometric focusing generates high acoustic-pressure amplitudes. (See figure 1.) If the cavitation is sufficiently intense, sonoluminescence occurs. In such "multiple-bubble sonoluminescence," many bubbles grow and collapse throughout the regions of most intense acoustic stress. Figure 2 shows typical MBSL, with a relatively large area of sonoluminescence activity containing many separate cavitation events, each emitting discrete bursts of light.

Sonoluminescence has been poorly understood because it is associated with the random growth and collapse of large numbers of cavitation bubbles. Moreover, the spatial scale of an individual event is on the order of a micron, and the temporal scale is on the order of a few nanoseconds. Thus, until recently, studies of sonoluminescence involved the time-averaged analysis of a cavitation field. Such a field contains many bubbles of various sizes, proba-

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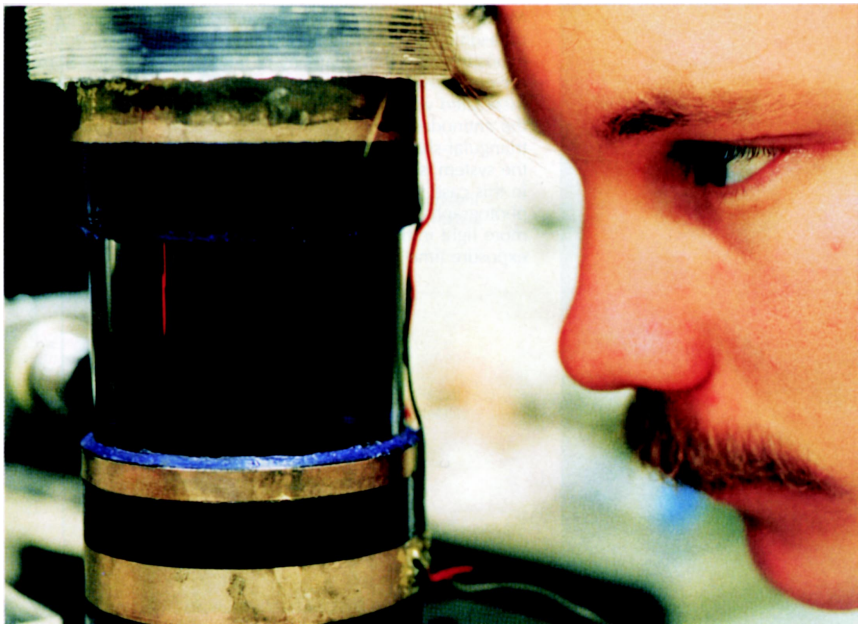


Acoustic cavitation and Sonoluminescence. This acoustic resonator consists of two transducers separated by a thin glass cylinder. Standing waves with frequencies from about 20 kHz to over 100 kHz and acoustic pressures up to about 3 bars can be generated in the liquid. If the acoustic-pressure amplitude is sufficiently large, many cavitation bubbles can be generated near the pressure anti nodes of the standing-wave system. If the pressure is considerably lower, it is possible to "acoustically levitate" individual gas bubbles, which under conditions described in the text can generate light each acoustic cycle. Graduate student Sean Cordry watches the blue sonoluminescence from such a bubble. The red streak is an artifact of the lighting. **Figure 1**

bly loosely coupled to each other in their dynamic behavior. These analyses were helpful in understanding gross aspects of the phenomenon, and proved useful in sonochemistry; however, because of the random nature of MBSL it was difficult to learn much about the physics of not only the individual cavitation events but also the resulting electromagnetic emissions.

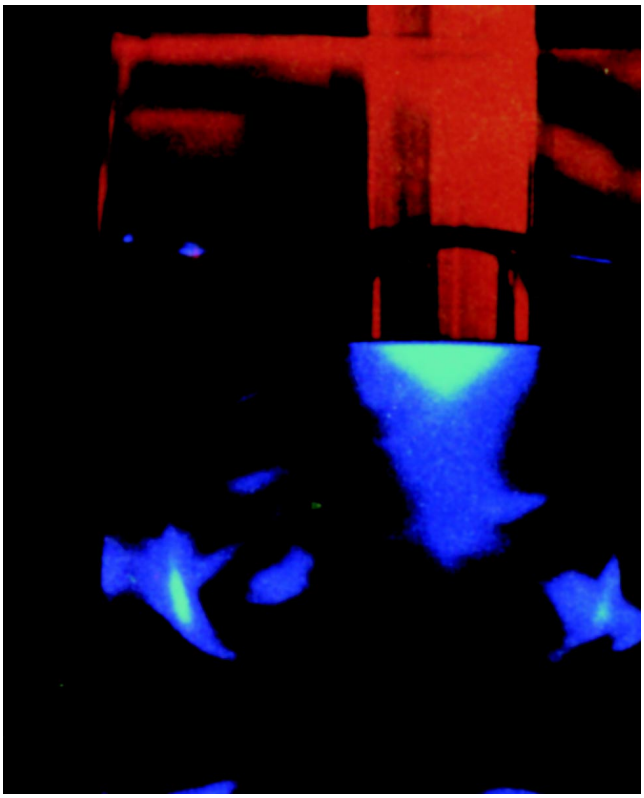
Single-bubble sonoluminescence

This situation was substantially improved in 1988 when Felipe Gaitan,[3] after a painstaking search, discovered the conditions under which a single, stable cavitation bubble would produce sonoluminescence each acoustic cycle. The achievement of repetitive single-bubble sonoluminescence enabled this phenomenon to be examined in considerable detail. That analysis has led to some remarkable discoveries.[4]

To attain SBSL, it is first necessary to drive a single bubble with an acoustic field intense enough to lead to relatively large radius excursions yet not so intense as to lead to self-destructive instabilities. The procedure Gaitan followed was to levitate a bubble in an acoustic standing wave. As the acoustic-pressure amplitude is slowly increased, a levitated gas bubble progresses through an evolution of states that can lead to SBSL; figure 3 diagrams this evolution. The "equilibrium radius" is obtained in the limit of no bubble oscillations. For relatively low pressures, the bubble undergoes low-amplitude radial pulsations and is positioned between the nodal and antinodal regions of the standing-wave field, where the buoyancy force is balanced by the acoustic radiation-pressure force. As the pressure amplitude is increased, the bubble moves closer to the antinode and eventually undergoes nonspherical pulsations (surface oscillations evidenced by a type of dancing motion of the bubble), which typically split the bubble into a number of small microbubbles. However, if the liquid is sufficiently degassed (say, to 10% of saturation), the dancing motion suddenly ceases. For an air bubble in pure water this happens at a pressure amplitude of about 1.1 bars. The bubble then becomes remarkably stable and emits a faint glow. This glow becomes brighter and brighter as the pressure amplitude is increased, eventually becoming bright enough to be visible even with the lights on in the room. (See figure 1.) When the pressure is increased above about 1.5 bars, the brightly glowing bubble suddenly disappears.

It is likely that diffusion of gas through the liquid-bubble interface plays an important role in bubble stability and restricts the conditions under which SBSL can occur.[5-7] Consider an oscillating bubble in a liquid that contains dissolved gas. When the bubble is in its expansion phase, gas will diffuse into the bubble; conversely, when it is in its compression phase, gas will diffuse out of the bubble. For small-scale oscillations and linear excursions of the bubble radius, the total acoustically induced mass flux of gas over one complete cycle will be zero, and the bubble will dissolve slowly as a consequence of surface tension. However, for larger oscillations (at higher acoustic-pressure amplitudes) there is considerable temporal asymmetry in these radius excursions: The time that the bubble spends in its expansion phase is large compared with the time it spends in its compression phase. Thus over a complete cycle, more gas will diffuse into the bubble than will diffuse out, and the bubble will grow.

This "rectified diffusion" is reduced if the amount of gas dissolved in the liquid is less than the saturation level. Consequently, if the liquid is considerably undersaturated with gas, stable bubble size can be achieved only for large displacement amplitudes. Of course, a balance of diffusion should occur only for a unique pair of values of the dis-



Multiple-bubble sonoluminescence produced by an ultrasonic horn at a frequency of 20 kHz. This is a double exposure: The thin, filamentary lines exist when the horn is driven at low acoustic intensity (2 W/cm^2) and are associated with microscopic cavitation bubbles located near the anti nodes of the standing-wave pattern. The bright, triangular-shaped area directly below the horn exists when the system is driven at a higher acoustic intensity (7 W/cm^2); in this case there are no standing waves. For these photographs, Luminol was added to the water to produce more light in the visible region of the spectrum. Each exposure time was about 5 minutes at *f* / 2.8. **Figure 2**

solved gas concentration and the driving pressure amplitude-which implies that the equilibrium is unstable. However, apparently because of nonlinearities in the bubble response, stable equilibrium conditions can occur.[5,7] Hence greatly reducing the dissolved gas concentration makes it possible to produce a single, stable cavitation bubble that undergoes large radius excursions each cycle. Gaitan was able to find the conditions necessary for these radial excursions to produce sonoluminescence in each oscillation. Once those conditions are achieved the system is amazingly robust: Unless there are significant changes in the acoustic or liquid parameters, SBSL can be maintained for unlimited periods of time.

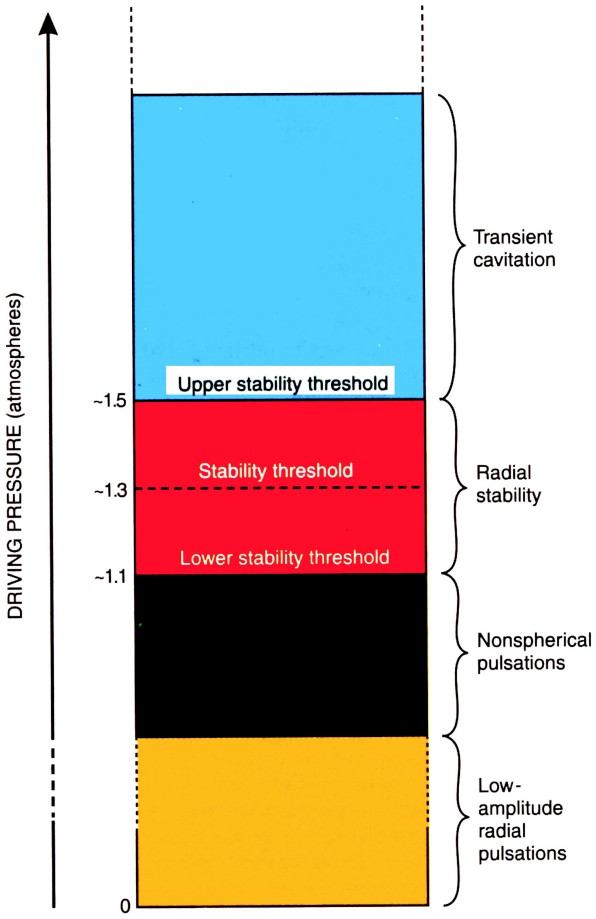
One can determine the conditions for the bubble dynamics that lead to SBSL rather straightforwardly with light-scattering techniques.[3,8] Using a laser, a photodetector and the applicable Mie-scattering algorithms, one can invert the scattered intensity and obtain a radius-versus-time curve for the bubble. One finds that the light emissions occur on bubble collapse and that the phase of those emissions stays rigorously fixed over a number of acoustic cycles. (See figure 4.)

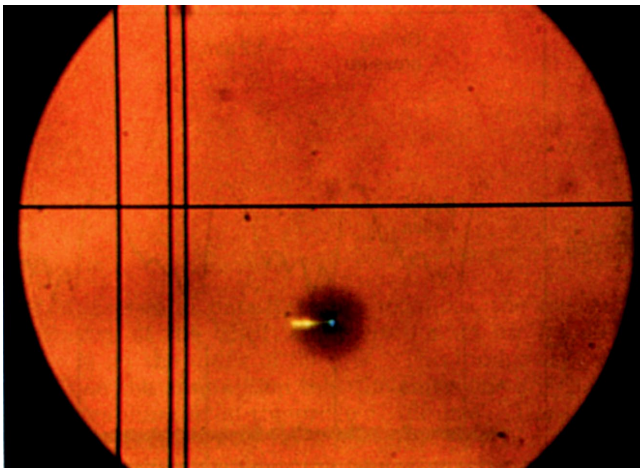
A group headed by Seth Putterman at the University of California, Los Angeles, has used the constant-phase result and a much improved light-scattering technique to obtain radius-time curves for SBSL to a high level of precision.[8,9] These curves, shown in figure 5, illustrate the transition from a nonsonoluminescing bubble to a sonoluminescing one and are very useful for understanding critical aspects of this phenomenon. As the acoustic-pressure amplitude is increased, there is a transition point at which the bubble's equilibrium radius (apparent at early and late times in figure 5), its maximum radius and its rebound from implosive collapse are all suddenly reduced. At this pressure sonoluminescence emissions begin to occur. Computations of these radius-time curves using standard models of nonlinear bubble dynamics predict the rebound reduction at the reduced bubble size; however, the sudden decrease in equilibrium radius is still not clearly understood. It is known that in most cases surface waves exist on the bubble just prior to the onset of sonoluminescence. However, when sonoluminescence conditions are met, the bubble becomes amazingly stable and shows no evidence of shape instabilities.

The parameter space for SBSL occurrence is a topic of current interest. To date, no liquids other than water and glycerin-water mixtures have been shown to demonstrate this phenomenon, although there is no *a priori* reason why it shouldn't exist in many liquids.

Putterman and his colleagues have examined SBSL in some detail and have discovered some of its remarkable properties.[2,6,8-11] One particularly interesting discovery arose from their attempts to measure the pulse duration of the sonoluminescence flash. They found that as they selected photomultiplier tubes with increasingly faster response times, they continued to measure only the impulse response of the tubes. Even when they used the world's fastest microchannel-plate photomultiplier tube they were unable to obtain a direct measurement of the SBSL pulse duration.[2] Furthermore, when they compared the impulse response of the SBSL flash with that of a 34-picosecond pulsed laser, they determined that the SBSL flash is extinguished faster than that of the laser, probably due to some residual ringing in the laser that is absent in SBSL. Attempts to measure the pulse duration with streak cameras and other high-speed devices have been unsuccessful. Although a precise value for the pulse duration has not yet been obtained, Putterman's group estimates an upper bound of 50 psec (see PHYSICS TODAY, November 1991, page 17). This extremely short time (as compared with the acoustic period of about 40 microseconds) is difficult to explain in terms of our conventional understanding of bubble dynamics.

A second remarkable aspect of SBSL is the degree of synchronicity of the flashes. If the relative phase angle between the zero-point crossing of the acoustic field and the emission of the sonoluminescence burst is measured, it is





Pressure regimes of single bubble sonoluminescence. The behavior of an acoustically levitated bubble in an aqueous liquid changes with acoustic driving pressure, as shown schematically at left and described in the text. A photograph of SBSL (above) shows light emissions from a single, stable cavitation bubble that is oscillating about an equilibrium radius of a few microns and emitting blue light each acoustic cycle. The sonoluminescence appears to be coming from the very center of the bubble. The diffuse background light shows that the maximum radius of the bubble is on the order of 50 microns (the outer fiducial lines are 105 *m* apart). Over this l-second exposure, the bubble underwent about 20 000 complete cycles. The horizontal white line is reflected light from an illuminator aimed directly at the bubble. **Figure 3**

found to be stable to within a degree for periods of several minutes.[3] When the pulse-to-pulse jitter was measured,[9] the standard deviation of the Gaussian curve that defines the jitter was on the order of 50 psec. This remarkable clock-like synchronicity is amazing when one considers that the jitter in the synchronous output of the frequency synthesizer used in the experiment was on the order of 3 nanoseconds. Phase-locking of the flashes is no longer guaranteed, however, if the levitation vessel is driven slightly off resonance.[12] In fact, for that case analysis of successive intervals between flashes shows period-doubling, quasiperiodic and even chaotic behavior.

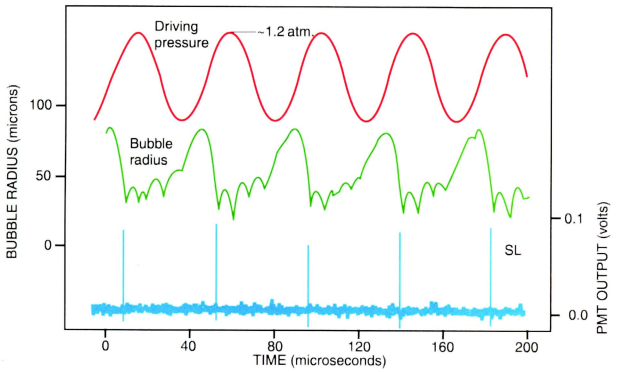
Sonoluminescence spectra

Because sonoluminescence is indicative of the high temperatures and pressures generated by cavitation collapse, measuring the spectrum of this light has been of interest for many years. Figure 6 shows some representative spectra. In the spectrum of MBSL generated within an organic liquid such as dodecane, one sees well-defined spectral bands that are characteristic of the host liquid. For example, the well-defined peaks in the dodecane spectrum shown in figure 6 are associated with diatomic carbon. By generating synthetic spectra that closely approximate the measured spectra, Kenneth Suslick and his colleagues[13] have obtained the "effective temperature" of the constituents that give rise to the sonoluminescence. This technique depends upon the ability to resolve recognizable emission bands generated by atomic and molecular transitions. Indeed, in hydrocarbon solutions containing dissolved metallic compounds or salts, one sees discrete metal line emissions. When the spectrum of dodecane was measured, with argon as the dissolved gas, the synthetic spectrum indicated that the effective temperature of the C_2 excited state was 5100 K These measurements were all performed under conditions of MBSL, as in figure 2. In this case bubble-bubble interactions are likely to occur.

Figure 6 also shows the spectrum of water generated under MBSL conditions.[14] This spectrum is considerably different from that of dodecane and shows a well-defined peak at 310 nm. This peak can be associated with molecular bands of the OH free radical, which is likely to be produced by the high temperatures and pressures within the bubble.

Extensive spectroscopic measurements of SBSL in water have also been undertaken[11] and show some intriguing results. For example, the SBSL spectrum is remarkably smooth, containing no significant peaks, and can be fit quite closely by a blackbody curve-giving an effective temperature as high as 30 000 K under some conditions. Furthermore, the sonoluminescence intensity of a pure nitrogen bubble is only a few percent of that of an air bubble, but with the addition of only 1% argon (its approximate abundance in air), the sonoluminescence intensity returns to that for air. With a pure xenon gas bubble, a broad maximum in the spectrum is observed near 300 nm. No such maximum is observed for a pure helium bubble. For both pure Ar and He the intensity increases with decreasing wavelength until the ultraviolet cutoff for water is reached. These results suggest that complicated physical chemistry is occurring within the sonoluminescing bubble.

A typical spectrum of SBSL in water, obtained by Anthony Atchley and his colleagues,[15] is shown in figure 6. When one compares this spectrum with that of MBSL in



Synchronous relationship between the acoustic field (top), the measured radius-versus-time curve (middle) and the SBSL emissions measured with a photomultiplier tube (PMT) (bottom). The emissions occur at a fixed phase of the acoustic field. (Adapted from ref. 3.) **Figure 4**

water, one sees that the 310-nm peak is barely visible and that the spectrum now extends deeply into the ultraviolet. In fact, there is still uncertainty about whether the peak at about 230 nm in the SBSL spectrum is real or is simply the result of the uv attenuation within the water and the measurement apparatus.

The SBSL spectrum doesn't appear to have any spectral bands or emission lines indicative of well-known atomic and molecular transitions and thus doesn't lend itself to a comparison with synthetic spectra. (Perhaps the bands are there but are so broadened by the high temperatures and pressures that they aren't recognizable.) It may be that the spectrum is more closely approximated by that of a blackbody and that the temperature of sonoluminescence is relatively high. The blackbody fit[15] of the SBSL spectrum in figure 6 indicates an effective temperature of approximately 16 000 K. When one lowers the temperature of the water, the SBSL spectrum shifts toward shorter wavelengths; indications of temperatures as high as 30 000 K are then found, provided the blackbody assumption is made.[11] This issue of the temperature of sonoluminescence is still unresolved. Of course, whether one can even have a "temperature" (which implies some sort of equilibrium) of 30 000 K for 50 psec is debatable.

Some basic theory

The theoretical analysis of acoustic cavitation and bubble dynamics in general is reasonably mature,[16] having been initiated, in some sense, by Lord Rayleigh. While MBSL is complicated by the presence of many bubbles, SBSL, in which a single bubble is driven into spherical pulsations at a relatively low driving pressure, seems to represent an idealized case that would be adequately described by existing theoretical models. Hence the discovery of SBSL has provided an exceptional opportunity to test existing theories of bubble dynamics.

Because the gas bubble is an inherently nonlinear system, the theoretical treatment of cavitation-bubble dynamics is necessarily complicated and is best approached through numerical methods. These analytical-numerical approaches usually involve an equation of motion for the bubble interface, an energy equation for both the liquid and the gas, and the application of momentum conservation across the gas-liquid interface. These coupled nonlinear differential equations are then solved, using an equation of state for the gas in the interior of the bubble. The solution describes the motion of the interface and allows one to infer values for the internal pressure and temperature.[5,16] Using such an approach, Bradley Barber and Putterman[8] obtained excellent agreement with their measured radius-time curves. (To be sure, because neither the equilibrium radius of the bubble nor the acoustic-pressure amplitude at the site of the bubble can be measured precisely, these variables were treated as adjustable parameters.) Thus it seemed reasonable to assume that the temperature and the sonoluminescence pulse duration also ought to be describable with this theoretical analysis.

Unfortunately, there is a major failure in the analysis. Figure 7 shows the predicted behavior of the radius and temperature as a function of time for typical conditions that give rise to SBSL: an acoustic-pressure amplitude of 1.3 bars, an equilibrium bubble radius of 5 microns and a driving frequency of 25 kHz. The initial 5-micron bubble radius expands to nearly 40 microns and then rapidly collapses to a value on the order of 0.1 micron. The temperature within the bubble is predicted to rise to values on the order of 7000 K. These numbers are in reasonable agreement with the measured or inferred values; the predicted duration of the sonoluminescence pulse is not. It can be seen from the expanded portion of the graph that the temperature is expected to exceed 2000 K for about 20 nsec. By contrast, it would be impossible to draw a line on this figure that would accurately represent the upper bound on the measured pulse duration of 50 psec! How can the contents of the bubble remain compressed for such a long period of time and not radiate?

Imploding shock waves

There are a variety of competing hypotheses that attempt to explain the observed behavior of both SBSL and MBSL. A particularly intriguing interpretation, proposed by the late Julian Schwinger,[17] is based on the dynamic Casmir effect. So far, this mechanism exists principally in mathematical form and has not been tested against experiments. A second hypothesis involves an electrical discharge mode in which asymmetric bubble collapse brings about charge separation.[18] This hypothesis can explain several observed phenomena of both SBSL and MBSL, but the model involves complicated bubble

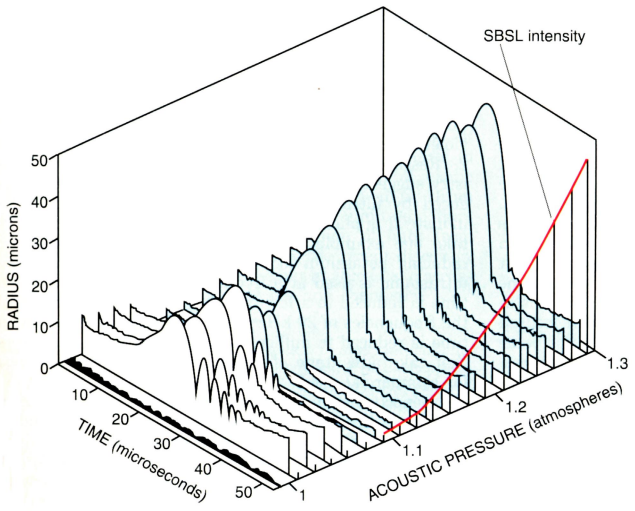
dynamics that do not reproduce the high level of synchronicity observed in SBSL.

It was suggested more than 20 years ago that MBSL originates from a shock wave in the gas contained within the bubble rather than from the adiabatic heating of the gas.[14] This concept has received renewed interest with the recent discovery of the extremely short duration of the SBSL flash. Theoretical studies of the generation of an imploding shock wave within the gas that gives rise to SBSL emissions give results consistent with much of the experimental data.[19,20] For example, the measured luminosity of the SBSL emissions for an air bubble in water is on the order of 30 mW. The luminosity calculated[19] on the assumption that the emissions are thermal bremsstrahlung is on the order of 100 mW. The velocity of the imploding shock wave has also been calculated; by finding the distance from the center at which the gas is heated to luminescence temperatures, the researchers obtained a pulse duration on the order of tens of picoseconds,21 in good agreement with experiment. However, they provided no information on the shock rebound, and whether or not this model would lead to the observed rapid extinction of the SBSL emissions remains unclear.

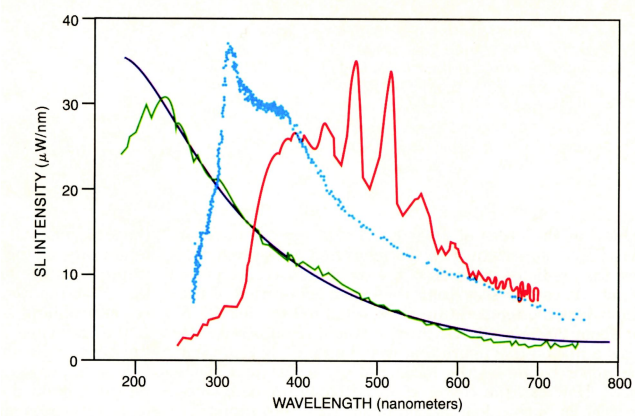
The strong probability that SBSL results from an imploding shock wave has now made this curious phenomenon one of considerable interest. Because the bubble is relatively far removed from the symmetry-breaking container boundaries, is driven at a relatively low acoustic pressure and is small enough that surface tension tends to force it to remain spherical, the imploding shock wave very likely remains symmetrical until the final stages of collapse. This spherically symmetric implosion has the potential for creating some exotic physics and chemistry. Calculations suggest that temperatures as high as 108 K are to be expected.[19] This result has in turn prompted calculations of the possibilities of inertial confinement fusion with a deuterium-tritium gas mixture, which yield a qualified estimate of 40 neutrons per second under ideal conditions.[9] While the possibilities of actual fusion in this system are remote, the likelihood that the gas in the bubble remains relatively cold until the final stages of collapse suggests that one could use this simple and inexpensive system to obtain information about inertial confinement fusion. In both cases, the stability of the imploding shock wave limits the ability to concentrate energy.

The imploding-shock-wave hypothesis has been critically examined only in SBSL, because this simple system lends itself much more readily to experimentation. The acoustic-pressure amplitude that drives the bubble in SBSL is quite low by cavitation standards-on the order of 1 bar-and a barely discernible shock wave is generated within the liquid.[7]

If the microscopic inhomogeneities that serve as cavitation nuclei for MBSL are removed from the water, dynamic tensile strengths as high as 250 bars can be momentarily achieved. Then when cavitation does occur (nucleated by an adventitious cosmic ray, for example), the "event" typically lasts for only a few acoustic cycles (it quickly destroys itself and can be extremely violent. For example, at this level of acoustic pressure the shock waves generated within the liquid as a result of bubble collapse are occasionally so intense that they can even destroy the resonator that produces the acoustic field. Such shock waves are often credited with the destructive effects of cavitation, such as the erosion of metal surfaces. If imploding shock waves exist within cavitation bubbles driven at these very large pressure amplitudes, then temperatures and pressures should be expected that greatly exceed those achieved in SBSL. Of course, if the shock wave is not launched before the inevitable instabilities in the air-liquid surface develop, then a focused shock-wave implosion in the gas probably will not occur and the contents will be heated by an adiabatic compression of the bubble itself. Thus one should expect MBSL type behavior in that case. However, it seems likely that in at least a few of these events internal shock waves would occur that would be similar to those postulated for SBSL but driven at much higher initial velocities. Because of the transient nature



Conditions for SBSL. These light-scattering measurements illustrate the change in the behavior of the radius-time curve when sonoluminescence conditions are achieved. The unshaded regions are for a nonsonoluminescing bubble; the blue-shaded regions are for a sonoluminescing bubble. For pressures insufficient for sonoluminescence, there are significant rebounds in the bubble radius. After sonoluminescence is achieved, the rebounds are nearly absent. Note also the sudden shift in the equilibrium radius (apparent at early and late times) to smaller values when sonoluminescence conditions are met. As the pressure is increased above about 1.3 bars, the bubble suddenly disappears. (Adapted from ref. 9.) **figure 5**



Sonoluminescence spectra. The red curve is for MBSL in dodecane.[13] The blue dots are for MBSL in water at a frequency of 16 kHz and a temperature of 25°C.[14] The green curve is for SBSL, also in 25°C. (water, driven at 43 kHz;15 the smooth curve is the tail of a blackbody curve for a temperature of 16 200 K (the maximum is off the scale). The scale on the left applies only to the green curve; the scales for the other two curves have been arbitrarily shifted for comparison purposes. **Figure 6**

of the phenomenon it would be very difficult to determine if and when these "supershocks" occurred. Perhaps by-products of such cataclysmic events could be detected.

Applications and future perspectives

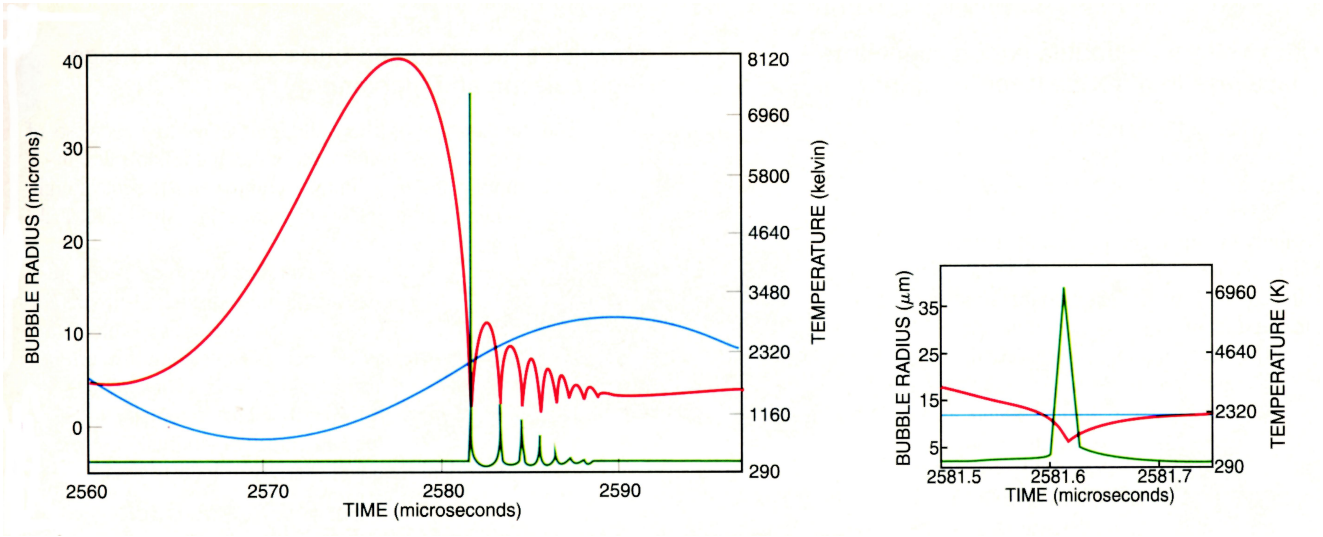
The amazing robustness of SBSL suggests that there may be technological applications in a variety of disciplines. Consider the measurements of the synchronicity of this phenomenon, which demonstrated that the stability of the system is on the order of five parts in 10^{11}. Those measurements were made without knowledge of the origin of this stability and there were no serious efforts to improve it. That suggests that it might be possible to develop a cheap precision frequency source based on SBSL.

Although sonoluminescence is intriguing in and of itself, this phenomenon is primarily a diagnostic indicator of the enormous energy concentration that can arise from the implosive collapse of a cavitation bubble. The technological use of this energy concentration has great promise. For example, there is considerable potential for influencing chemical reactions in an extended region of violent cavitation activity, as in the MBSL shown in figure 2. Research in the relatively new discipline of sonochemistry suggests that many chemical reactions can be influenced by ultrasound--a technology whose potential for industrial applications is gradually being recognized. To take one example, the conventional reactor process for reducing potassium iodide to iodine takes hours; when ultrasound is used at a frequency of 20 kHz the reaction time is reduced to a few minutes; when a combination of the frequencies of 20 kHz and 1 MHz is used the reaction time is reduced to milliseconds. Industrial-sized reactors that take advantage of these gains are being developed for commercial use.[22]

Sonochemistry takes advantage of the unique characteristics of acoustic cavitation to concentrate mechanical energy onto microscopic scales. When a cavitation bubble collapses, the resulting high temperatures most likely last on the order of nanoseconds or less. In standard chemical procedures a short-lived, newly created high-temperature species will revert back to its initial constituents before the high temperatures can be reduced. In acoustic cavitation, on the other hand, the rapid quenching of the reaction "freezes out" the new species. Consider the production of amorphous (noncrystallized) iron, a product of considerable commercial interest for its catalytic capabilities. It is difficult to cool a liquid metal rapidly enough to prevent crystallization. However, in the chemical reactor within a cavitation bubble, ferrous compounds can be decomposed into free atoms and then quenched on such short time scales that solidification of the iron can occur before crystallization.[23] Amorphous iron is easily produced on a laboratory scale by this technique.

To date, SBSL has been demonstrated only in water and mixtures of glycerin and water. It is known from MBSL studies that the intensity of sonoluminescence scales with σ^2/P_V, where σ is the surface tension and P_V is the vapor pressure.[24] MBSL is known to occur in liquid metals such as mercury. If SBSL could be demonstrated in mercury, and the σ^2/P_V scaling parameter holds, then one should expect sonoluminescence intensities nearly 10 000 times greater than what one finds for water.

Energy concentrations of 10^{11}, temperatures of 30 000 K, optical pulse synchronicities to a few parts in 10^{11}, pulse durations of 50 psec, production of exotic



Expected behavior of the bubble radius and internal temperature during SBSL. The purple curve is the acoustic pressure with a driving frequency of 25 kHz. The pressure amplitude is 1.3 bars. The red curve is the bubble radius after the transients have died down (about 60 cycles into the oscillations). Temperature is shown by the green curve. On the right is an expansion of the data around the bubble collapse region. Theory predicts that the temperature of the contents of the bubble should be about 2000 K for over 20 nsec; however, the measured sonoluminescence pulse duration is only 50 psec-a time so short that it can't be drawn to scale on the figure. (Results courtesy of Vinod Kamath.) **Figure 7**

chemical species and imploding shock waves-all this from a simple mechanical system costing a few hundred dollars to construct! Although the phenomenon of light from sound has been known for 60 years, the recent discovery of single-bubble sonoluminescence has enabled us to access a remarkable laboratory for physics and chemistry.

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References

1. H. Frenzel, H. Schultes, Z. Phys. Chern. **27B,** 421 (1934).
2. B. P. Barber, R. Hiller, K. Arisaka, H. Fetterman, S. J. Putterman, J. Acoust. Soc. Am. **91**, 3061 (1992).
3. D. F. Gaitan, L. A. Crum, in *Frontiers of Nonlinear Acoustics,* Proc. 12th Int. Symp. on Nonlinear Acoustics, M. Hamilton, D. T. Blackstock, eds., Elsevier, New York (1990), p. 459. D. F. Gaitan, L. A. Crum, R. A. Roy, C. C. Church, J. Acoust. Soc. Am. **91**, 3166 (1992).
4. L. A. Crum, J. Acoust. Soc. Am. **68**, 203 (1980); 95, 559 (1994). R. G. Holt, L. A. Crum, J. Acoust. Soc. Am. **91**, 1924 (1992).
5. V. Kamath, A. Prosperetti, F. N. Egolfopoulos, J. Acoust. Soc. Am. **94**, 248 (1993).
6. R. Lofstedt, B. P. Barber, S. J. Putterman, Phys. Fluids A **5**, 2911 (1993).
7. L. A. Crum, S. Cordry, in *Proc. IUTAM Symp. on Bubble Dynamics and Interface Phenomena*, J. R. Blake, N. H. Thomas, eds., Kluwer, Dordrecht, The Netherlands, in press.
8. B. P. Barber, S. J. Putterman, Phys. Rev. Lett. **69**, 3839 (1992).
9. B. P. Barber, C. C. Wu, R. Lofstedt, P. H. Roberts, S. J. Putterman, Phys. Rev. Lett. **72**, 1380 (1994).
10. B. P. Barber, S. J. Putterman, Nature **352**, 318 (1991).
11. R. Hiller, S. J. Putterman, B. P. Barber, Phys. Rev. Lett. **69**, 1182 (1992). R. Hiller, B. P. Barber, J. Acoust. Soc. Am. **94**, 1794 (1993). R. Hiller, K. Weninger, S. J. Putterman, B. P. Barber, Science, in press.
12. R. G. Holt, D. F. Gaitan, A. A. Atchley, J. Holzfuss, Phys. Rev. Lett. **72**, 1376 (1994).
13. K. S. Suslick, Science **247**, 1439 (1990). K. S. Suslick, E. B. Flint, M. W. Grinstaff, K. A. Kemper, J. Phys. Chem. **97**, 3098 (1993).
14. K. J. Taylor, P. D. Jarman, Aust. J. Phys. **23**, 319 (1970). P. D. Jarman, J. Acoust. Soc. Am. **32**, 1459 (1960).
15. A. A. Atchley, in *Advances in Nonlinear Acoustics,* H. Hobaek, ed., World Scientific, Singapore (1993), p. 36.
16. A. Prosperetti, L. A. Crum, K. W. Commander, J. Acoust. Soc. Am. **83,** 502 (1988). W. Lauterborn, J. Acoust. Soc. Am. **59**, 283 (1976). R. E. Apfel, J. Acoust. Soc. Am. **69**, 1624 (1981).
17. J. Schwinger, Proc. Natl. Acad. Sci. USA **89**, 1118, 4091 (1992).
18. T. Lepoint, F. Mullie, Ultrasonics Sonochem. **1**, S13 (1994). M. A. Margulis, Ultrasonics **30**, 152 (1992).
19. C. C. Wu, P. H. Roberts, Phys. Rev. Lett. **70**, 3424 (1993).
20. H. P. Greenspan, A. Nadim, Phys. Fluids A **5**,1065 (1993).
21. A. Nadim, A. D. Pierce, G. V. H. Sandri, J. Acoust. Soc. Am. (Suppl.) **95**, 2938 (1994).
22. R. J. Zanetti, Chern. Eng. **99**, 37 (1992).
23. K. S. Suslick, S. B. Choe, A. A. Cichowlas, M. W. Grinstaff, Nature **353**, 414 (1991).
24. A. J. Walton, G. T. Reynolds, Adv. Phys. **33**, 595 (1984). ■