Sonoluminescence

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Abstract

By creating a strong acoustic field, gas bubbles that emit luminescence are created. We discover the characteristics of this sonoluminescence, such as the time dependence of the light pulse and the dynamics of the bubble's oscillation.

Introduction

Theory

To set up the idea, we must first create an air bubble trapped in place by acoustic waves, in water. Usually, this air bubble would float to the top of the water due to its lesser density, but in this case, the acoustic waves will keep it trapped in the center of the water. This bubble is a certain ambient size, until the expansion part of the sound field acts on it. This causes the bubble to swell up to its maximum size, until the sound field begins to compress. As the bubble swells, the amount of air molecules inside stays constant, but the volume increases drastically. This creates a near-vacuum within the bubble. The disparity between the inside of the bubble and the pressure of the water outside causes the bubble to collapse near-instantaneously. It is speculated the minimum size of the bubble is due to the repulsive forces of the molecules onto one another at that size. Another interesting thing that happens after the bubble collapses is the "bouncing" effect. As the bubble shrinks to its minimum size, it also rebounds up and down and few times, just as if a ball were dropped from some height. If we consider the idea about the repulsive molecular forces to be true, at this stage, the molecular forces and the pressure force from the water outside ebb and flow with one another, as the bubble finds its equilibrium again – until the next sound compression hits. The luminescence of the bubble comes from the rapid expansion and compression of the molecules in the bubble. One idea is that the molecules heat up to a point where their bonds begin to break down and combine again to release visual energy. However, this idea does not take into account the vast amounts of ultra-violet spectrum that is observed from this experiment. There are many other ideas to explain the cause of sonoluminescence, which I may bring up later in this report.

Apparatus and Procedure

Our basic setup is a cylinder filled with water, with two piezoelectric drivers on the top and the bottom. The piezoelectric transducer or PZT converts electricity into mechanical stress, generating our acoustic drive. We also have a heater filament in the water. This is used to generate a bubble by running a current through the wire. If our PZT is tuned correctly, there will be a antinode at the center of the container, which the bubble will be attracted to, and then trapped in place.

To measure properties of the bubble, we use a laser. By shining the beam onto the bubble, we can measure the light scattering off the bubble with a process known as Mie scattering. We can capture this scattering with a photomultiplier, which feeds into our oscilliscope, allowing us to see the amplitude over time.

Data and Analysis

After much trial and error, we finally achieved SL at around 1.21V for the amplitude and 32,250 Hz for the frequency.

Bubble Radius

One can use Mie scattering to determine the radius of the bubble. Our photo-multiplier intakes light, and as the bubble's radius increases, so does our input. We can approximate this relation as the following expression:

$$Voltage \propto R^2(t) \tag{1}$$

Below is a graph of the this, normalized to the maximum radius ($5\mu m$).

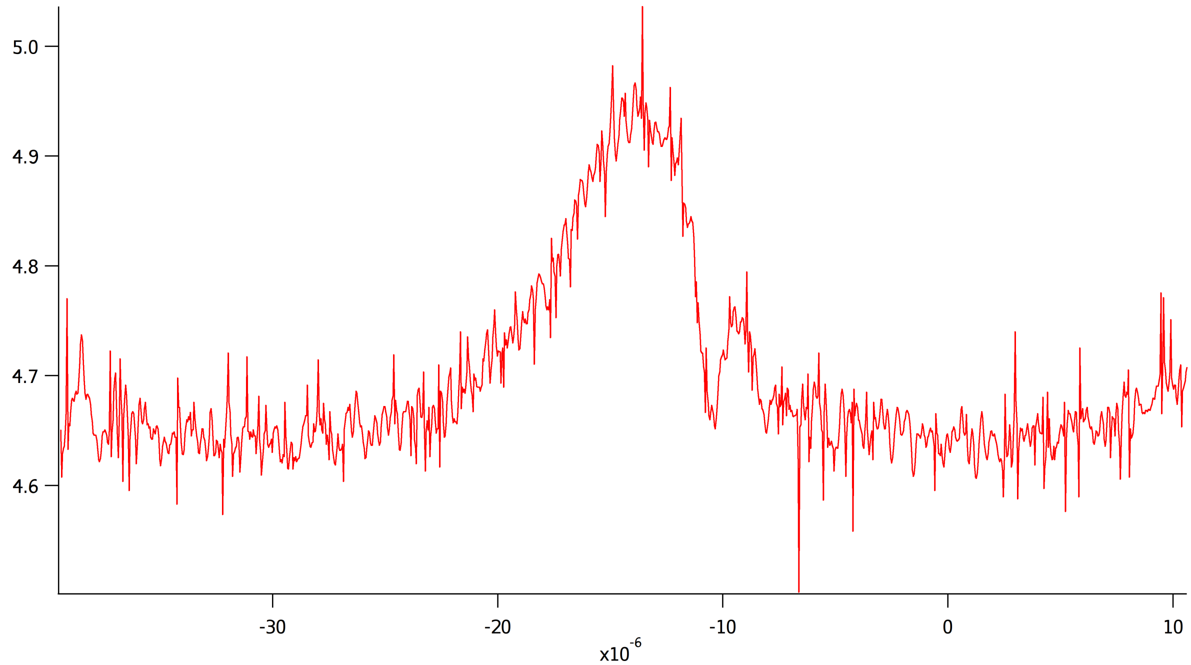

Figure 1: Bubble Radius (μm) vs Time (s)

Though this graph has a lot of noise, we can still make out the peak of the radius, and the subsequent bounce afterwards, as the bubble collapses.

Increasing Drive Amplitude

As we increase the drive amplitude, we are increasing the strength of the sound waves in the water. We should expect to see the bubble's radius to increase proportionately. In the five plots below, we increased the amplitude, beginning from the lowest amplitude to the highest. I should also mention that the voltage received from the photo-multiplier is directly proportional to the radius squared of the bubble. As shown in the last section, where we used Mie scattering to determine the bubble radius, the same can be done for the plots below. We increased the amplitude by variable amounts, until our maximum aplitude of around 1.40V.

Remember, we are using the starting amplitude of 1.21V and frequency of 32250Hz. Although we did not increase the ampltude at a fixed value, it is still in increasing order and can thus still demonstrate the relationship between the amplitude and the bubble radius.

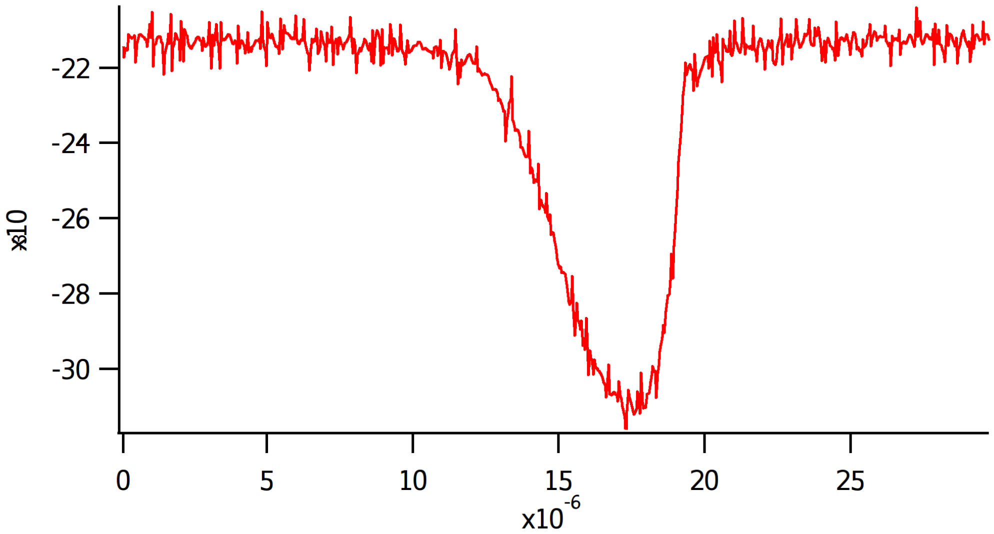

Figure 2: Voltage (V) vs. Time (s) (Starting Amplitude, 1.21V)

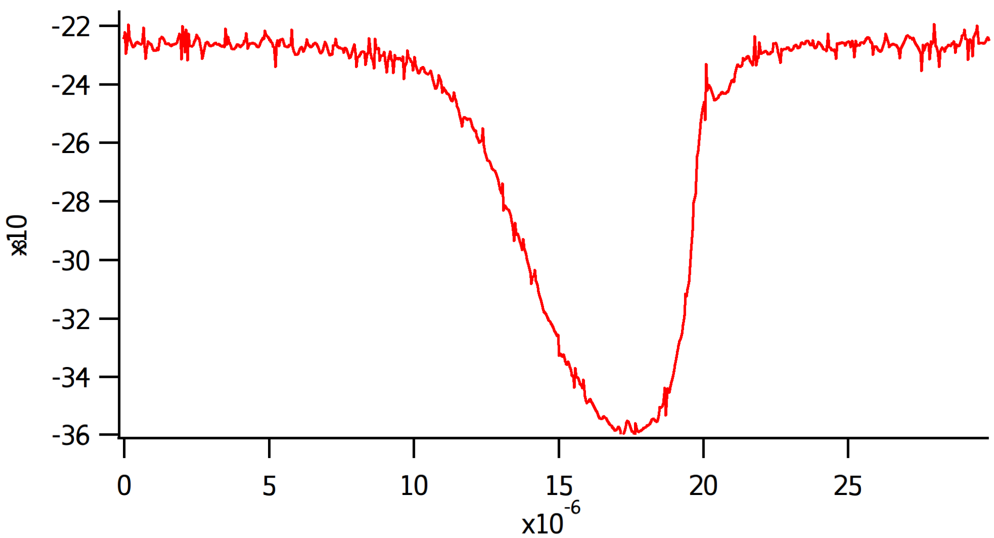

Figure 3: Voltage (V) vs. Time (s) (Increased Amplitude)

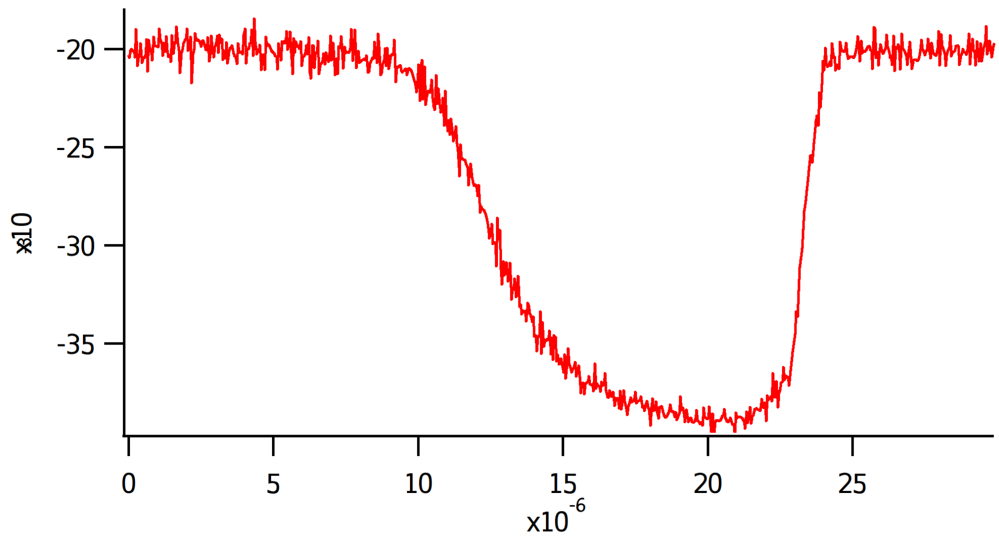

Figure 4: Voltage (V) vs. Time (s) (Increased Amplitude)

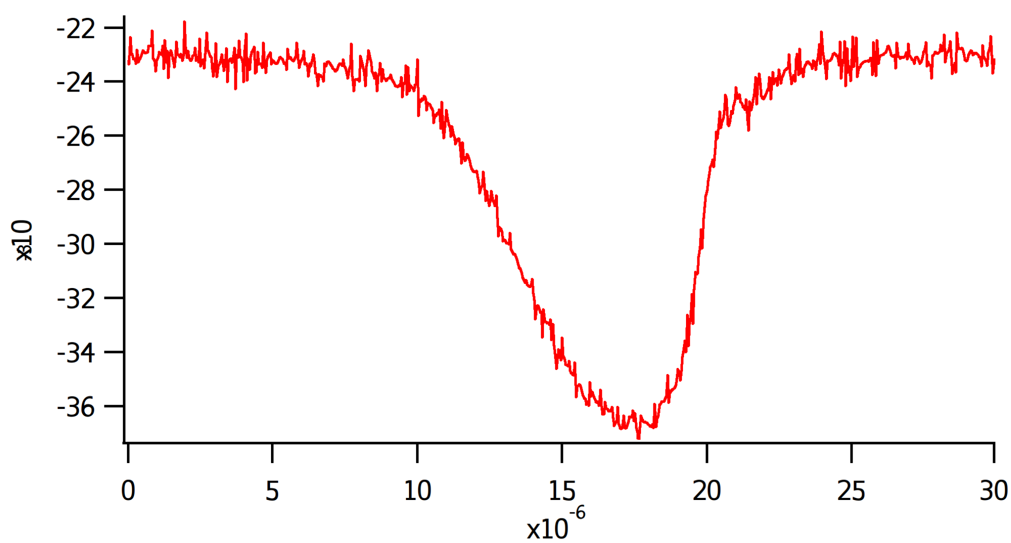

Figure 5: Voltage (V) vs. Time (s) (Increased Amplitude)

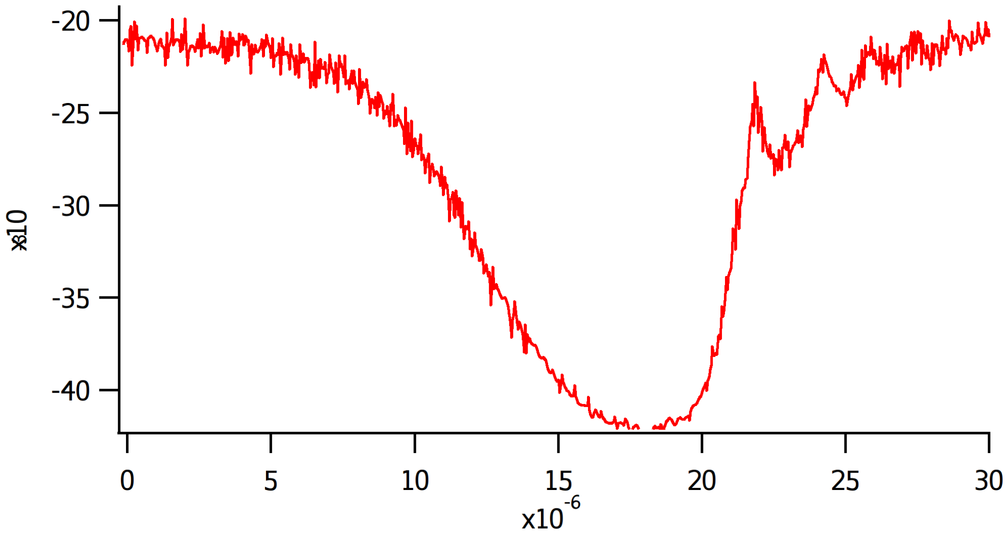

Figure 6: Voltage (V) vs. Time (s) (Maximum Amplitude 1.40V)

If it is not evidently clear in the plots above that the radius of the bubble increases as the amplitude increases, the plot below shows all of them overlaying one another. Though I may not be able to print this report out in color, and the plots are clearly not starting at the same point in time, it can still be understood that each of the curves have different maximum radii.

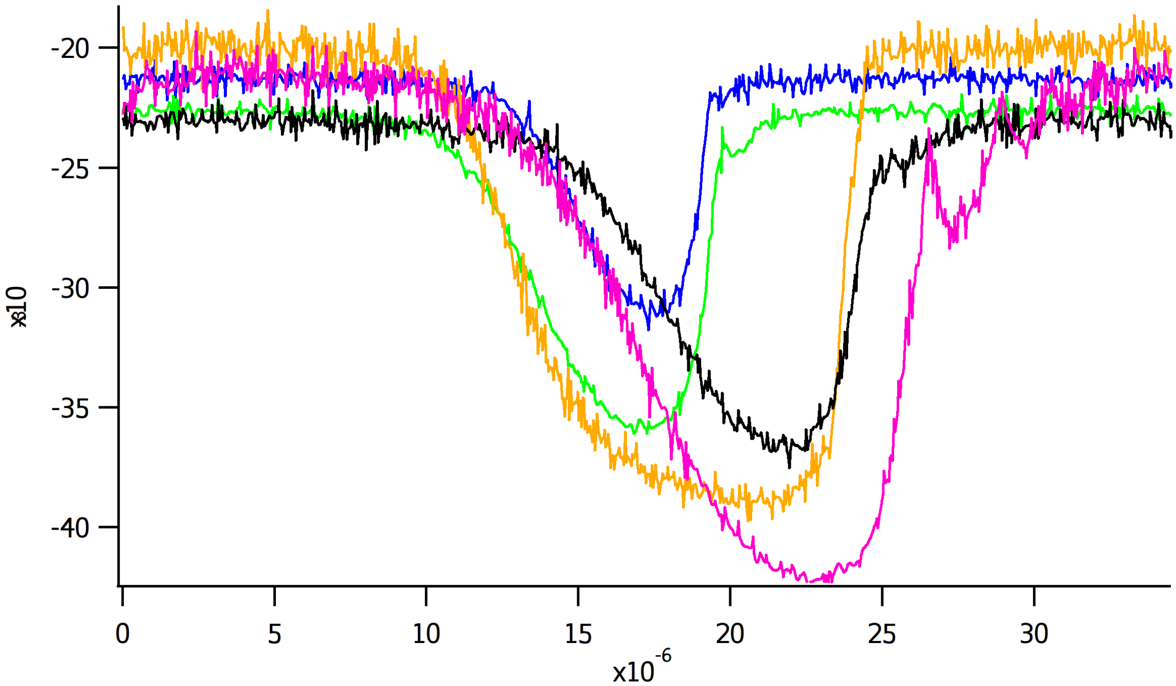

Figure 7: Voltage (V) vs. Time (s); Combination of the previous plots to demonstrate the relation btwn the drive amplitude and the radii of the bubbles. Blue = plot 1; green = plot 2; black = plot 3; orange = plot 4; pink = plot 5.

We can notice that there is a sharp spike at the minimum radius of the bubble. This is the onset of sonoluminescence. After the last graph, where the aplitude is the highest, we could not collect data anymore, as the bubble did not stay trapped in place, and it is quite difficult to find it.

Recall that these plots are only of the voltage recorded by the photomultiplier. This voltage can be converted into the bubble radius by simply taking the square root of the magnitude of the voltage, and the same relationships can be observed.

Period

To measure the period of the SL pulses, we simply measure the width between the pulses on the nano-second time scale, and remove the jitter by using an average of the data. Below, all the data is in units of $10^{-5}s$.

Run	First Period	Second	Third	Fourth	Fifth	Average Difference
1	3.04	3.14	3.08	3.04	3.03	3.07
2	3.02	3.06	3.14	3.20	3.06	3.10

The frequency of this period T is:

$$f = 1/T = \frac{1}{3.10 * 10^{-5}} = 32300Hz \tag{2}$$

$$\frac{1}{3.07 * 10^{-5}} = 32500Hz \tag{3}$$

Considering the frequency our drive is set to is 32250 Hz, these values are nearly the same. Both of these values have an error of less than one percent, verifying that the period of the bubble expansion and compression is the same at the period of the driving force.

Optical Spectrum

Various filters which we apply to the photo-multiplier allow us to observe the spectrum of the light coming from the bubble. We use a blue filter and a yellow filter which will filter out their respective wavelengths. In the plot below, we can see unfiltered, blue filter, and yellow filter, together.

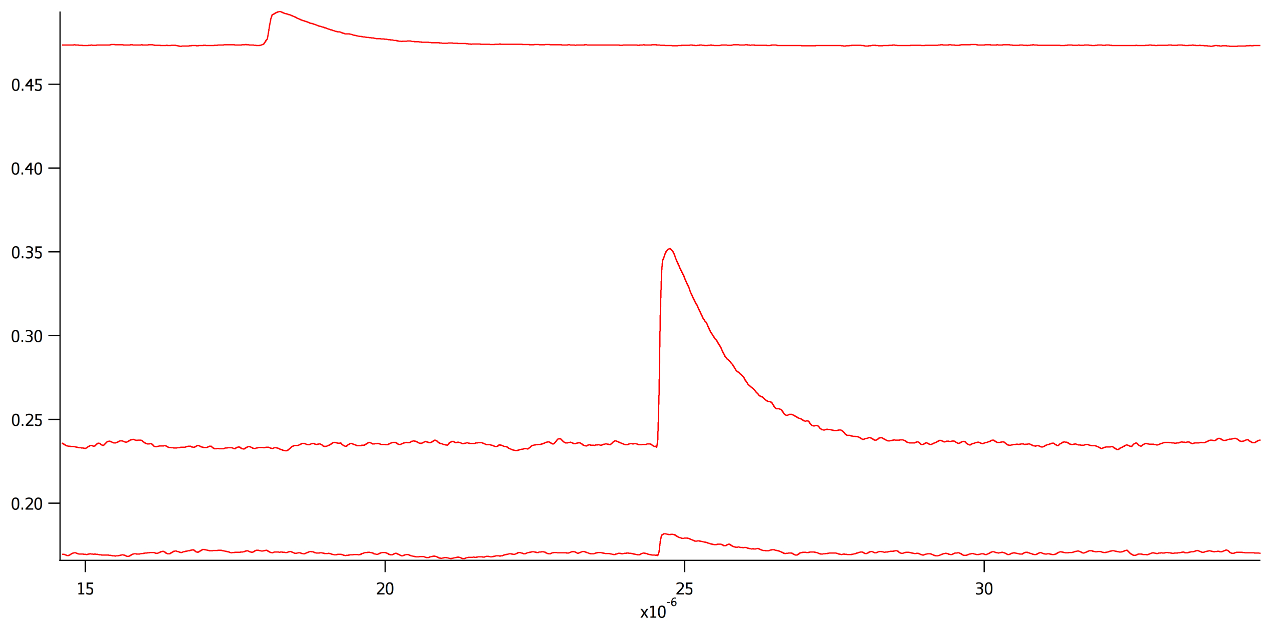

Figure 8: Bubble Radius vs. Time (s); The top one is unfiltered; the middle one is the blue filter; and the bottom one is the yellow filter.

One thing to keep in mind is that the bubble radius is not actually changing, as is depicted, but simply the light that the photo-multiplier can intake. The topmost one is obvious, as all light can go in, depending on the range that the photo-multiplier can detect. Nevertheless, it is much higher than either filtered option. Since the blue filter is higher than the yellow filter, we can deduce that the light from the bubble depends more heavily on the yellow spectrum than the blue spectrum.

We compare this to the blackbody spectrum between the limits of the PMT sensitivity, 250 nm to 800nm. To do this, we use Planck's formula for the radiation using the wavelength is:

$$B_\lambda(\lambda, T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1} \tag{4}$$

where h is Planck's constant, c is the speed of light, k_B is Boltzmann's constant, λ is the wavelength, and T is the temperature. We set the temperature to 17000K and integrate between the lower and higher bounds of the wavelength to find the radiance.

This integral is rather difficult to compute. Luckily, we can use Wien's approximation to determine the maximum wavelength to give us a sense of what the 17000K spectrum looks like. This is:

$$\lambda_{max} = \frac{0.00288m}{17000} = 0.17\mu m \tag{5}$$

From this maximum, we can generalize the spectrum from percentiles. The wavelength peak occurs at the 25th percentile. Our lower bound is 0.250 μm and our upper bound is 0.800 μm. These occur around the 55th and 95th percentile, respectively. Thus we can approximate the black body spectra between these two wavelengths to be 40% of the total spectrum, integrated from 0 to ∞.

Conclusions

In this experiment, we studied the properties of sonoluminescence. We essentially got a first hand look at how the bubble radius changes as the amplitude of the driving force changes. This showed us how quickly and how much the bubble changes size, which allowed us to theorize many different ways of how this bubble suddenly starts emitting light. One theory is the chemilumiscent theory, where the bonds of the molecules of the air are being broken and recombined since the temperatures are very, very high. Another theory is that the temperature creates a plasma, which emits light as the free electrons in the plasma collide with ions.

It was interesting to see how the spectrum of the light from the bubble was affected as we applied various filters. This allowed us to see at what wavelength the light is usually at.

References

[1] Experiment 3 Lab Manual

[2] Scientific American, "Sonoluminescence: Sound into Light" by Seth Putterman

[3] Sonoluminescence by F. Ronald Young