Twelve years of single bubble sonoluminescence: A review

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Single bubble sonoluminescence occurs when an acoustically trapped and periodically driven gas bubble collapse so strongly that the energy focusing at collapse leads to light emission. Detailed experiments have demonstrated the unique properties of this system: the spectrum of the light emission tends to peak in the ultraviolet and depends strongly on the type of gas dissolved in the liquid; small amounts of trace noble gases or other impurities can dramatically change the amount of light emission; small changes in the operating parameters (forcing pressure, dissolved gas concentration, liquid temperature, etc.) can lead to large changes in the light emission. This talk reviews experimental and theoretical efforts for understanding this phenomenon. The present understanding is that the bubble is adiabatically heated at collapse, leading to partial ionization of the gas inside the bubble and eventually to thermal bremsstrahlung. After presenting a brief historical review of single bubble sonoluminescence, we describe the major areas of research: First, we describe the classical theory of bubble dynamics, as developed by Rayleigh, Plesset, Prosperetti and others. Then we summarize the research on the gas dynamics inside the bubble. Shock waves inside the bubble do not seem to play a prominent role in the process. Next we discuss the hydrodynamic and chemical stability of the bubble. Sonoluminescence requires that the bubble must be shape stable and diffusively stable which determines the parameter space where light emission occurs. A summary of experiments and models addressing the origin of the light emission follows. The final part of the talk presents an overview of what is known and unknown, and outlines some directions for future research.

Single bubble sonoluminescence was discovered in 1989 by Felipe Gaitan, then a graduate student at the University of Mississippi working with Larry Crum [1, 2]. Crum had seen first hints for light emission from a single bubble back in 1985, see ref. [3], and Gaitan's objective for his thesis was to systematically search for it. Gaitan was carrying out a set of experiments on the oscillation and collapse of bubbles, using a flask of liquid lined with transducers tuned to set up an acoustic standing wave at the resonant frequency at the jar.

In his search for single bubble sonoluminescence, Gaitan at some point worked in a regime with a moderate forcing pressure $P_a/P_0 \approx 1.2-1.4$ and with the water degassed to around twenty percent of its saturated concentration of air. Then he indeed observed that "as the pressure was increased, the degassing action of the sound field was reducing the number of bubbles, causing the cavitation streamers to become very thin until only a single bubble remained. The remaining bubble was approximately 20μm in radius and [...] was remarkably stable in position and shape, remained constant in size and seemed to be pulsating in a purely radial mode. With the room lights dimmed, a greenish luminous spot the size of a pinpoint could be seen with the unaided eye, near the bubble's position in the liquid" [2].

Only through a detailed investigation of the bubble dynamics through Mie scattering one could demonstrate that it was a *single* bubble which was emitting light. With that method Gaitan et al. [1, 2] demonstrated that indeed it was a single bubble, undergoing its oscillations at a fixed,

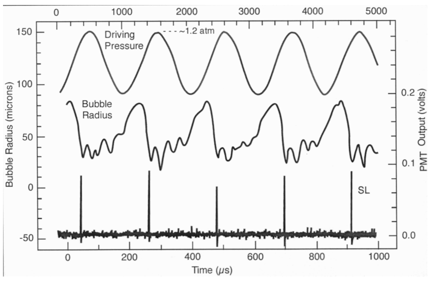

FIGURE 1. Figure of the radius, the driving pressure, and the light intensity from ref. [4], as measured in ref. [2]. A negative driving pressure causes the bubble to expand; when the driving pressure changes sign, the bubble collapses, resulting in a short pulse of light.

stable position at the pressure antinode of the ultrasound field in the flask. The oscillation frequency is that of the sinusoidal driving sound (typically 20-40 kHz), but the dynamics of the bubble radius is strongly nonlinear. Once during each oscillation period, a bubble whose undriven (ambient) radius is typically around 5μm collapses very rapidly from its maximum radius $\sim 50\mu$m to a minimum radius of $\sim 0.5\mu$m, changing its volume by a factor of one million. Figure 1 shows the radius, forcing pressure, and the light intensity during this process [4]. The bubble expansion caused by the negative pressure is followed by a violent collapse, where light is emitted. The process repeats itself with extraordinary precision, as demonstrated by measurements of the phase of the light emission relative to the driving. It had been that figure that established single bubble sonoluminescence.

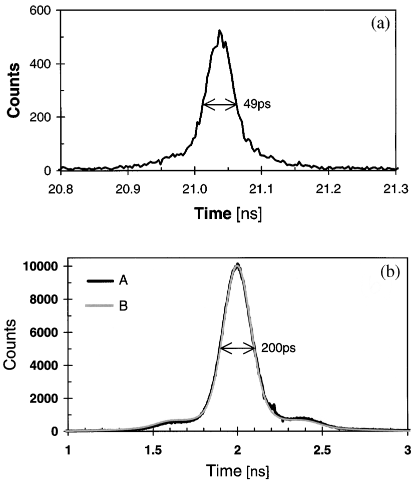

FIGURE 2. Shape of the light pulse as measured in ref. [6]. curve (A): SL pulse as measured with time correlated single photon counting with a UV filter (300-400nm). The two smaller peaks left and right of the main peak are due to reflections of the SL pulse off the glass flask. curve (B): convolution of a theoretical model (based on uniform heating of the bubble) with the experimental response function.

Gaitan's discovery set off speculations in the scientific community about the limits of the energy focusing potential of a bubble, and the mechanism by which the energy was converted into light. A tidal wave of research ensued. This research aimed at elucidating the essential principles governing SBSL, with the hope of harnessing its energy focusing power. In the intervening years much has been learned about how and why single bubble sonoluminescence occurs.

Though in the beginning of the research on SBSL it had been suspected that 50ps is an upper bound for the length of the light pulse [5], Gompf and collaborators [6] discovered that the width of the light pulse is actually of order a few hundred picoseconds, using time-correlated single-photon counting (see figure 2). Moreover, since Gompf et al. could now resolve the shape of the light pulse, it was possible to study the dependence of the width on external parameters (the forcing pressure and dissolved gas concentration), giving benchmarks for all theoretical efforts.

The goal of this talk is to clarify the basic ideas that have proven necessary for a quantitative understanding of single bubble sonoluminescence, and to present an overview of the current state of the field, of what is known and what is yet to be fully understood. The talk is based on the review article [7].

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