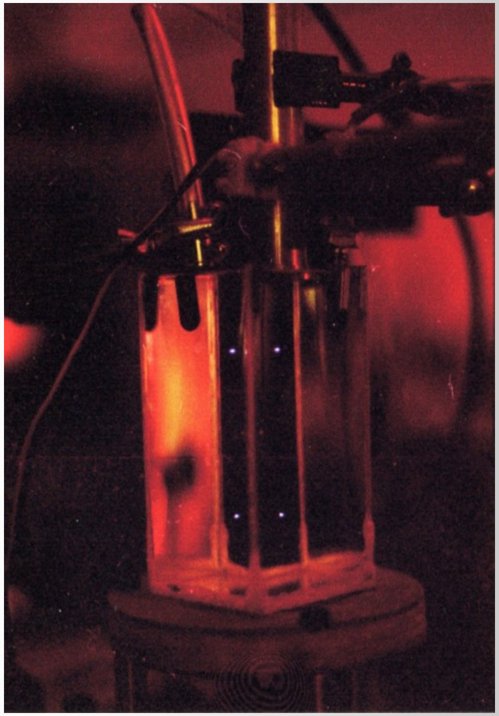
Sonoluminescence



has a long story in scientific literature

(can be obtained in two “flavours”!)

“Multibubble”

* Discovered in 1933 by Marinesco and Trillat, during ultrasonic emulsification experiments

* Investigated by means of photographic techniques from 1935, Marinesco e Reggiani (multiple bubbles)

“Single-Bubble”

* Discovered in 1962 by Yosioka and Omura.

> “The light emission from a single bubble driven by ultrasound and the spectra of acoustic oscillation”, Proc. Annual Meet. Acoust. Soc. Jpn, pp 125-126, in Japanese

* Re-discovered in 1992 by Gaitan and Crum.

Actually:
Cavitation Luminescence
(no direct conversion from sound to light)

THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 25, NUMBER 6 NOVEMBER, 1953

A Simple Calibration Technique for Low-Sensitivity Transducers

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Department of Physics, University of California at Los Angeles, Los Angeles, California

(Received August 7, 1953)

The cavitation threshold of water supersaturated with air at hydrostatic pressure is utilized as a pressure reference level against which the output of a transducer may be referred. The threshold may be determined within 0.2 decibel in a purely radial standing-wave field. A simple system is described for performing the measurements.

ACCELERATED interest in studies of high-amplitude acoustic waves in both water and air has made practical the use of small probe mounted trans-

acoustic pressure against which the pressure response of the transducer may be comp

extremely simple and may be i

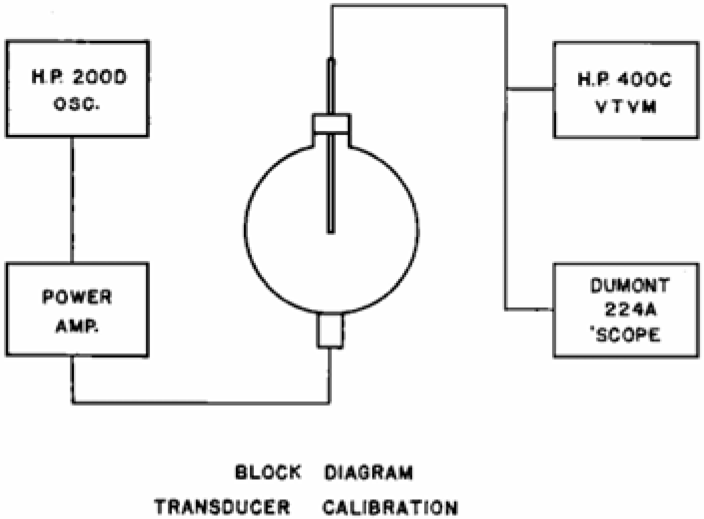


Fig. 1. Block diagram—transducer calibration.

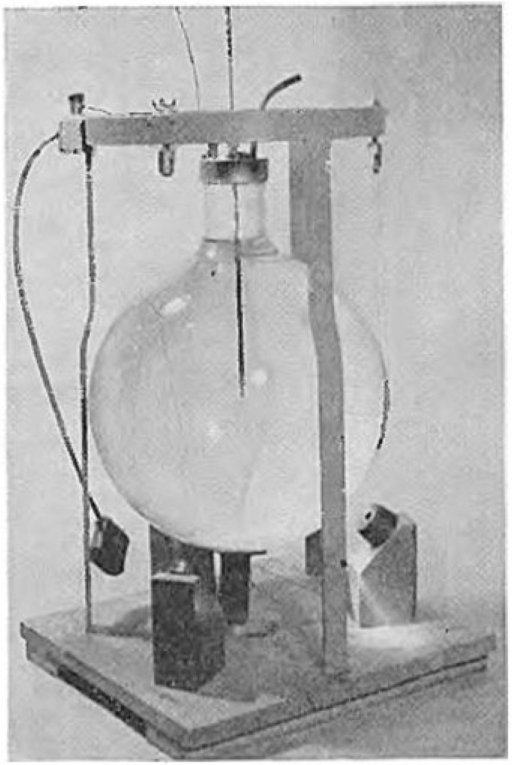
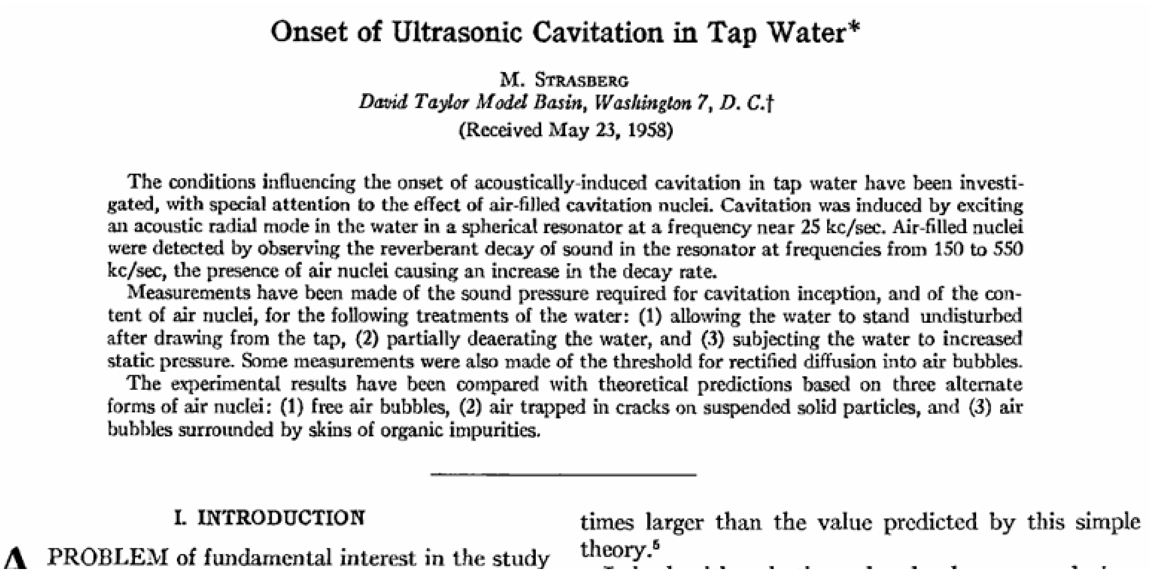


Fig. 2. "Resonator" suspension.



Onset of Ultrasonic Cavitation in Tap Water*

M. STRASBERG
David Taylor Model Basin, Washington 7, D. C.†

(Received May 23, 1958)

The conditions influencing the onset of acoustically-induced cavitation in tap water have been investigated, with special attention to the effect of air-filled cavitation nuclei. Cavitation was induced by exciting an acoustic radial mode in the water in a spherical resonator at a frequency near 25 kc/sec. Air-filled nuclei were detected by observing the reverberant decay of sound in the resonator at frequencies from 150 to 550 kc/sec, the presence of air nuclei causing an increase in the decay rate.

Measurements have been made of the sound pressure required for cavitation inception, and of the content of air nuclei, for the following treatments of the water: (1) allowing the water to stand undisturbed after drawing from the tap, (2) partially deaerating the water, and (3) subjecting the water to increased static pressure. Some measurements were also made of the threshold for rectified diffusion into air bubbles.

The experimental results have been compared with theoretical predictions based on three alternate forms of air nuclei: (1) free air bubbles, (2) air trapped in cracks on suspended solid particles, and (3) air bubbles surrounded by skins of organic impurities.

I. INTRODUCTION

A PROBLEM of fundamental interest in the study

times larger than the value predicted by this simple theory.[5]

THE JOURNAL OF THE ACOUSTICAL SOCIETY OF AMERICA VOLUME 31, NUMBER 2 · FEBRUARY, 1959

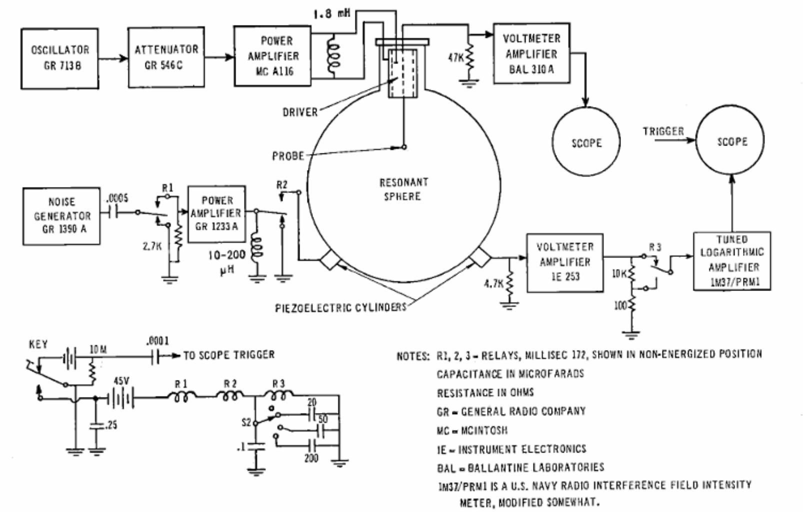


FIG. 2. The electronic instrumentation. The instruments for measuring the threshold for cavitation are along the top row. The other equipment is for the detection of gas-filled nuclei by measuring the reverberation decay.

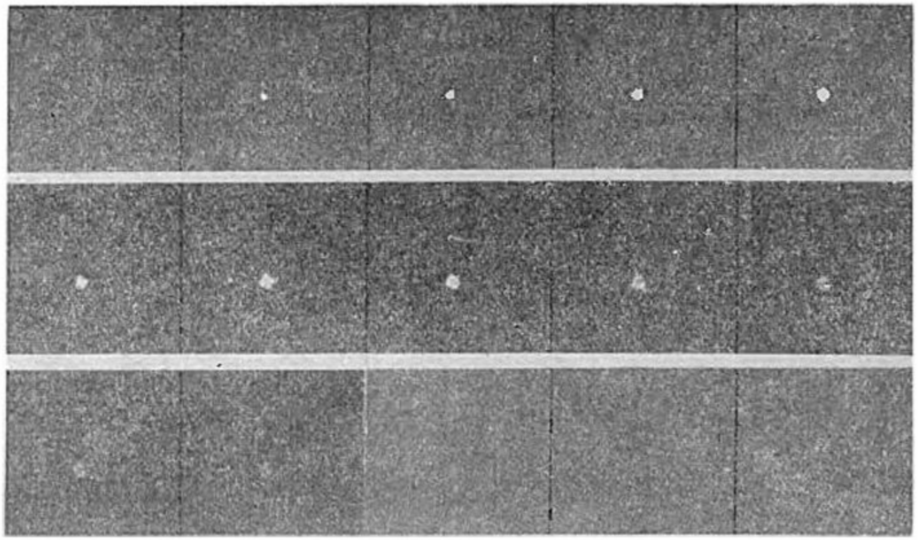


FIG. 10. Frames from a motion picture showing the formation and disappearance of a transient vaporous cavity. Time→ 5000 frames/sec.

Sonoluminescence and bubble dynamics for a single, stable, cavitation bubble

D. Felipe Gaitan,[a] Lawrence A. Crum, Charles C. Church, and Ronald A. Roy
National Center for Physical Acoustics, University of Mississippi, Coliseum Drive, University, Mississippi 38677

(Received 8 July 1991; revised 28 January 1992; accepted 29 January 1992)

High-amplitude radial pulsations of a single gas bubble in several glycerine and water mixtures have been observed in an acoustic stationary wave system at acoustic pressure amplitudes on the order of 150 kPa (1.5 atm) at 21–25 kHz. Sonoluminescence (SL), a phenomenon generally attributed to the high temperatures generated during the collapse of cavitation bubbles, was observed as short light pulses occurring once every acoustic period. These emissions can be seen to originate at the geometric center of the bubble when observed through a microscope. It was observed that the light emissions occurred simultaneously with the bubble collapse. Using a laser scattering technique, experimental radius-time curves have been obtained which confirm the absence of surface waves, which are expected at pressure amplitudes above 100 kPa. [S. Horsburgh, Ph.D. dissertation, University of Mississippi (1990)]. Also from these radius-time curves, measurements of the pulsation amplitude, the timing of the major bubble collapse, and the number of rebounds were made and compared with several theories. The implications of this research on the current understanding of cavitation related phenomena such as rectified diffusion, surface wave excitation, and sonoluminescence are discussed.

PACS numbers: 43.25.Yw, 43.35.Sx

INTRODUCTION

The subject of this paper is the dynamics of bubbles in acoustic cavitation fields of moderate intensities. Acoustic

under these conditions. Researchers therefore have been forced to describe such cavitation systems in terms of ensemble average quantities, or to assume that SL was produced only for a small range of parameter values. In this paper, we

3166 J. Acoust. Soc. Am. 91 (6), June 1992

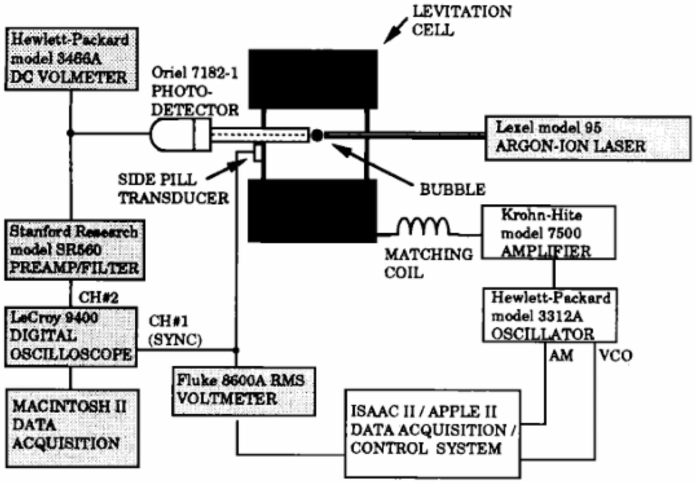


FIG. 1. A sonoluminescing bubble. The dot in the center of the jar is the bubble emitting light. From Crum, 1994.

Single-Bubble Sonoluminescence


I.E.N.G.F. 1999

Repeated light flashes emission from a single (and the same?) cavitating gas bubble in a stationary sound field.

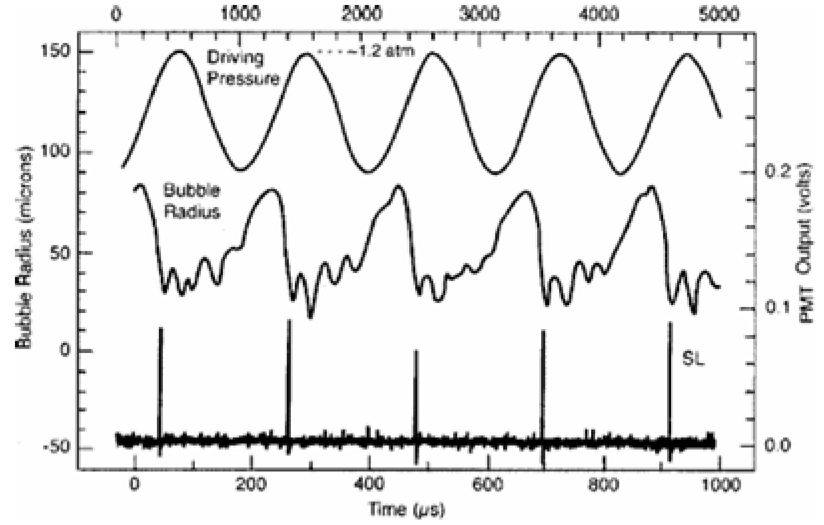


FIG. 3. Radius $R(t)$, driving pressure $P(t)$, and light intensity $I(t)$ from Crum (1994), as measured by Gaitan *et al.* (1992). A negative driving pressure causes the bubble to expand; when the driving pressure changes sign, the bubble collapses, resulting in a short pulse of light, marked SL.

Acoustic Period:
T~50μs

Collapse time scale:
T~20ns

Light flash duration:
Δt~100ps

Single-Bubble Sonoluminescence:

Light Flashes: featureless spectra from Single Bubbles in (salt) Water

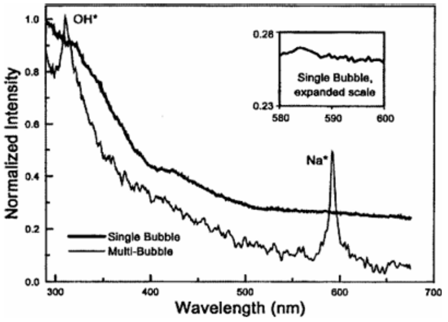
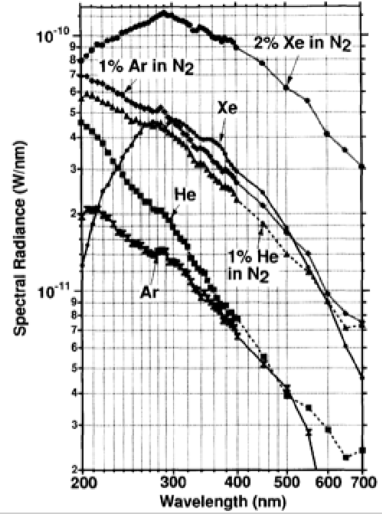


FIG. 6. MBSL (thin line) and SBSL (thick line) spectra in a 0.1M sodium chloride solution. Each spectrum was normalized to its highest intensity. Note the prominence (MBSL) and absence (SBSL, see the inset for an enlargement) of the sodium line near 589 nm. Figure reproduced from Matula *et al.* (1995).



Single-bubble sonoluminescence

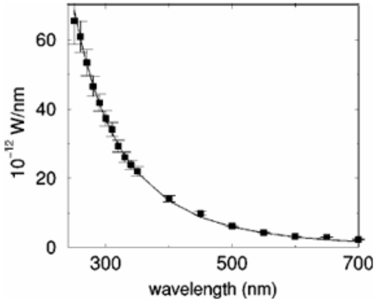


FIG. 5. Spectrum of single-bubble sonoluminescence, for water at 22 °C. The data points are redrawn from Fig. 1 of Hiller *et al.* (1992). Fits to a blackbody spectrum can be attempted for different temperatures, with best results for about 40 000 K (solid line), higher than the 25 000 K suggested by Hiller *et al.* (1992).

… but not in Sulphuric Acid:

PRL **95,** 044301 (2005) PHYSICAL REVIEW LETTERS week ending 22 JULY 2005

Plasma Line Emission during Single-Bubble Cavitation

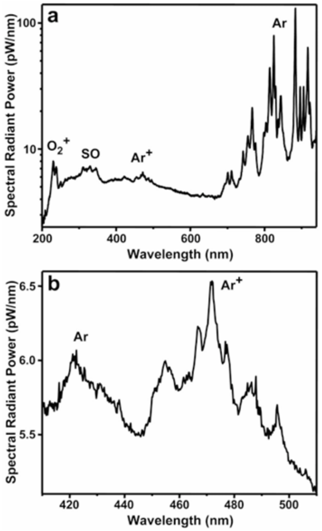
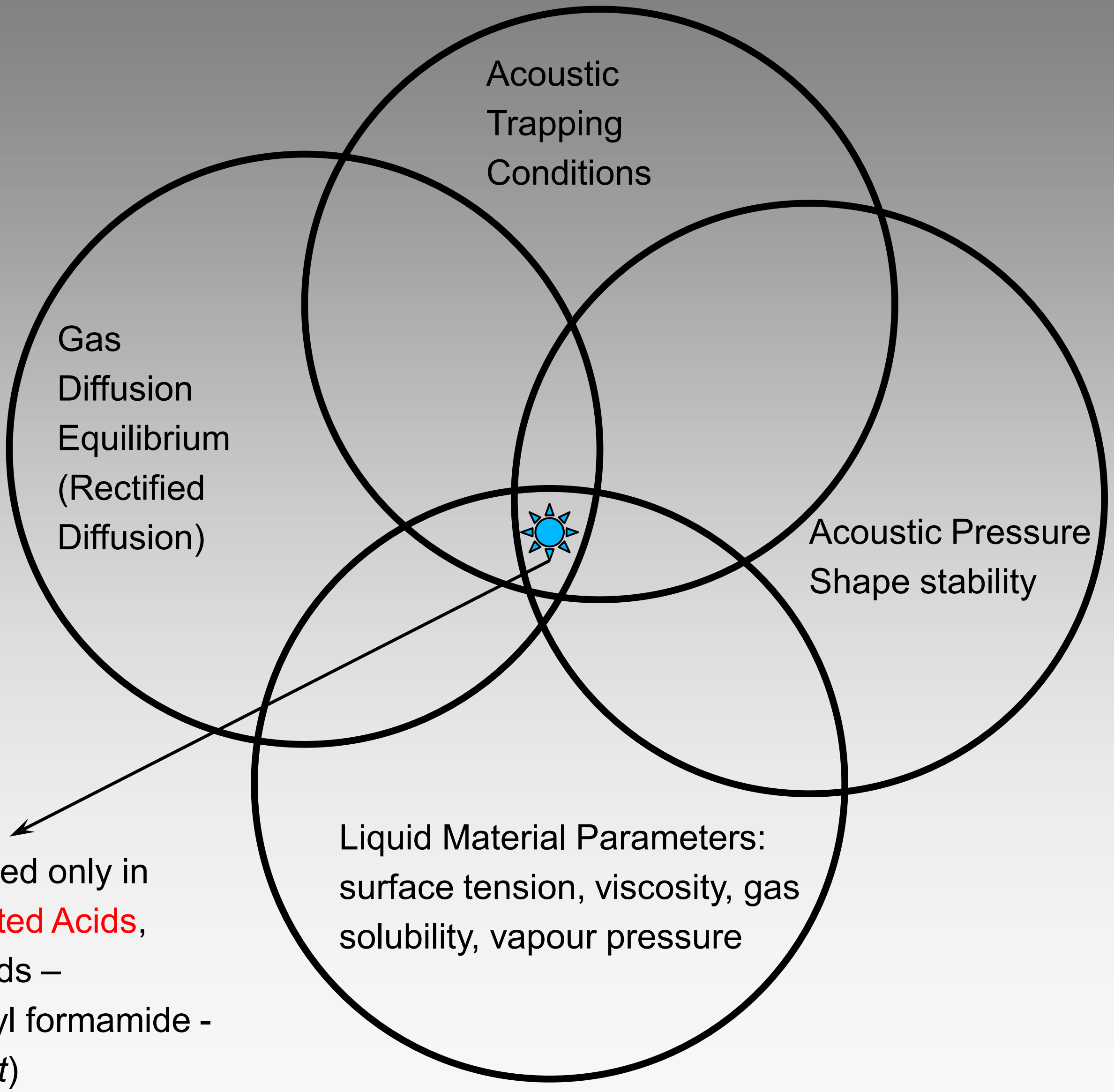


FIG. 1. SBSL spectra from 85% H_2SO_4 with 50 torr Ar and $P_a = 2.2$ bar. (a) SBSL spectrum showing emission from Ar^+ as well as Ar, O_2^+, and SO. States in the $4p$-$4s$ manifold involved in emission of the red and near-IR atomic Ar lines (> 690 nm) lie at 13.1–13.5 and 11.5–11.8 eV, respectively [20]. (b) Enlarged region of the SBSL spectrum from 410 to 510 nm. The states in the $5p$-$4s$ manifold involved in emission of the Ar lines in the visible (410–450 nm) lie at 14.5–14.7 and 11.5–11.8 eV, respectively. The states involved in the observed Ar^+ emission (450–500 nm) are in the $4p$-$4s$ manifold; the Ar^+ $4p$ and $4s$ states lie at 35.0–37.1 and 32.4–34.2 eV above the Ar ground state ($3p^6$), respectively [20].

Single-Bubble Sonoluminescence

This phenomenon requires a fine tuning of parameters.

Main Actors:



Acoustic
Trapping
Conditions

Gas
Diffusion
Equilibrium
(Rectified
Diffusion)

Acoustic Pressure
Shape stability

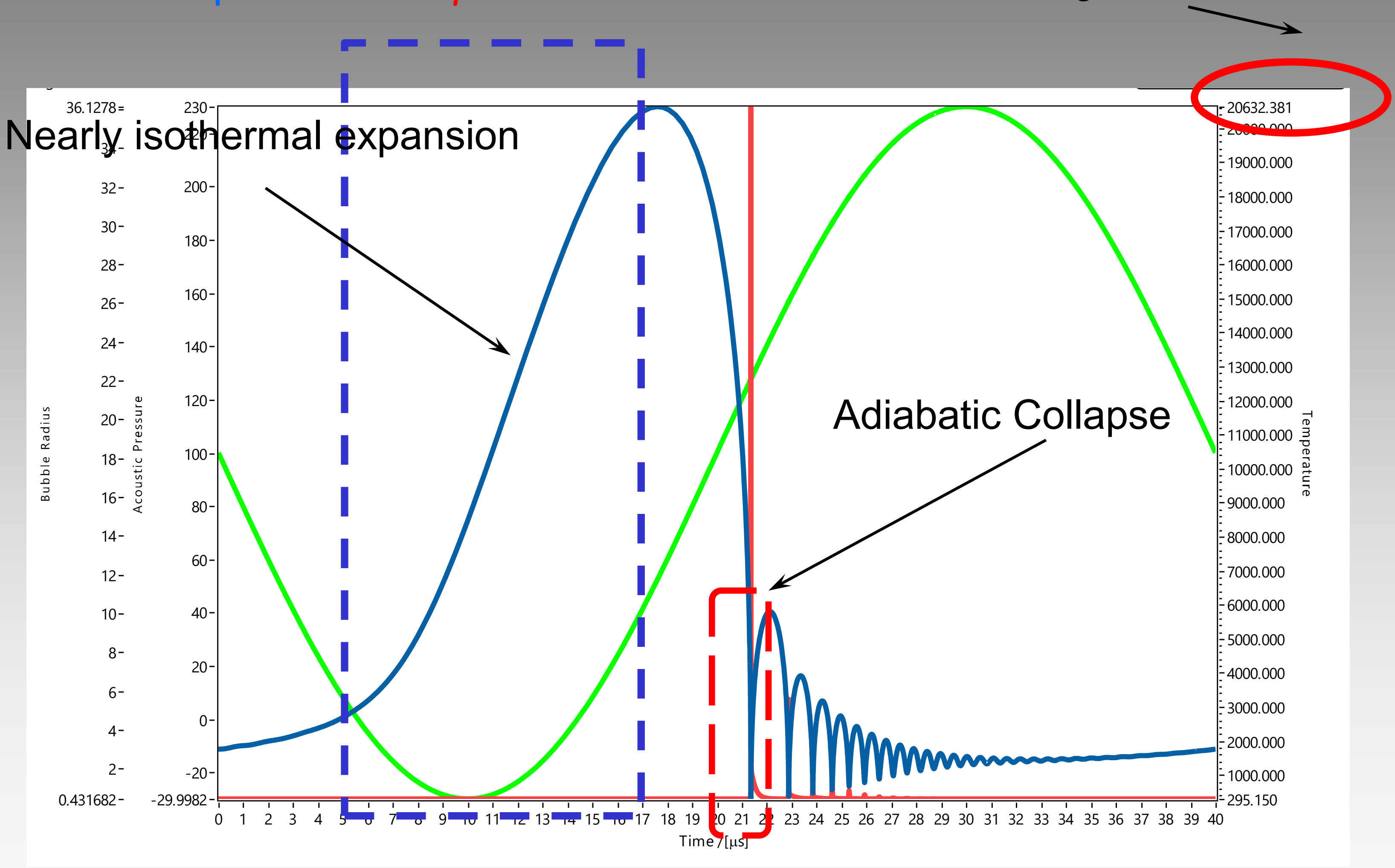
Liquid Material Parameters:
surface tension, viscosity, gas
solubility, vapour pressure

SBSL was observed only in
Water, Concentrated Acids,
Polar Aprotic liquids –
adiponitrile, methyl formamide -
(with some *caveat*)

Single-Bubble Sonoluminescence

Why SBSL is so interesting for physicists?.

Is it possible to *upscale* the emission?.


High Pressure and Temperature

Nearly isothermal expansion

Adiabatic Collapse

Gas bubble as a thermodynamic motor

Single-Bubble Sonoluminescence

A very useful TOY MODEL:

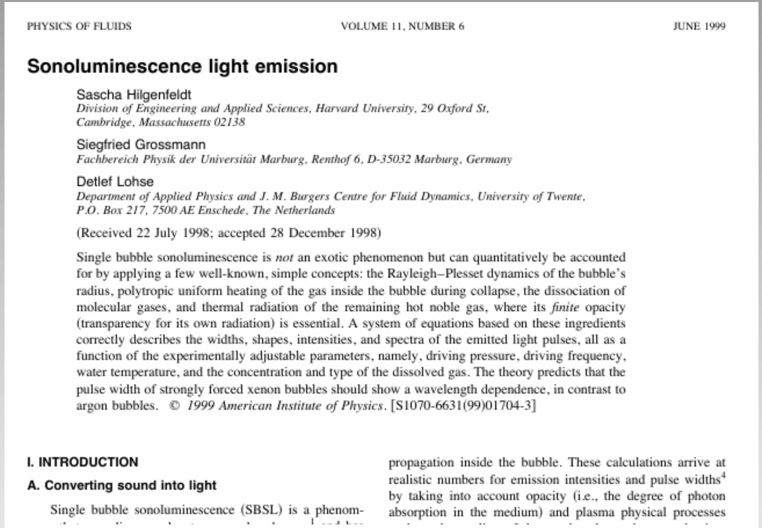
-Bubble-wall dynamics -> simplified Keller-Prosperetti equation:

$$\left[1-(\lambda+1)\frac{\dot{R}}{c_\infty}\right]R\ddot{R}+\frac{3}{2}\left[1-\frac{1}{3}(3\lambda+1)\frac{\dot{R}}{c_\infty}\right]\dot{R}^2=\left[1+(1-\lambda)\frac{\dot{R}}{c_\infty}+\frac{R}{c_\infty}\frac{d}{dt}\right]\left(h_B-\frac{P_{ac}}{\rho_\infty}\right)$$

-Gas bubble -> uniform pressure, uniform temperature, constant gas content

-Liquid -> Isothermal

- Simple heat-exchange equation, gas γ depends on T R, R'



PHYSICS OF FLUIDS VOLUME 11, NUMBER 6 JUNE 1999

Sonoluminescence light emission

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(Received 22 July 1998; accepted 28 December 1998)

Single bubble sonoluminescence is *not* an exotic phenomenon but can quantitatively be accounted for by applying a few well-known, simple concepts: the Rayleigh–Plesset dynamics of the bubble's radius, polytropic uniform heating of the gas inside the bubble during collapse, the dissociation of molecular gases, and thermal radiation of the remaining hot noble gas, where its *finite* opacity (transparency for its own radiation) is essential. A system of equations based on these ingredients correctly describes the widths, shapes, intensities, and spectra of the emitted light pulses, all as a function of the experimentally adjustable parameters, namely, driving pressure, driving frequency, water temperature, and the concentration and type of the dissolved gas. The theory predicts that the pulse width of strongly forced xenon bubbles should show a wavelength dependence, in contrast to argon bubbles. © 1999 *American Institute of Physics*. [S1070-6631(99)01704-3]

I. INTRODUCTION

A. Converting sound into light

Single bubble sonoluminescence (SBSL) is a phenom-

propagation inside the bubble. These calculations arrive at realistic numbers for emission intensities and pulse widths[4] by taking into account opacity (i.e., the degree of photon absorption in the medium) and plasma physical processes

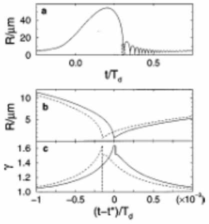
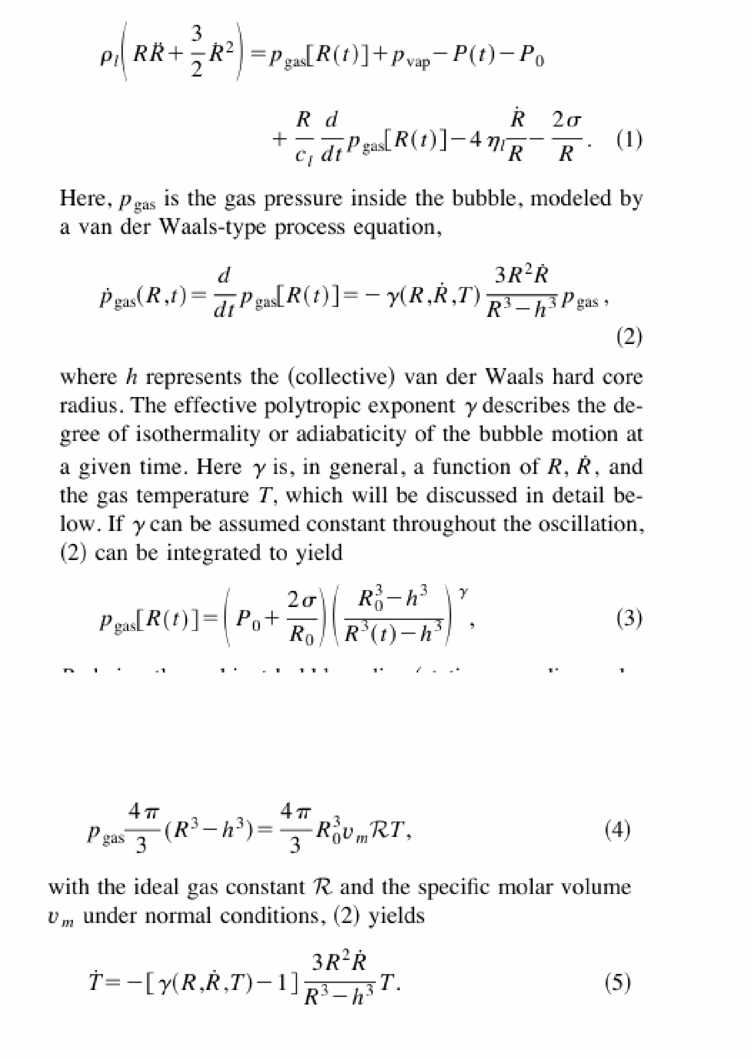


FIG. 1. (a) Time series $R(t)$ for $f=20$ kHz, $P_a=1.3$ atm, and $R_0=5.0\ \mu$m, computed from the complete system (1), (4), (6)–(10), (11) over one driving cycle. The time axis is normalized with the driving period $T_d=1/f$. The dashed box indicates the range of plots (b) and (c). (b) A close-up of $R(t)$ (solid line) around the instant t^* of minimum radius. Note the asymmetric collapse–rebound behavior. The dashed line gives the dynamics as computed without the $\gamma(t)$ modification discussed in Sec. II E. On the scale of (a) these two graphs are indistinguishable. For the same two cases, (c) gives the variation of γ in time. The modification only affects the innermost $\sim 10^{-5}T_d$ around t^*.



$$\rho_l\left(R\ddot{R}+\frac{3}{2}\dot{R}^2\right)=p_{\rm gas}[R(t)]+p_{\rm vap}-P(t)-P_0$$

$$+\frac{R}{c_l}\frac{d}{dt}p_{\rm gas}[R(t)]-4\eta_l\frac{\dot{R}}{R}-\frac{2\sigma}{R}. \quad (1)$$

Here, $p_{\rm gas}$ is the gas pressure inside the bubble, modeled by a van der Waals-type process equation,

$$\dot{p}_{\rm gas}(R,t)=\frac{d}{dt}p_{\rm gas}[R(t)]=-\gamma(R,\dot{R},T)\frac{3R^2\dot{R}}{R^3-h^3}p_{\rm gas}, \quad (2)$$

where h represents the (collective) van der Waals hard core radius. The effective polytropic exponent γ describes the degree of isothermality or adiabaticity of the bubble motion at a given time. Here γ is, in general, a function of R, $\dot{R}$, and the gas temperature T, which will be discussed in detail below. If γ can be assumed constant throughout the oscillation, (2) can be integrated to yield

$$p_{\rm gas}[R(t)]=\left(P_0+\frac{2\sigma}{R_0}\right)\left(\frac{R_0^3-h^3}{R^3(t)-h^3}\right)^\gamma, \quad (3)$$

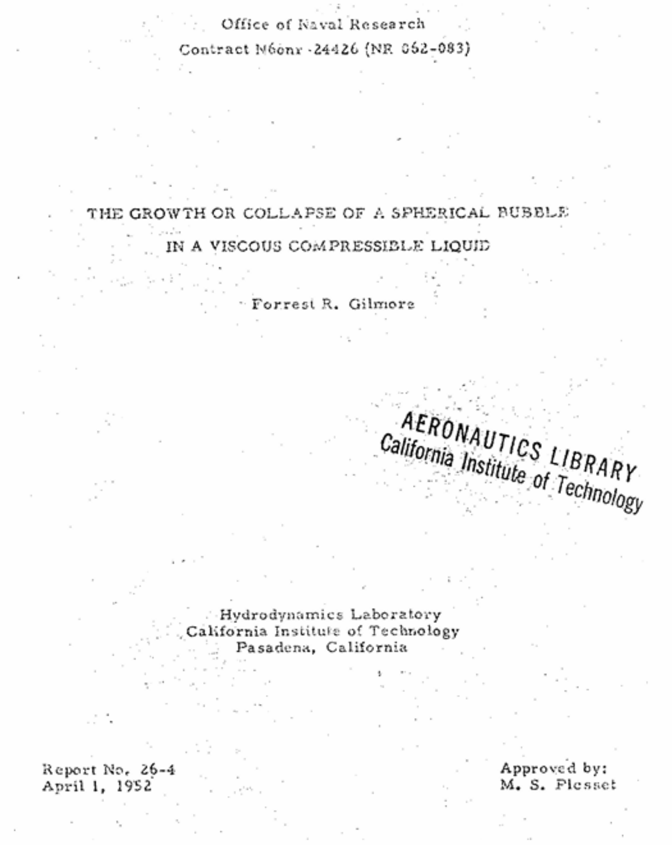
$$p_{\rm gas}\frac{4\pi}{3}(R^3-h^3)=\frac{4\pi}{3}R_0^3 v_m\mathcal{R}T, \quad (4)$$

with the ideal gas constant $\mathcal{R}$ and the specific molar volume v_m under normal conditions, (2) yields

$$\dot{T}=-[\gamma(R,\dot{R},T)-1]\frac{3R^2\dot{R}}{R^3-h^3}T. \quad (5)$$

Single-Bubble Sonoluminescence

Bubble-wall dynamics can be slightly improved using the GILMORE equation, 1952 (in SBSL conditions, the bubble wall motion remains subsonic…)



Office of Naval Research
Contract N6onr-24426 (NR 062-083)

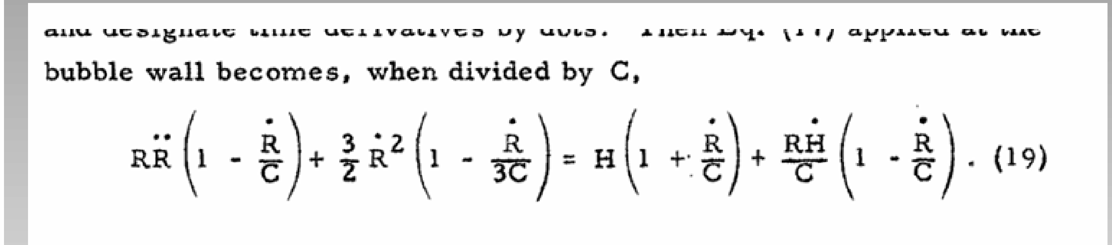
THE GROWTH OR COLLAPSE OF A SPHERICAL BUBBLE
IN A VISCOUS COMPRESSIBLE LIQUID

Forrest R. Gilmore

Hydrodynamics Laboratory
California Institute of Technology
Pasadena, California

Report No. 26-4
April 1, 1952

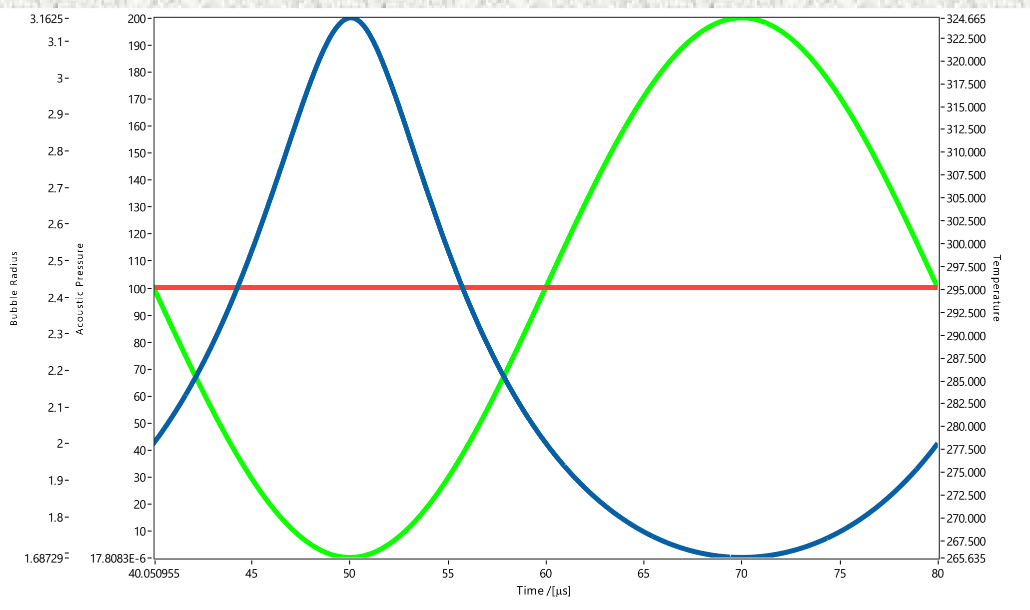
Approved by:
M. S. Plesset



and designate time derivatives by dots. Then Eq. (17) applied at the bubble wall becomes, when divided by C,

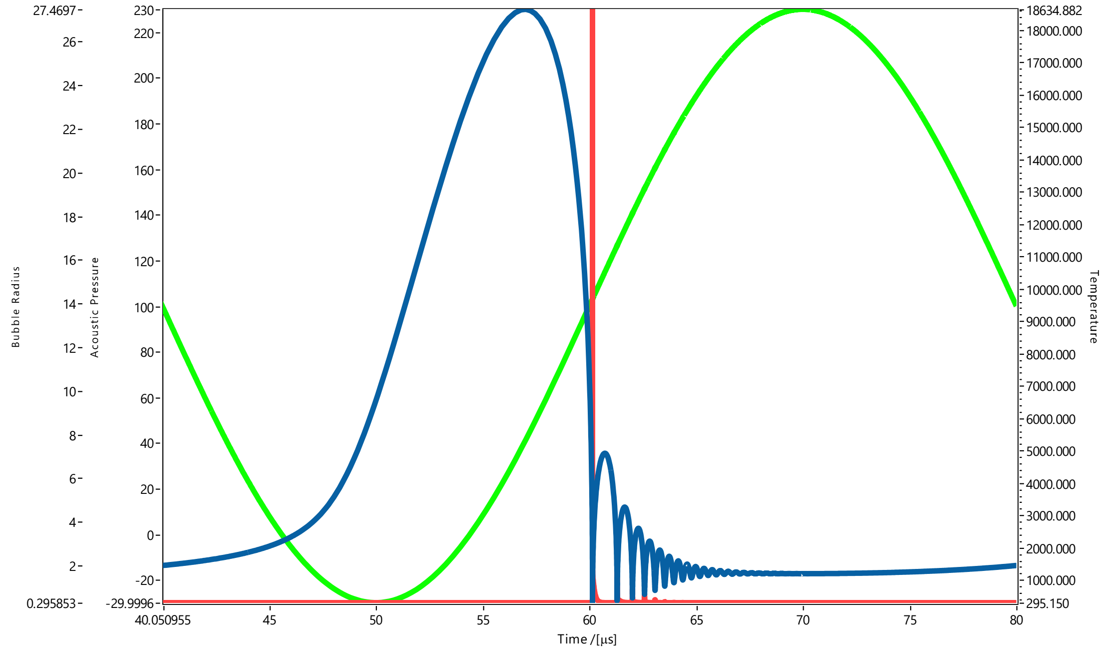
$$R\ddot{R}\left(1-\frac{\dot{R}}{C}\right)+\frac{3}{2}\dot{R}^{2}\left(1-\frac{\dot{R}}{3C}\right)=H\left(1+\frac{\dot{R}}{C}\right)+\frac{R\dot{H}}{C}\left(1-\frac{\dot{R}}{C}\right). \qquad (19)$$

Role of the Acoustic Pressure Level: non-linear oscillations



R_o=2.0 µm, P_{ac}=0.1 MPa

R_o=2.0 µm, P_{ac}=0.13 MPa



Single-Bubble Sonoluminescence

Acoustic Trapping/Levitation: Primary Bjerknes Force

$$\langle \vec{F}(\vec{x},\ t)\rangle = -\langle V(t)\,\nabla P_{liq}(\vec{x},\ t)\rangle$$

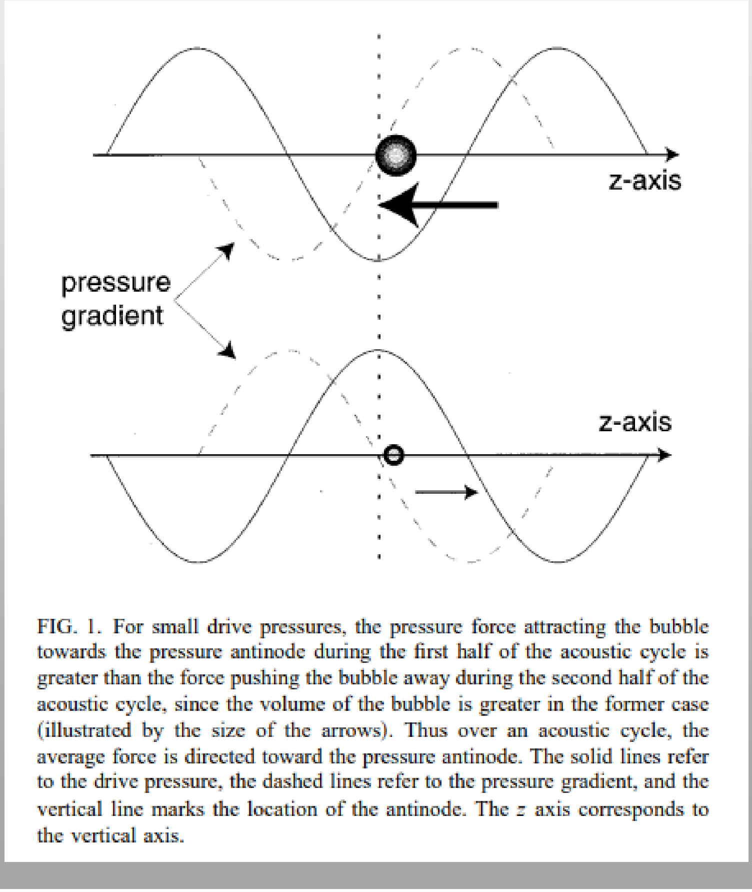
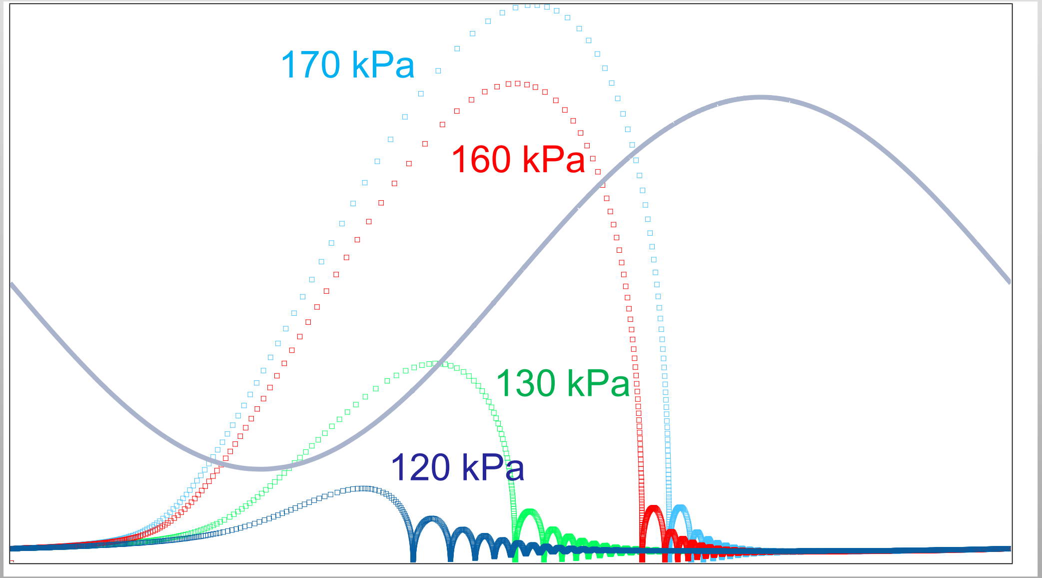


FIG. 1. For small drive pressures, the pressure force attracting the bubble towards the pressure antinode during the first half of the acoustic cycle is greater than the force pushing the bubble away during the second half of the acoustic cycle, since the volume of the bubble is greater in the former case (illustrated by the size of the arrows). Thus over an acoustic cycle, the average force is directed toward the pressure antinode. The solid lines refer to the drive pressure, the dashed lines refer to the pressure gradient, and the vertical line marks the location of the antinode. The z axis corresponds to the vertical axis.

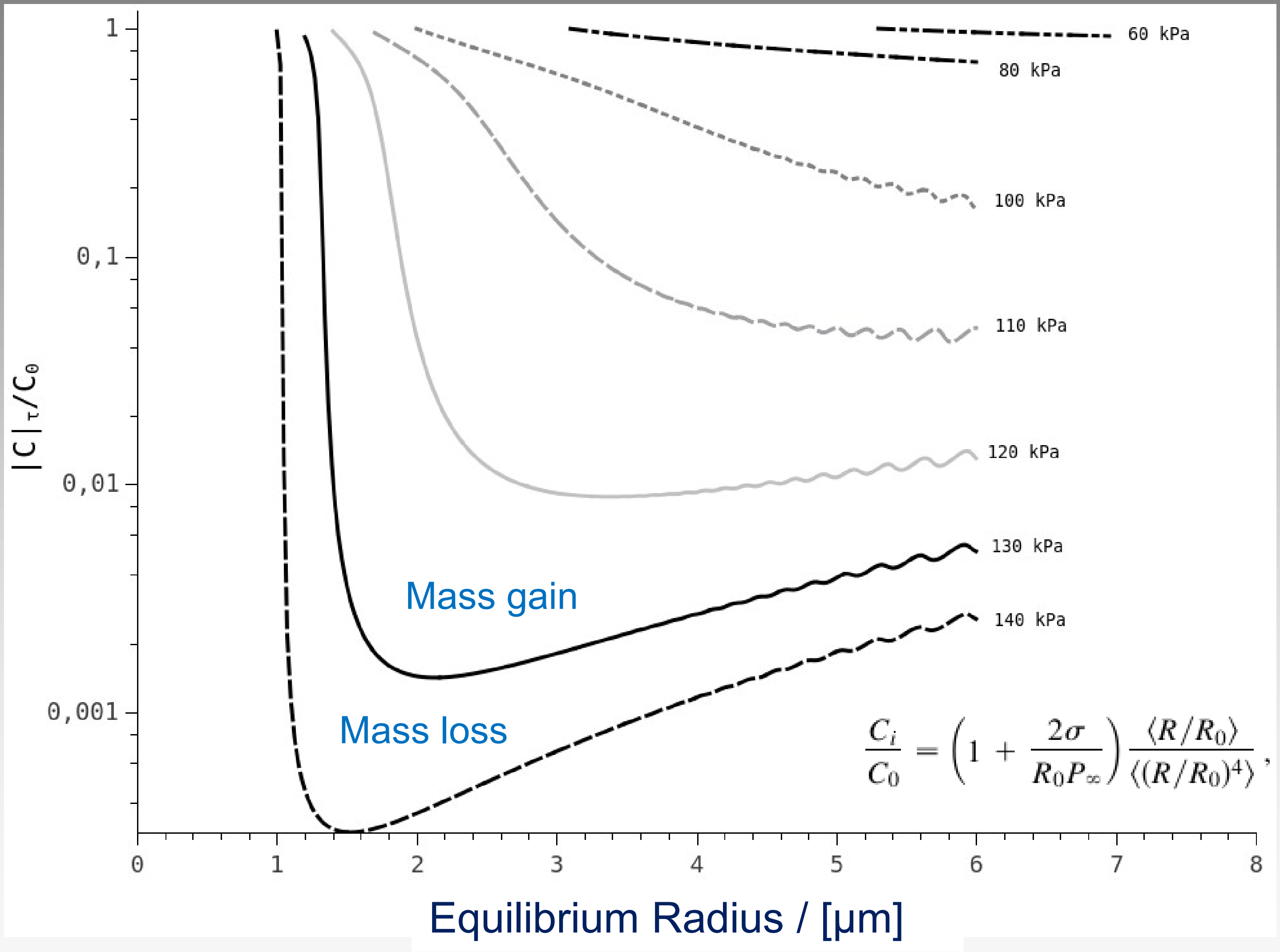
J. Acoust. Soc. Am., Vol. 102, No. 3, September 1997 Matula *et al.*: Bjerknes force and bubble levitation 1523



The Acoustic antinode trap becomes less effective at high driving pressure

Single-Bubble Sonoluminescence

- Diffusive Stability

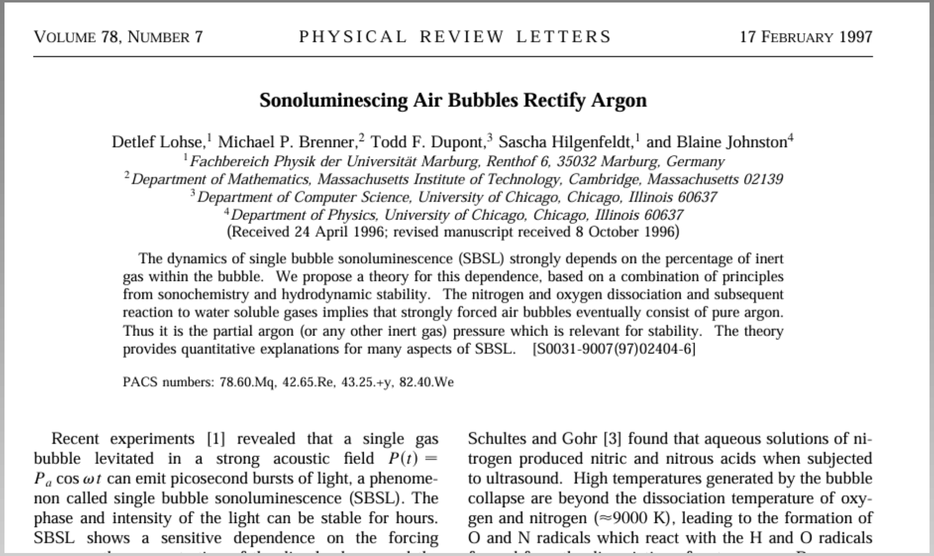


$$\frac{C_i}{C_0} = \left(1 + \frac{2\sigma}{R_0 P_\infty}\right) \frac{\langle R/R_0 \rangle}{\langle (R/R_0)^4 \rangle},$$

ISTITUTO NAZIONALE DI RICERCA METROLOGICA

Single-Bubble Sonoluminescence

- Diffusive Stability: Sonoluminescing Bubbles Rectify Argon



VOLUME 78, NUMBER 7 PHYSICAL REVIEW LETTERS 17 FEBRUARY 1997

Sonoluminescing Air Bubbles Rectify Argon

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(Received 24 April 1996; revised manuscript received 8 October 1996)

The dynamics of single bubble sonoluminescence (SBSL) strongly depends on the percentage of inert gas within the bubble. We propose a theory for this dependence, based on a combination of principles from sonochemistry and hydrodynamic stability. The nitrogen and oxygen dissociation and subsequent reaction to water soluble gases implies that strongly forced air bubbles eventually consist of pure argon. Thus it is the partial argon (or any other inert gas) pressure which is relevant for stability. The theory provides quantitative explanations for many aspects of SBSL. [S0031-9007(97)02404-6]

PACS numbers: 78.60.Mq, 42.65.Re, 43.25.+y, 82.40.We

Recent experiments [1] revealed that a single gas bubble levitated in a strong acoustic field $P(t) = P_a \cos \omega t$ can emit picosecond bursts of light, a phenomenon called single bubble sonoluminescence (SBSL). The phase and intensity of the light can be stable for hours. SBSL shows a sensitive dependence on the forcing

Schultes and Gohr [3] found that aqueous solutions of nitrogen produced nitric and nitrous acids when subjected to ultrasound. High temperatures generated by the bubble collapse are beyond the dissociation temperature of oxygen and nitrogen (≈9000 K), leading to the formation of O and N radicals which react with the H and O radicals

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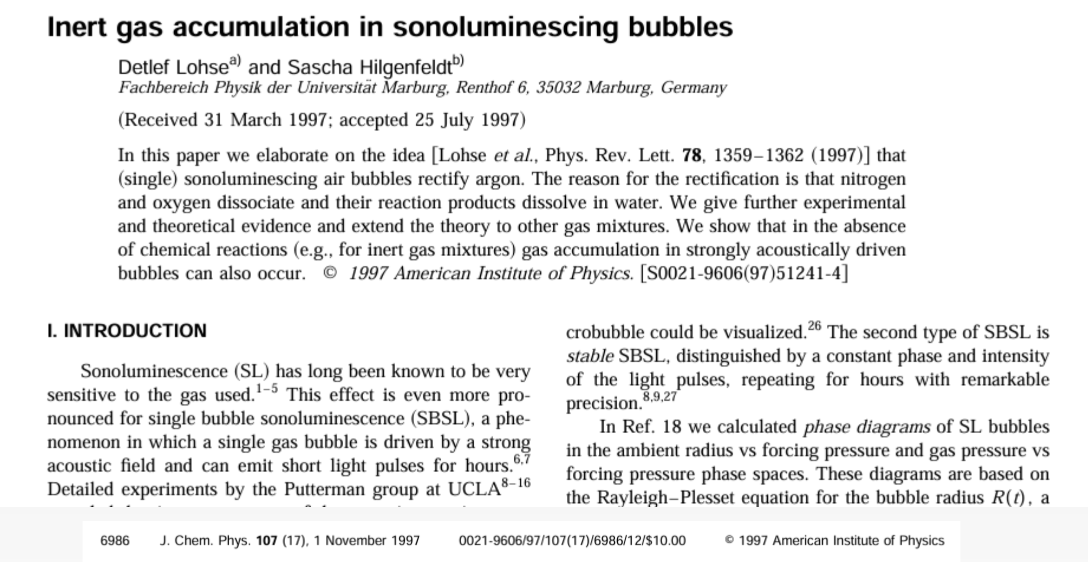

Inert gas accumulation in sonoluminescing bubbles

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(Received 31 March 1997; accepted 25 July 1997)

In this paper we elaborate on the idea [Lohse *et al.*, Phys. Rev. Lett. **78**, 1359–1362 (1997)] that (single) sonoluminescing air bubbles rectify argon. The reason for the rectification is that nitrogen and oxygen dissociate and their reaction products dissolve in water. We give further experimental and theoretical evidence and extend the theory to other gas mixtures. We show that in the absence of chemical reactions (e.g., for inert gas mixtures) gas accumulation in strongly acoustically driven bubbles can also occur. © *1997 American Institute of Physics.* [S0021-9606(97)51241-4]

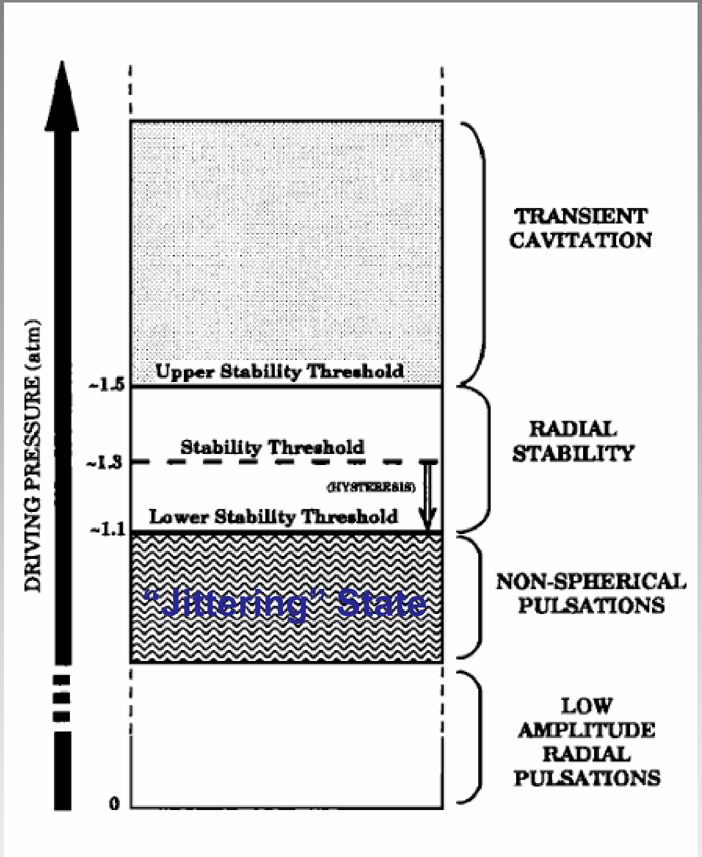
I. INTRODUCTION

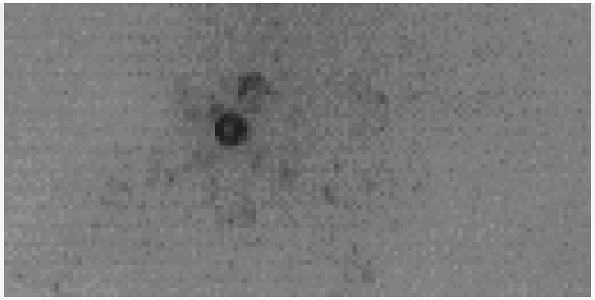
Sonoluminescence (SL) has long been known to be very sensitive to the gas used.[1–5] This effect is even more pronounced for single bubble sonoluminescence (SBSL), a phenomenon in which a single gas bubble is driven by a strong acoustic field and can emit short light pulses for hours.[6,7] Detailed experiments by the Putterman group at UCLA[8–16]

crobubble could be visualized.[26] The second type of SBSL is *stable* SBSL, distinguished by a constant phase and intensity of the light pulses, repeating for hours with remarkable precision.[8,9,27]

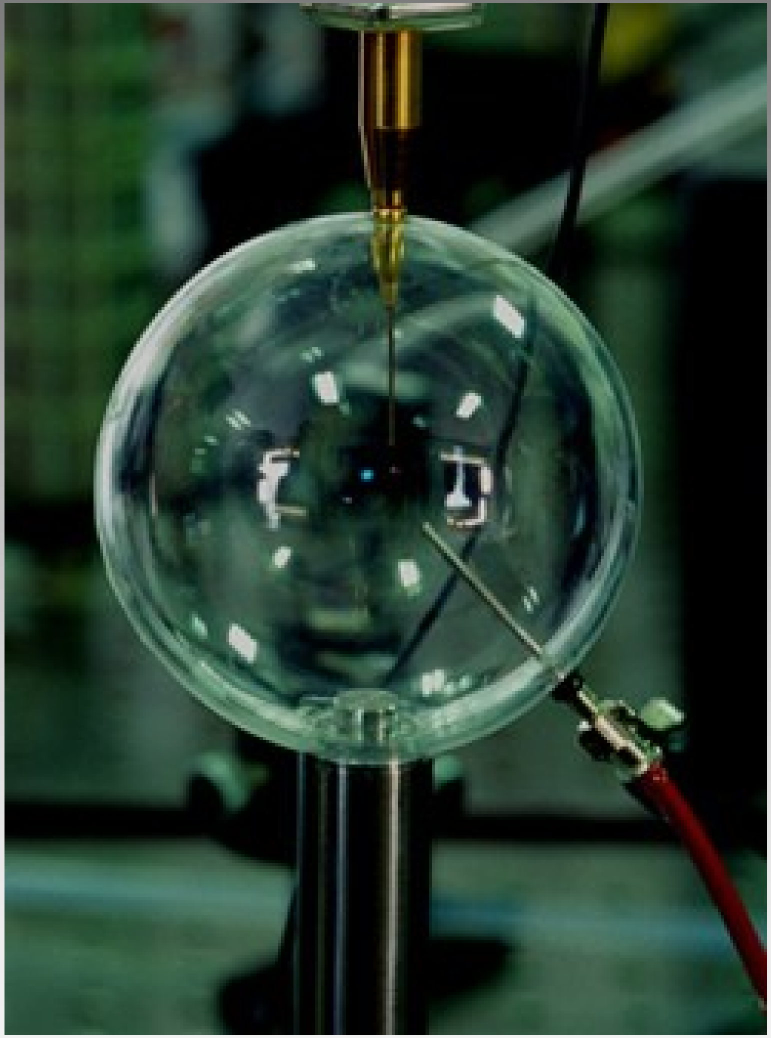
In Ref. 18 we calculated *phase diagrams* of SL bubbles in the ambient radius vs forcing pressure and gas pressure vs forcing pressure phase spaces. These diagrams are based on the Rayleigh–Plesset equation for the bubble radius $R(t)$, a

6986 J. Chem. Phys. **107** (17), 1 November 1997 0021-9606/97/107(17)/6986/12/$10.00 © 1997 American Institute of Physics

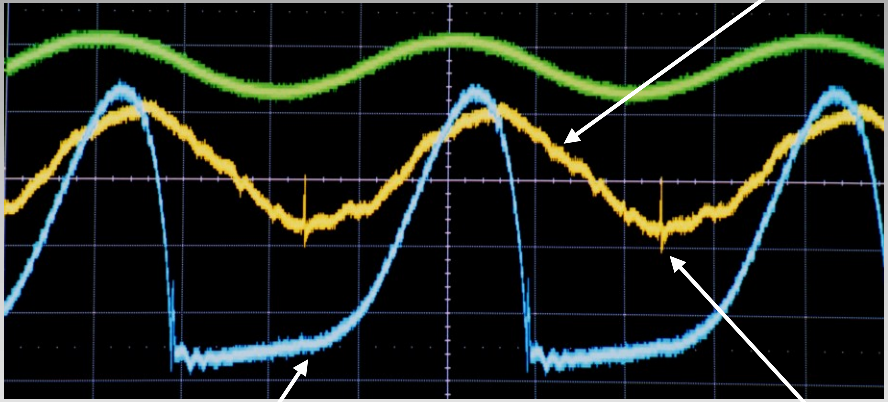




Single-Bubble Sonoluminescence



INRiM experimental apparatus: plastic spherical resonator (not so good for spectra collection).
Degassed water + Air

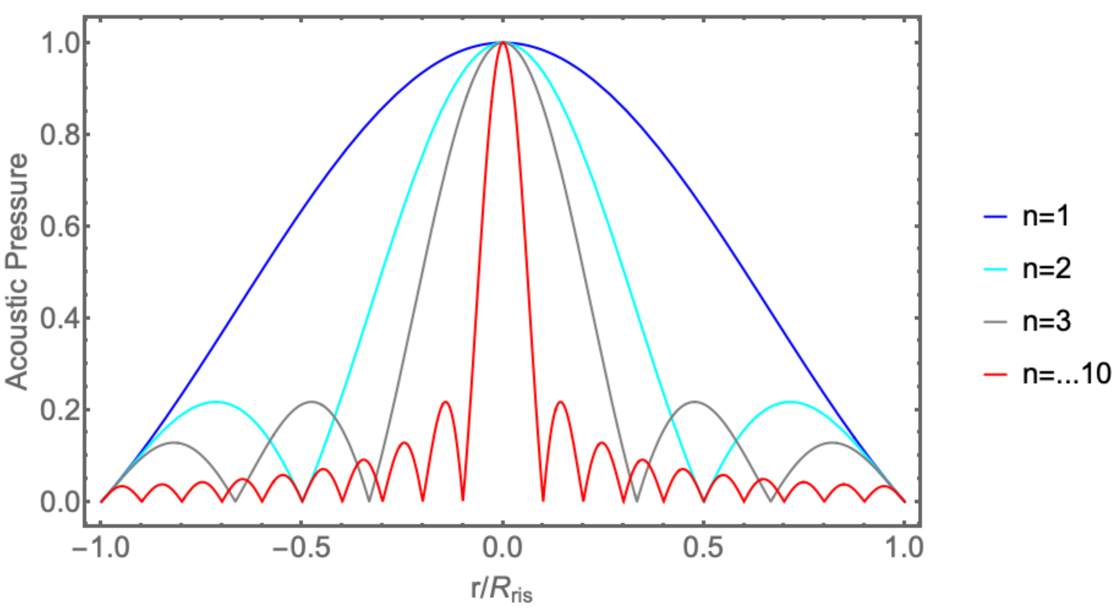


Acoustic Pressure-hydrophone Signal

Shock Wave from implosion

Mie Scattering:
Bubble Section ~ R^2

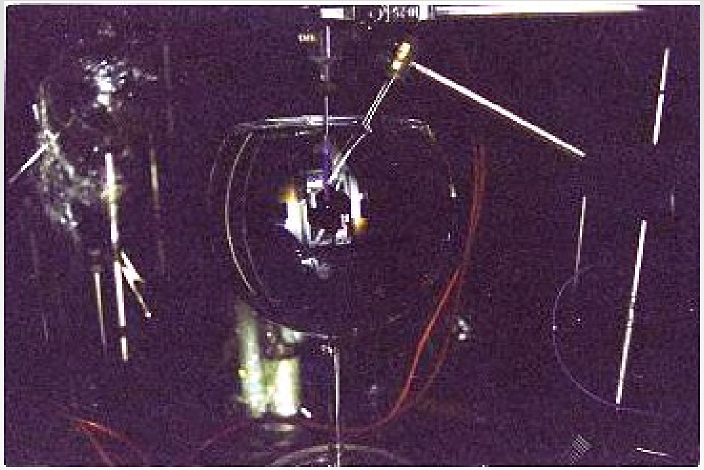
Single-Bubble Sonoluminescence



Advantages of spherical resonators:

- All radial modes can trap a bubble at the same position
- Imaging by means of spherical lenses is simpler
- Higher quality factors: less electrical power needed

INRiM 60 mm diameter polycarbonate resonator can sustain SBSL in the frequency range 25kHz-250 kHz

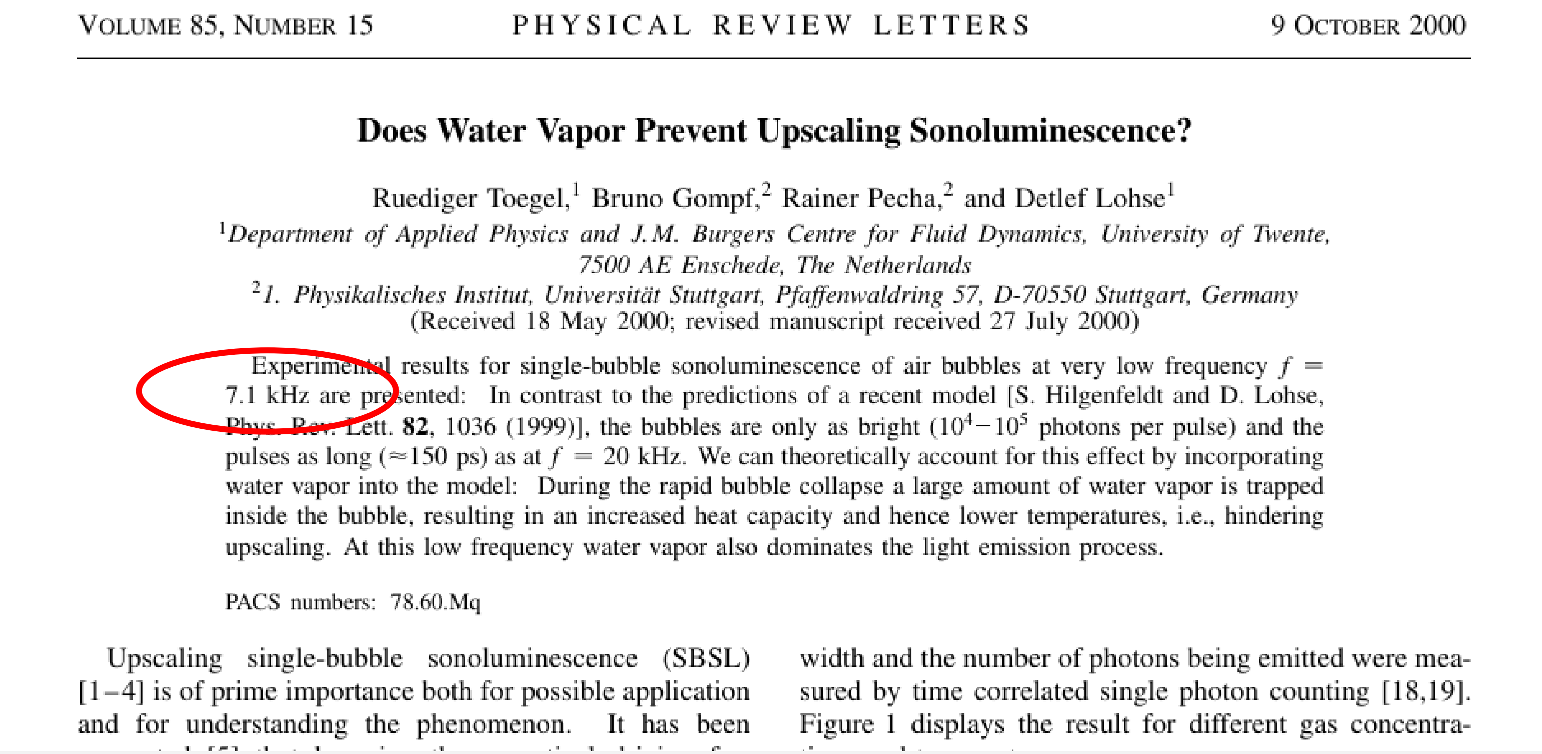


The shape of the resonator is not so important - if you have a needle hydrophone…!
A "wine-bar glass" SBSL apparatus

Single-Bubble Sonoluminescence

The upscaling problem-1: Hilgenfeldt's toy model predicts stronger collapses ***lowering*** the forcing acoustic frequency

… but:



VOLUME 85, NUMBER 15 PHYSICAL REVIEW LETTERS 9 OCTOBER 2000

Does Water Vapor Prevent Upscaling Sonoluminescence?

Ruediger Toegel,[1] Bruno Gompf,[2] Rainer Pecha,[2] and Detlef Lohse[1]

[1]*Department of Applied Physics and J.M. Burgers Centre for Fluid Dynamics, University of Twente, 7500 AE Enschede, The Netherlands*

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(Received 18 May 2000; revised manuscript received 27 July 2000)

Experimental results for single-bubble sonoluminescence of air bubbles at very low frequency $f = 7.1$ kHz are presented: In contrast to the predictions of a recent model [S. Hilgenfeldt and D. Lohse, Phys. Rev. Lett. **82**, 1036 (1999)], the bubbles are only as bright ($10^4 - 10^5$ photons per pulse) and the pulses as long (≈150 ps) as at $f = 20$ kHz. We can theoretically account for this effect by incorporating water vapor into the model: During the rapid bubble collapse a large amount of water vapor is trapped inside the bubble, resulting in an increased heat capacity and hence lower temperatures, i.e., hindering upscaling. At this low frequency water vapor also dominates the light emission process.

PACS numbers: 78.60.Mq

Upscaling single-bubble sonoluminescence (SBSL) [1–4] is of prime importance both for possible application and for understanding the phenomenon. It has been

width and the number of photons being emitted were measured by time correlated single photon counting [18,19]. Figure 1 displays the result for different gas concentra-

Single-Bubble Sonoluminescence

The upscaling problem-1: Hilgenfeldt's toy model predicts stronger collapses ***lowering*** the forcing acoustic frequency

We tried this experiment in water, with the same disappointing results…

The "fat" resonator:
- 20 litres volume
- Inner diameter about 330 mm
- Lowest trapping and sonoluminescing frequency: 4.7 kHz

Single-Bubble Sonoluminescence

The upscaling problem-2: high frequency drive (1 MHz)

Lower water vapour content

Smaller bubbles < 1 μm: the emitting region becomes transparent -> no black-body radiation

Bremsstrahlung fit ≥ 500 000 K (=> gas T~ 100 000K)

Acoustic Pressure: 500 kPa

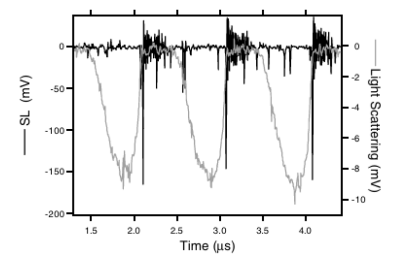
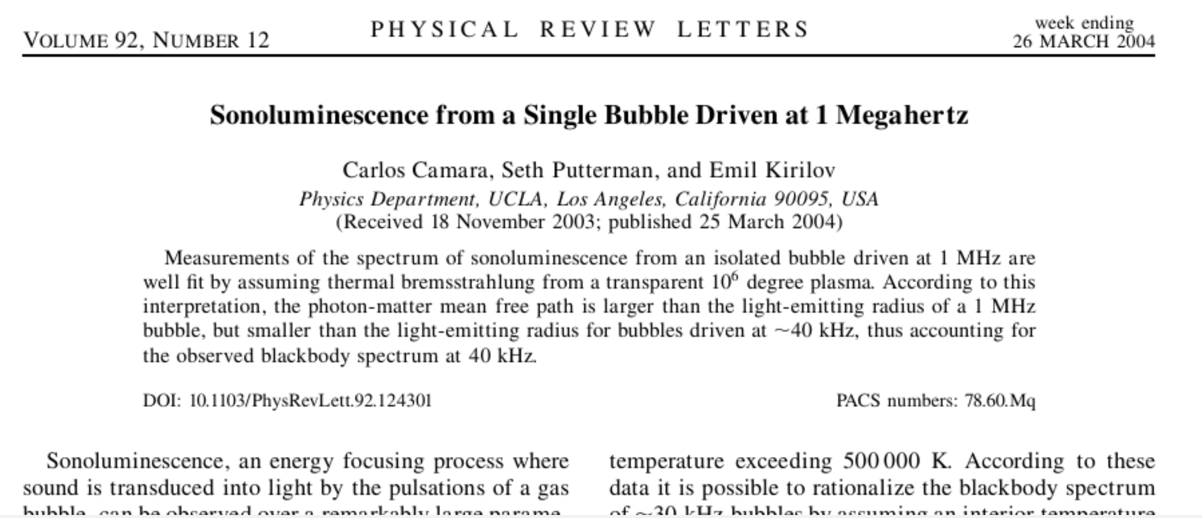


FIG. 3. Light scattering from a single SL bubble at 1 MHz.. Raw unaveraged data of light scattering (right axis) and light emission (left axis), taken with a photomultiplier tube (Hamamatsu R2027). The light scattering is taken with a low gain (−600 V) and through a neutral density 1/100 filter (ND2) to avoid saturating the PMT. The SL is taken for the same bubble by blocking the laser and removing the ND2 filter and increasing the gain to its maximum (−1200 V). All traces are timed relative to a fixed phase of the drive (Wavetek 186). The SL signals generate about two photoelectrons.



VOLUME 92, NUMBER 12 PHYSICAL REVIEW LETTERS week ending 26 MARCH 2004

Sonoluminescence from a Single Bubble Driven at 1 Megahertz

Carlos Camara, Seth Putterman, and Emil Kirilov

Physics Department, UCLA, Los Angeles, California 90095, USA

(Received 18 November 2003; published 25 March 2004)

Measurements of the spectrum of sonoluminescence from an isolated bubble driven at 1 MHz are well fit by assuming thermal bremsstrahlung from a transparent 10^6 degree plasma. According to this interpretation, the photon-matter mean free path is larger than the light-emitting radius of a 1 MHz bubble, but smaller than the light-emitting radius for bubbles driven at ~40 kHz, thus accounting for the observed blackbody spectrum at 40 kHz.

DOI: 10.1103/PhysRevLett.92.124301 PACS numbers: 78.60.Mq

Sonoluminescence, an energy focusing process where sound is transduced into light by the pulsations of a gas bubble, can be observed over a remarkably large parame

temperature exceeding 500 000 K. According to these data it is possible to rationalize the blackbody spectrum of ~30 kHz bubbles by assuming an interior temperature

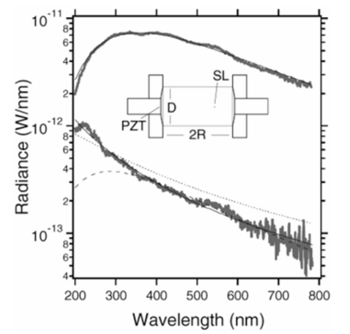


FIG. 1. Spectrum of single bubble sonoluminescence. Top trace (data) is for a bubble driven at 42 kHz in water with 3 Torr of dissolved xenon, taken with a resolution of 12 nm FWHM. These data are fit to blackbody radiation with a temperature of 8000° (top thin line). Bottom trace (data) is for a bubble driven at 1 MHz in water with 600 Torr of dissolved xenon, with a resolution of 70 nm FWHM. The solid line is a fit to bremsstrahlung radiation, with a temperature of 1×10^6 deg. The fine dashed line is also bremsstrahlung but with a temperature of 65 000°. The thick dashed line is blackbody radiation with a temperature of 10 000°. The inset is a diagram of the 1 MHz resonator used to generate and trap single bubbles. It consists of two thin ceramic transducers (PZTs) housed inside brass reflectors with a radius of curvature $R = 2.125$ in. The water was contained in a quartz cylinder of diameter $D = 3.1$ in between the reflectors.

Single-Bubble Sonoluminescence

The upscaling problem-3: is it possible to reach higher temperature levels or emission intensity, perhaps abandoning some of the constrains imposed by the “classical” SBSL apparatus?

- Not the “same” trapped bubble; resonators used only to produce very high acoustic pressure levels.

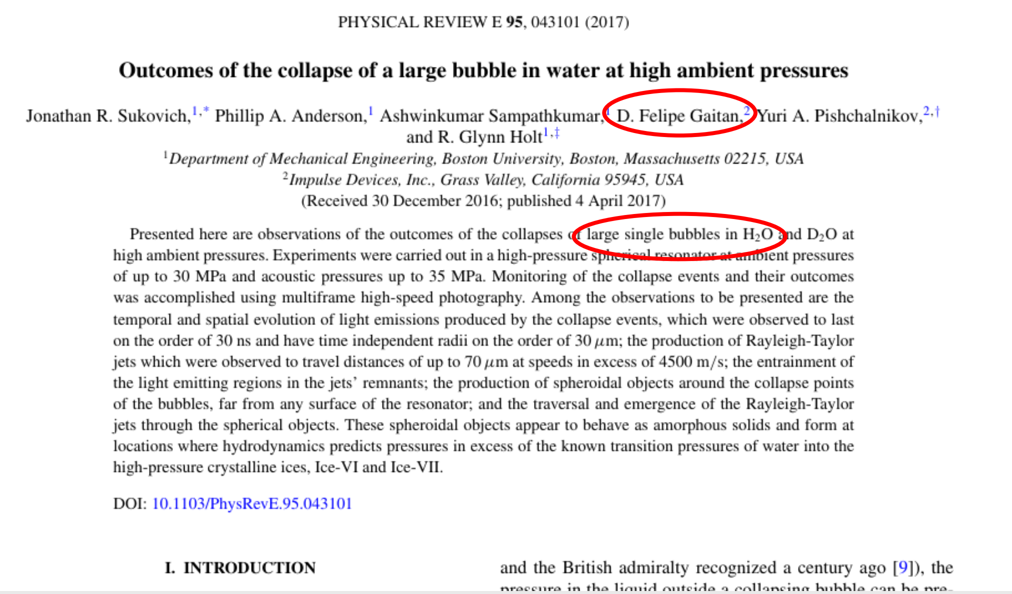
↓

Transient Cavitation (as Galloway or Strasberg original layout!)

Single-Bubble Sonoluminescence

The upscaling problem-3: is it possible to reach higher temperature levels or emission intensity, perhaps abandoning some of the constrains imposed by the "classical" SBSL apparatus?

- SL Flashes 1000 times brighter than SBSL!



PHYSICAL REVIEW E **95**, 043101 (2017)

Outcomes of the collapse of a large bubble in water at high ambient pressures

Jonathan R. Sukovich,[1,*] Phillip A. Anderson,[1] Ashwinkumar Sampathkumar,[1] D. Felipe Gaitan,[2] Yuri A. Pishchalnikov,[2,†] and R. Glynn Holt[1,‡]
[1]*Department of Mechanical Engineering, Boston University, Boston, Massachusetts 02215, USA*
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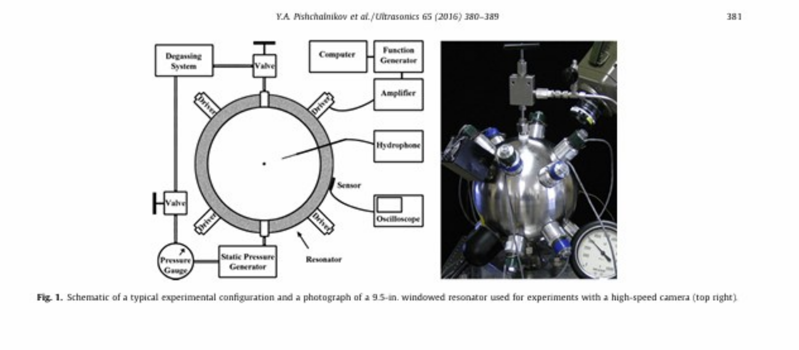
(Received 30 December 2016; published 4 April 2017)

Presented here are observations of the outcomes of the collapses of large single bubbles in H_2O and D_2O at high ambient pressures. Experiments were carried out in a high-pressure spherical resonator at ambient pressures of up to 30 MPa and acoustic pressures up to 35 MPa. Monitoring of the collapse events and their outcomes was accomplished using multiframe high-speed photography. Among the observations to be presented are the temporal and spatial evolution of light emissions produced by the collapse events, which were observed to last on the order of 30 ns and have time independent radii on the order of 30 μm; the production of Rayleigh-Taylor jets which were observed to travel distances of up to 70 μm at speeds in excess of 4500 m/s; the entrainment of the light emitting regions in the jets' remnants; the production of spheroidal objects around the collapse points of the bubbles, far from any surface of the resonator; and the traversal and emergence of the Rayleigh-Taylor jets through the spherical objects. These spheroidal objects appear to behave as amorphous solids and form at locations where hydrodynamics predicts pressures in excess of the known transition pressures of water into the high-pressure crystalline ices, Ice-VI and Ice-VII.

DOI: 10.1103/PhysRevE.95.043101

I. INTRODUCTION

and the British admiralty recognized a century ago [9]), the



Y.A. Pishchalnikov et al./Ultrasonics 65 (2016) 380–389 381

Fig. 1. Schematic of a typical experimental configuration and a photograph of a 9.5-in. windowed resonator used for experiments with a high-speed camera (top right).

- High ambient pressure: 30 MPa (no degassing needed)
- High acoustic pressure: 35 MPa
- Sinusoidal Drive
- Single bubble generated by Laser

Single-Bubble Sonoluminescence

The upscaling problem-3: is it possible to reach higher temperature levels or emission intensity, perhaps abandoning some of the constrains imposed by the "classical" SBSL apparatus?

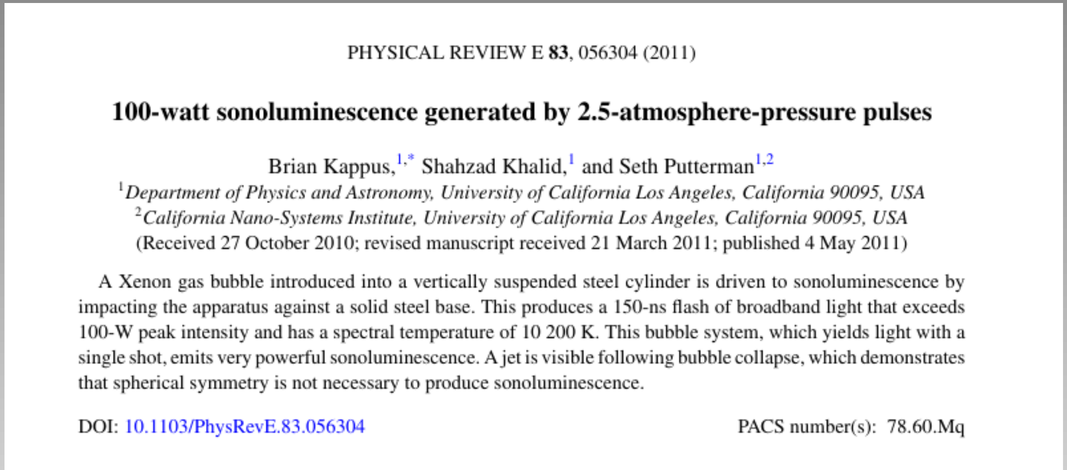
- Single, but not conserved bubbles; NO periodic acoustic drive
- Bubbles are laser-generated or directly injected from a gas reservoir

↓

- Arrest Tube under vacuum
- Shock waves

Single-Bubble Sonoluminescence

- Drop Tube: big bubbles, 3.5 mm radius; high positive pressure drive, 250 KPa; liquid vapour pressure = ambient pressure.



PHYSICAL REVIEW E **83**, 056304 (2011)

100-watt sonoluminescence generated by 2.5-atmosphere-pressure pulses

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(Received 27 October 2010; revised manuscript received 21 March 2011; published 4 May 2011)

A Xenon gas bubble introduced into a vertically suspended steel cylinder is driven to sonoluminescence by impacting the apparatus against a solid steel base. This produces a 150-ns flash of broadband light that exceeds 100-W peak intensity and has a spectral temperature of 10 200 K. This bubble system, which yields light with a single shot, emits very powerful sonoluminescence. A jet is visible following bubble collapse, which demonstrates that spherical symmetry is not necessary to produce sonoluminescence.

DOI: 10.1103/PhysRevE.83.056304 PACS number(s): 78.60.Mq

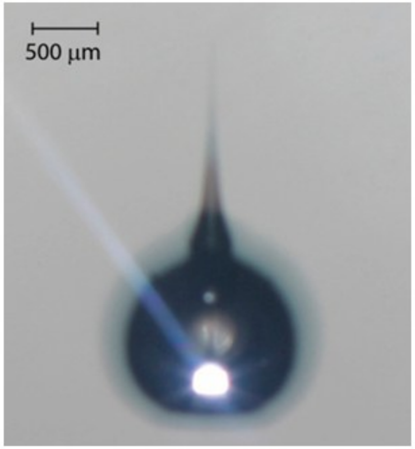


FIG. 4. (Color online) A backlit photograph of the jet formed during collapse. The bright blue light near the bottom of the bubble is the sonoluminescence. The strobe time is 50 μs, which causes considerable blurring in the bubble wall.

Light Flashes: very intense, but not so "hot", 10 000K

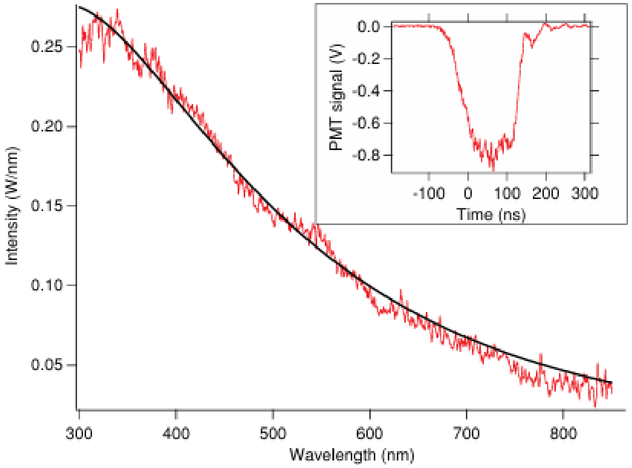
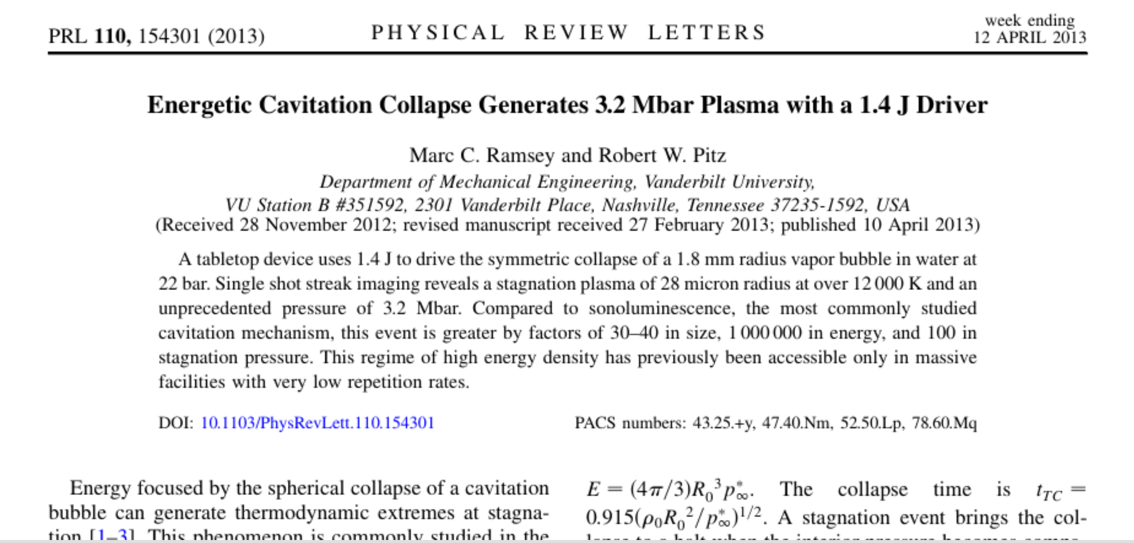


FIG. 3. (Color online) Diagram showing a representative spectrum compiled from 4 separate flashes. The fit is a 10 200-K black body spectrum with an emission radius of 125 μm. This radius is sufficiently close to the measured radius for us to conclude that the emission is that of a black body. The inset is a typical PMT trace.

Single-Bubble Sonoluminescence

- Shock waves: positive pressure step, 2.2 MPa; laser induced, 1.8 mm radius, vapour bubble .



PRL **110,** 154301 (2013) PHYSICAL REVIEW LETTERS week ending 12 APRIL 2013

Energetic Cavitation Collapse Generates 3.2 Mbar Plasma with a 1.4 J Driver

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(Received 28 November 2012; revised manuscript received 27 February 2013; published 10 April 2013)

A tabletop device uses 1.4 J to drive the symmetric collapse of a 1.8 mm radius vapor bubble in water at 22 bar. Single shot streak imaging reveals a stagnation plasma of 28 micron radius at over 12 000 K and an unprecedented pressure of 3.2 Mbar. Compared to sonoluminescence, the most commonly studied cavitation mechanism, this event is greater by factors of 30–40 in size, 1 000 000 in energy, and 100 in stagnation pressure. This regime of high energy density has previously been accessible only in massive facilities with very low repetition rates.

DOI: 10.1103/PhysRevLett.110.154301 PACS numbers: 43.25.+y, 47.40.Nm, 52.50.Lp, 78.60.Mq

Energy focused by the spherical collapse of a cavitation bubble can generate thermodynamic extremes at stagnation [1–3]. This phenomenon is commonly studied in the

$E = (4\pi/3)R_0^3 p_\infty^*$. The collapse time is $t_{TC} = 0.915(\rho_0 R_0^2/p_\infty^*)^{1/2}$. A stagnation event brings the col-

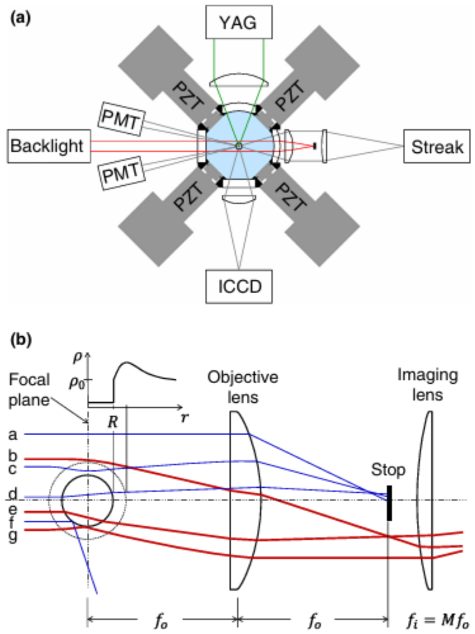
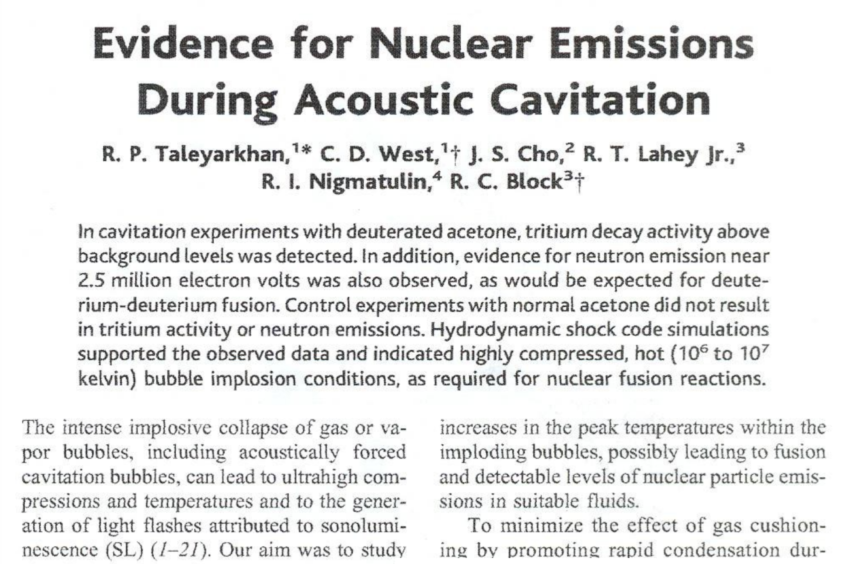


FIG. 1 (color online). A flattened top section view of the cavitation vessel (a) shows 4 of the 8 piezo (PZT) elements and diagnostics arranged for spatial streak imaging. Illustrative diagram (b) (not to scale) shows representative rays of the collimated backlight deflected by the bubble and density gradients [2] of the compressible collapse phase. The infinity corrected plan-apochromatic objective (numerical aperture 0.23) and imaging lenses have focal lengths (f.l.) f_o and f_i for magnification M, and resolve about 2 μm. The spherical-dome vacuum window is designed to be optically passive and is shown in (a) but not in (b).

What next?

From Sonoluminescence to sonofusion



Evidence for Nuclear Emissions During Acoustic Cavitation

R. P. Taleyarkhan,[1]* C. D. West,[1]† J. S. Cho,[2] R. T. Lahey Jr.,[3]
R. I. Nigmatulin,[4] R. C. Block[3]†

In cavitation experiments with deuterated acetone, tritium decay activity above background levels was detected. In addition, evidence for neutron emission near 2.5 million electron volts was also observed, as would be expected for deuterium-deuterium fusion. Control experiments with normal acetone did not result in tritium activity or neutron emissions. Hydrodynamic shock code simulations supported the observed data and indicated highly compressed, hot (10^6 to 10^7 kelvin) bubble implosion conditions, as required for nuclear fusion reactions.

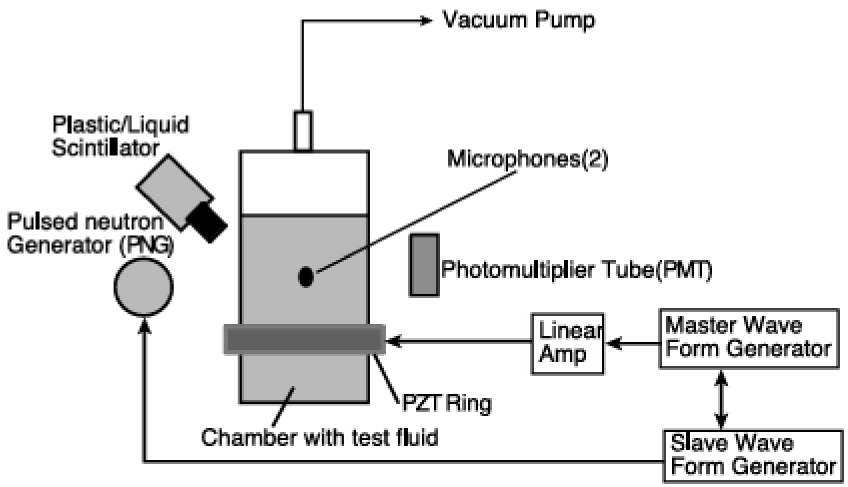
The intense implosive collapse of gas or vapor bubbles, including acoustically forced cavitation bubbles, can lead to ultrahigh compressions and temperatures and to the generation of light flashes attributed to sonoluminescence (SL) (*1–21*). Our aim was to study ultrahigh compression and temperatures i bubbles nucleated by means of fast neutron whereby bubble nucleation center

increases in the peak temperatures within the imploding bubbles, possibly leading to fusion and detectable levels of nuclear particle emissions in suitable fluids.

To minimize the effect of gas cushioning by promoting rapid condensation dur-

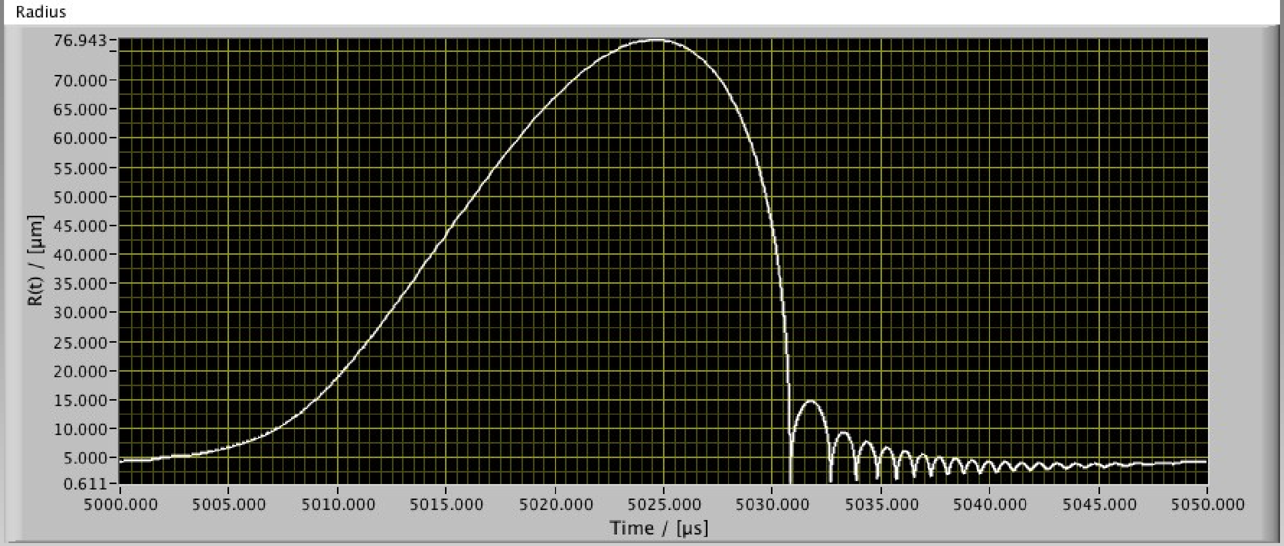
Taleyarkan et al., Science (2002)

Fig. 1. Schematic of the experimental setup. The distance from the scintillator head to the PNG is ~15 cm; from the scintillator head to the chamber surface, ~0 to 2 cm; from the chamber center to the PNG, ~20 cm; and from the PMT to the chamber surface, ~5 cm. The system (the chamber, PNG, and PMT) is ~1.5 m above the floor.

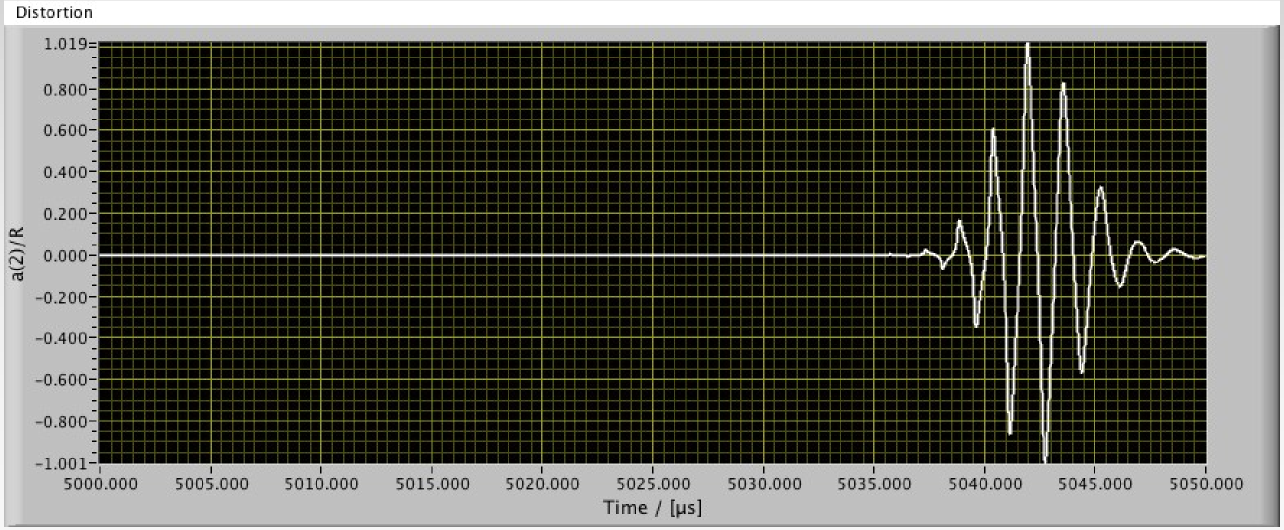


Single-Bubble Sonoluminescence

*Shape instability problem



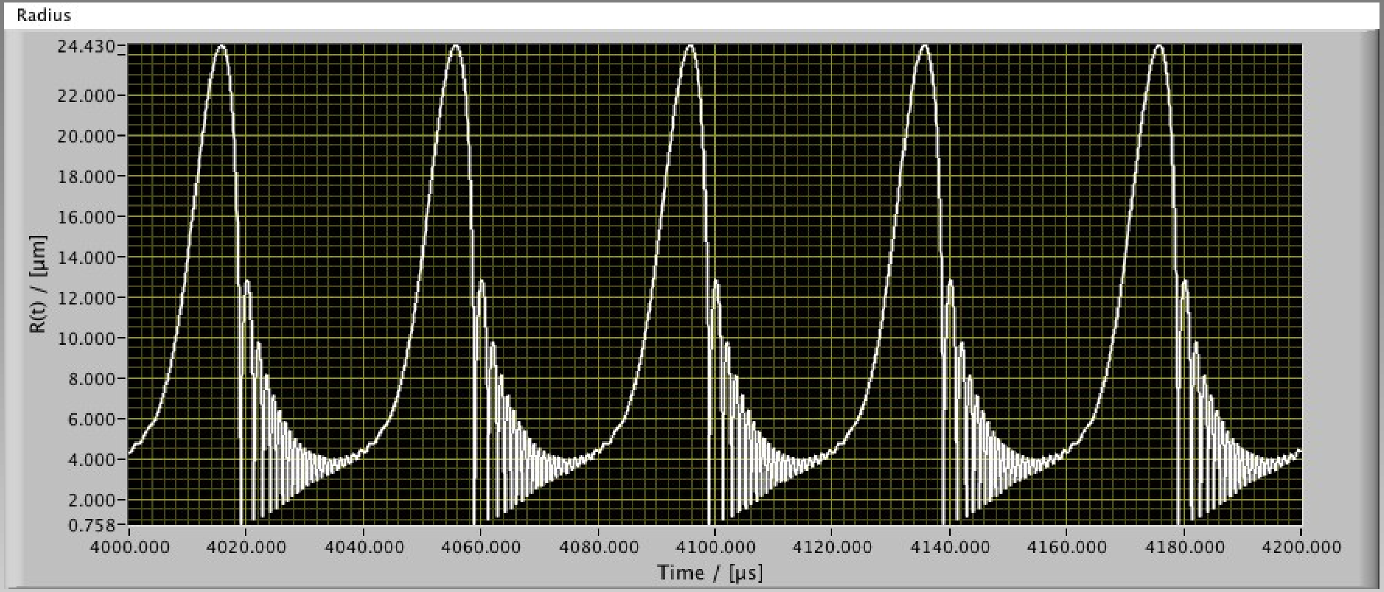
“Afterbounce” instability

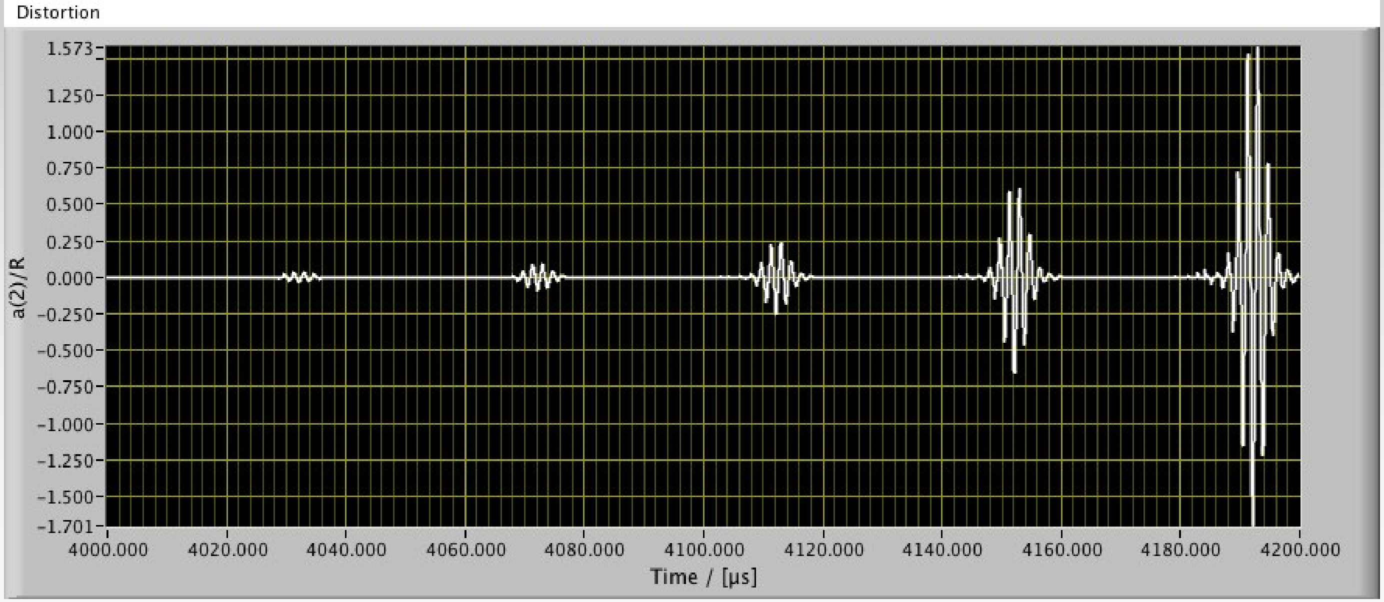


Single-Bubble Sonoluminescence

INRiM ISTITUTO NAZIONALE DI RICERCA METROLOGICA

*Shape instability problem

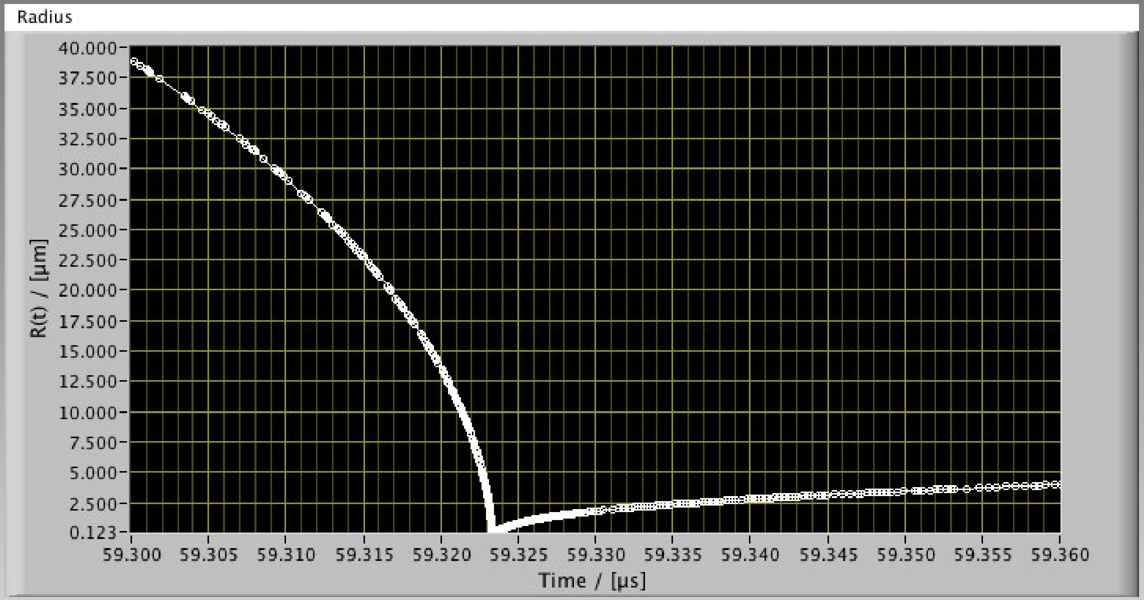


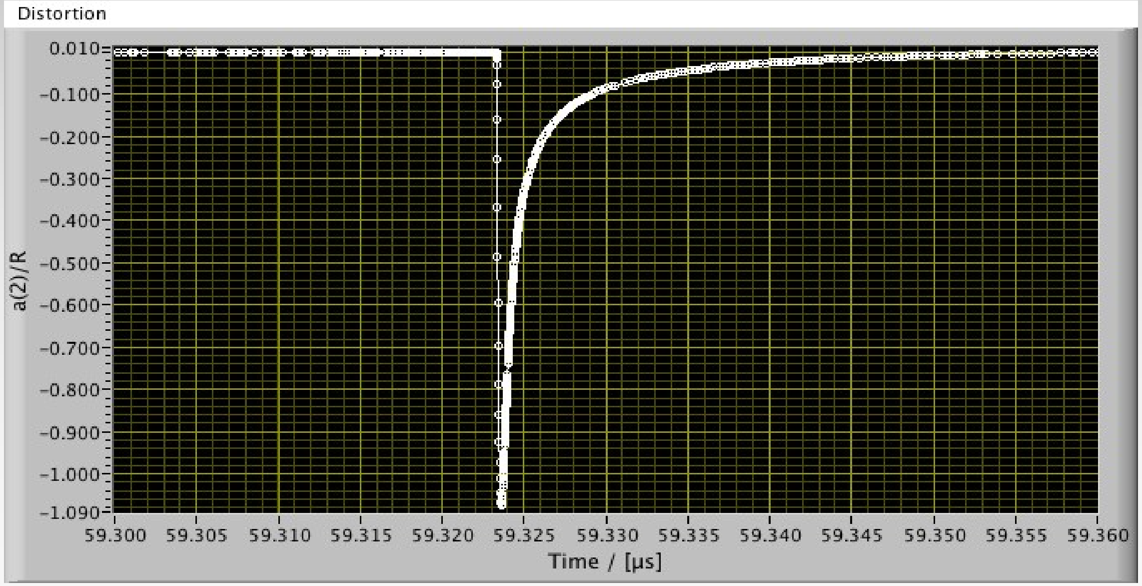


Parametric instability

Single-Bubble Sonoluminescence

*Shape instability problem





Rayleigh-Taylor instability