Single-bubble Sonoluminescence

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http://en.wikipedia.org/wiki/File:Single_bubble_cropped.jpg

Outline

- Background
  - What is sonoluminescence?
  - History
- Bubble Motion
  - Radial and translational
- Parameters
  - Fluid temperature, bubble composition, etc.
- Spectra
  - Surrounding fluid and bubble
- Theories
- Conclusions

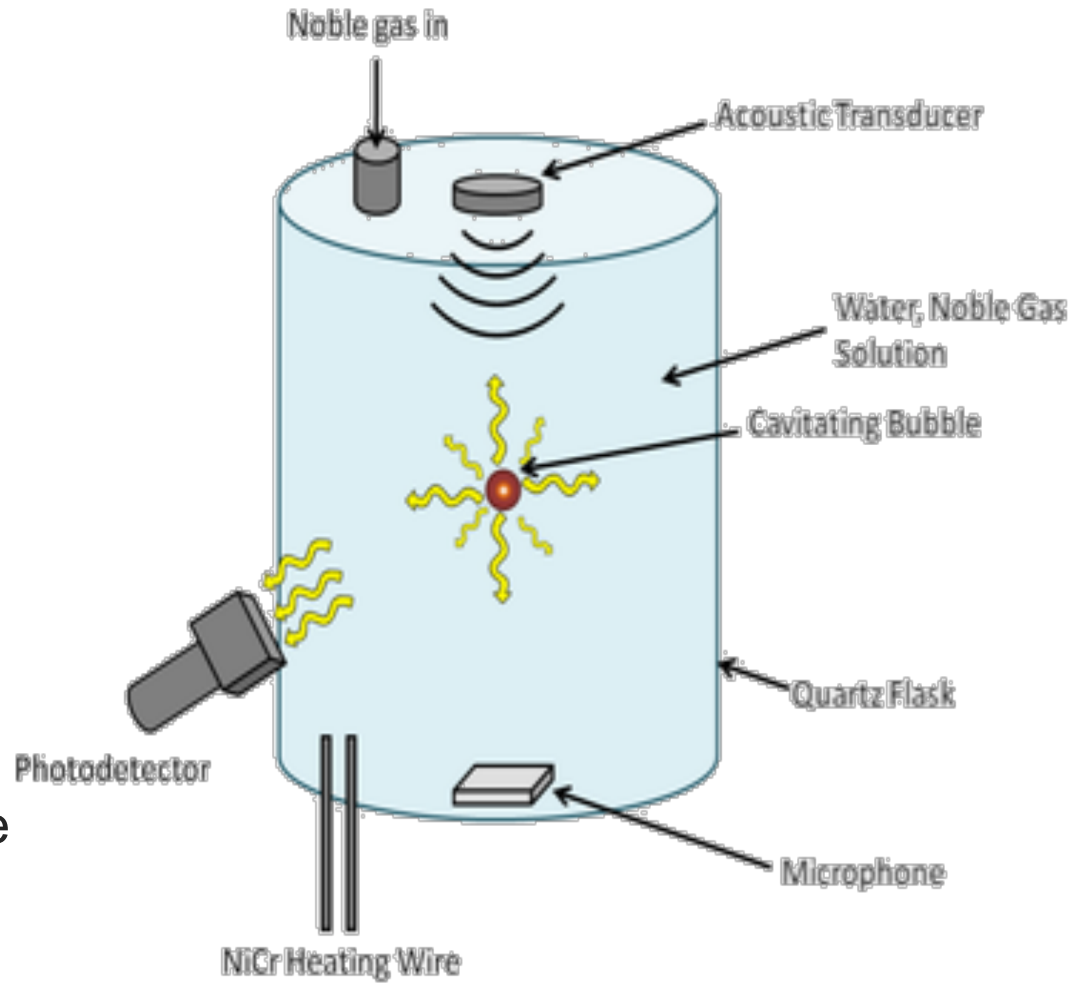


Diagram of sonoluminescence apparatus

http://upload.wikimedia.org/wikipedia/commons/thumb/2/2a/Sonoluminescence_Setup.png

Background-What is Sonoluminescence?

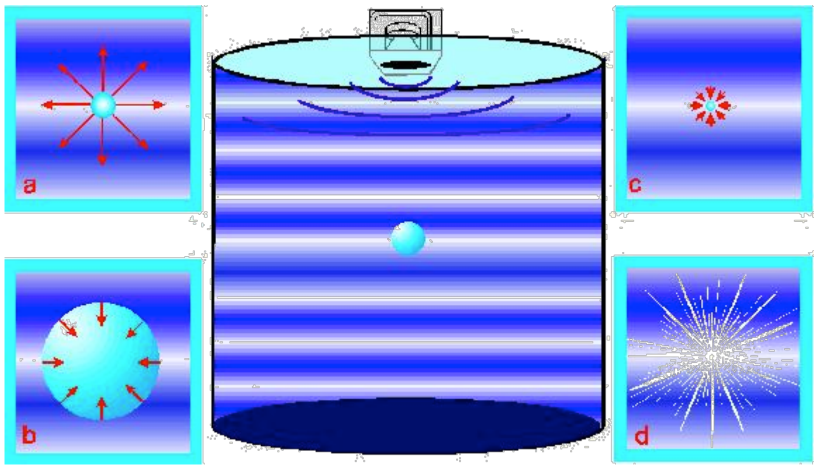
- Sonoluminescence is visible light emitted from an acoustically driven bubble
- Bubble oscillates non-linearly in micrometer range
- The average temperature of the bubble at collapse is ~10^3 K
- Light is emitted in picosecond pulse widths depending on bubble composition
- Sonoluminescence has been maintained continuously for billions of cycles
- Sonoluminescence is producible in many fluids

http://www.osel.cz/_popisky/130_/1304002384.jpg

Sonoluminescent bubble

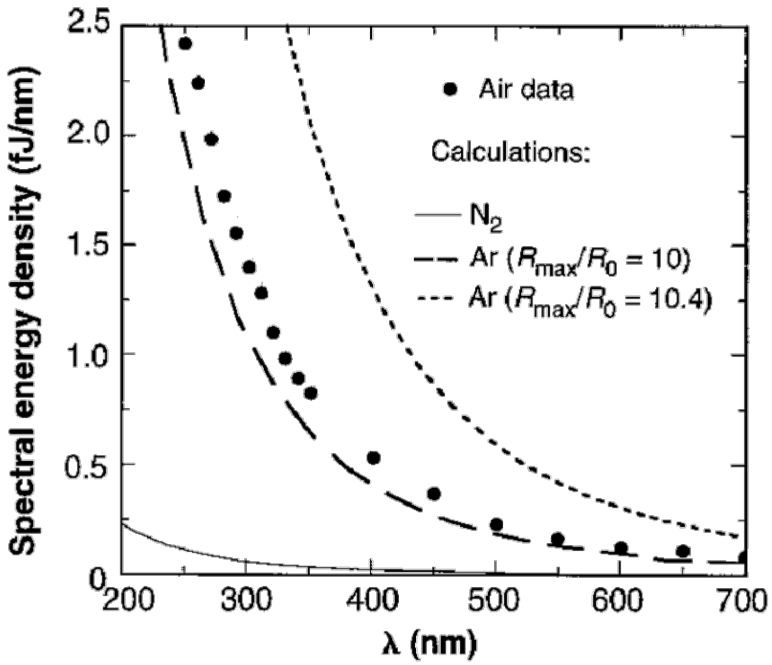
Background-What is Sonoluminescence?

- Acoustically driven 0.5-50 µm radius bubble oscillates ~20 kHz
- Light is usually emitted in 100-200 picosecond window around minimum radius
  - Composition of bubble effects pulse width
- Center of bubble believed to be hottest
- Requires non-reactive molecules
  - Typically noble gases
- Spectral lines visible for low enough driving frequency and depending on fluid used



(a) Bubble expands from equilibrium radius ~ 5 micrometers
(b) Bubble expands to maximum radius of ~ 50 micrometers
(c) Bubble collapses to minimum radius ~ 0.5 micrometers
(d) Bubble emits 100-200 picosecond pulse of light

http://www.aip.org/png/html/sono1.htm



-- Nitrogen is relatively non-reactive
-- Air contains argon and trace amounts of other noble gases

DOI: 10.1126/science.276.5317.1398

Background-History

- Late 19th century – Lord Rayleigh first studied cavitation
  - Work led to Rayleigh-Plesset Equation
- 1934 - multi-bubble sonoluminescence discovered by Frenzel and Schultes
- 1989 - single-bubble sonoluminescence discovered by Gaitan
- 1994 - Hiller *et al.* discovered dependence of light emission on type of gas in bubble

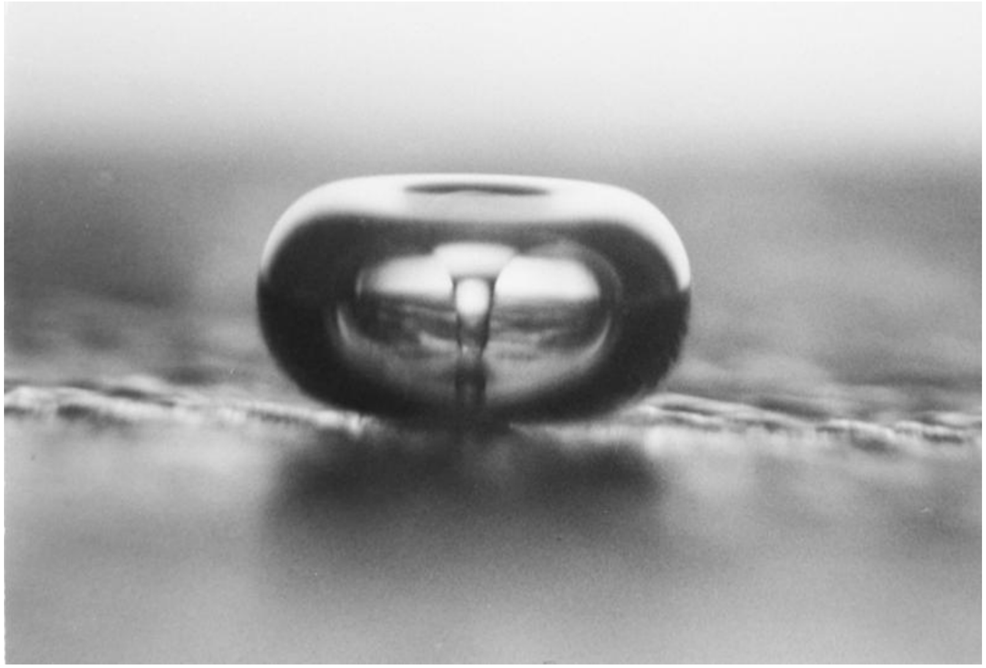


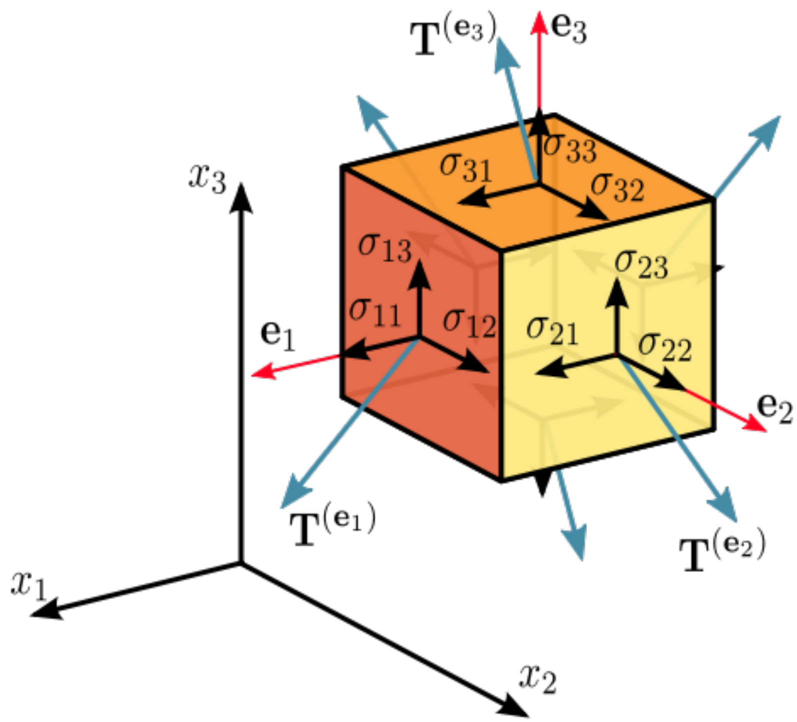
Image of a collapsing bubble

http://www.acosoc.org/galleryofacoustics.htm

Navier-Stokes Equation

- Models fluid motion
- Non-linear partial differential equation
  - From Newton's second law and (classical) conservation laws
- Comes from conservation of momentum, energy and mass
- Rayleigh-Plesset equation is derived from this
  - Used to solve for radial motion of bubble

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v}\cdot\nabla\mathbf{v}\right) = -\nabla p + \nabla\cdot\mathbf{T} + \mathbf{f}$$



ρ - fluid density

$\mathbf{v}$ - fluid velocity

p - pressure

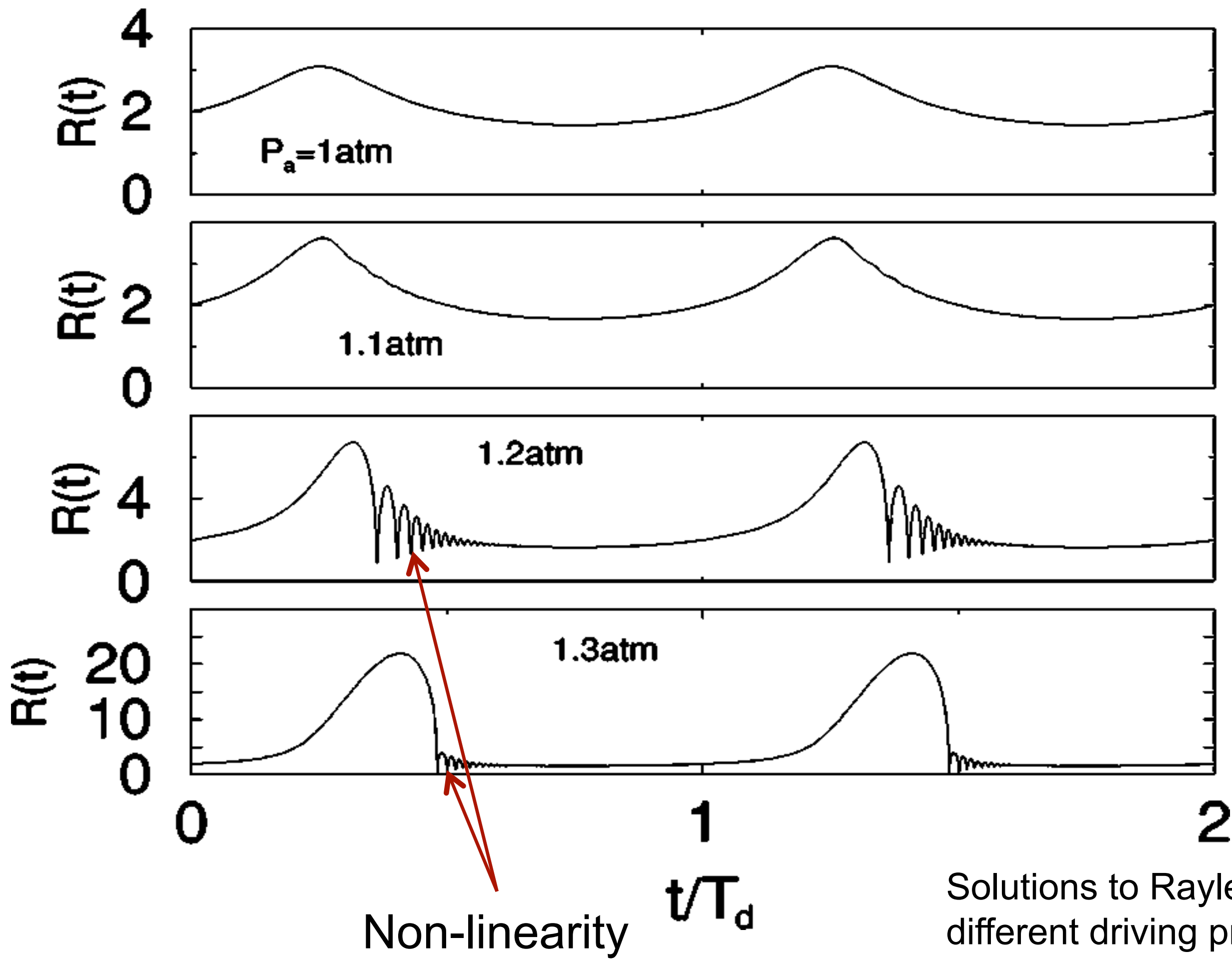
$\mathbf{T}$ - stress deviator tensor

$\mathbf{f}$ - force density

http://en.wikipedia.org/wiki/Cauchy_stress_tensor

Rayleigh Plesset Equation

$$\rho\left(R\ddot{R}+\frac{3}{2}\dot{R}^{2}\right)=\left[p_{g}(R,t)-P_{0}-P(t)\right]-4\mu\frac{\dot{R}}{R}-2\frac{\sigma}{R}+\frac{R}{c}\frac{d}{dt}p_{g}$$



ρ – density of liquid

R – bubble radius

p_g – pressure in bubble

P_0 – pressure far from bubble

$P(t)$ – driving pressure

μ – shear viscosity of liquid

σ – surface tension at interface

c - speed of sound in liquid

h - van der Waal's hard core radius

$\kappa \approx 1$, effective polytropic exponent (isothermal)

Solutions to Rayleigh-Plesset Equation for different driving pressures (equilibrium radius, 2 μm; frequency, 26.5k Hz

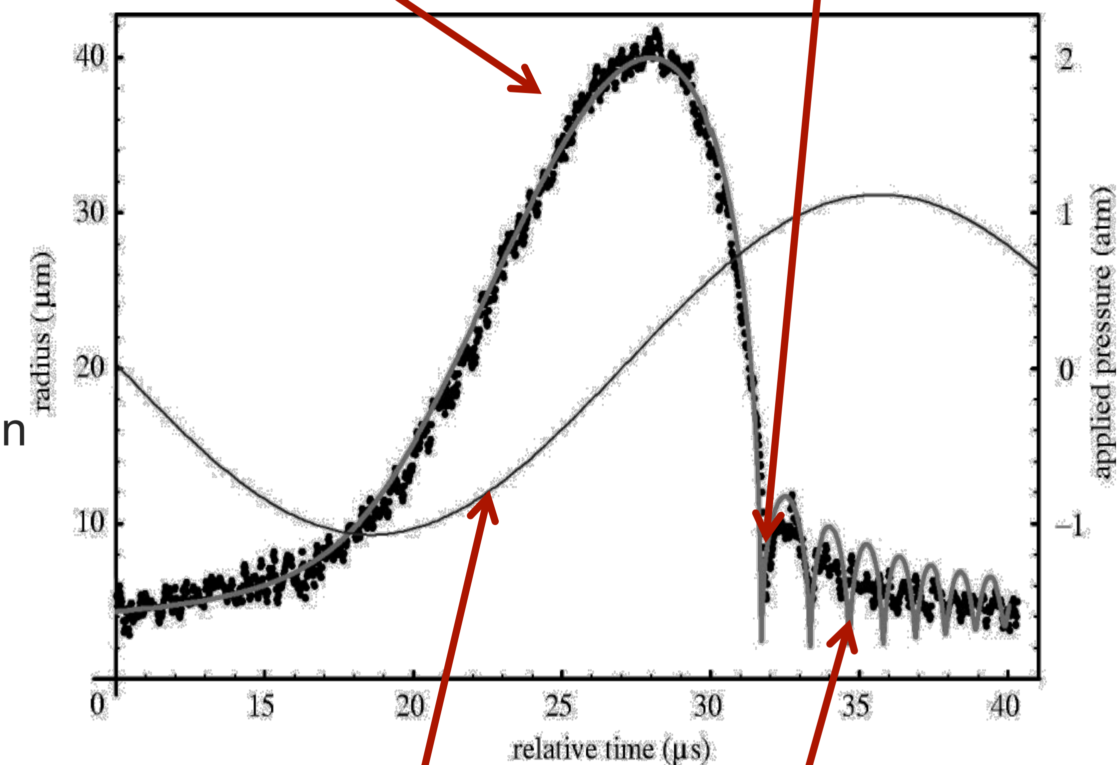
Rev. Mod. Phys., Vol. 74, No. 2, April 2002

Rayleigh-Plesset Equation

- Rayleigh-Plesset Equation describes motion of spherical bubble
  - Small perturbations are allowed but can cause fragmentation if too large
- Approximate surrounding liquid (typically water) as incompressible
- Assume there to be no thin-film
- Extremely sensitive to changes in conditions
- Approximate isothermal expansion and adiabatic compression
- Breakdown when $\frac{\dot{R}}{c} \sim 1$ and during collapse
- Numerically solvable, large amount of approximation required for analytic solution

Equation solution and data

Period of light emission

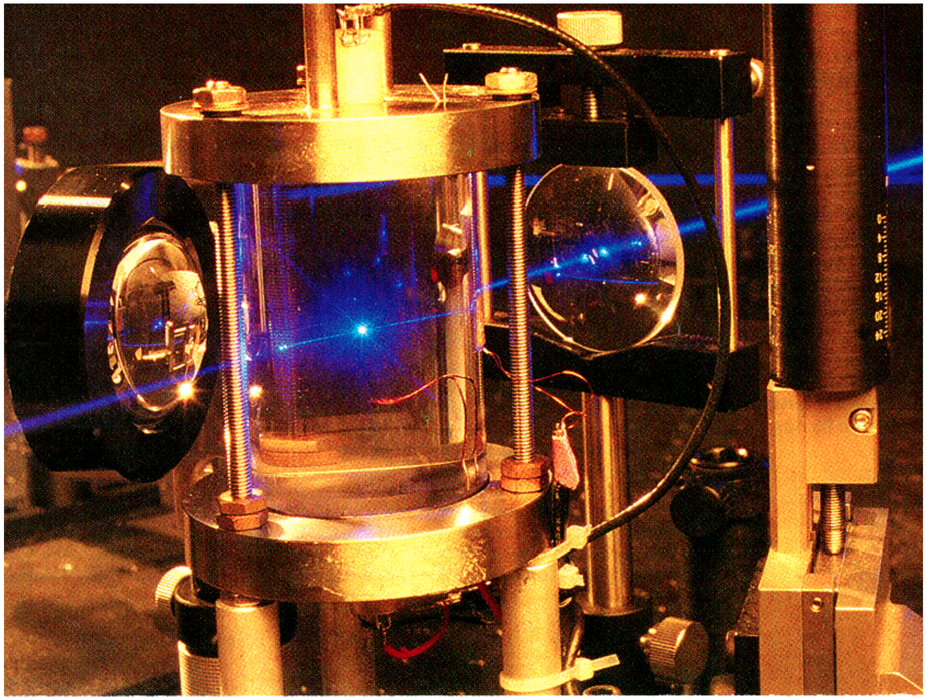


Driving Pressure

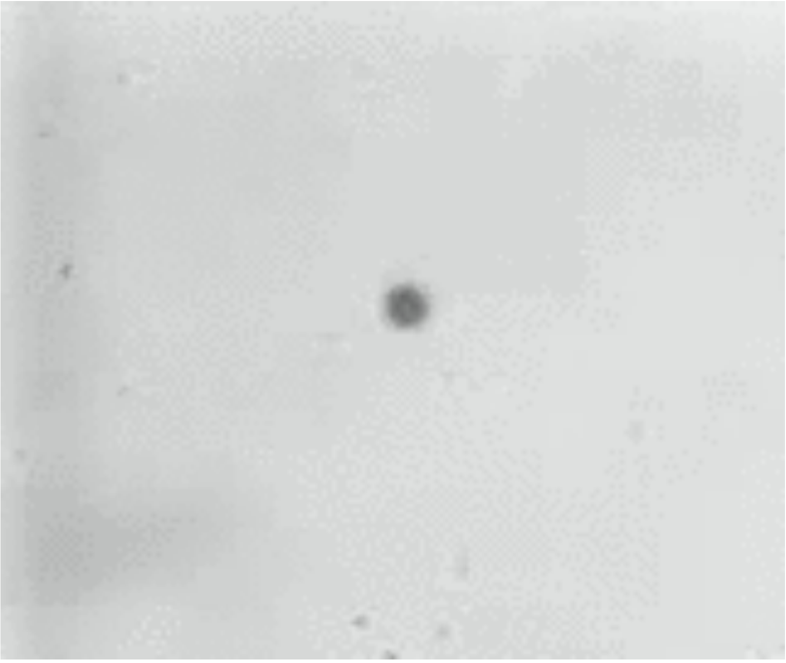
Afterbounces at approximately resonant frequency of bubble

Measuring Bubble Radius

- Light from laser is incident on the bubble
- Light scattered from bubble is used to determine bubble radius because number of photons that reach photomultiplier is reduced



Laser used to measure radius of bubble



Oscillating bubble

Putterman,Seth. Sonoluminescence: Sound into Light. 1995.

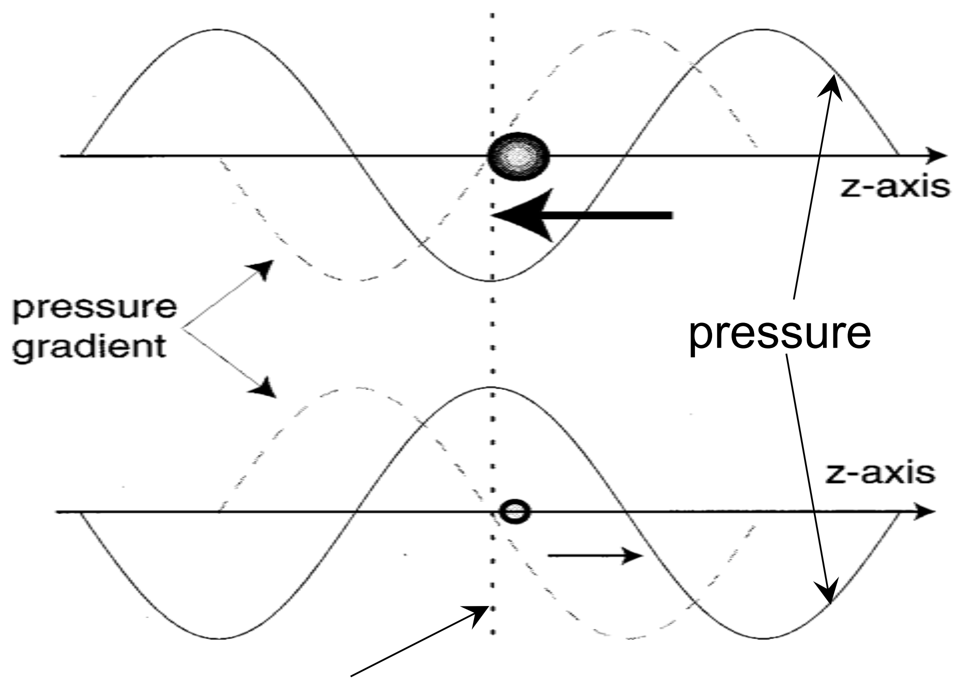
http://www.youtube.com/watch?v=HuDyy4MTosA

Translational Motion-Bjerknes Force

- Bubble forced toward pressure antinode (maxima) because resonant frequency of bubble is greater than driving frequency, $\omega_0 > \omega$
- Bjerknes force due to pressure gradient across bubble
- Bubble position comes from buoyancy and Bjerknes forces

$$\vec{F}_{Bjerk} = \left\langle \hat{b} \cdot \vec{F}_{bubble} \right\rangle = \left\langle -\frac{4}{3}\pi R(t)^3 \nabla p \right\rangle$$

Pressure gradient is zero in pressure minima or maxima

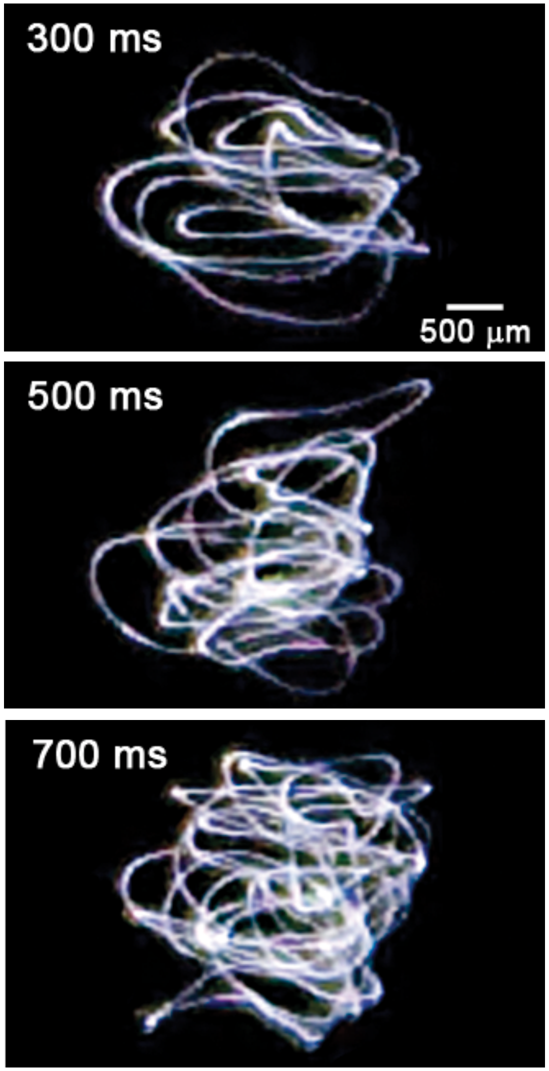


$$F_{buoyancy} = \frac{\rho g}{T} \int_0^{T_d} V(t)dt$$

PACS numbers: 43.35.Ei [HEB]

Bubble Motion

- In simple model, Bjerknes and buoyancy forces are equated, but they are not actually equal
- Bubble has translational motion in additional to radial motion
- Viscosity of fluid influences form of translational motion
  - Lower viscosity fluids (water) have circular paths
  - Higher viscosity fluids (H_3PO_4) have elliptical paths



Argon bubble in H_3PO_4 seen with translational motion

PRL 104, 244301 (2010)

Surrounding Temperature and Bubble Radius

- Surface tension and viscosity constrict bubble expansion
    - Lower surrounding temperature constricts bubble expansion
- Higher surrounding temperature causes more water vapor to enter bubble, causing less light emission

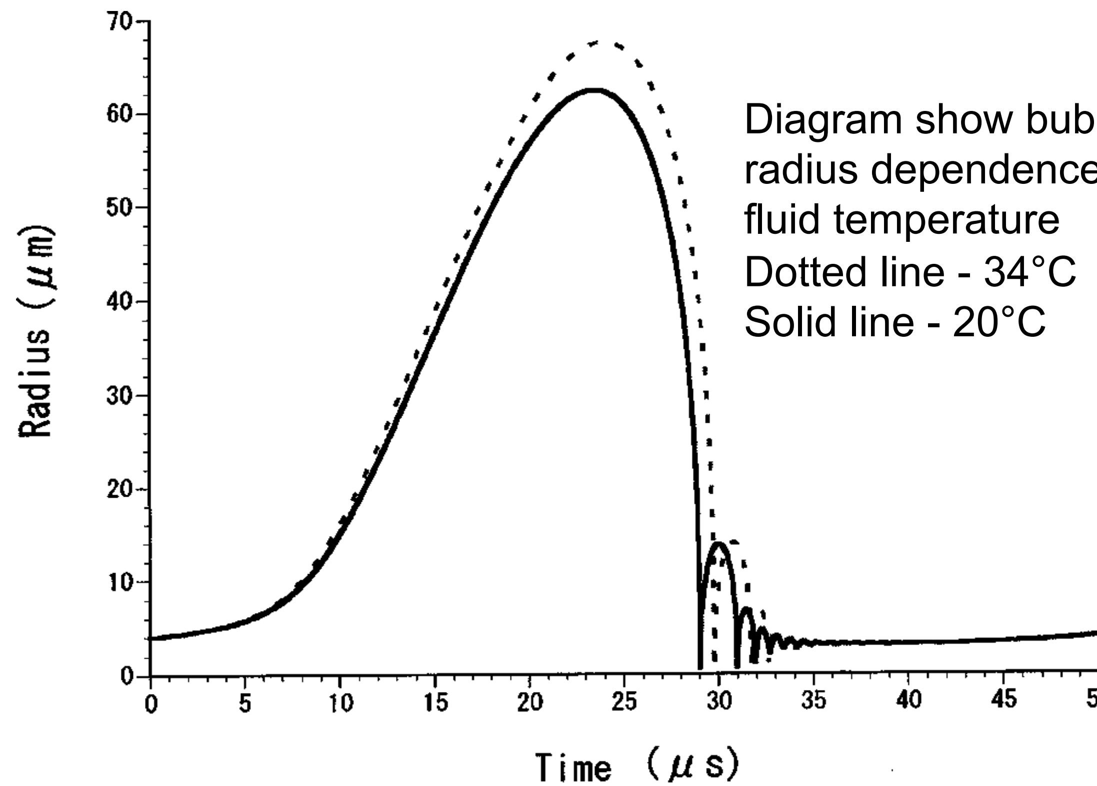


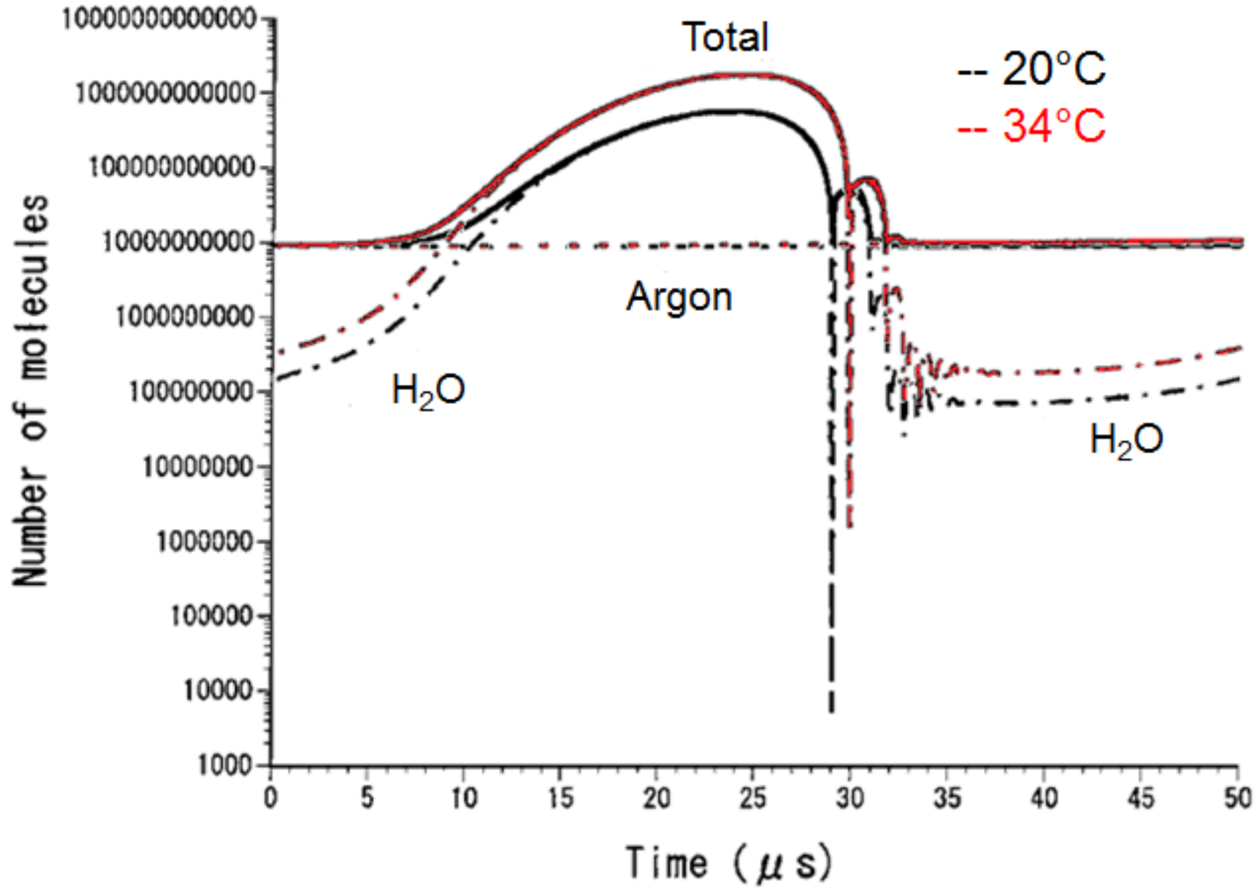
Diagram show bubble radius dependence on fluid temperature
Dotted line - 34°C
Solid line - 20°C

Water Temperature °C	Surface Tension $\sigma \cdot 10^{-3}$ N/m	Viscosity $\mu \cdot 10^{-3}$ Pa•s	Vapor Pressure $p_v \cdot 10^3$ Pa
20	72.8	1.0	2.3
34	70.5	0.74	5.3

DOI: 10.1103/PhysRevE.64.016310

Fluid Temperature and Bubble Composition

- Pressure from fluid causes influx of molecules when radius is large and outflow when radius is small
- Bubble temperature at collapse is higher in colder fluid because less water vapor is trapped inside bubble at the collapse due to the lower-saturated vapor pressure

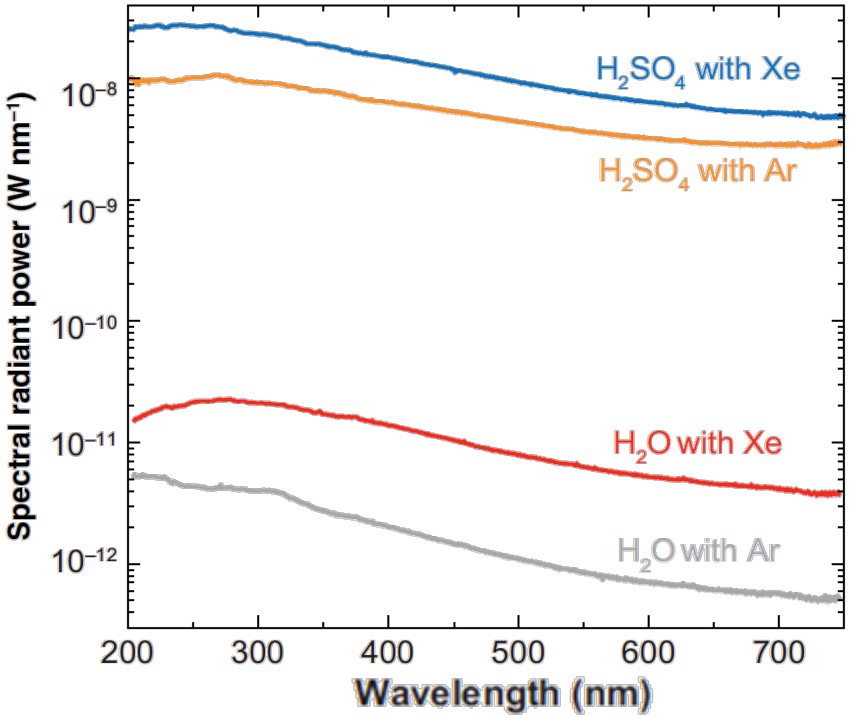


Number of molecules in bubble for one acoustic cycle for two temperatures

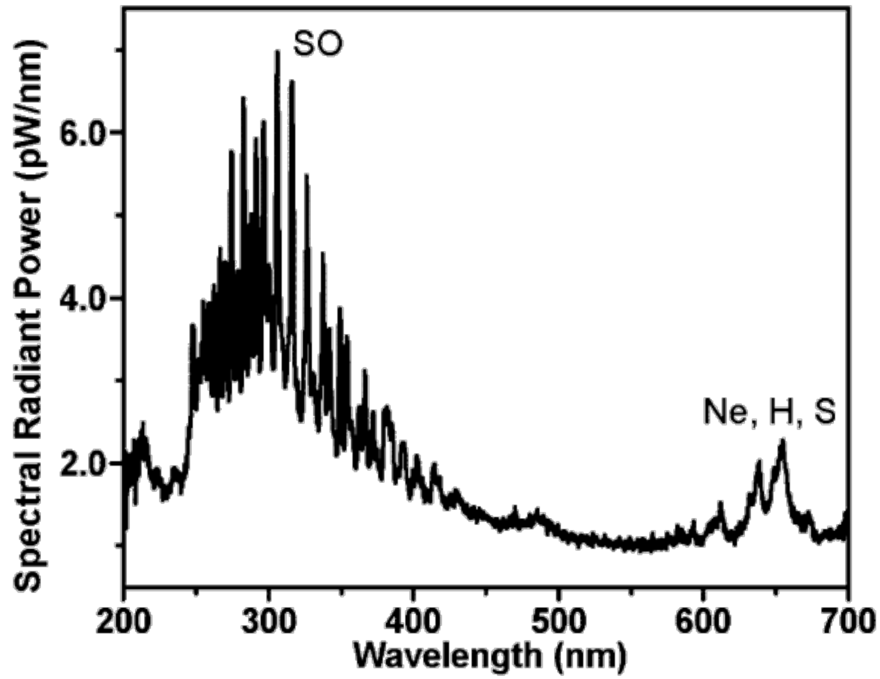
DOI: 10.1103/PhysRevE.64.016310

Sonoluminescence Spectrum

- Fluid and noble gas both affect sonoluminescence spectrum
- Vibrational frequencies are visible
- Water has higher specific heat than sulfuric acid



Spectra from argon and xenon bubbles in both water and 85 wt% H_2SO_4



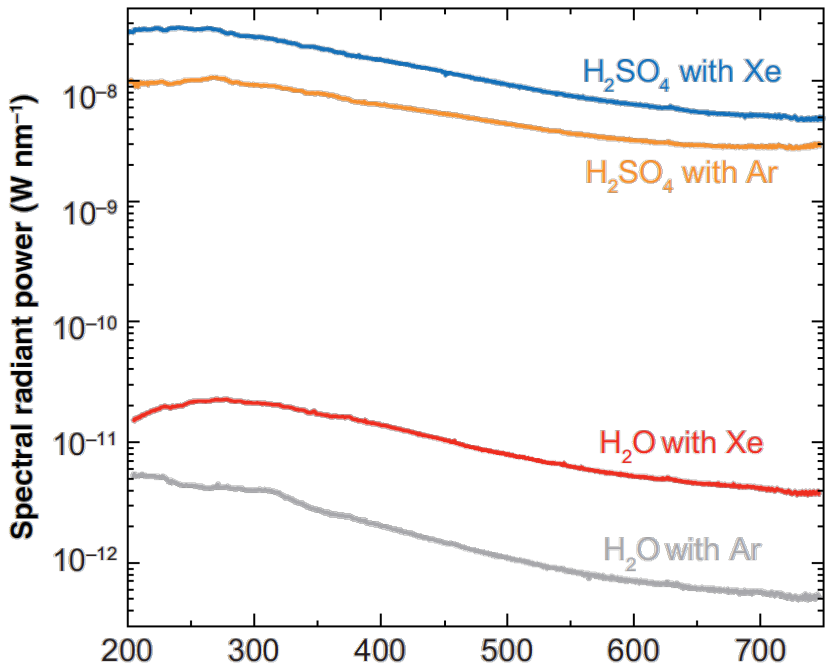
Spectrum from neon bubble in 80 wt% H_2SO_4

dx.doi.org/10.1021/jz301100j | J. Phys. Chem. Lett. 2012, 3, 2401−2404

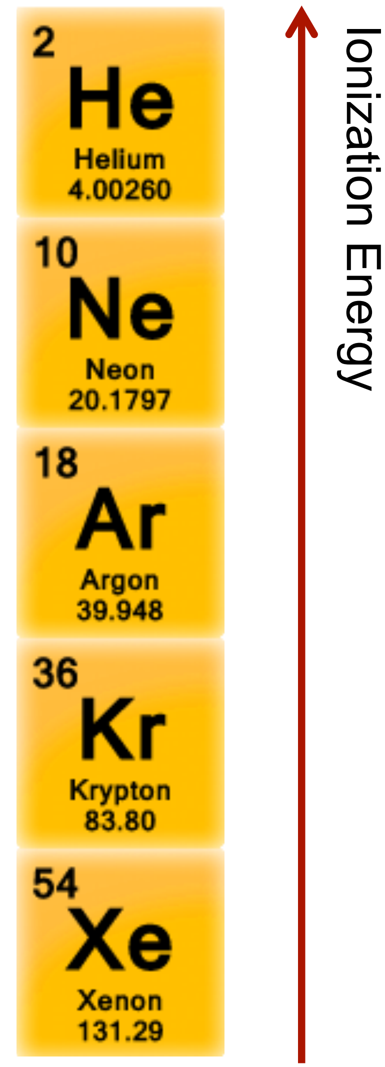
Annu. Rev. Phys. Chem. 2008. 59:659–83

Ionization Energy

- Ionization energy increases as atomic number decreases
- More of the bubble is light emitting when bubble consists of lower ionization atoms



Annu. Rev. Phys. Chem. 2008. 59:659–83



http://0.tqn.com/d/chemistry/1/0/8/d/1/PeriodicTableWallpaper.png

Noble Gases and Sonoluminescence

- Aside from radiant power increasing for larger noble gas bubbles, pulse emission also increases
- Air contains 1.28 wt% argon

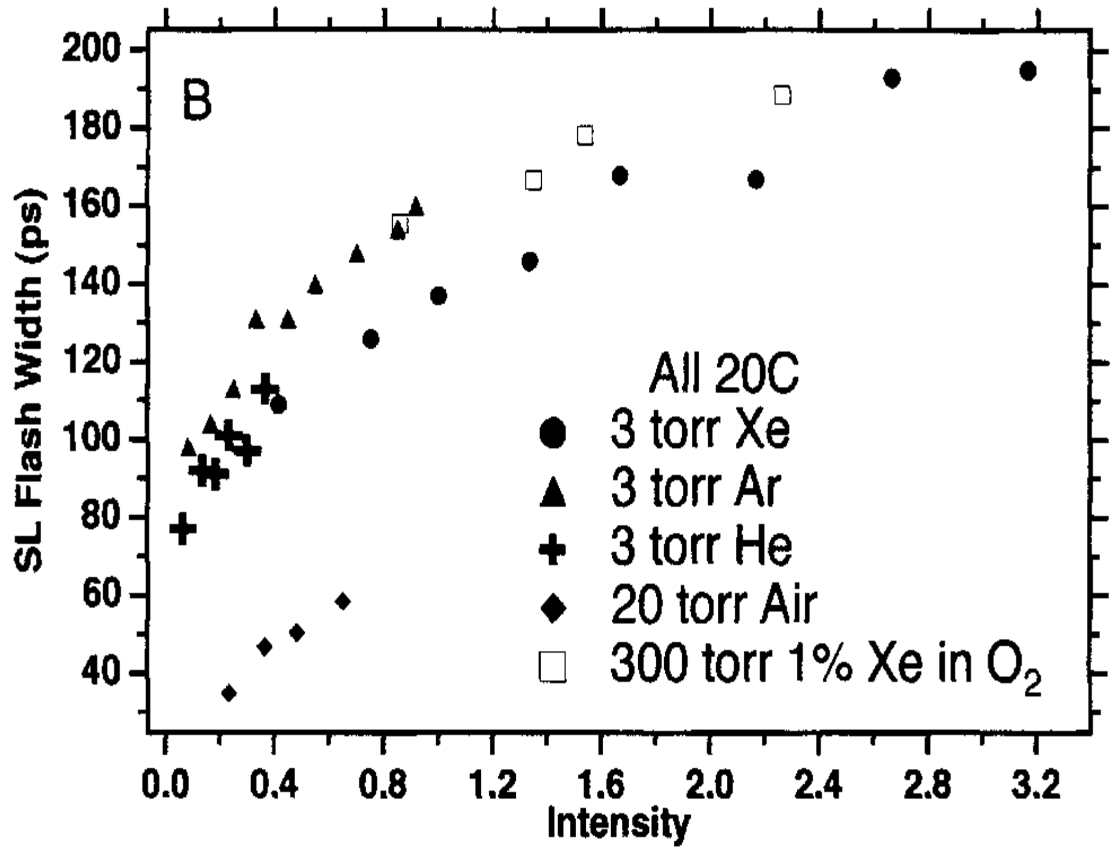
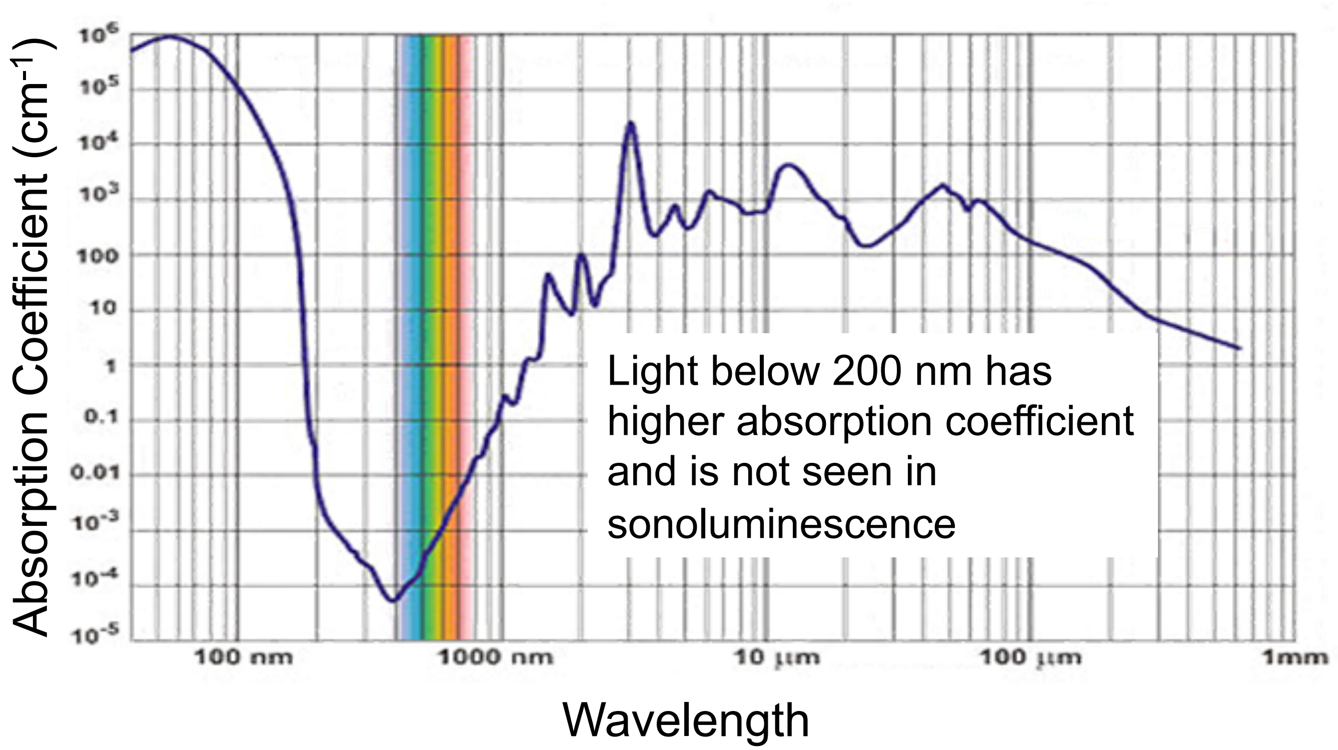


Diagram showing sonoluminescence dependence on noble gas

Annu. Rev. Fluid Mech. 2000. 32:445–476

Sonoluminescence Spectrum - Water absorption

- Absorption coefficient of water keeps spectrum of sonoluminescence from appearing lower than 200 nm
- Sonoluminescence wavelength window is 200-800 nm



http://www.uv-tackle.com/images/light_absorption.jpg

When is light emitted?

- Majority of light emission occurs at end of bubble collapse

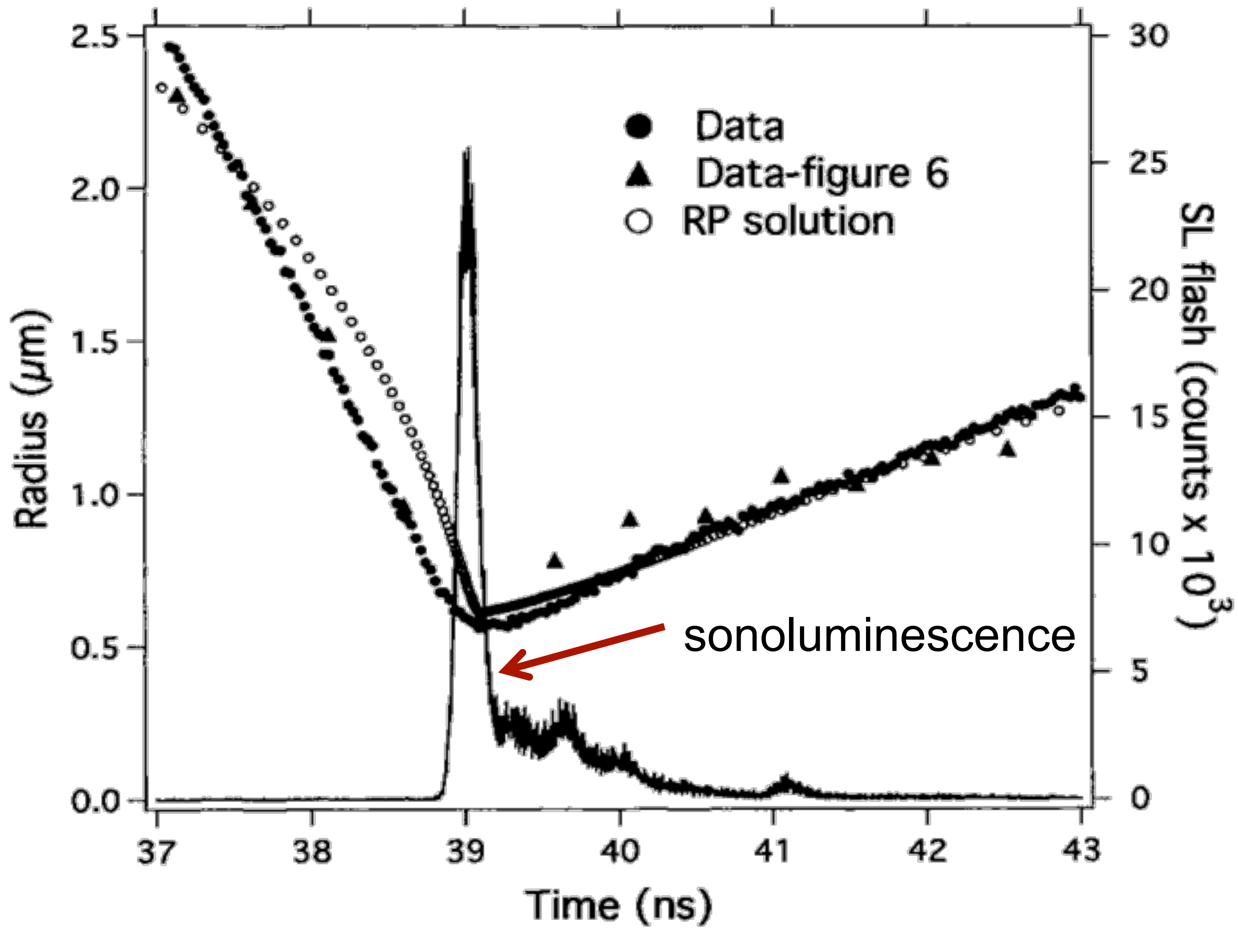


Diagram of light emission and bubble radius

Annu. Rev. Fluid Mech. 2000. 32:445–476

Diagram of radius and light flash versus time of bubble with 1% xenon and oxygen

What Causes Sonoluminescence?

- Theories for Cause of Sonoluminescence
  - Casimir Effect
  - Black-body radiation
  - Shockwave model
  - Quasi-adiabatic compression model

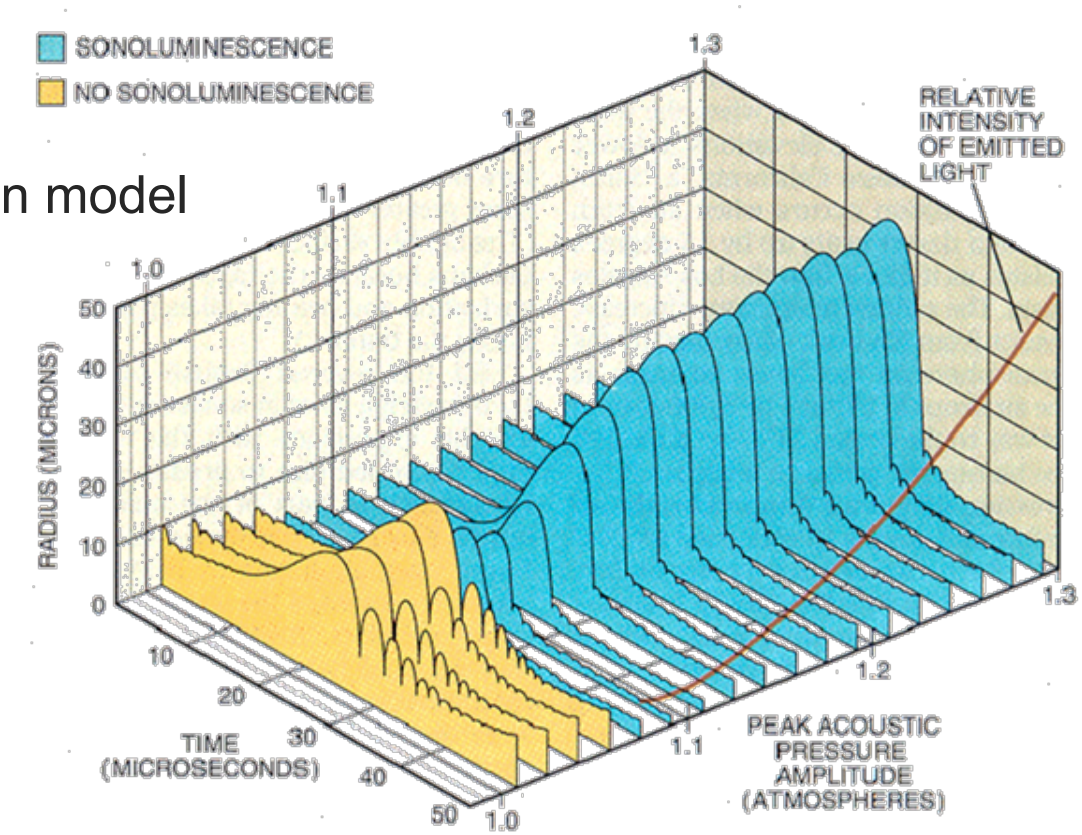


Diagram showing sonoluminescence dependence on acoustic pressure and how radial motion changes in sonoluminescence and non-sonoluminescence regime

Putterman,Seth. Sonoluminescence: Sound into Light. 1995.

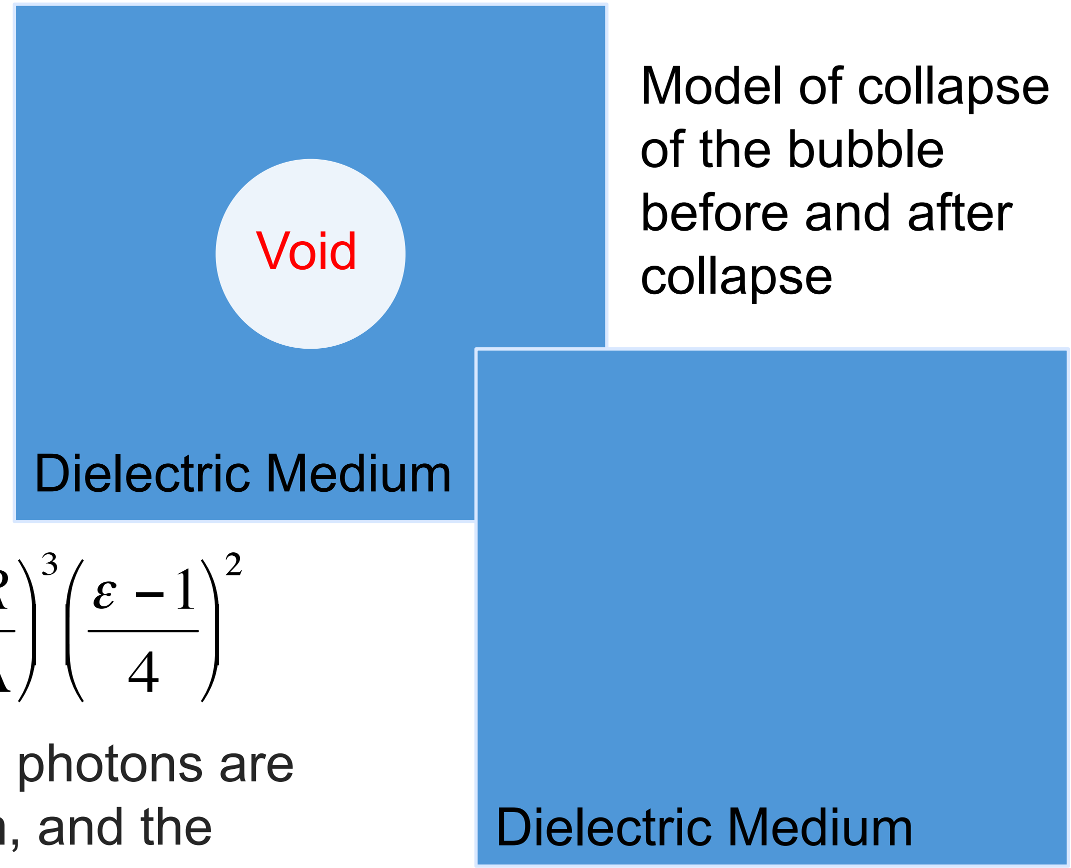
Casimir Effect

- The Casimir effect was postulated as being a possible cause for sonoluminescence

- A simplified model would be the collapse of a void in a dielectric medium in a collapse time, τ_c

- Result of Milton, $N = \left(\frac{4\pi}{3}\right)^2 \left(\frac{R}{\Lambda}\right)^3 \left(\frac{\varepsilon - 1}{4}\right)^2$

- Where R is the radius at which photons are approximately emitted, 0.5 μm, and the cutoff wavelength ~ 200 nm, the number of photons produced is N ~ 10 photons five orders of magnitude too small



Model of collapse of the bubble before and after collapse

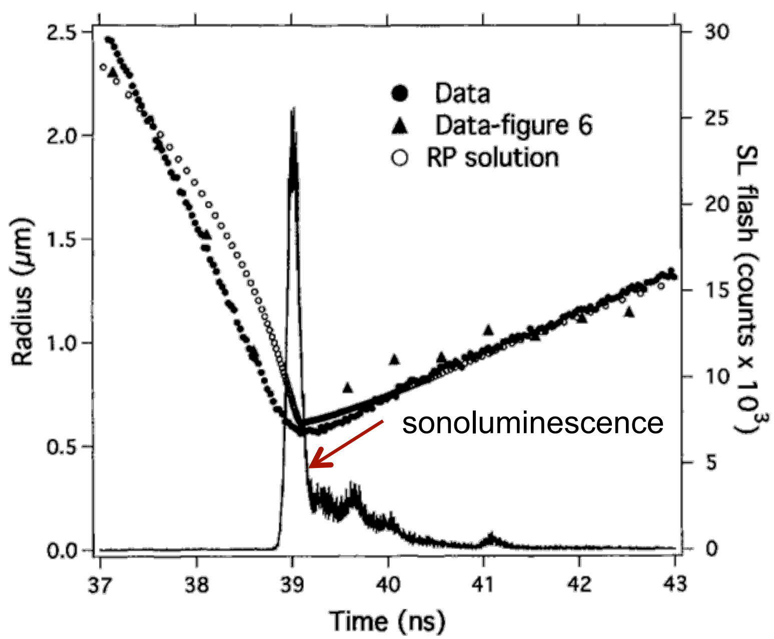
N - photons produced

Λ - cutoff wavelength

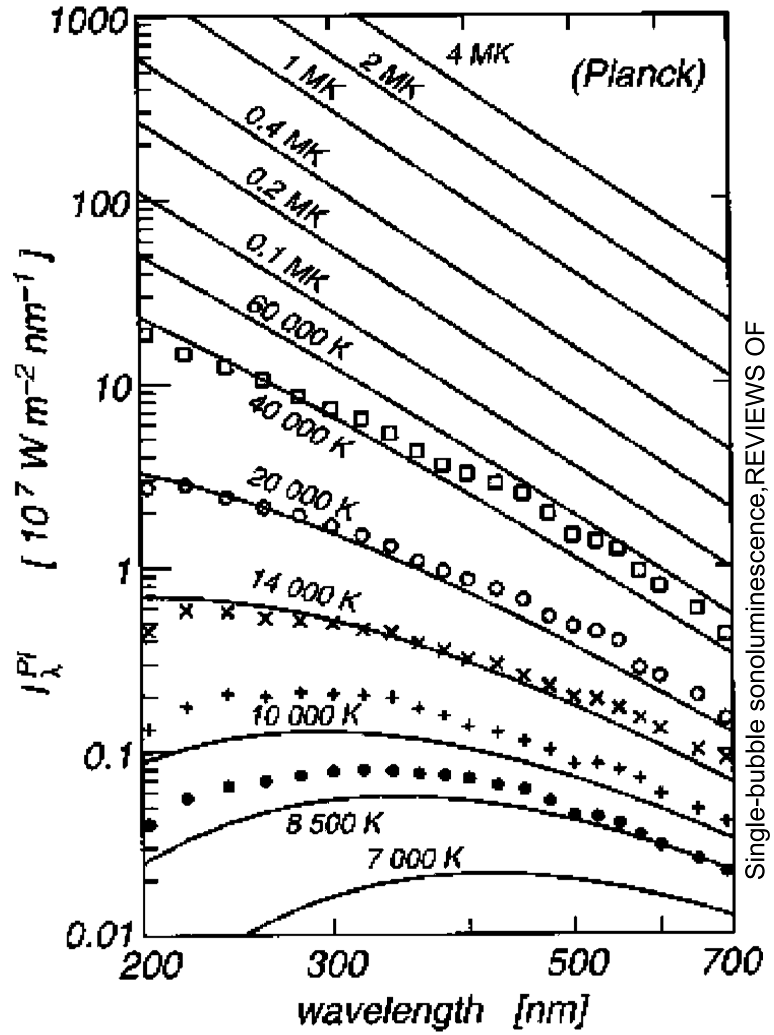
ε - relative permittivity

Black-body Radiation

- Light would be emitted from surface
  - Bubble is a volume emitter
- During emission, bubble has larger radius for longer time
  - Bubble heats as radius decreases
  - According to model pulse width of longer wavelengths should be longer
- Red and ultraviolet pulse width are approximately equal, which contradicts black-body model



Annu. Rev. Fluid Mech. 2000. 32:445–476

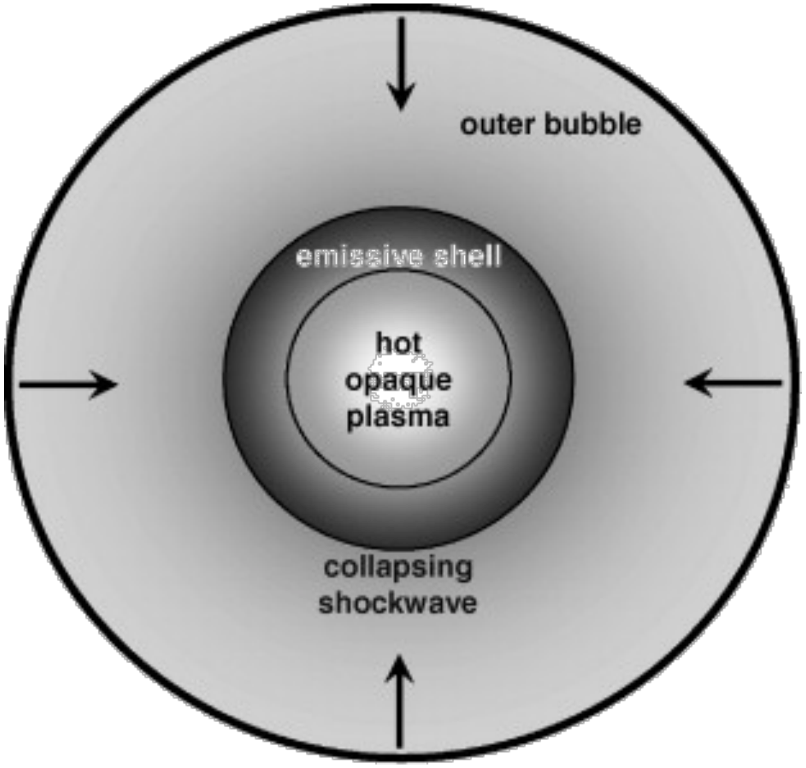


Single-bubble sonoluminescence, REVIEWS OF MODERN PHYSICS, VOLUME 74, APRIL 2002

Black-body intensity for various temperatures plotted with helium, neon, argon, krypton, and xenon from top to bottom. Fit decreases as molecular weight increases

Shockwave Model

- Center of bubble is largest source of light emission
- Center heated from shockwaves in bubble interior
- Temperature increases as shockwave reaches minimum radius
  - Heating ionizes gas at center, light emitted when gas is plasma
- Temperature decreases as shockwave expands
  - Gas ceases to be plasma
- Shockwaves not readily observed
  - Small distortions in spherical shape and low temperature gradients disrupt shockwaves



http://ars.els-cdn.com/content/image/1-s2.0-S1350417710002634-gr6.jpg

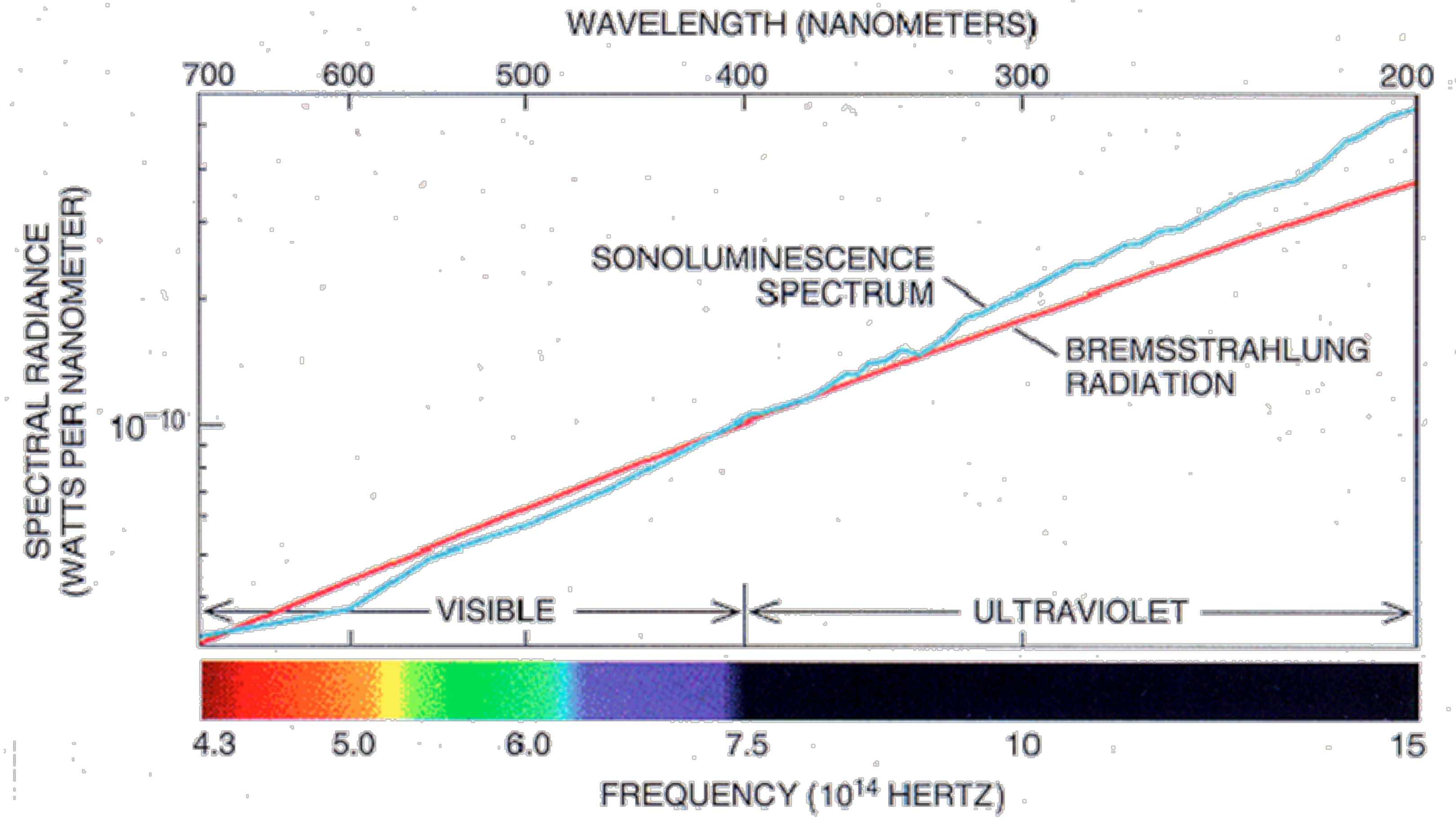
Diagram of shockwave model

Light emitted from accelerating free electrons (Bremsstrahlung radiation)

Model fits well to spectrum provided that the shockwave reaches minimum ~ 0.1μm

Spectrum – Sonoluminescence and Bremsstrahlung

- This spectrum would require the plasma in the center of the bubble to reach 100,000K, requiring that the shockwave reach a radius of 0.1μm
  - To reach the such a small radius, bubble asphericity would need to be minimal, as well as radiation damping and thermal diffusion



http://www.physics.ucla.edu/Sonoluminescence/sono.pdf

Quasi-adiabatic compression model

- Quasi-adiabatic compression heats bubble to ionization temperatures
- Vapor at interface reduces level of ionization
- The proportions of each emission source is influenced by internal temperature of bubble
  - Electron-ion Bremsstrahlung causes less emission when surrounding temperature is hotter

Causes of Light Emission:

-Radiative attachment: $A+e^- \rightarrow A^- + hv$

$$P_{att} = \langle \sigma_{att} v_e \rangle n_o n_e \frac{3}{2} kT / V$$

-Radiative recombination: $A^+ + e^- \rightarrow A + hv$

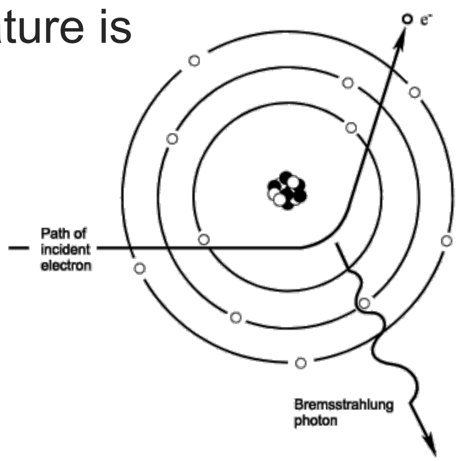
$$P_{rec} = \langle \sigma_{rec} v_e \rangle n_e^2 \frac{3}{2} kT / V \propto T^{1/2}$$

-Electron-atom Bremsstrahlung radiation

$$P_{brem,atom} = 4.6 \times 10^{-44} n_e n_{ar} T / V$$

-Electron-ion Bremsstrahlung radiation

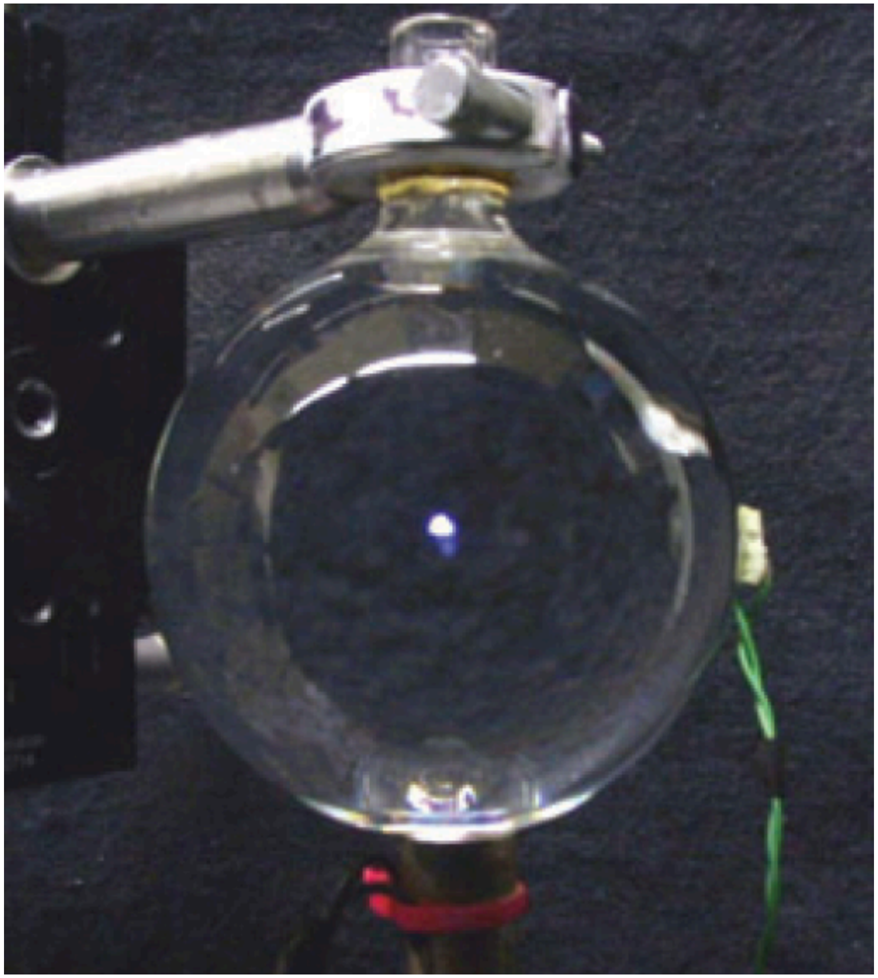
$$P_{brem,ion} = 1.57 \times 10^{-40} n_e^2 T^{1/2} / V$$



http://www4.nau.edu/microanalysis/Microprobe-SEM/Images/Bremsstrahlung.jpg

Conclusions

- Sonoluminescence is visible light emitted from a bubble driven acoustically
- The average temperature of the bubble at collapse is ~10^3 K
- Light is emitted in picosecond pulse widths
- Sonoluminescence is extremely sensitive to conditions
- No theory currently is agreed upon as to the cause of sonoluminescence



http://www.scs.illinois.edu/~suslick/documents/arpc.08.659.pdf

Sonoluminescent bubble of Xe in 85 wt% H_2SO_4 in 3cm radius flask

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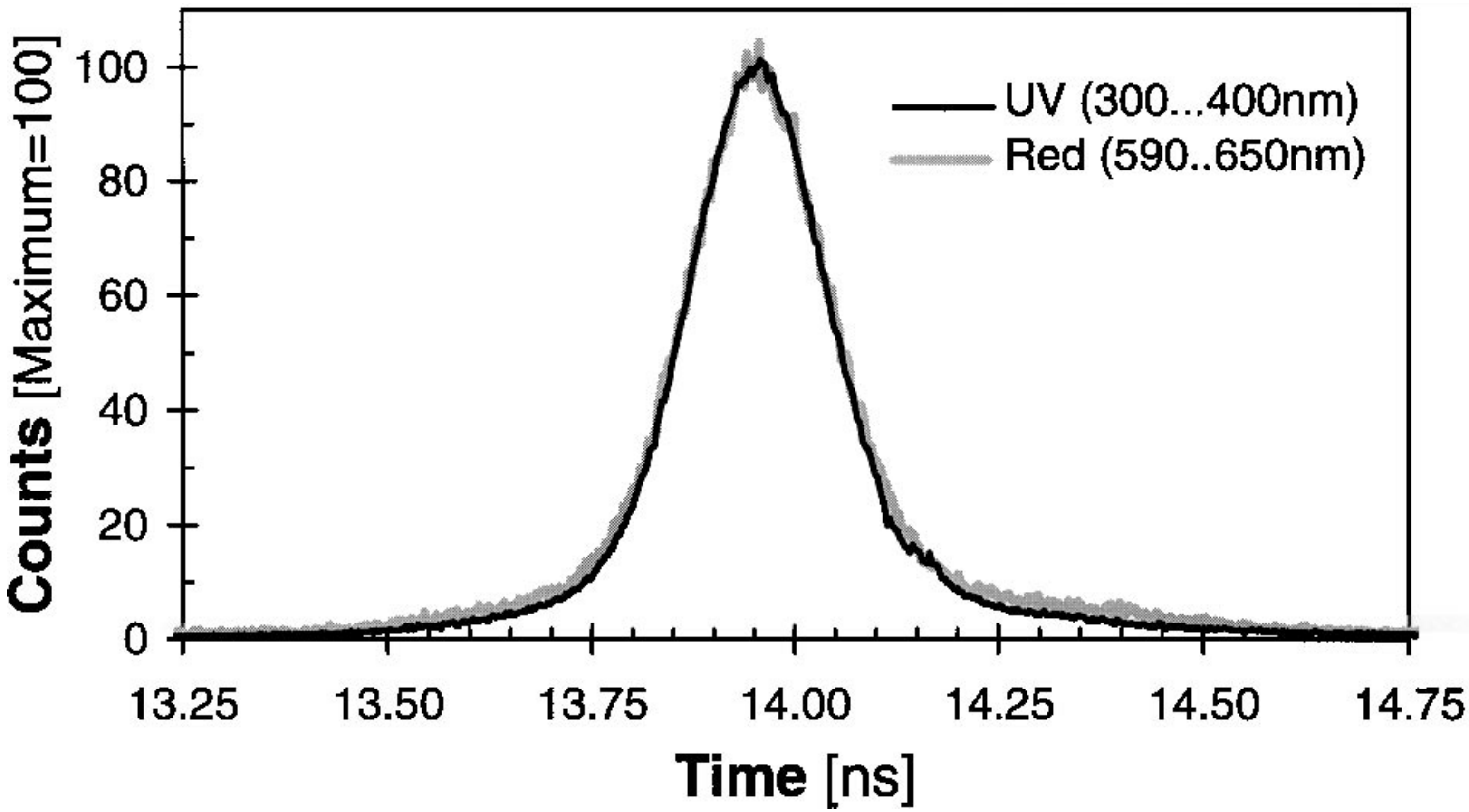
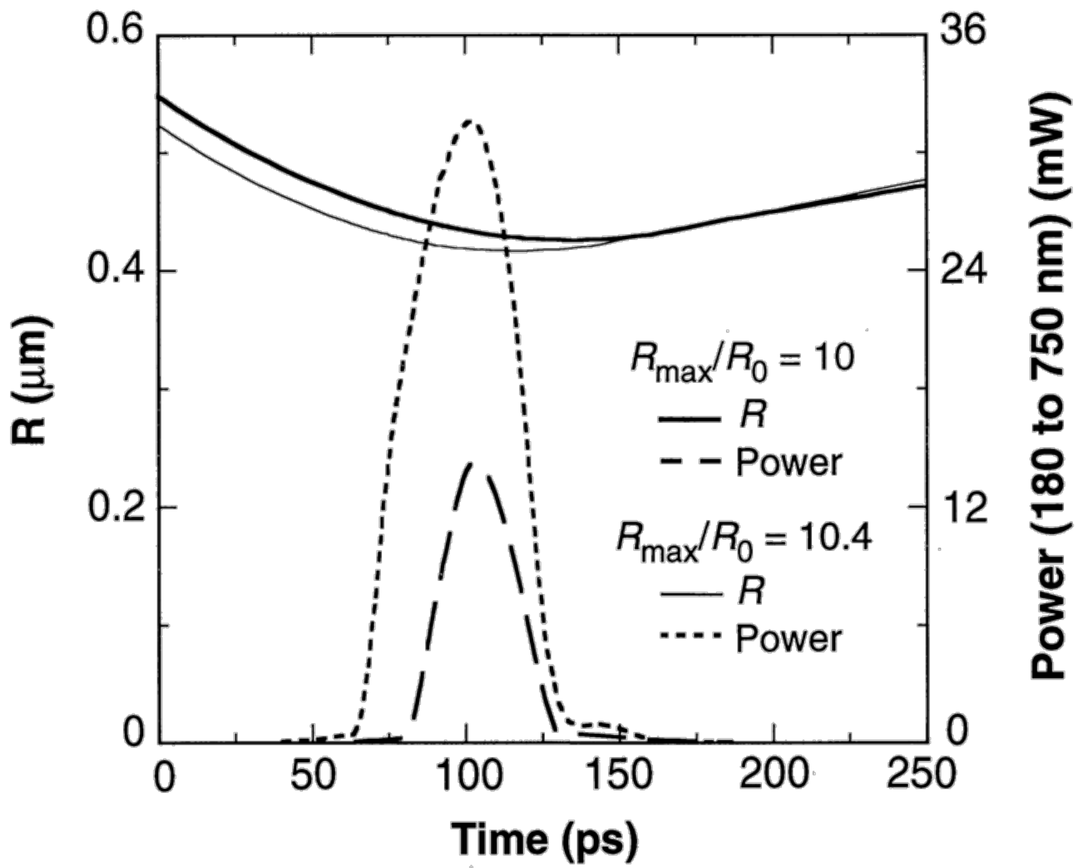
Pulse Width for UV and Red

Red and UV parts of spectrum are nearly identical, ruling out black-body radiation



Pressure and Sonoluminescence

- Power output is increased by factor of 2 with change in driving pressure of $7 \bullet 10^3$ Pa
  - No change in surrounding fluid temperature



Power from light emission from two bubbles with different maximum radius from difference in driving pressure of 7 kilopascal