SONOLUMINESCENCE IN SPACE: THE CRITICAL ROLE OF BUOYANCY IN STABILITY AND EMISSION MECHANISMS

Charles R. Thomas (crt@bu.edu) ,R. Glynn Holt (rgholt@bu.edu) and Ronald A. Roy
(ronroy@bu.edu), Boston University, Dept. of Aerospace and Mechanical Engineering, 110
Cummington St, Boston, MA 02215

INTRODUCTION AND MOTIVATION

Sonoluminescence is the term used to describe the emission of light from a violently collapsing bubble. Sonoluminescence ("light from sound") is the result of extremely nonlinear pulsations of gas/vapor bubbles in liquids when subject to sufficiently high amplitude acoustic pressures. In a single collapse, a bubble's volume can be compressed more than a thousand-fold in the span of less than a microsecond. Even the simplest consideration of the thermodynamics yields pressures on the order of 10,000 ATM. and temperatures of at least 10,000K. On the face of things, it is not surprising that light should be emitted from such an extreme process. Since 1990 (the year that Gaitan discovered light from a single bubble) there has been a tremendous amount of experimental and theoretical research in stable, single-bubble sonoluminescence (SBSL), yet there remain at least four unexplained phenomena associated with SBSL in 1g:

- *the light emission mechanism itself,*
- *the existence of anisotropies in the emitted light,*
- *the disappearance of the bubble at some critical acoustic pressure, and*
- *the appearance of quasiperiodic and chaotic oscillations in the flash timing.*

Gravity, in the context of the buoyant force, is implicated in all four of these.

We are developing KC-135 experiments probing the effect of gravity on single bubble sonoluminescence. By determining the stability boundaries experimentally in microgravity, and measuring not only light emission but mechanical bubble response, we will be able to directly test the predictions of existing theories. By exploiting the microgravity environment we will gain new knowledge impossible to obtain in earth-based labs that will enable explanations for the above problems. We will also be in a position to make new discoveries about light-emitting bubbles.

OBJECTIVES

The objectives of the investigation are:

(1) To develop an experimental apparatus to fly on the KC-135 that will monitor cabin pressure, water temperature, bubble position and size, acceleration, emitted light intensity, and acoustic pressure.

(2) To model the hydrodynamic effects of acceleration on bubble dynamics and SBSL in realistic acoustic resonators. The primary Bjerknes force, buoyancy, ambient pressure, drag, mass diffusion, shape stability and (empirically) light emission will be accounted for in the model.

(3) To measure (as a function of acceleration during parabolic flight) a bubble's position, equilibrium radius, maximum radius, oscillatory radius, and spatially and temporally resolved light emission. This will be done for a range of dissolved gas concentrations in order to compare with predictions of our hydrodynamic model.

(4) To measure (as a function of acceleration during parabolic flight) the precise values of acoustic pressure and equilibrium radius that leads to the extinction of a light-emitting bubble, a phenomenon which occurs at a well defined critical acoustic pressure in 1g experiments. This will test theories that postulate either a nonlinear levitation instability, or a Rayleigh-Taylor instability mechanism for the bubble disappearance.

RESULTS

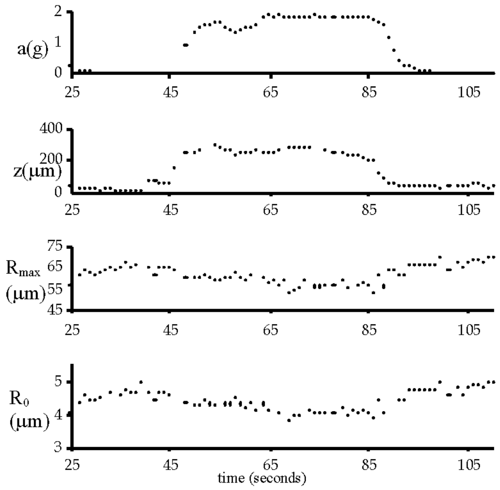

Figure 1. Measured (R_0 inferred) bubble dynamics during KC-135 parabolic maneuver.

We have completed 3 KC-135 flight campaigns. We attempted to test the prediction of our model [1] that hydrodynamics alone dictate a 5 – 35 % change in SBSL intensity, (depending approximately linearly on the dissolved gas concentration) for the 10^{-4}g to 1.8g swing typical of a K-135 parabolic maneuver. The driving mechanism for this effect is the small change in head pressure experienced by the bubble when the acceleration changes. Figure 1 shows the measured bubble dynamics during a single parabola. The main result [2] is that for nearly 0g, the bubble grows and emits more light, while at 2g the bubble shrinks and emits less light. The results are in rough agreement with our model. We have completely overhauled the data acquisition system to make better use of available computer resources. We have installed a joystick-controlled three axis positioning system, using this system we can better position the cell and track its motion. We have completely replaced the light intensity detection system, including fabrication of a NIM-BIN style gated peak detector. Finally we have divided the apparatus into two equipment racks to facilitate transporting the experiment.

MICROGRAVITY RELEVANCE

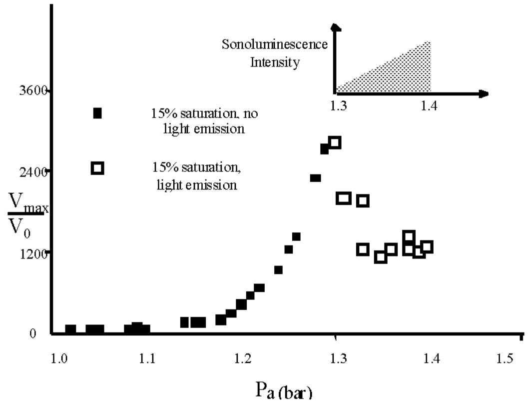

Figure 2. The measured (1g) ratio of V_{max} / V_0 during 1 acoustic cycle as a function of acoustic

SBSL bubbles experience a time-varying buoyancy (quantified by the oscillatory volume ratio V_{max}/V_0, see Fig. 2) which reaches maximal excursions precisely where sonoluminescence is observed. This results in a strong nonlinear coupling between volume and translatory motions. Removing the acceleration of gravity from the system will eliminate buoyancy-driven translatory oscillations of the bubble. This would be a decisive test of light emission mechanisms, and will also shed light on the chemical reaction theory of mass flux for volume stability as well as the resonance-controlled shape oscillation instability. Thus, a microgravity environment will change the geography of the parameter space, and the only hope for a clear understanding of the SBSL phenomenon is to perform experiments which locate light emission within the context of the instability boundaries that exist in the parameter space.

REFERENCES

[1] Holt, RG, RA Roy and SC Wyatt, J. Acoust. Soc. Am. 105, No. 2, Pt. 2, p. 960. (Joint EAA/ASA/DAGA meeting, Berlin, 1999)

[2] Thomas, CR, SC Wyatt, RA Roy, R. Glynn Holt, J. Acoust. Soc. Am. 108, No. 5, Pt. 2, p. 2493. (ASA Meeting, Newport Beach, California)

Charles R. Thomas
R. Glynn Holt
Ronald A. Roy

Boston University
Dept. of Aerospace and
Mechanical Engineering
110 Cummington Street
Boston, MA 02215

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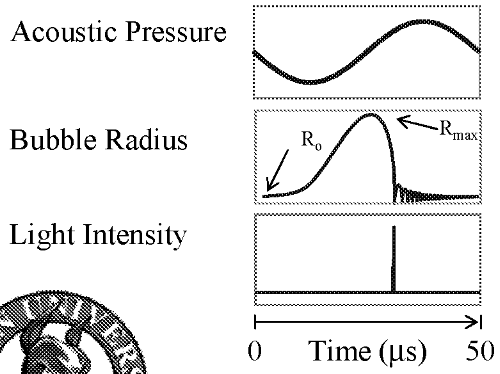
Bubble Dynamics

$$\left(1-\frac{\dot{R}}{c}\right)R\ddot{R}+\frac{3}{2}\dot{R}^2\left(1-\frac{\dot{R}}{3c}\right)=\left(1-\frac{\dot{R}}{c}\right)\frac{P}{\rho}+\frac{R}{\rho c}\frac{dP}{dt}$$

$$P_{stat}=\rho gh+P_{cabin}$$

$$P\left(R,\dot{R},t\right)=\left(P_{stat}-P_v+\frac{2\sigma}{R_o}\right)\left(\frac{R_o}{R}\right)^{3\kappa}-\frac{2\sigma}{R}-4\mu\frac{\dot{R}}{R}-P_{stat}+P_v-P_a\sin(2\pi\nu t)$$



Parameters that can affect the bubble dynamics:

Ambient Acceleration: changes the buoyant force of the bubble, and the hydrostatic force on the bubble

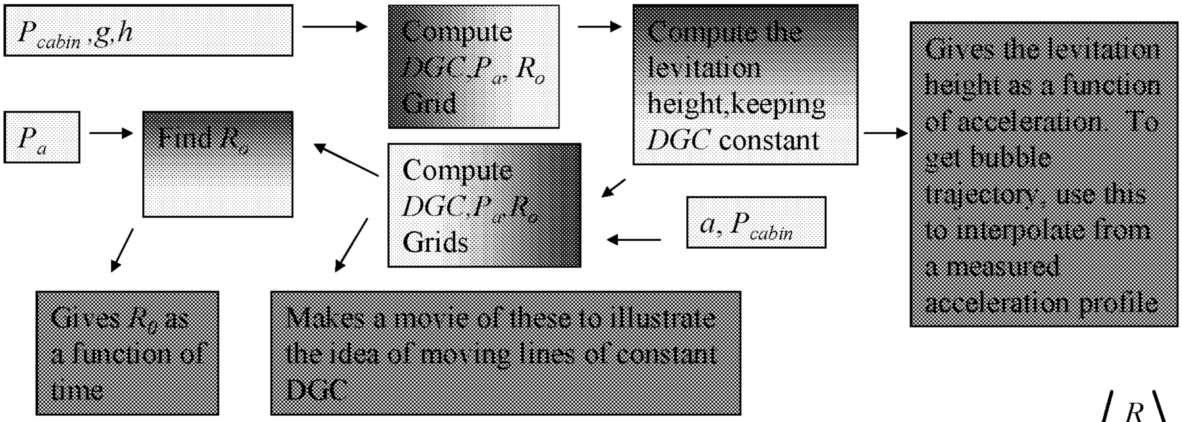
Cabin Pressure in the airplane

Acoustic Pressure

Temperature

Dissolved gas concentration

Quasi-static Model



P_{cabin} ,g,h

Compute DGC,P_a, R_o Grid

Compute the levitation height,keeping DGC constant

Gives the levitation height as a function of acceleration. To get bubble trajectory, use this to interpolate from a measured acceleration profile

P_a

Find R_o

Compute DGC,P_a,R_o Grids

a, P_{cabin}

Gives R_0 as a function of time

Makes a movie of these to illustrate the idea of moving lines of constant DGC

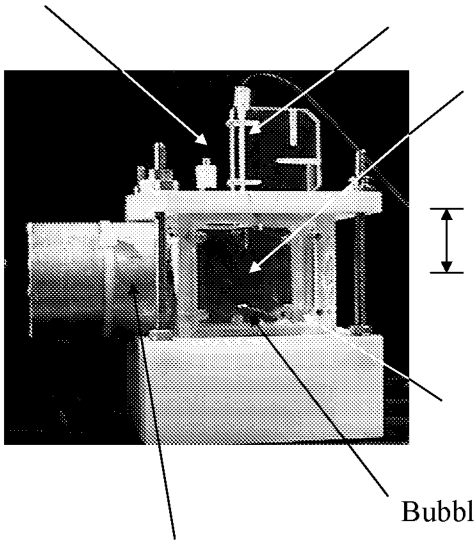
- Levitation height, *z,* found by making buoyant force equal Bjerknes force
- *Ro* found by requiring the dissolve concentration of AR not to change

$$c_i = kP_{cabin}\left(1 + \frac{\rho a h}{P_{cabin}} + \frac{2\sigma}{R_o P_{cabin}}\right)\frac{\left\langle \frac{R}{R_0} \right\rangle}{\left\langle \left(\frac{R}{R_0}\right)^4 \right\rangle}$$

- *k* is Henry’s law constant for argon

SL Cell

- Cubical geometry
- Antinode of sound field near center of cube
- Driving frequency is 14.620 kHz
- Ports on top and bottom to fill cell
- Thermocouple in water to record water temperature



Top fill port

Needle hydrophone

Bubble levitates here

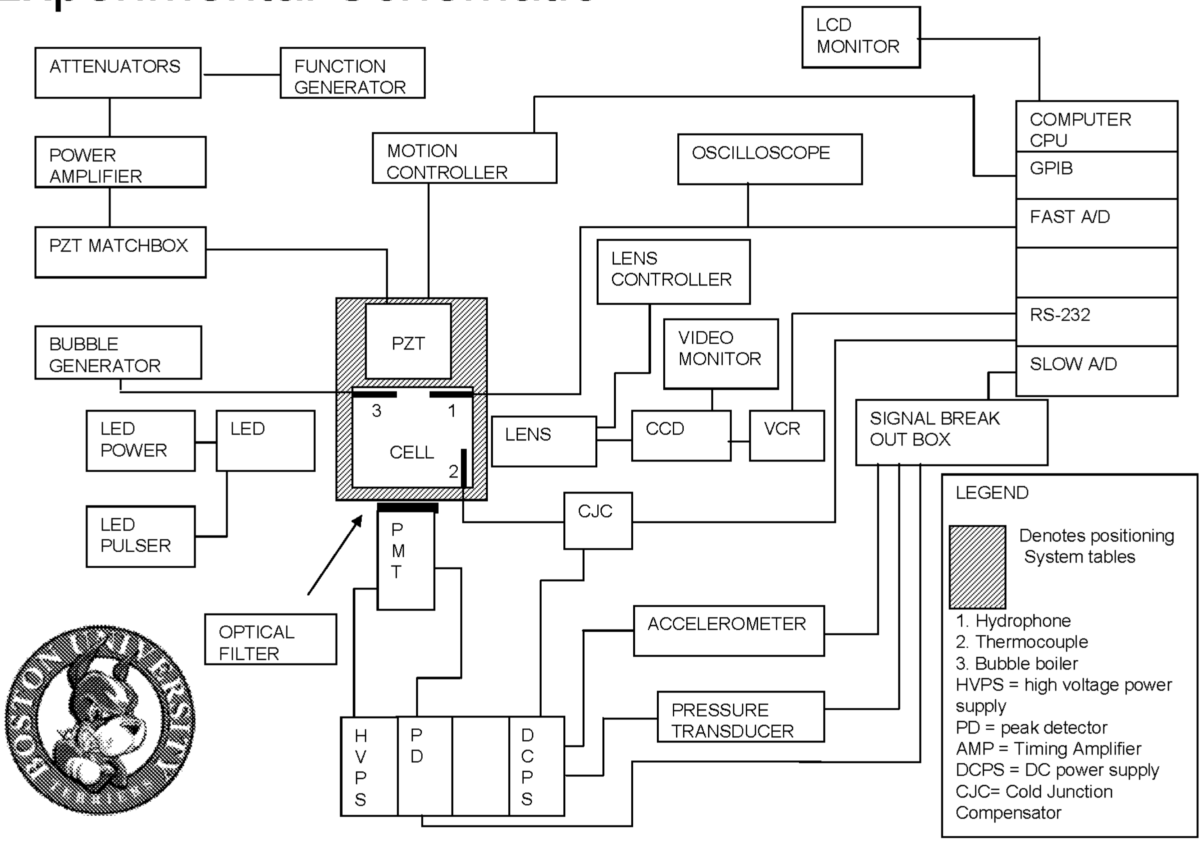
h: distance from top of cell to vertical position of bubble

Thermocouple

Bubble generator

PZT Driving Transducer

Experimental Schematic



LEGEND

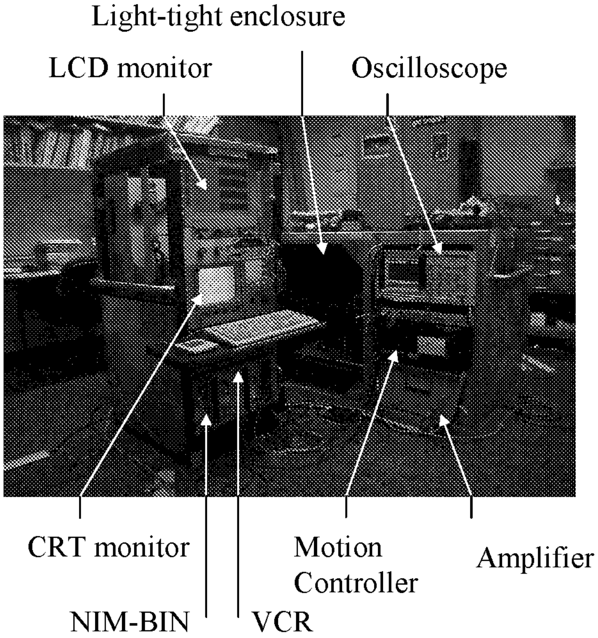
▨ Denotes positioning System tables

1. Hydrophone
2. Thermocouple
3. Bubble boiler

HVPS = high voltage power supply
PD = peak detector
AMP = Timing Amplifier
DCPS = DC power supply
CJC= Cold Junction Compensator

Experimental Apparatus

The experiment is housed in two equipment racks, pictured to the right. The taller one is a modified AMCO engineering equipment rack that holds the data acquisition computer, VCR, NIM-BIN and function generator. The shorter one is a custom built rack with a section that can be made light tight. It is in this section that the cell resides, along with the various transducers used to make the measurements of the bubble dynamics and the light emission.



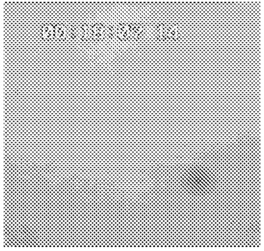
Results: Bubble Images

In 0g the bubble grows larger due to both diffusion and the *reduced* ambient pressure. It also moves toward the antinode of the sound field

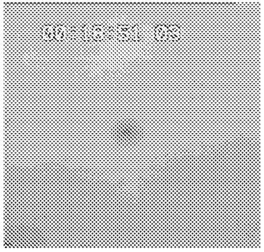
In 1.8g, the bubble gets smaller, this time due to both diffusion and *increased* ambient pressure. With an increased buoyant force, the bubble moves further above antinode than in 1g.

As the plots on the slide following illustrate, in addition to growing in size, the light intensity of the bubble also increases during periods of 0g. Conversely, during periods of 1.8g, light intensity emitted by the bubble decreases.

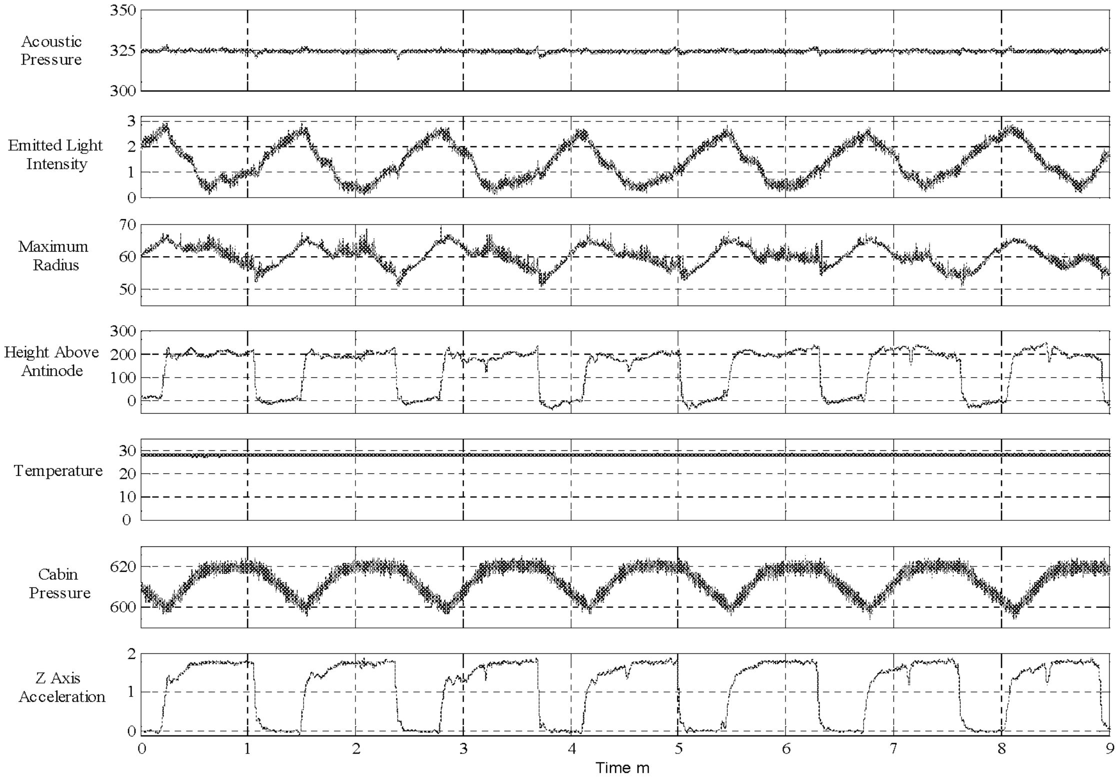
Bubble at 0g Acceleration



Bubble at 1.8g Acceleration



Results: Measured Variables vs Time



Conclusions and Future Work

Conclusions:

We have successfully completed the first of our objectives – developing an experiment to measure various quantities associated with how the behavior of a bubble changes in a variable acceleration environment.

We have made measurements at two different dissolved gas concentrations during flights on the KC-135, thus partially completing our third objective.

Future Work:

Though a model has been developed (Wyatt Master's Thesis, 00; Thomas, ASA Newport Beach, 99) it needs to be refined to better incorporate changing cabin pressure and effects due to diffusion.

Possibly one more flight on the KC-135 in September 2002 to finish taking data to complete objectives 3 and 4.