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The Investigation of the Effects of Gravity on Single Bubble Sonoluminescence

Ben Dzikowicz, David B. Thiessen, Philip Marston, Washington State University, Department of Physics, Pullman, WA, 99164

Abstract

In single bubble sonoluminescence (SBSL), a bubble in water emits a flash of light following its rapid collapse each cycle of oscillation of an ultrasonic field. Since widely varying length and time scales affect the bubble dynamics and optical emission processes, it is difficult to anticipate the importance of the effects of gravity present for observations on earth.

Our bubble is driven in a spherical cavity at its fundamental mode. The acoustical radiation pressure (Bjerknes force) will then keep it suspended close to the center near the pressure antinode. When driven in a region where the diffusive processes balance the bubble it acts in a nonlinear but regular way [1], emitting a short (approx. 200ps) burst of light each acoustic cycle.

Balancing the Bjerknes force with buoyancy, as in [2], we can see that the bubble should be displaced from the velocity node approximately 20μm at normal gravity. Therefore, water flows past the bubble at the time of collapse. Changes in gravity also change the ambient pressure at the bubble's location, as $\Delta P = \rho g h$, where h is the depth of the bubble. This gives a change of approximately –0.5% in our experiment when going from 1.8g to 0g. Studies of ambient pressure changes were also done in order to assess these effects.

Inside a pressure sealed chamber a spherical glass cell is filled with distilled water that has been degassed to 120mmHg. A bubble is then trapped in the center and driven by a piezoelectric transducer at 32.2kHz attached to the side of the cell. An optical system is then set up to take strobed video images and light emission data simultaneously. Temperature, pressure, drive voltage, and listener voltage are also monitored.

Figure 2 (two rows down on the left) shows the change in light output with the change in acceleration on the KC-135 aircraft. Figure 3 (below Fig 2) shows the bubble radii for the same set of data. Note that each 'spike' in the radius plot represents the growth and collapse of many cycles over a one-second period. From these graphs we can see that the light output and the maximum bubble radius both increase as the gravity decreases.

The radii of the bubbles for both experiments are fit using the Rayleigh-Plesset equation and the acoustic drive amplitude and the ambient bubble radius are found. There is little change in the acoustic drive amplitude as we expect, since we are not varying the drive voltage. However, the ambient bubble radius goes up considerably. These changes (increased light output, increased maximum bubble radius, and increased ambient bubble radius) are also observed when the ambient pressure is varied in the laboratory by an amount similar to that due to effective changes in the acceleration. The changes in the ambient bubble radius and light output with a change in ambient pressure are predicted by the "dissociation hypothesis"[3] and have been observed by other groups in the laboratory [4]. It seems clear that buoyancy's effect on light output and bubble radius are at best on the same order as the effects of ambient pressure.

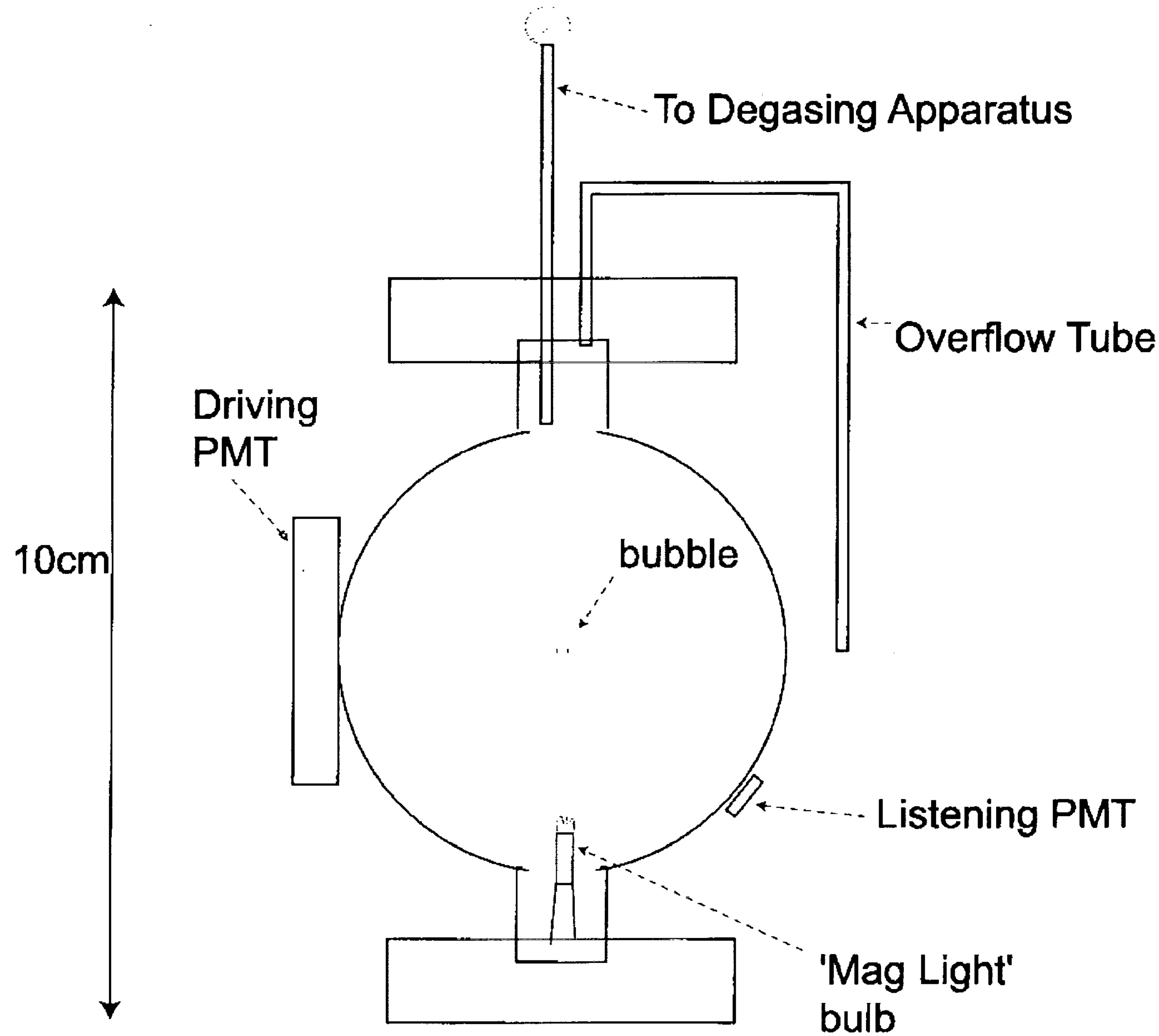
Work funded by NASA NAG3-2114

[1]Holt, R.G., Gaitan, D.F., Observation of Stability Boundaries in the Parameter Space of Single Bubble Sonoluminescence, Phys. Rev. Lett., vol 77, 3791-3794, 1996

[2]Matula, T.J., Cordry, S.M., Roy, R.A., Crum, L.A., Bjerknes force and Bubble Levitation Under Single-Bubble Sonoluminescence Conditions, J. Acoust. Soc. Am., vol 102, 1522-1525, 1997

[3]Kondic, L., Yuan, C., Chan, C.K., Ambient Pressure and Single-Bubble Sonoluminescence, Phys. Rev. E, vol 57, R32-R35, 1998

[4]Dan, M., Cheeke, J. D. N., Kondic, L., Ambient Pressure Effect on Single Bubble Sonoluminescence, Phys. Rev. Lett., vol 83, 1870-1873, 1999



- Driving Frequency ~ 32.4kHz
- Water is degased to ~ 120mmHg
- Maximum bubble size for this frequency ~50 microns.
- Driven at first radial mode.
- Velocity Node and Pressure Anti-Node at Center.
- Light flash occurs at collapse, each acoustic cycle primarily UV and visible light.

Top View of Microgravity Sonoluminescence Experiment Showing PMT/Laser Diode Switcher and Piezoelectric Devices

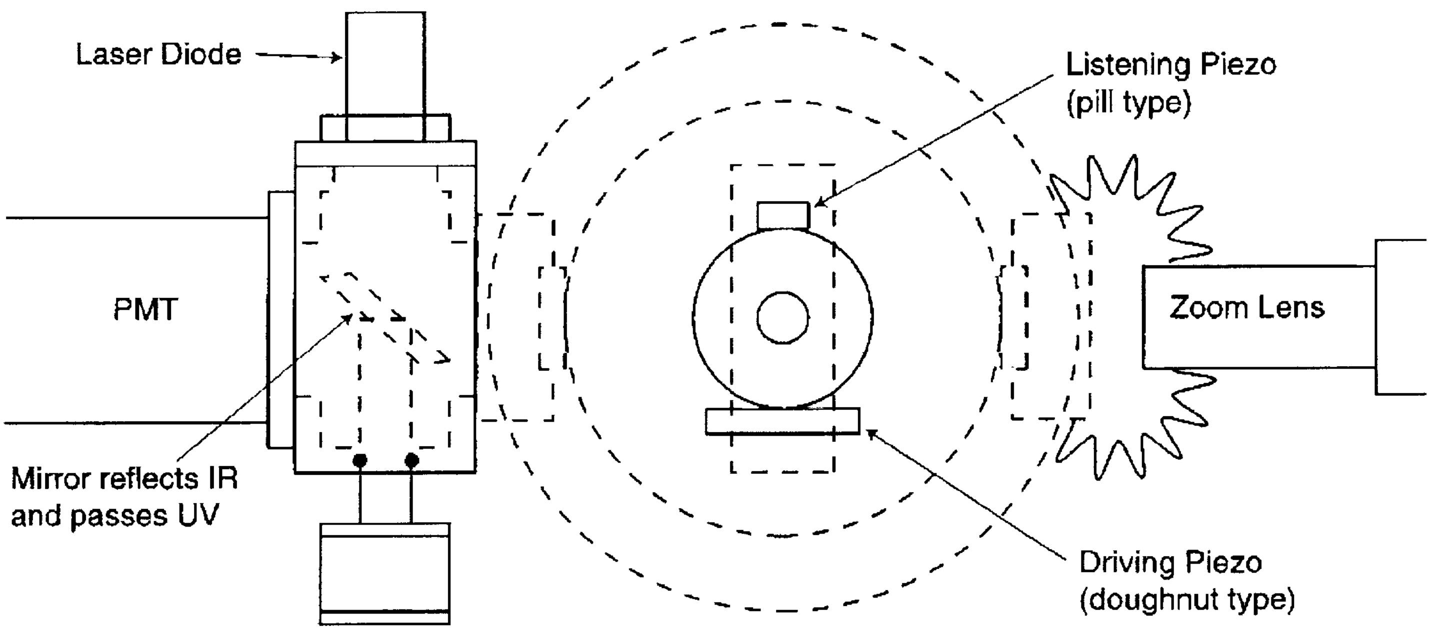


Figure 1

Video Investigation of the Effects of Gravity on Single-Bubble Sonoluminescence

Ben Dzikowicz, David B. Thiessen, Philip L. Marston
Washington State University
Physics Department
Pullman, WA 99164
dzikowic@wsunix.wsu.edu

In single bubble sonoluminescence (SBSL), a bubble in water emits a flash of light following its rapid collapse each cycle of oscillation of an ultrasonic field. Since widely varying length and time scales affect the bubble dynamics and optical emission processes, it is difficult to anticipate the importance of the effects of gravity present for observations on earth. In normal gravity, buoyancy displaces the bubble from the velocity node of the sound field so that water is flowing past the bubble at the time of collapse. Other gravitational effects include the variation in ambient pressure. Our measurements of SBSL light emission for a spherical resonator in NASA's KC-135 aircraft confirm that emission is not automatically quenched in the reduced and enhanced effective gravity conditions created during parabolic flight trajectories. We also measured the bubble radius as a function of time in the reduced gravity environment using strobed video. These measurements were fit to the Rayleigh-Plesset equation to infer the size and pressure conditions of spherical bubble oscillations. These were found to be similar to those reported by other groups for measurements in normal gravity. There are also indications that changes in the effective gravity are accompanied by small changes in the maximum bubble radius as well as by more easily observed changes in the light emission. Work supported by NASA.

Introduction

An air bubble in water will naturally rise due to the effects of buoyancy. We can prevent this from happening by placing the bubble in an acoustically resonating cavity driven at its first harmonic mode. The Bjerknes force will then keep it suspended in the center near the pressure antinode. The sinusoidally changing pressure will then drive the bubble to react as described by the Rayleigh-Plesset equation[1]:

$$R\ddot{R}+\frac{3}{2}\dot{R}^2=\frac{1}{\rho}(P_g(R)-P_0-P_a(0,t))-\frac{4\eta\dot{R}}{\rho R}-\frac{2\sigma}{\rho R}+\frac{R}{\rho c}\frac{d}{dt}(P_g-P_a)$$

Where P_a is the acoustical pressure, P_g is the pressure of the gas in the liquid and P_0 is the ambient pressure. At low pressure amplitudes the bubble simply reacts sinusoidally. At higher amplitudes the concentration of the gas in the water becomes important (related to P_g). When P_g is too small the bubble will eventually dissolve in the water, when P_g is too big then the bubble will grow too large and the buoyancy will take over[2]. However, there is a large region where the neither of these two things occurs and the bubble acts in a nonlinear but regular way.

In this region the bubble will slowly grow to a large size (50 to 200μm) and then collapse violently, only to rebound a few times and then repeat the process. In a resonant cell of about 4cm radius this occurs at a rate of about 34kHz. This is much slower than the monopole resonance of the bubble itself. At the collapse a short burst of broad spectrum, UV and visible light appears. This burst lasts a very short time, around 150ps[3]. Light output due to cavitation is only beginning to be understood.

Gravitational Issues

For some time the symmetry of the collapse and its contribution to the light output has been debated. The bubble is not exactly at the velocity node[4], as the buoyant force is acting on the bubble as well as the Bjerknes force to push the bubble away from the node. Therefore there is fluid motion around the bubble which may cause it to react to the pressure change in a non-symmetrical way. It is difficult to directly observe the collapse of a bubble since it happens so fast and is so small at its final collapse (~1μm). We cannot then tell if the bubble is still spherical when it emits light. We can, however, remove gravity and observe changes in the bubble's light output, maximum bubble size, and bubble position to try and understand the effects of buoyancy.

There is a problem however, removing gravity does not only change the buoyancy of the bubble, but it also changes the hydrostatic pressure around the bubble. This pressure change appears as a change in ambient pressure, P_0, in the Rayleigh-Plesset equation. There is a pressure drop of about 4mmHg for a change of 1.8g to 0g (a typical transition on NASA's KC-135 aircraft). Other ground based work indicates that with constant driving pressure a decrease in ambient pressure should be accompanied by an increase in light output and maximum bubble radius[5]. Increased maximum bubble radius typically accompanies increased light output when various parameters are altered, and is therefore a good indication that nothing unexpected is going on. With larger size comes more violent collapse and hence brighter light, but without larger size brighter light would indicate another mechanism is affecting the light output.

Not only is the ambient pressure at the bubble's location affected, but when gravity is present, there is a pressure gradient from the top of the cavity to the bottom. At reduced gravity this gradient is gone and the whole cavity is at atmospheric pressure. This may alter the acoustic field in a manner that would affect light output.

Experimental Set Up

We use a 4cm radius spherical glass cell with necks at the top and bottom. Then distilled water, which has been degassed to a pressure of about 120mmHg, is drawn into the top neck of the flask. The entire water system is continuous and sealed so the gas concentration remains constant during filling. Epoxied to one side of the flask is a doughnut shaped piezoelectric transducer to drive the cell, and on the other is a smaller transducer that we monitor in order to tune the system. The system is driven using a function generator into an audio amplifier then into a step-up matching transformer. This allows us to get the 100 to 300V signal we use to drive the cell. The frequency of our system is about 34.2kHz, this varies day to day with temperature and other environmental factors. Once the cell is in the correct mode a 'MagLite' flashlight bulb, which extends through the bottom neck of the flask, is used to create a bubble. By sending a short burst of current through the filament the water is quickly boiled and a bubble rises quickly to the center of the cell. We can then adjust the drive amplitude to give us good light output.

The entire cell is enclosed in a pressure tight chamber in order to block cabin pressure changes that occur on the KC-135 due to dramatic altitude changes. There are quartz windows on each side of the chamber. Into one goes a CCD camera to take strobed video of the bubble, and into the other goes a Photomultiplier Tube (PMT) for the measurement of the bubble's light output. Since the camera needs be strongly backlit to get good images and the PMT must measure the very small light output of the bubble simultaneously, a system was developed to keep these separate using separate wavelengths for each measurement. A mirror which passes UV and visible but reflects IR is placed at a 45° angle and the PMT is placed behind it. In addition a colored glass filter is placed on the PMT to keep stray IR light out. An IR laser diode pointing into the mirror is then able to provide the backlighting necessary for the CCD. This diode is then set to deliver a 100ns pulse, 1Hz slower than the drive frequency. Then we are able to observe 30μs bubble collapses over a period of one second. This setup is unique and allows us to obtain both light output and bubble simultaneously [Figure 1.].

This whole apparatus is then strapped to the floor of NASA's low-gravity KC-135 aircraft which flies in a parabolic trajectory giving cycles consisting of about 20 seconds of 0g and 45s of 1.8g. During the flight we monitor many parameters, besides the light output and the video data, we also record pressure and temperature within the chamber, drive transducer voltage, listener transducer voltage and acceleration. These are recorded at a rate of 20Hz using LabView software.

In order to simulate a change in pressure due to the varying gravity lab experiments were also done. The sealed chamber was attached to a small volume of low pressure, this was then used to draw the ambient pressure around the bubble down 5mmHg from atmospheric. Then the pressure was released simulating the change in pressure due to gravity. This data was analyzed in the same manner as the flight data.

Data Analysis

The 20Hz parameter data is averaged using a sliding average over 0.5 seconds. The video data is less straightforward, since the optical system used limits the contrast of the images. First the frames are deinterlaced, and then background subtraction is done. After that a FFT filter is applied to reduce high frequency noise. An edge finding program is used to extract the radius and location of the bubble. Events such as turning on and off the PMT and the backlighting simultaneously are then used to line up the two data sets.

Results and Conclusions

Note: Accompanying graphs of radii show peaks not smooth lines. This is due to time scale differences, each peak is actually an acoustic cycle showing the growth and collapse of the sonoluminescing bubble. At this scale these appear as spikes.

Preliminary analysis shows, as confirmed elsewhere[6], that the light output increases as the gravity is reduced [Figure 2.]. We have also shown that the maximum bubble radius increases along with the light output [Figure 3.]. The bubble also moves, but not in a vertical direction as we would expect by just removing the buoyancy. It moves instead in a diagonal direction. For further insight into these results we can look to the ambient pressure tests done in the laboratory.

The tests done in the lab to mimic the pressure changes due to gravity show very similar results. Light output increases and maximum bubble radius increases [Figures 4 and 5.]. This suggests that the increase in light output is due, at least in part, by the change in hydrostatic pressure. As for the bubble's location, it also moves in a similar diagonal way as the bubble in the flight. This is more difficult to interpret, but it suggests that the sound field in the cell is changing in manner not anticipated as the pressure changes. In attempting to predict results the assumption is made that the geometry of the acoustic field is symmetrical and static. This may not be the case, as the changes in pressure and gravity may be altering the field near the center of the flask.

In conclusion, any changes in the light output due to buoyancy will not be easy to detect. Changes in the ambient pressure and the acoustic field make buoyant effects and the symmetry of the collapse difficult to measure. Running the experiment at a lower frequency (i.e. a larger cell) would produce bubbles with higher volume and hence greater buoyancy. This upscaling may allow the observation of buoyant effects. However, the bubble's response to ambient pressure may prove at least as interesting as the changes in buoyancy.

Figures

Figure 1. Top View of Microgravity Sonoluminescence Experiment Showing PMT, Laser Diode, and Piezoelectric Devices.

Figure 2. Gravity and Light Output

Figure 3. Gravity and Bubble Radius

Figure 4. Pressure and Light Output

Figure 5. Pressure and Bubble Radius

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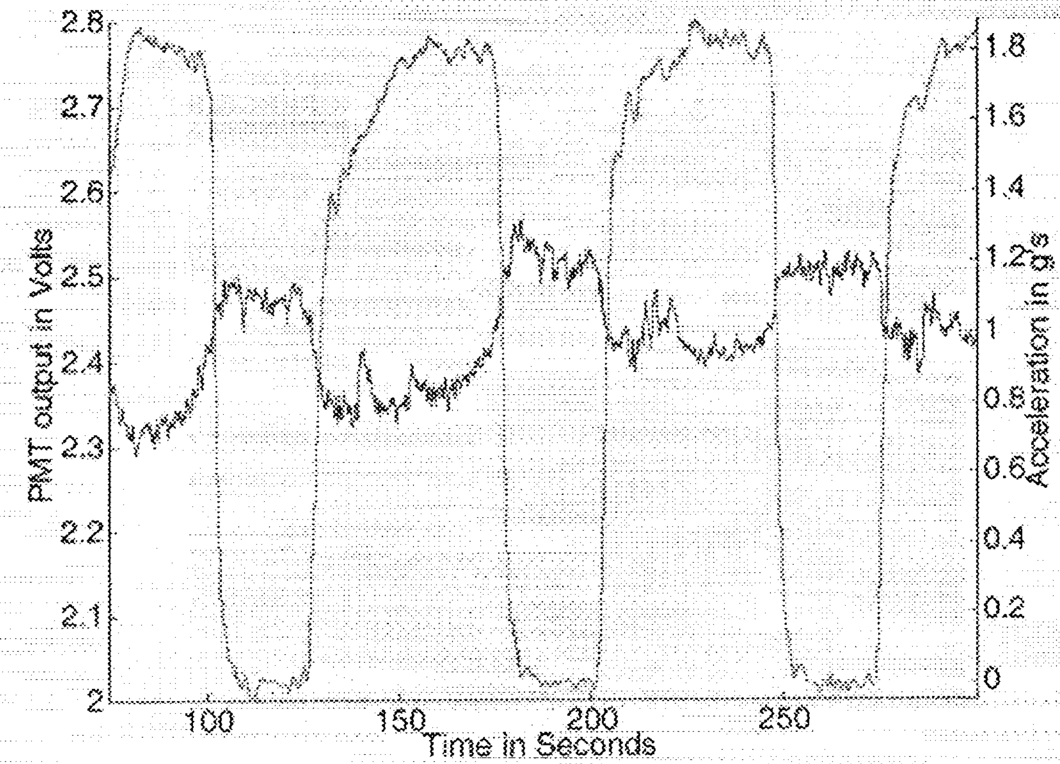


Figure 2 – Acceleration in red

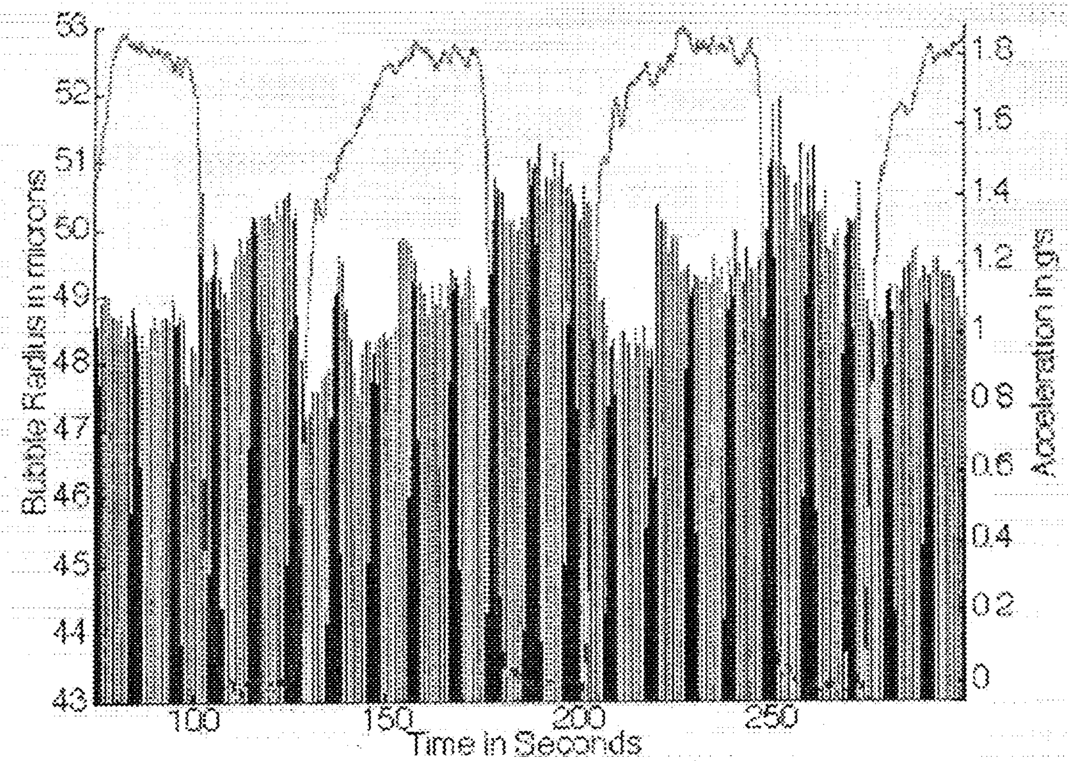


Figure 3 – Acceleration in red

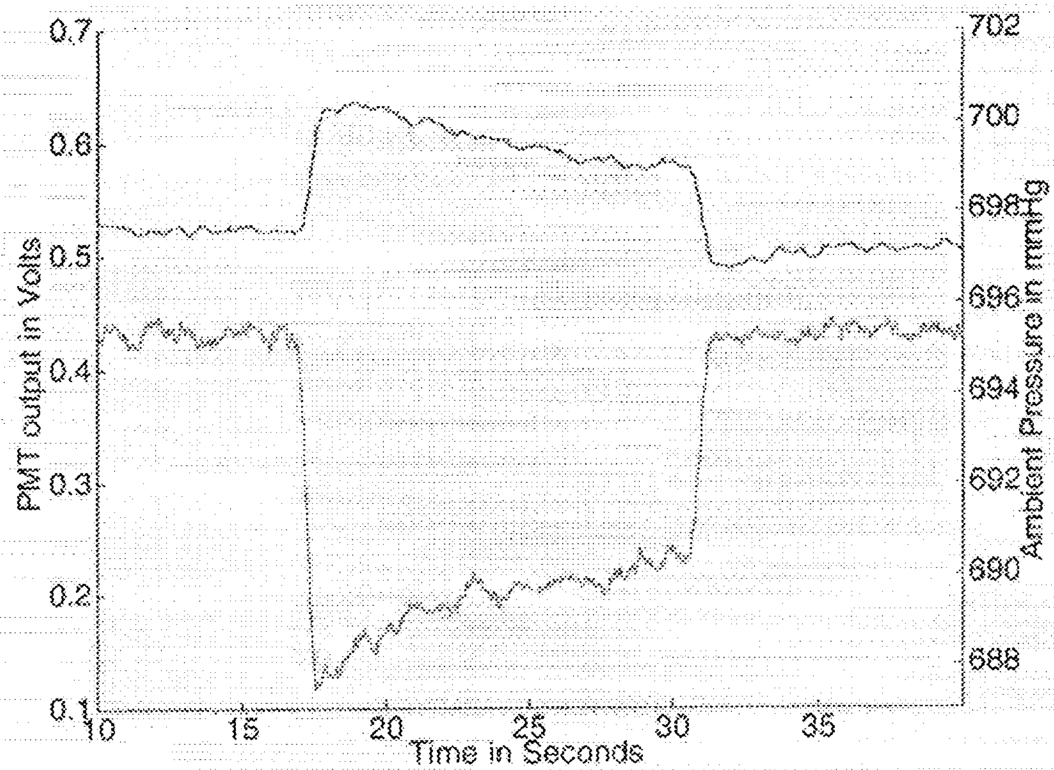


Figure 4 – Ambient Pressure in red

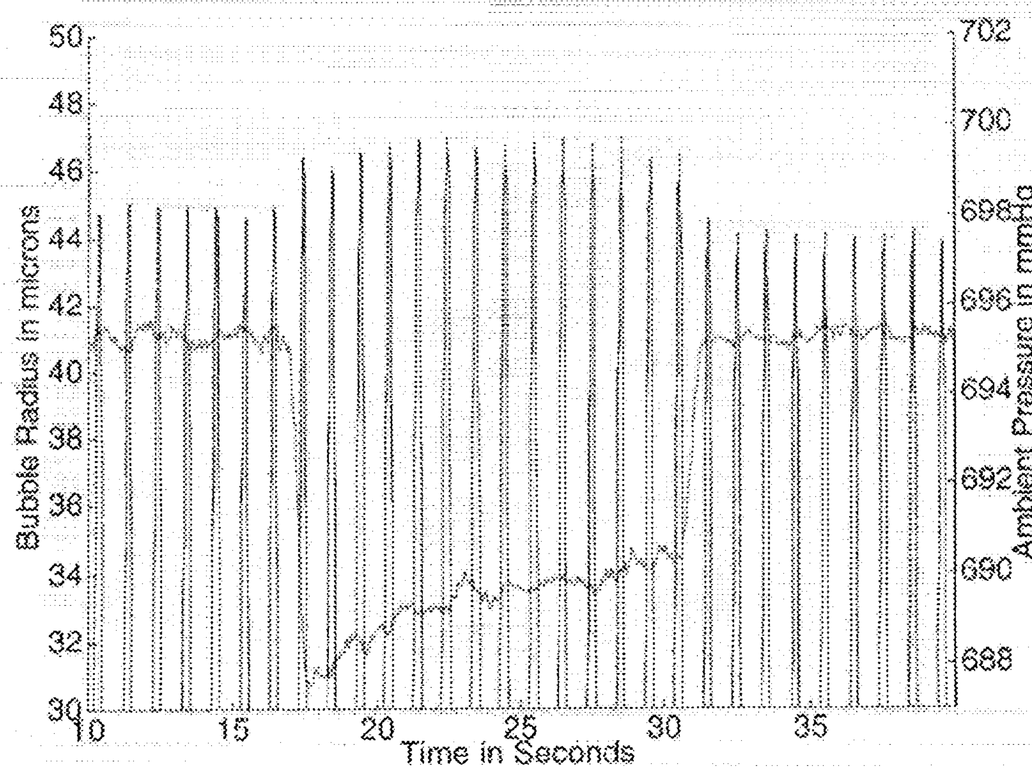
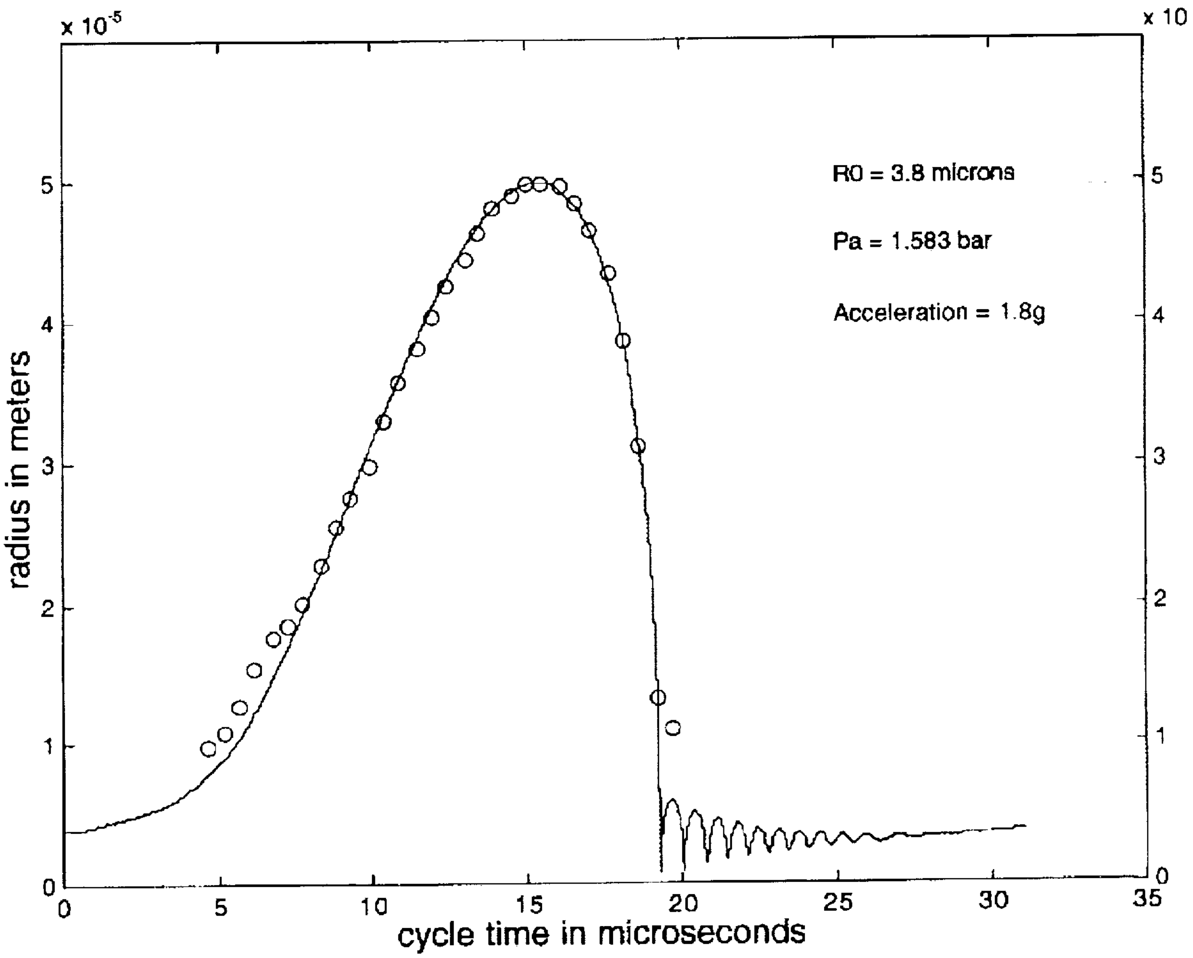
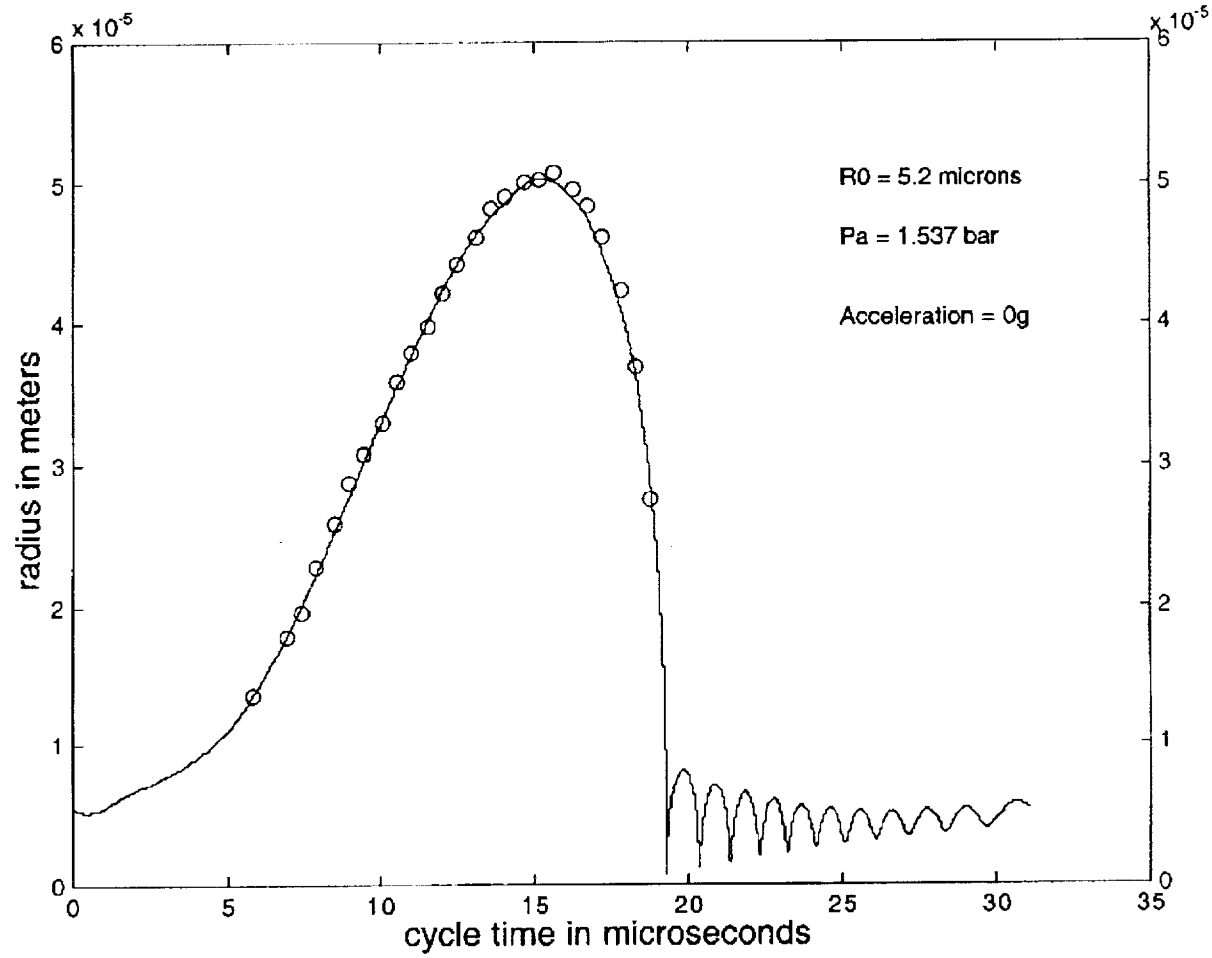


Figure 5 – Ambient pressure in red

Rayleigh – Plesset equation fit to radius data at high g, showing reduced R0

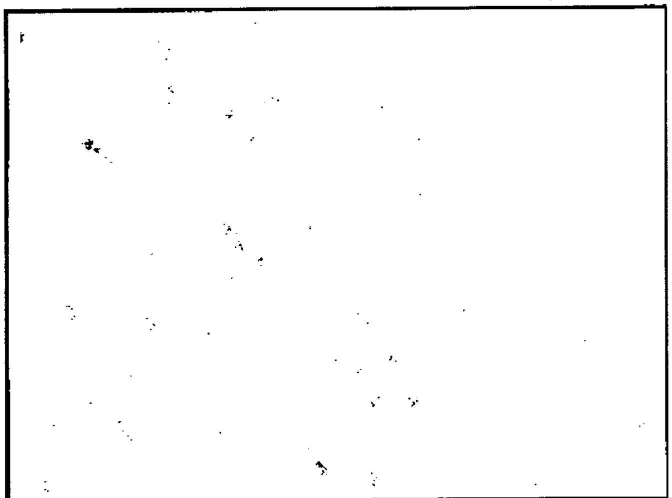


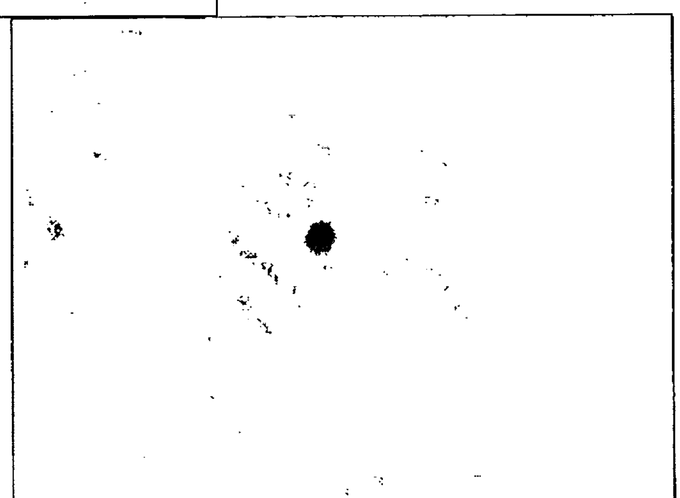
Rayleigh – Plesset equation fit to radius data at low g, showing increased R0

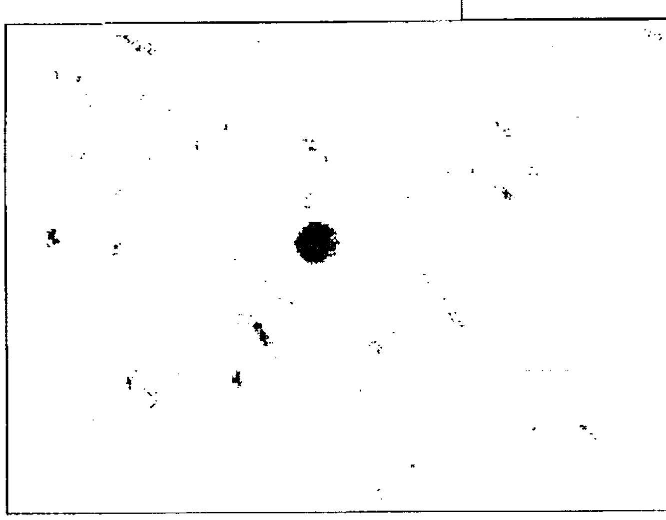


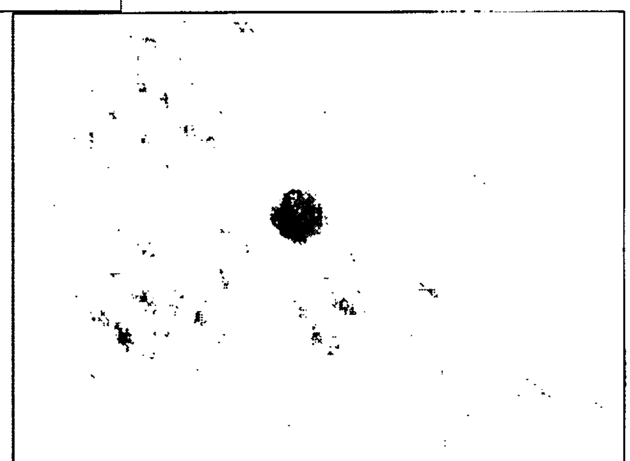
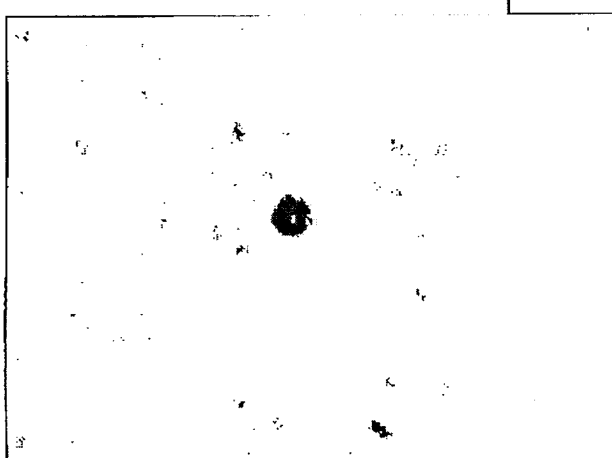
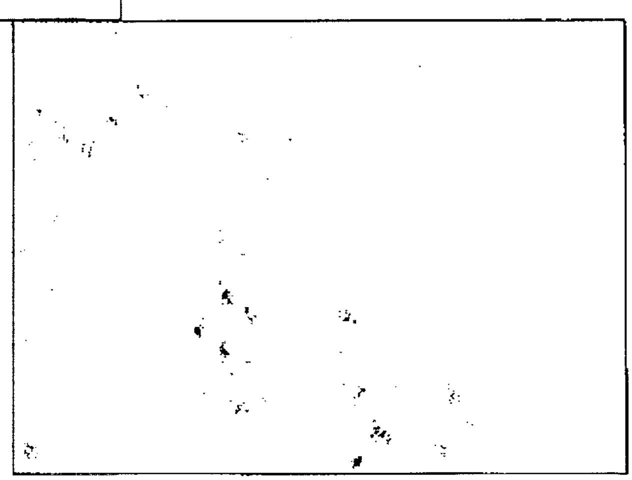
This series of images is taken from the video data at reduced gravity. Each frame represents about 2 microseconds of time. It is actually strobed data taken with a standard video camera; therefore each image is actually thousands of images averaged together.

The frames are deinterlaced and a blank frame is chosen as a background image and subtracted from the remainder of the frames.







Approximate changes

		flight data	lab data
Ambient Pressure	$\Delta P_0/P_0$	-0.45%	-0.70%
Light Output	$\Delta I/I$	5%	15%
Maximum Bubble Radius	$\Delta R_{max}/R_{max}$	5%	5%
Ambient Bubble Radius	$\Delta R_0/R_0$	25%	27%

flight data -

Data taken on the KC-135 from two cycles 20s apart the first at 1.8g and the second at 0g.

lab data-

Data taken in the lab from two cycles 10s apart, the first at atmospheric pressure and the second .007 bar below that.

Conclusions

- Light output is not quenched with reduced gravity.

- Light output increases with reduced gravity.

- Maximum bubble radius increases with reduced gravity.

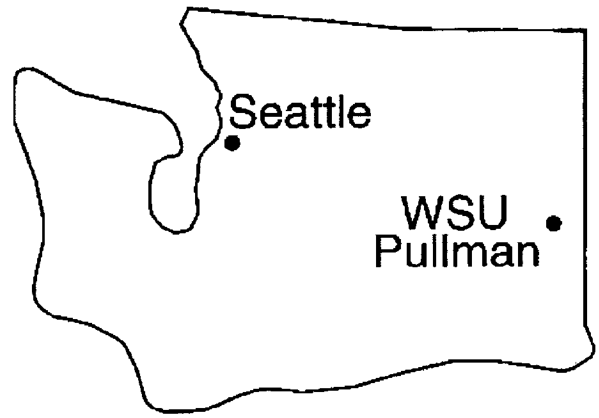
- R_0 increases with reduced gravity

- Diffusion models and lab experiments suggest that much of the light and radius increases may be due in part to hydrostatic changes.

- Asymmetries in the acoustic field make buoyant effects difficult to detect.

Optical manipulation of bubbles in water using solid-state laser technology

P. S. Jian
W. E. Torruellas*
D. B. Thiessen
Philip L. Marston



Department of Physics
Washington State University
Pullman, WA 99164-2814
marston@wsu.edu
*Present address: Corvis Corp., Columbia, MD.

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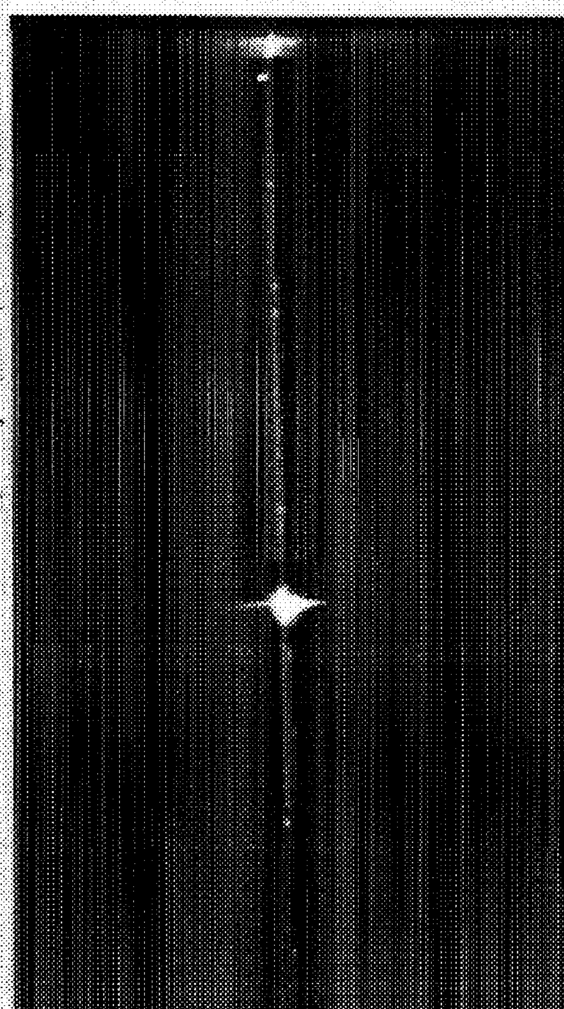
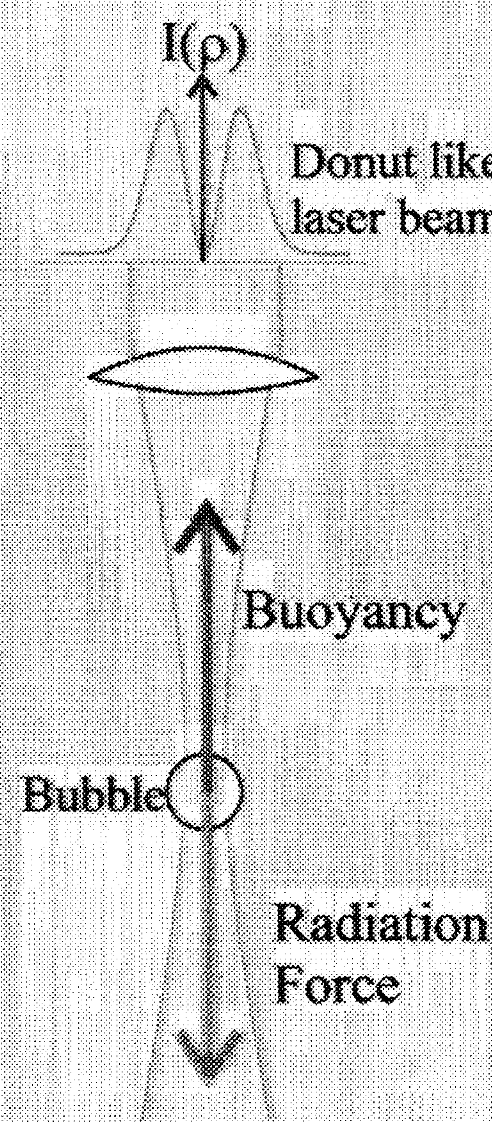
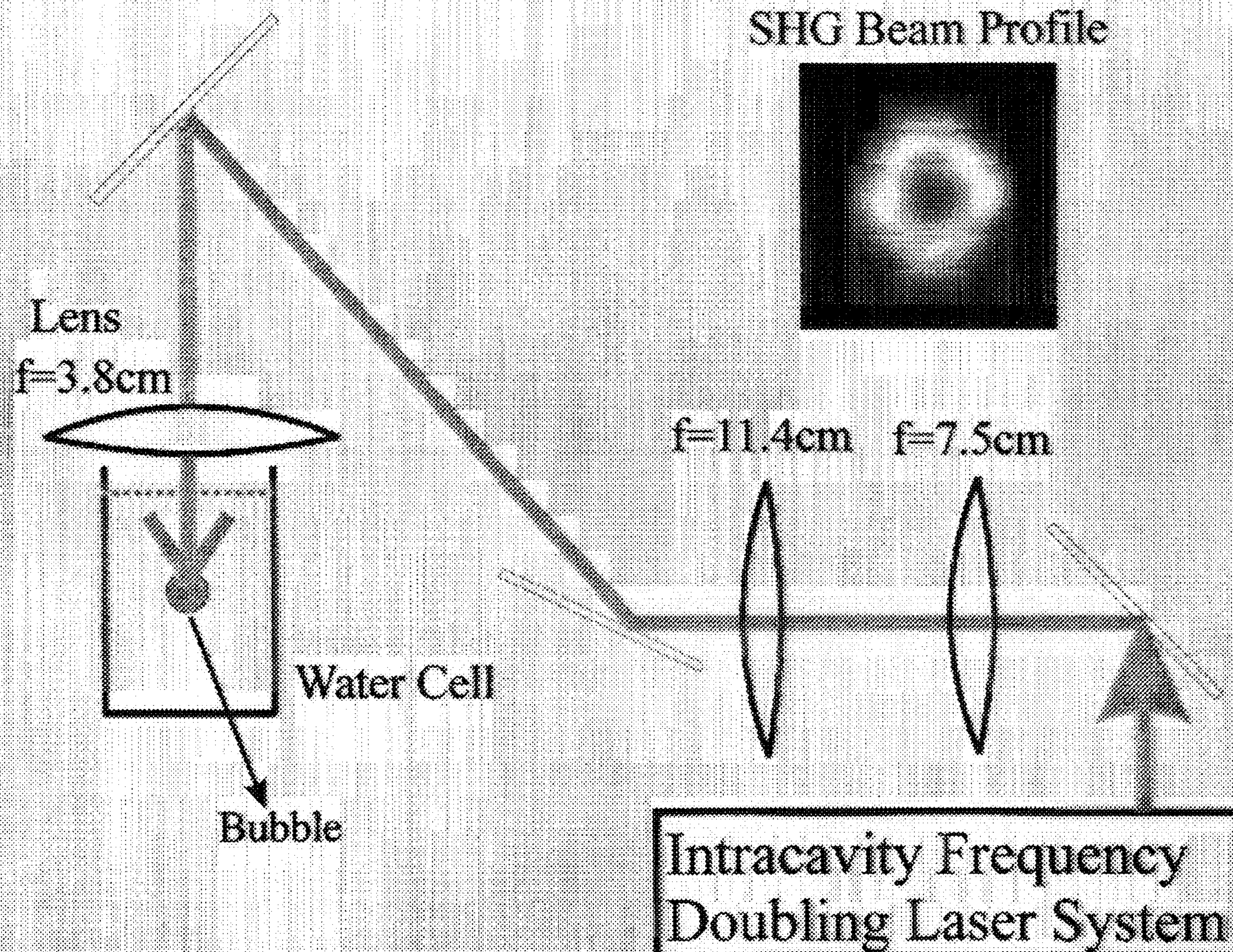
Optical Trapping of a Bubble in a Focused Beam

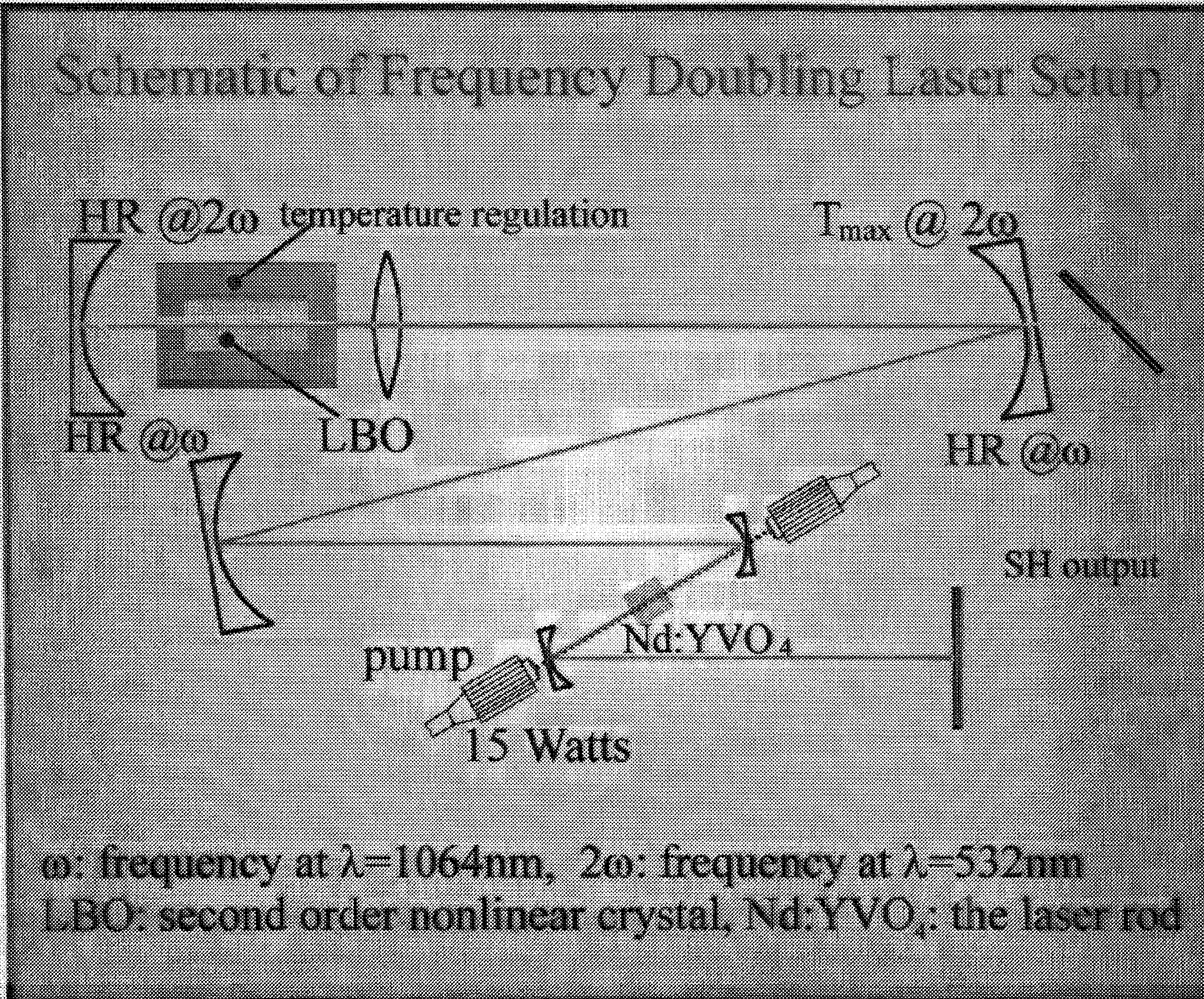
Bubbles are trapped near the high intensity focal region of a beam with a minimum intensity at the center as a result a donut-like laser beam is required.





Experimental Setup and the Beam Profile used to Trap the Bubbles in the Water




Schematic of Frequency Doubling Laser Setup
HR @2ω
temperature regulation
T_{max} @ 2ω
HR @ω
LBO
HR @ω
SH output
$Nd:YVO_4$
pump
15 Watts
ω: frequency at λ=1064nm, 2ω: frequency at λ=532nm
LBO: second order nonlinear crystal, $Nd:YVO_4$: the laser rod

Laser Crystal:

Neodymium doped Yttrium-Vanadate ($Nd:YVO_4$)

Wavelength = 1064 nm

Pumped with water cooled CW diode lasers

Second Harmonic Crystal:

Lithium-TriBorate (LBO)

Second Harmonic Wavelength = 532 nm

CW Power Output: 5.5 W

Laser and second-harmonic generation model in:

"Generation of doughnut-like patterns in intracavity-second-harmonic-generation" submitted to JOSA B.

R. Iliew, P. Jian, Y. Frignac, W. Torruellas, F. Lederer

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