The effects of buoyancy on sonoluminescing bubbles

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Abstract: Sonoluminescence from a single bubble was studied under microgravity and hypergravity environments to determine how buoyancy affects the light emission. The long-term objective of these experiments is to determine if buoyancy-related instabilities play a role in limiting the parameter space of single-bubble sonoluminescence. Understanding the parameter space limitations may ultimately lead to novel approaches for enhancing the extreme conditions within the bubble. Our results reveal several buoyancy-related effects, which should be further investigated in an extended microgravity environment.

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1. Introduction

Single-bubble sonoluminescence (SBSL) refers to the emission of light from an acoustically trapped bubble undergoing large-amplitude, predominantly radial oscillations.[1,2] The growth of a bubble during the negative or tensile portion of a sound field is followed by an inertially dominated collapse resulting in light emission at or near the final compressed state of the bubble.[3] Although the light emission mechanism appears to be somewhat understood,[4-7] many issues pertaining to the bubble's motion and the bubble-fluid interaction have yet to be thoroughly investigated. In particular, there is interest in expanding the parameter space that currently defines and confines SBSL.

SBSL is achieved by levitating a bubble in a container of fluid (usually water). Assuming a spherical bubble,[8] the forces on the bubble include the gravitational force (buoyancy), given by $F_b = \rho g V(t)$, where ρ is the fluid density, g is the gravitational acceleration, and $V(t) = 4/3\pi R^3$ is the time-dependent volume of the bubble (R is the radius), and the acoustic radiation force, given by $F_a = -V(t)\nabla P$, where ∇P is the gradient of the acoustic pressure field parallel to the gravitational acceleration vector. A balance between the time averages of these two forces results in the bubble being suspended - e.g., bubble levitation (we consider only the vertical dependence, since the net horizontal forces must vanish). For sonoluminescence bubbles, this balance occurs slightly above the pressure antinode.

Although the average buoyancy and acoustic radiation forces must balance to levitate a bubble in an acoustic field, the instantaneous forces can vary considerably during a given acoustic cycle. The buoyancy force, which is always directed against the gravitational field, can change by over 5 orders of magnitude during the growth and collapse sequence of a sonoluminescence bubble (where $R_{\max}$ may reach $50\mu\text{m}$ and $R_{\min}$ is less than $1\mu\text{m}$). The acoustic radiation force, conversely, actually changes direction (depending on the sign of ∇P) during a

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given acoustic cycle. During the bubble's growth phase, the acoustic radiation force is directed opposite to the buoyancy force, whereas after the collapse, the acoustic radiation force points along the same direction as the buoyancy force (the direction of F_a depends on the sign of ∇P). Thus, these forces generate a periodic translational force on the levitated bubble.[9,10]

The actual translational movement of the bubble during a given acoustic cycle is small. By imaging the bubble near its maximum radius (around $50\mu\mathrm{m}$) and again near the limit of our system's resolution (about $2\mu\mathrm{m}$ radius) we find that the estimated upper bound for linear translational motion between these radii is approximately $2\mu\mathrm{m}$ in a $1g$ environment. We are unable to clearly resolve the bubble below about $1-2\mu\mathrm{m}$ radius, and thus are unable to further quantify these measurements. Although the translations are small, the velocity and acceleration of the bubble center of mass may be large.[9]

Detailed calculations by Longuet-Higgins for even low acoustic forcing pressures[11,12] show dipole-like fluid streaming around an oscillating bubble. This asymmetry in fluid motion around the bubble can thus lead to surface perturbations that may ultimately be responsible for the bubble's extinction at high drive pressures. It is well known that with larger bubbles, spherical asymmetries and instabilities such as liquid jetting, capillary waves, and shape oscillations are clearly observed. If allowed to translate, even sonoluminescence bubbles are predicted to develop asymmetric collapses resulting in liquid jetting.[13] The question is not *if* sonoluminescence bubbles develop asymmetries but, rather, are the time scales over which asymmetries develop great enough to become a factor that can influence the bubble's stability and/or light emission mechanism?

Evidence for asymmetries and instabilities has been noted by several investigators. Weninger et al. [14] found evidence that a SBSL bubble occasionally appears slightly flattened at the time of light emission. Holt and Gaitan[15] found that the parametric instability threshold approached the extinction threshold—the maximum forcing pressure that can be applied before the bubble self-destructs. Matula and Crum[16] were able to observe the radial motion of the bubble, cycle-to-cycle, as the drive pressure was increased beyond the extinction threshold. They found that at the extinction threshold, the bubble apparently self-destructed in a dramatically rapid fashion. Ketterling and Apfel[17] observed that in some cases, the threshold for shape instabilities coincided with the extinction threshold, suggesting that the extinction threshold is related to the development of instabilities. Calculations of the n=2 shape instability threshold appear to agree well with some experimental extinction data,[18−20] although in some cases, higher order modes appear to play a more significant role.[17]

We hypothesize that a mechanism for instabilities that limits the maximum forcing pressure for stable SBSL may be related to buoyancy-driven instabilities. Aspects of this work have been presented in summary form.[21,22]

2. Experiment

A reduction in the buoyancy force should result in the bubble being levitated closer to the pressure antinode. Under these conditions, the translational forces should be diminished, and the bubble should be more stable, possibly resulting in a more energetic collapse and hence a higher light output. We tested this hypothesis by flying our SBSL apparatus aboard NASA's Parabolic Research Aircraft. The parabolic arcs flown by the aircraft (Fig.) generate brief periods of hypergravity ($\approx 1.8g_0$; $g_0 = 9.8\mathrm{m/s}^2$) and microgravity ($< 0.04g_0$). These brief periods lasting approximately 20 seconds are long enough for a bubble in our 30 kHz sound field to undergo approximately 600,000 growth and collapse cycles.

The major objectives for this study were to determine if gravity influenced the light emission from stable SBSL, and whether the extinction threshold was influenced by gravity. Secondary objectives included quantifying the effects of a nonstationary laboratory (the aircraft). Variables that were affected by the nonstationary laboratory included buoyancy (directly

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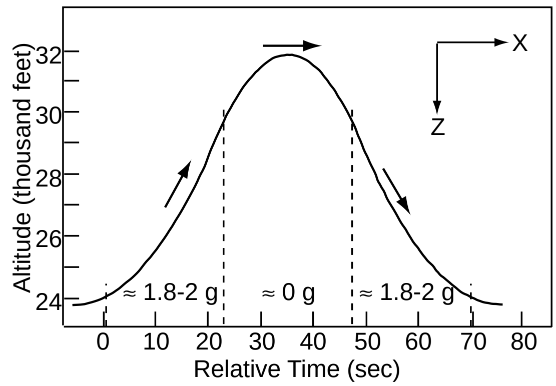

Fig. 1: Profile flown by NASA's KC-135A Parabolic Research Aircraft to generate brief periods of microgravity.

affecting the bubble position and hydrostatic pressure) and barometric pressure. These influences are examined in more detail in the next section.

A 100 ml spherical SBSL cell was filled with partially degased ($\approx 100\mathrm{mmHg}$), deionized water and completely sealed (at 1 atm) prior to each flight. During the flight, a short current pulse applied to a small nichrome wire protruding into the cell caused the water immediately surrounding the wire to boil. The small vapor cavities quickly filled with air and coalesced, thus creating a bubble for our experiments. We were able to use this method to generate bubbles at any time during the parabolic maneuver. A computer program was developed to perform all of the tasks normally undertaken by researchers, including monitoring the existence and stability of the bubble, generating a bubble if and when needed, and collecting the data.

Fig. 2 shows how the sonoluminescence intensity varied during the parabolic maneuvers under otherwise constant conditions. Gravity transitions from about $1.8g_0$ to microgravity over approximately 3 seconds as the aircraft transitions into a free-fall (the bubble moves downward approximately $0.4\mathrm{mm}$ during the transition, as expected due to the loss of buoyancy). During this transitional time, the sonoluminescence intensity increased by approximately 20% overall in this particular plot and as much as 40% under some conditions (the change is apparently a function of the initial drive pressure amplitude). Also of interest in Fig. 2 is that after gravity transitions, the intensity of SBSL continued to change over long time scales. This is consistent with gas diffusion time scales. That is, after the transition, the bubble's equilibrium conditions change (apparently from the loss of hydrostatic pressure), resulting in gas diffusion to match that new equilibrium. It is highly likely that the bubble's ambient size changed between microgravity and hypergravity, as supported by calculations of the diffusive equilibria,[23] although we were unable to verify this supposition experimentally at the time.

Fig. 3 shows the relative change in the extinction threshold for several parabolas. Due to detuning, we were not able to obtain extinction data for all the parabolas. Although the data shows some scatter, it is interesting to note that the extinction threshold for most of the parabolas is greater in microgravity than in hypergravity (the average change is +10%). Because of gas diffusion, relative vibrations, and g-jitter, it is difficult to assess the gravitational effects on the extinction threshold; extended microgravity conditions would permit such assessments.

3. Discussion and Conclusion

The results in Figs. and show that gravity plays a role in SBSL; the light intensity increases by as much as 40% in microgravity, whereas the extinction threshold appears to increase somewhat

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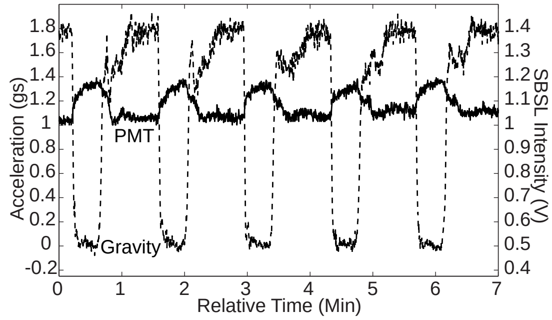

Fig. 2: Gravitational (z) acceleration during several parabolas (dashed line), together with the corresponding light intensity from the sonoluminescence bubble (solid line). Note that the light intensity abruptly increases during the transition into microgravity, and continues to increase well into the microgravity phase.

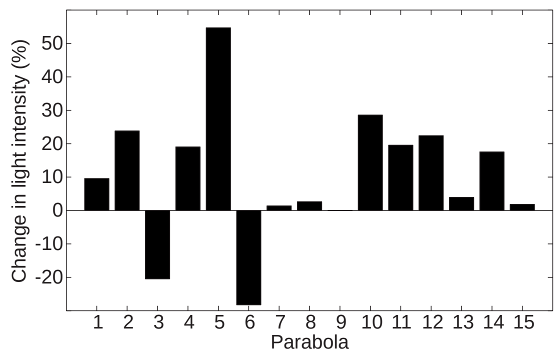

Fig. 3: After the aircraft transitions into microgravity or hypergravity, the computer waits approximately 10 seconds before ramping up the forcing pressure. The ratio of the maximum light intensity recorded in microgravity to that in the subsequent hypergravity phase is plotted here for the first 15 parabolas.

in microgravity. Some of the observed increase can be explained by considering the conditions experienced by the bubble. Although factors such as aircraft orientation and vibrations due to engine thrust (the major frequency component was about 150 Hz) were considered, the most important factors appear to be bubble displacement due to a loss of the hydrostatic pressure and the buoyancy force.

The reduction in the buoyancy force during the transition from hypergravity to microgravity caused the bubble's equilibrium levitation position to shift downwards by approximately 0.4mm. This translation showed no effect on the amount of light gathered by the photomultiplier tube (PMT); however the pressure felt by the bubble does change slightly. We can estimate the magnitude of this effect by assuming that the pressure field in the spherical cell approximates a spherical Bessel function with a pressure maximum at the center of the cell. For our 25mm radius cell, the pressure at a point displaced $0.4mm$ from the center is decreased by approximately 0.045%. In laboratory tests, we find that a 0.045% change in drive pressure amplitude results in a light intensity change of approximately 0.8% (extrapolated from the linear dependence of the light intensity on the drive pressure amplitude). Although perceptible, this change is not significant, and we conclude that the change in location of the bubble and the associated change in the pressure amplitude cannot account for the 20%-40% change in light intensity observed due to gravity variations. Furthermore, measurements of the pressure field in a (different) levitation cell in the presence of a bubble show a flattened pressure profile near the bubble.[9] Thus the effect of bubble displacement over such a small distance may be decreased

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even more than the calculation implies.

Whereas the equilibrium bubble displacement due to the buoyancy force can be neglected, the hydrostatic pressure (ρgh, where $\rho = 1000\mathrm{kg/m}^3$, and the height of the liquid column h above the bubble is $\approx 2.5\mathrm{cm}$) has a significant affect on the bubble. In laboratory tests, we found that changing the ambient pressure within the cell by an equivalent amount ($\approx 440\mathrm{Pa}$, or 0.43% of an atmosphere) resulted in a change in the relative light intensity by about 5%.[24] That is, during the transition from hypergravity to microgravity, the light intensity should increase by about 5% due to the decrease in ambient pressure. These laboratory observations exhibit qualitative agreement with recent model predictions based in part on gas diffusion stability considerations.[25] This effect appears to account for at least some of the observed change in the light intensity.

We should also note that the cabin pressure also varied during a given parabola by $\approx 12\mathrm{mmHg}$. If our cell were not completely closed, this change in the ambient pressure would have significantly affected our results. Laboratory tests in a bell jar before and after the flights confirmed that ambient pressure changes of many times the values found on the aircraft had no effect on our apparatus.

We also considered a possible detuning effect that might occur throughout a given parabola. We found that the optimized tuning during hypergravity also corresponded to the optimized tuning during microgravity. However, a hydrophone placed a centimeter above the bubble did show variations in the amplitude of the acoustic pressure with changes in gravity, even in the absence of the bubble. Although the hydrophone records appear to show a slightly larger signal (indicating a higher pressure) during the hypergravity phase (which would normally translate into a higher sonoluminescence intensity), we believe these data are too inconclusive to make a definitive statement regarding the effects of gravity on the cell.

In summary, a reduction in the hydrostatic pressure and buoyancy force can result in an increase in light intensity by about 6%. The change in the bubble size due to gas diffusion can lead to another ≈ 4% increase in the light intensity.[21] Because some of our data show variations by as much as 40%, it may be that a portion of the increase in sonoluminescence intensity in microgravity is the result of a decrease in the translational oscillations of the bubble, resulting in a more stable, radial pulsation. The increase in the extinction threshold in microgravity is consistent with this hypothesis. However, further studies are needed to verify this conjecture. Gas diffusion occurs over such long time scales as to partially obscure the results. The influence of buoyancy-related instabilities can be measured accurately and consistently in an extended microgravity environment, such as the space shuttle, or the International Space Station (ISS). If the extinction threshold should be dramatically increased in a microgravity environment, a dramatic increase in energy emission from SBSL is expected to occur, leading to perhaps even more exciting physics.

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