The underwater sounds produced by impacting snowflakes

Lawrence A. Crum
Applied Physics Laboratory, University of Washington, Seattle, Washington 98105

Hugh C. Pumphrey
Department of Meterology, The University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, Scotland, United Kingdom

Ronald A. Roy
Department of Aerospace and Mechanical Engineering, Boston University, 110 Cummington Street, Boston, Massachusetts 02215

Andrea Prosperetti
Department of Mechanical Engineering, Johns Hopkins University, Baltimore, Maryland 21218

(Received 11 August 1998; revised 2 June 1999; accepted 14 June 1999)

In 1985, Scrimger [Nature **318**, 647 (1985)] reported measurements of noise levels significantly above the ambient level for snow falling on a quiet freshwater lake. He examined only the time-averaged sound levels and did not report measurements of individual snowflake impacts. Subsequently, the noise produced by individual and multiple snowflake impacts was examined for a number of different snowfalls. The radiated acoustic signals generated by the impact of individual snowflakes upon a body of water have a remarkable similarity to each other and differ principally in the frequency of the emitted sound wave. The acoustic signal of a snowflake impact thus generates a characteristic signature for snowfall that is clearly distinct from other forms of precipitation noise. Various aspects of this signature suggest that the radiated acoustic waveform from a snowflake impacting with water is due to the entrainment of a gas bubble into the liquid, and the subsequent oscillation of this bubble as it establishes its equilibrium state. Various scenarios are presented for bubble entrainment and approximations to the amplitude of the radiated signal and the acoustic waveform are obtained.
[S0001-4966(99)02710-1]

PACS numbers: 43.30.Lz, 43.30.Nb [DLB]

INTRODUCTION

In 1985, while instruments were in place for the determination of the underwater sound produced in a fresh water lake by rain, Scrimger[1] observed significant noise above the background when it chanced to snow. Although he was unable to determine the source mechanism for the sound production, or even the complete frequency spectrum (his hydrophone had a high-frequency cutoff at about 50 kHz), these measurements seem to be the first reports of underwater acoustic emissions produced by falling snow.

Scrimger's initial reports of the noise produced by precipitation[1,2] have been followed by extensive investigations of rain noise by other investigators[3–12] and also some preliminary reports of noise produced by hail.[2,13] McConnell *et al.*[14] also have reported evidence of significant increases in the ambient noise level in an Alaskan fjord during snowfall. A brief review of precipitation noise has been given by Crum *et al.*[15]

We present in this paper some further, yet still preliminary, studies of the acoustic emissions associated with the impact of individual snowflakes on a quiescent water surface, provide evidence that these emissions are associated with gas bubble oscillations, and also present some estimates for the shape of the acoustic waveforms, and the amplitude of the radiated acoustic pressures. Some of the results described in this report were presented at the 122nd meeting of the Acoustical Society of America.[16]

I. RESULTS

After reading the intriguing reports by Scrimger[1,2] of the noise produced by precipitation, a chance snowfall in Mississippi in 1987 enabled us to obtain some measurements of the sound radiated by an individual ''impacting'' snowflake when it struck the surface of the water contained in a small container, and to obtain an average power spectrum of a number of these impacts. The initial traces were so unique and contrary to our intuitions and expectations that it has inspired us to accumulate data from a number of storms in a number of different locations over the last few years.

We wish to present at this time a brief description of our collected data and offer an explanation for the results that we have of this curious phenomenon. Because the acoustic signal produced by an impacting snowflake is of relatively high frequency and short duration, the apparatus required to obtain these measurements can be quite simple. A small container of water will suffice—the reverberation is insignificant, and one can easily detect reflections from the container walls. Furthermore, the duration of an acoustic pulse (on the order of a few tens of microseconds) is substantially shorter than the time between impacts (a few tenths of a second). Together with a sensitive hydrophone (we used a B&K

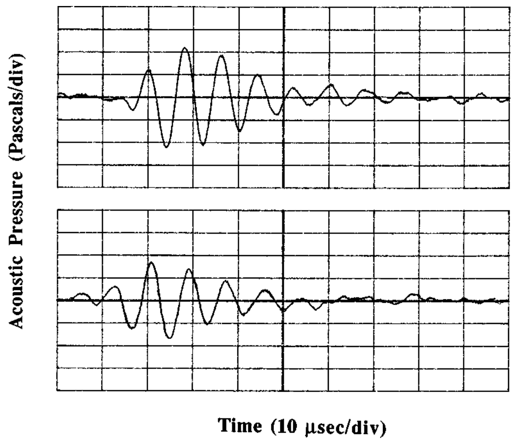


FIG. 1. Pressure-time traces of two individual snowflake impacts obtained for a snowfall in Mississippi. The two traces were obtained for fluffy flakes falling into a container of water; the calibrated hydrophone was positioned about 10 cm below the impact site.

8103), a modern storage oscilloscope with internal memory and mathematical function capability, and a chart recorder for hard output, one can obtain the requisite data. With such an apparatus, we have acquired data for four different snow storms in two different States of the U.S. In these measurements, we commonly looked for the pressure-time history of the event and then computed an average power spectrum from a number of events.

We show in Fig. 1 two pressure-time traces of ''light, fluffy'' snowflakes impacting a water surface during a snow shower in Mississippi. Note the similarity of the traces. Shown in Fig. 2 are ten pressure-time traces of impacting snowflakes, including those from a snow storm in Virginia, about 2 years later. Also shown is the average power spectrum obtained from 50 such traces. Note again in Fig. 2 the similarity of the traces. Although the various snow storms provided snowflakes of different sizes and shapes, we did not categorize individual pressure-time histories with snowflake morphology. Furthermore, we did not measure the temperature of the water on which the snowflakes fell, although it was significantly higher than 0 °C.

It will be seen from these and other data that an individual, impacting snowflake gives rise to a characteristic underwater signature. We now examine certain features of these traces in an attempt to understand the physical mechanism(s) that gives rise to these signatures.

One characteristic feature of these traces is the decay of the pressure with time. Because these decays resemble the sounds emitted by an oscillating gas bubble, we used these traces to obtain a measurement of the damping constant. Specifically, if the natural log of the ratio of successive maxima and minima is plotted versus cycle number, then the slope of this line is equal to (β/f), where β is the damping constant and f is the frequency.[7] Likewise, this slope is equal to (π/Q), where Q is the quality factor. Shown in Fig. 3 are measurements of Q as a function of frequency for a number of snowflake impacts. Plotted also on this figure are the calculated values of Q for a gas bubble, taken from the theory of Prosperetti.[17] It is seen from this figure that the pressure-time traces are probably the result of oscillating gas bubbles somehow entrained by the snowflake impact. Since we have previously investigated gas bubble entrainment from rainfall, a review of that process serves to educate us to the possible scenario for the snowfall case.

Consider Fig. 4, which shows three pressure-time traces. The top trace is the pressure-time history of an impacting raindrop whose radius was 1.5 mm and whose impact velocity was 2.0 m/s. The first bump on the trace, occurring at a time of about 12 ms, corresponds to the impulse noise radiated from the water-hammer effect of the impact of the drop a with the water surface. The second feature, commencing at about 32 ms, is the sound that results from gas bubble entrainment. This signal is expanded in time and shown in the middle trace of Fig. 4. Note that there is an initial, positive-pressure peak followed by a steady decay to background. The quality factor measured from this oscillation agrees closely with the calculated decay curve shown in Fig. 3.[7] The analysis of similar such traces enabled us to determine that a peak in the light-rainfall spectrum near 15 kHz was due to bubble entrainment.[6]

Also shown in Fig. 4, as the bottom trace, is a pressure-time history resulting from the impact of a snowflake. If one compares this bottom trace with the middle one, it is possible to demonstrate that they both have the characteristic decay of an oscillating gas bubble, and that the quality factors are nearly equal. Beyond this favorable comparison, however, the traces are quite dissimilar. We believe we can offer a plausible explanation for the characteristic shape of this pressure-time history, and thus of the noise produced by snowfall.

Suppose a slowly falling snowflake strikes the flat surface of a large volume of water. Unlike the case for falling raindrops or hailstones, there is little momentum delivered to the surface as a result of the impact. However, a close examination of the water surface indicates a radiating capillary wave subsequent to this impact. It seems likely that, rather than the snowflake creating a depression in the water surface, surface tension and capillary forces cause the water to rise up along the many surfaces of the snowflake, creating a small protuberance or bump. The subsequent relaxation of this slight elevation results in the radiating capillary wave. We suggest that the encapsulation of a gas bubble within this small protuberance is the reason the snowflake trace has its characteristic shape. If the oscillating bubble produced by the snowflake is contained in a projection extending above the surface, it becomes an inefficient radiator; however, when the surface tension and gravitation forces pull the bubble down below the surface, it can radiate much more efficiently. It is noted from the various pressure traces of snowflake impacts that the first peak in these traces may be either positive or negative. In the case of a raindrop impact that produces a bubble, the first peak is always positive. If the snowflake/bubble is ''inserted,'' rather than ''produced,'' underwater, the polarity of the first peak would depend upon the insertion time, and could be either positive or negative.

We can also offer some quantitative arguments for this hypothesis. Suppose that a bubble of radius R is encapsulated within a protuberance generated by snowflake impact. Consider the time required for the protuberance to recede. We

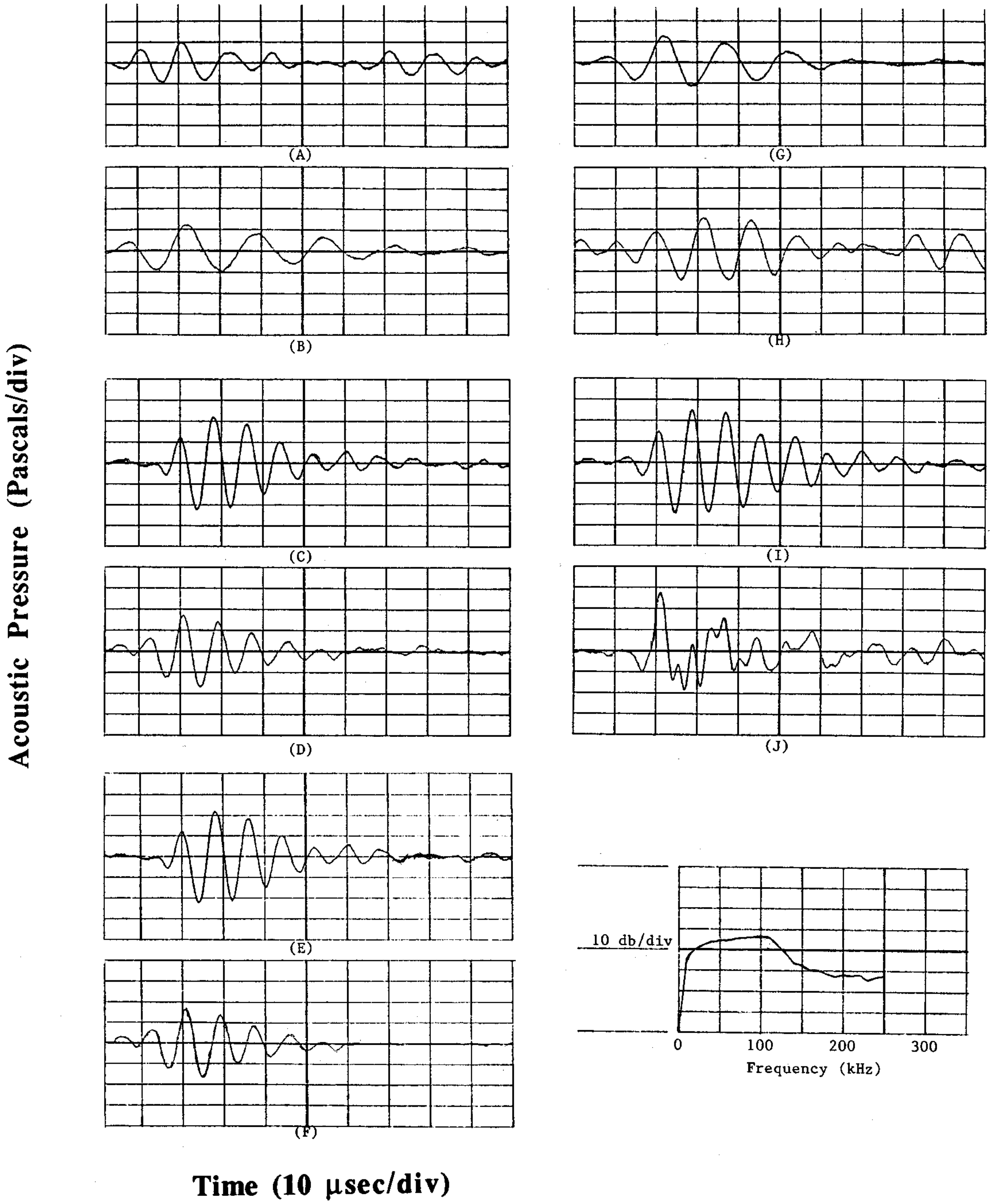


FIG. 2. A collection of some representative pressure-time traces obtained from different snow storms in different States of the U.S. Note the similarity of the curves, and that multiple events (trace J) are uncommon, although successive ones are not (traces A and H). The insert in the lower right is an average power spectrum for 50 traces during a single storm. The falloff in the spectrum above 100 kHz matches that for the hydrophone frequency response.

can estimate this time by examining the characteristic times associated with the propagation of a capillary wave. The velocity of a capillary wave is given by

$$v=(2\pi\sigma/\rho\lambda)^{1/2}, \tag{1}$$

where σ is the surface tension, ρ the density, and λ the wavelength, all of the liquid medium, such as water. The time required for the bump to be withdrawn completely below the liquid surface is one-half the period T. Thus, the bubble ''insertion time,'' t_i, is given approximately by

$$t_i=T/2=[\rho\lambda^3/8\pi\sigma]^{1/2}. \tag{2a}$$

A reasonable estimate for the wavelength of the capillary wave would be twice the bubble radius, R. For frequencies in the range of 25–100 kHz, the relation between the bubble radius, R, and its natural frequency of oscillation, f, is given approximately by $Rf=310$ (cgs units). Using the values for water of $\rho=1.0\,\mathrm{gm/cm^3}$ and $\sigma=72\,\mathrm{dyn/cm}$, we can rewrite Eq. (2a) as

$$t_i=363/f^{3/2}. \tag{2b}$$

We thus find that for a frequency of 25 kHz, the insertion time should be approximately 92 μs; for a frequency of 100 kHz, it should be about 11 μs. If we examine the pressure-

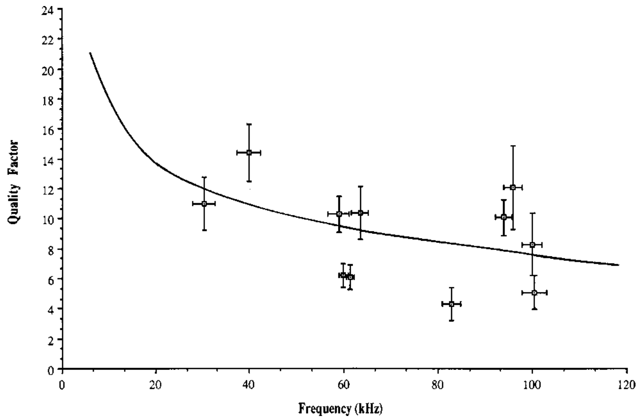


FIG. 3. Measurements of the quality factor associated with gas bubble oscillations produced by impacting snowflakes. The symbols refer to values of the quality factor obtained from pressure-time traces similar to those shown in Figs. 1 and 2. The solid line is the theoretical dependence of this factor on the frequency as obtained by Prosperetti (Ref. 17). This figure demonstrates that impacting snowflakes generate underwater signals that are probably associated with gas bubble oscillations.

time traces for snowflake impacts shown in Figs. 1, 2, and 4, we see that the time required for growth of the signal to a maximum amplitude, a measure of the insertion time, is on the order of 40 μs. Thus, we see that our rough estimate of the insertion time is about right.

Consider next an examination of the absolute magnitude of the signal produced by the impacting snowflake. Later in this paper, we shall address the issue of the origin of the entrained gas bubble. Let us assume at this time that it exists and we wish to estimate the magnitude of the radiated pressure wave, which, of course, can be measured.

The bubble is radiating near the surface; we write as the expression for the pressure radiated by a dipole source of radius R_0 at a distance d below the water surface,[18]

$$p(r,\theta,t)=\frac{2\rho c k^2 R_0^2 d}{r} U_0 e^{-\beta(t-r/c)} \cos\theta e^{i(\omega t-kr)}, \quad (3)$$

where r, θ, t are the respective radial, angular, and temporal variables, c is the velocity of sound, k is the wave number, and β is the damping constant. The quantity U_0 is the velocity amplitude, given by $U=\omega_0 \Delta R$, where ΔR is the displacement amplitude and ω_0 is the natural angular resonance frequency of the bubble. It is assumed that when the bubble is created, it changes its equilibrium radius due to the force of surface tension, and the reestablishment of equilibrium results in radiated acoustic energy. We can find the magnitude of the source strength by considering the following equation that describes the work required to create the bubble:

$$(4\pi R_i^3/3)P_0=(4\pi R_f^3/3)(P_0+2\sigma/R_f), \quad (4)$$

where R_i and R_f are initial and final bubble radii, P_0 is the magnitude of the ambient pressure, and $2\sigma/R_f$ is the ''Laplace pressure'' associated with surface tension. This relation leads to

$$\Delta R=R_i-R_f=2\sigma/3P_0. \quad (5)$$

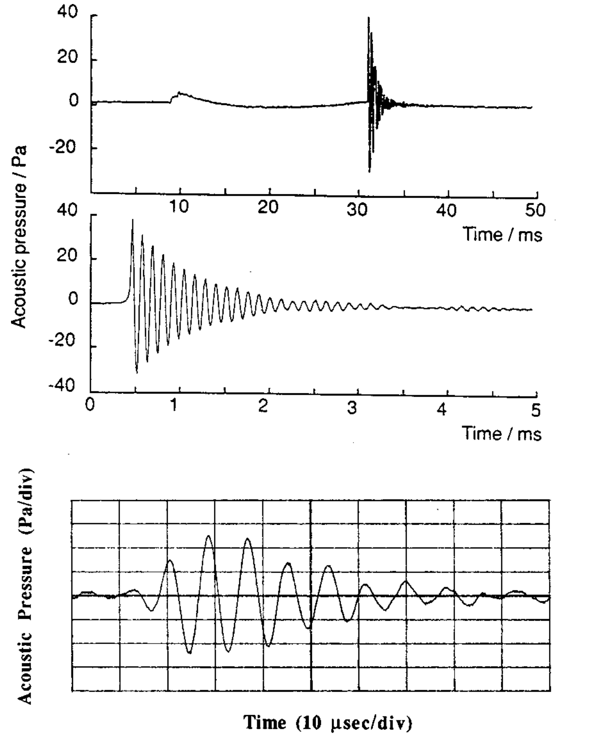


FIG. 4. Comparison of underwater acoustic emissions from raindrop and snowflake impacts. The top trace shows the underwater noise produced by an impacting raindrop. The first bump on the curve is associated with the direct impact of the drop with the surface and is mostly hydrodynamic in nature; the second bump, which is expanded in the second trace, shows a decaying sinusoid that is associated with the entrainment of a gas bubble by the impact process (see for example, Refs. 5 and 10). The bottom trace shows a pressure-time trace for a snowflake impact. Because the decay constant of these two traces are essentially identical and equal to that for freely oscillating gas bubbles, it can be presumed that gas bubbles are involved in both cases. The initial growth in the snowflake trace, which is absent in the raindrop case, indicates the existence of a physical mechanism that is not clearly understood. It is noted that similar geometries (size of container, position of hydrophone) were utilized in both the raindrop and snowflake impact measurements.

When Eq. (5) is used to express the source strength in Eq. (3), then the magnitude of the peak acoustic pressure amplitude, P_m, is given by

$$P_m=\frac{4}{3}\frac{(2\pi)^3 \rho f^3 R_0^2 d\sigma}{P_0 c r}. \quad (6)$$

If we use the following typical values of the relevant quantities, $\rho=1.0\ \mathrm{gm/cm^3}$, $f=100$ kHz, $R_0=30\ \mu$m, $d=1$ mm, $\sigma=72$ dyn/cm, $P_0=1.0\times10^6\ \mathrm{dyn/cm^2}$, and $c=1.5\times10^5$ cm/s, then the peak pressure observed on the dipole axis at a distance of 5 cm below the surface is given by Eq. (6) to be about 2.8 Pa. It can be seen from Fig. 2 that some representative *measured* values were 2.3, 3.0, 2.2, and 2.0 Pa. We see that this comparison between estimated and measured absolute pressure values is rather good, recognizing the crudeness of the approximations. We also note that the amplitude of these acoustic pressures is of the same order of magnitude of those for individual raindrop impacts. However, because the frequency of the noise radiated by individual snowflakes is rarely lower than 50 kHz, one does not hear the ''plunk'' of an impacting snowflake.

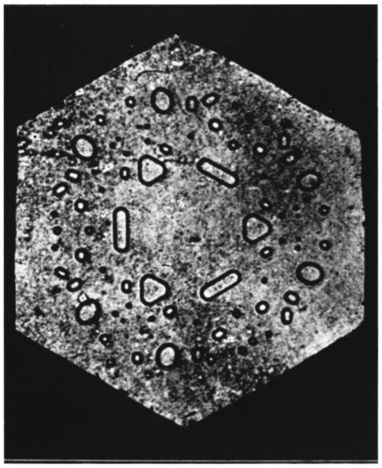


FIG. 5. Photograph of an ice crystal containing gas bubbles. If this crystal were to melt quickly, while immersed, the escaping gas could lead to acoustic emissions. The size of these crystals depends upon the local temperature at formation and may range from 5 μm to 5 mm (from Ref. 19).

II. DISCUSSION

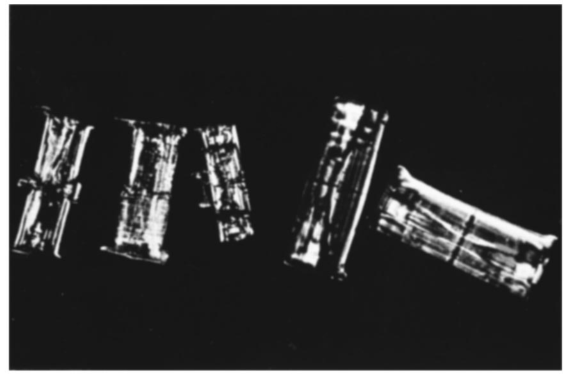
Our analysis of the data presented in this study suggests that a snowflake striking a body of water produces a sound most likely by entraining a gas bubble into the liquid, and by the subsequent oscillation of this bubble. We offer now some suggestions as to possible mechanisms for bubble entrainment:

A. Air engulfment

Snowflakes are usually loose agglomerates of individual ice crystals with a significant air content as indicated by the fact that their mean density is usually only 10% of that of water.[19] When such a fluffy snowflake strikes a water surface, it almost immediately stops, having no momentum to depress the surface. It seems likely that water would rapidly move upward through the flake by capillary action and lead to a rapid melting of the individual ice crystals. The end result would be the formation of a small ''foam patch'' that, even though it consists of more than one bubble, would radiate as a single entity due to the near-field acoustic coupling of its constituents. An alternative scenario is that the individual small bubbles could quickly coalescence into a single one if the thin liquid membranes separating them burst. It would probably be difficult to distinguish between these two possibilities on the basis of their acoustic radiation properties and it appears that, in both cases, acoustic emissions of the type observed in this study would be likely. This emission process depends on a series of events whose precise sequence and timing may not occur with every flake. Indeed, our casual observation indicates that only a small fraction (say, 1 in 10) of falling snowflakes produces a pressure trace.

B. Frozen bubble release

Snowflake experts tell us that many individual ice crystals contain small pockets of air trapped within the ice itself.[19] Figure 5 shows an example of such a flake. If this crystal were to melt rapidly, the bubble would be released from its ambient state, and oscillate—indeed, the gas within the bubble might be either compressed or rarefied. In this case, a different source mechanism for the acoustic energy is suggested, and the bubble oscillation amplitude should be significantly larger—the volume change during the freezing of water is on the order of 10%, and a bubble volume displacement of this magnitude (that would occur unless some of the entrapped air diffused out of the cavity) is relatively large.



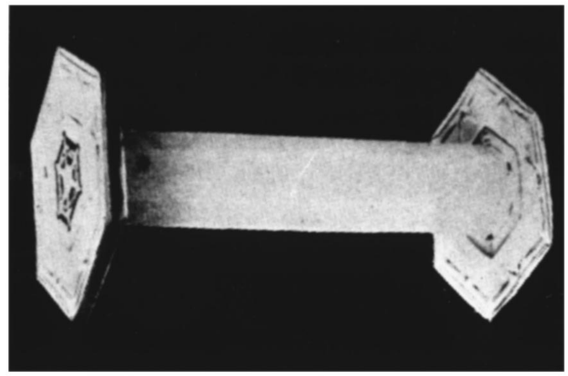


FIG. 6. Photograph of hollow ice crystals. If these crystals were to be quickly immersed in water, they could act as the source of the gas bubbles that apparently lead to acoustic emissions from impacting snowflakes from Ref. 20.

C. Hollow ice crystals

Although relatively rare, some snowflakes take the geometrical shape of hollow objects such as cylinders and rectangles. Figure 6 shows photographs of some hollow ice crystals.[20] For this scenario, one could expect that only the occasional snowflake would possess such a configuration. Similarly, one would expect this mechanism to provide easy encapsulation of air. Moreover, little energy would be stored in the air encapsulation and thus our previous arguments apply that suggest surface tension as the principal oscillation forcing mechanism.

III. SUMMARY AND CONCLUSION

We have observed that snowflakes falling into a body of water produce noise levels significantly in excess of background. An analysis of individual flake impacts suggests that the principal noise source is an oscillating gas bubble that is somehow entrained within the water. We have speculated about mechanisms for bubble entrainment and have made some order-of-magnitude calculations that tend to support our hypothesis. Additional experiments must be performed of the encapsulation process and the dynamics of bubble oscillation before an adequate explanation of this phenomenon can be given. In particular, high speed movies of the entrainment process coupled with simultaneous acoustic waveform measurements would be particularly revealing. Also, if ice crystal melting is important, then the temperature of the host liquid should have an effect on the pressure waveforms.

ACKNOWLEDGMENTS

We wish to acknowledge the assistance of Ed Gardner with data acquisition for the Virginia snowfall and we offer a special thanks to Bob Apfel, who loaned us his car and some apparatus for this storm. We also wish to acknowledge that part of this work (a general study of precipitation noise) was supported by the Office of Naval Research.

[1] J. A. Scrimger, ''Underwater noise caused by precipitation,'' Nature (London) **318**, 647–649 (1985).
[2] J. A. Scrimger, D. J. Evans, G. A. McBean, D. M. Farmer, and B. R. Kerman, ''Underwater noise due to rain, hail, and snow,'' J. Acoust. Soc. Am. **81**, 79–85 (1987).
[3] J. A. Nystuen, ''Rainfall measurements using underwater ambient noise,'' J. Acoust. Soc. Am. **79**, 972–980 (1986).
[4] H. C. Pumphrey and L. A. Crum, ''Acoustic emissions associated with drop impacts,'' in *Sea Surface Sound*, edited by B. R. Kerman (Kluwer Academic, Norwell, Massachusetts, 1988), pp. 463–484.
[5] H. C. Pumphrey, L. A. Crum, and L. Bjørnø, ''Underwater sound produced by individual drop impacts and rainfall,'' J. Acoust. Soc. Am. **85**, 1518–1526 (1989).
[6] A. Prosperetti, L. A. Crum, and H. C. Pumphrey, ''The underwater noise of rain,'' J. Geophys. Res. **94**, 32–39 (1989).
[7] H. C. Pumphrey and L. A. Crum, ''Free oscillations of near-surface bubbles as a source of the underwater noise of rain,'' J. Acoust. Soc. Am. **87**, 142–150 (1990).
[8] M. S. Longuet-Higgins, ''An analytical model of sound production by raindrops,'' J. Fluid Mech. **214**, 395–402 (1990).
[9] H. N. Oguz and A. Prosperetti, ''Bubble entrainment by the impact of drops on liquid surfaces,'' J. Fluid Mech. **219**, 143–153 (1990).
[10] H. N. Oguz and A. Prosperetti, ''The underwater noise of rain,'' J. Fluid Mech. **228**, 417–431 (1991).
[11] H. C. Pumphrey and P. A. Elmore, ''The entrainment of bubbles by drop impacts,'' J. Fluid Mech. **220**, 539–549 (1990).
[12] H. Medwin, J. A. Nystuen, P. W. Jacobus, D. E. Snyder, and L. H. Ostwald, ''The anatomy of underwater rain noise,'' J. Acoust. Soc. Am. **92**, 1613–1624 (1992).
[13] M. Nicholas, R. A. Roy, and L. A. Crum, ''The underwater sound produced by the impact of solid objects,'' J. Acoust. Soc. Am. **89**, 1863–1864 (1991).
[14] S. O. McConnell, M. P. Scott, and J. G. Dworski, ''Ambient noise measurements from 100 Hz to 80 kHz in an Alaskan fjord,'' J. Acoust. Soc. Am. **91**, 1990–1997 (1992).
[15] L. A. Crum, R. A. Roy, and A. Prosperetti, ''The underwater noise of precipitation,'' Nav. Res. Rev. **24**, 2–11 (1992).
[16] L. A. Crum, R. A. Roy, H. C. Pumphrey, and A. Prosperetti, ''The underwater sounds of falling snow,'' J. Acoust. Soc. Am. **90**, 2318–2319 (1991).
[17] A. Prosperetti, ''Bubble phenomena in sound fields,'' Ultrasonics **22**, 69–82 (1984).
[18] L. E. Kinsler, A. R. Frey, A. B. Coppens, and J. V. Sanders, *Fundamentals of Acoustics* (Wiley, New York, 1982).
[19] B. J. Mason, *The Physics of Clouds* (Clarendon Press, Oxford, 1971), Chap. 5.
[20] W. A. Bentley and W. J. Humphreys, *Snow Crystals* (Dover, New York, 1962).