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The Acoustical Society of America

ECHOES

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Sonoluminescence: Light from sound

by E. Carr Everbach

Sonoluminescence is the production of light by sound. How is such a thing possible? The details of the answer are still emerging in a quest that is providing important insights into fundamental physical processes.

Recently several members of the Acoustical Society of America have shown that, with an apparatus costing a few hundred dollars, it is possible to create in a glass of water tiny points at which temperatures exceed that of the sun and pressures are greater than that of the deepest sea trench. The light pulses that emerge from these minuscule maelstroms are so short in duration that they are better for some applications, such as ultra-fast fiberoptic communication, than lasers costing hundreds of thousands of dollars. The flashes of light are also so well synchronized that they rival the best quartz clocks for regularity of timing.

A photograph of sonoluminescence from a vibrating horn (1 centimeter diameter) is shown. [Photograph by E.B. Flint, J.A. Gray, and K.S. Suslick; University of Illinois at Urbana-Champaign.]

Sonoluminescence demonstrates an awesome concentrating power of relatively weak acoustic energies into the electrons of individual atoms that is unparalleled in nature.

Sonoluminescence was first reported over fifty years ago by two German physicists who noticed that photographic emulsions were fogged when immersed in a liquid that was subjected to intense ultrasound—ultrasound with acoustic pressure amplitudes of several atmospheres.

Careful examination of the films showed that what at first appeared to be a continuous fogging was actually made up of many very small points of darkened emulsion. Each of these points must have been produced by a flash of light emitted nearby, suggesting a localized mechanism of light production in the fluid surrounding the film.

The phenomenon proved erratic, however, with transient light flashes appearing only occasionally and under unpredictable conditions. Attempts to explain sonoluminescence in terms of static-electricity discharge, such as can occur when one's shoes rub on a carpet, failed to account for all the observed characteristics of the sparks occurring within the fluid.

An apparently unrelated phenomenon was cavitation, the collapse of bubbles within a liquid that occurs when the liquid is subjected to negative pressures (suction). Lord Rayleigh had shown that collapsing bubbles were responsible for such diverse phenomena as the pitting damage on ships' propellers and the crackling of teakettles set to boil. In each case, pre-existing bubbles in a liquid are subjected to a strong

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We hear that . . .

The Gold Medal at the upcoming ASA meeting in Ottawa will be presented to **David T. Blackstock** of the Applied Research Laboratories, University of Texas at Austin. Receiving the R. Bruce Lindsay Award will be **Michael D. Collins** of the Naval Research Laboratory in Washington, D.C.

Also in Ottawa, **Elaine Moran** will receive a certificate of appreciation for her years of outstanding and devoted service as ASA's office manager, her participation in meeting arrangements, and for her "diplomatic assistance in turning potential crises into successful solutions for the Society."

ASA's treasurer, **Robert T. Beyer** of Brown University's Department of Physics, has recently retired from the Governing Board of the American Institute of Physics after 24 years of service. Taking his place for a term ending in 1996 will be **Richard Stern** of the Applied Research Laboratory at Pennsylvania State University.

Elliott Berger of the Cabot Safety Corporation was presented an award in February of this year by the National Hearing Conservation Association. The award recognized him for outstanding contributions to the field of hearing conservation.

K. Anthony Hoover, a principal consultant on the staff of Cavanaugh Tocci Associates, Inc., has been awarded the second Theodore John Schultz Grant, sponsored by the Newman Student Award Fund. His grant will help to fund the further development of a text on the fundamentals of acoustics.

ECHOES

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Walter M. Madigosky recently received the John Adolphis Dahlgren award for his contributions to the theory and development of acoustical materials for shipboard use. The award is the highest technical honor bestowed on scientists and engineers at the Naval Surface Warfare Center at Dahlgren, Virginia and Silver Spring, Maryland.

The Architecture School of the College of the City of New York has appointed **Christopher Jaffe,** principal of Jaffe Holden Scarborough Acoustics, Inc., to the position of Adjunct Professor.

Marvin C. Ziskin received the 1993 William J. Fry Memorial Lecture Award from the American Institute of Ultrasound in Medicine in recognition of his outstanding contributions to the growth and development of diagnostic ultrasound. The award was presented at the March meeting of the AIUM in Honolulu.

Did you know that . . . ?

Group insurance rates available

Group insurance rates are available to all ASA members through the American Physical Society Group Insurance Trust. Available plans include:

Life	$10,000 to $500,000
AD&D	$20,000 to $300,000
Hospital Indemnity	$50 to $200 per day
Disability Income	$400 to $4,000 per month

These programs are underwritten by the Hartford Life Insurance Company. For further information call the Herbert Friedman Company at 1-800-272-1637.

Nominations accepted for awards

Any member of ASA may nominate any other member or former member of the Society for the **Distinguished Service Citation,** which is awarded from time to time in recognition of outstanding service to the Society. **Honorary Fellowship** is awarded on occasion to an individual who is generally not a member of the Society, but who is known for eminence in, or outstanding contributions to, acoustics. Also, as mentioned in the previous issue of *Echoes* (Winter 1992-1993), acousticians may nominate themselves or any other professional in acoustics for the new **Science Writing Award in Acoustics**. In addition, non-acoustician journalists are also eligible for the **Science Writing Award in Acoustics for Journalists**. For further information about these awards, contact Elaine Moran at (516) 576-2360.

Society Pages

Publication Policy Committee schedules all-day meeting

On Sunday, May 16, ASA's Publications Policy Committee (PPC) will hold an all-day meeting. At the October meeting in New Orleans, the Executive Council passed a motion that the PPC should "discuss the cost and financial impact of separating the Journal." PPC Chair W. Dixon Ward has appointed Floyd Dunn to chair a subcommittee to study that subject. The committee will also hear a progress report from an ad-hoc committee chaired by Richard Stern on the possible initiation of a "Popular Acoustics Journal." This publication would incorporate material from the back pages of the Journal, as well as articles and other newsworthy items.

In the morning session, the PPC will hear reports from various committee members and other interested individuals, and will discuss issues concerning ASA publications, such as pricing. The committee will also hear presentations by various Technical Committee chairs about the publications of other scientific societies and the possible use of CD-ROM for back issues of the Journal.

New noise publication now available from INCE

Noise News International is the new publication generated by combining the editorial forces of INCE USA and International INCE. (INCE stands for the Institute of Noise Control Engineering.) The combined circulation is expected to be about 4000, which includes those belonging to the 32 Member Societies of International INCE. The publication will be a quarterly, containing a substantial feature article in each issue, and will be produced by "IEEE Magazines." The editors are:

George Maling ..... Managing Editor
William Lang ..... Feature Editor
Anita Lawrence ..... Asia/Pacific
Andre Cops ..... Europe

Subscriptions in the U.S. will be $40 (or free for INCE members). Information may be obtained by writing to INCE USA, P.O. Box 3206, Arlington Branch, Poughkeepsie, NY 12603.

Acoustics in the News

The New York Times

The Environment section of *The New York Times,* Tuesday, February 23, carried the article, "Loud noise may offer a way to save fish from electric plants." Author Steven Prokesch describes a program developed by Sonalysts, Inc. to scare away fish that might otherwise be drawn in with the water used by electric utilities.

The system uses underwater sound sources emitting frequencies of about 125 kHz at level of 158 dB (presumably re 1 micropascal) or higher.

Prototypes of the system have succeeded in scaring away clupeids, fish in the herring family that include alewives, American shad, and blueback herring.

This kind of inexpensive system may prove to be a boon to utilities that are being pressured by Federal and state governments to modify their plants to prevent fish-kills.

National Public Radio

In another fish story, Jennifer Schmidt of NPR's "Morning Edition" reported January 27, 1993 on the use of high levels of underwater ultrasound to scare away sea lions. The purpose of the ultrasonic bombardment is to prevent the sea lions from dining on steelheads as they climb the fish ladder at the Seattle Locks.

Audio

A page of acoustics news is featured in the January 1993 issue of *Audio* magazine (p. 50). One item discusses the use of noise cancellation at dinner dances to afford sufficient quiet for diners while allowing dancers full sound intensity. Another reports on the use of active acoustic coatings, developed by Prof. Vijay Varadan of Pennsylvania State University, that will keep submarines from reflecting sonar pulses. A third item, entitled "Soothing Rock Music," tells about the "soundscape" formed by rocks along a municipal path in the Japanese city of Shizouka. These artificial stones contain loudspeakers that play the sounds of rolling pebbles and rocks supplemented with New Age music.

Science

Two recent articles in *Science* may be of interest to physiological acousticians. The December 4, 1992 issue (vol. 258, pp. 1668-1670) features an article entitled "Behavioral lifetime of human auditory sensory memory predicted by physiological measures" by Z.L. Lu, S.J. Williamson, and L. Kaufman of New York University. The January 1, 1993 issue (vol. 259, pp. 68-71) contains the article, "A travelling wave amplifier model of the cochlea" by Allyn Hubbard of Boston University.

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negative pressure, which causes them to grow to many times their original size. For instance, the rapid movement of the screw propellers of ships causes sufficient suction of the water that hydrodynamic cavitation can result. Likewise, if a bubble encounters the rarefactional portion of an intense sound wave, it may grow rapidly from a few micrometers in diameter to several hundred times that size. If the negative pressure is removed, or the compressional portion of a sound wave sweeps by, the bubble may collapse violently enough so that it shatters, or it may merely collapse, rebound, and repeat the process with the passing of the next sound wave. If the bubble collapses and shatters in response to an acoustic wave, the phenomenon is called "transient" acoustic cavitation; if it rebounds and survives to repeat its motion, the appropriate term is "stable" cavitation.

In the 1950s, sonoluminescence and acoustic cavitation were linked when it was discovered that collapsing bubbles always accompanied the observed flashes of light. The discovery that sonoluminescence accompanied bubbles undergoing rapid expansion and contraction was the first clue toward understanding how the light was produced. The link between sonoluminescence and acoustic cavitation, however, soon became so well established that sonoluminescence became a detection method for acoustic cavitation rather than the focus of interest in its own right. Acoustic cavitation had been of interest both as a source of underwater noise near transducers and of damage to biological tissues, which was thought to occur when the bubbles' violent collapse disrupted fragile cells nearby.

The light produced in sonoluminescence obeys certain spectral and temporal statistics due to the large number of bubbles typically present in the sound field. Lauterborn and colleagues at Göttingen examined the light of sonoluminescence and its accompanying noise generation and showed that in some cases the bubble dynamics followed a period-doubling route to chaotic motion. Thresholds of acoustic intensity above which acoustic cavitation would occur, assumed to accompany the inception of sonoluminescence, were measured for several physical and acoustic variables by different researchers. Data were compiled concerning how the spectrum of light output changed with different gases used to saturate the host liquid, but there remained no way to isolate the individual contributions of the millions of collapsing bubbles to the overall eerie blue glow that was observed in the liquid.

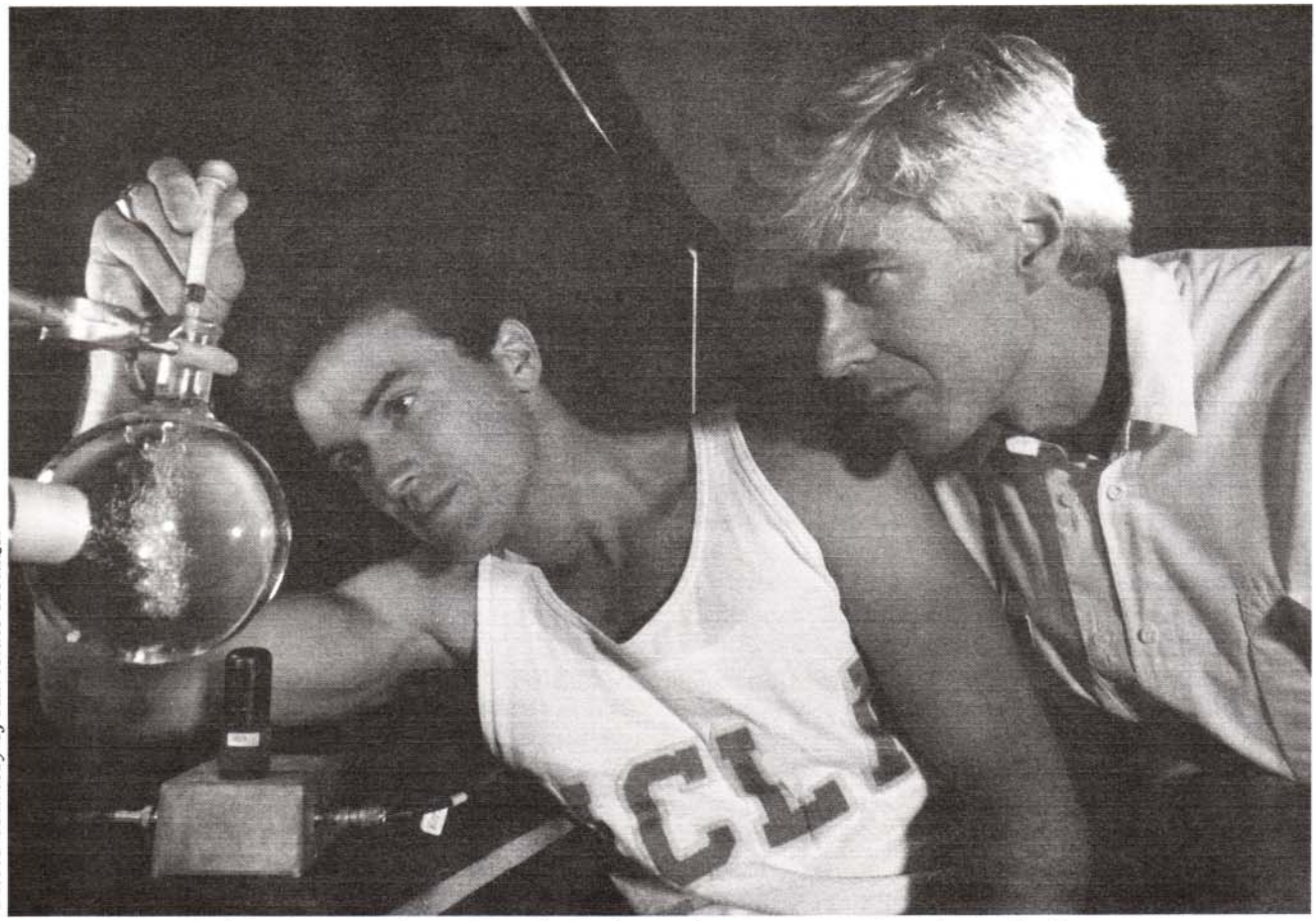

Photo courtesy of Adrienne Helitzer

Seth Putterman (right) and Bradley Barber performing an experiment in sonoluminescence.

Light from Sound

In 1991, sonoluminescence finally got the attention it deserves and the benefits are continuing to accrue. While Felipe Gaitan and Larry Crum worked at the National Center for Physical Acoustics (NCPA) in Oxford, Mississippi, they and their colleagues developed a technique for levitating acoustically a single bubble and driving it at its resonance frequency. Like the legendary singer exciting a wine glass, the bubble can be driven into oscillations of greater and greater amplitude by the acoustic signal. At a certain oscillation amplitude, the bubble begins to give off flashes of light, but unlike the wine glass, the bubble survives from one period to the next, preserving in its subsequent motion the memory of the dynamics of the previous cycle. The fact that the bubble volume grows and then shrinks by a factor of 100,000 in a few billionths of a second and yet somehow survives to repeat the cycle is amazing, but more amazing still is the light that the bubble produces. The levitated-bubble system allowed each flash to be examined in detail; "the hydrogen atom of sonoluminescence," Seth Putterman has called it.

Putterman and Bradley P. Barber at UCLA set to work examining the light pulses from one oscillating bubble and discovered their remarkable characteristics. The light is coherent, like laser light, and comes in flashes that are less than 50 picoseconds long, a brevity hitherto obtainable only via expensive lasers. Says Gaitan, "No one can explain why the flashes are so short, or how the atoms talk to each other and emit their photons at precisely the same time." The flashes, one per acoustic cycle, are so well synchronized to the sound field that the variation in the time between flashes from one period to the next is less than 50 picoseconds. This regularity is all the more remarkable considering that the acoustic drive frequency in the experiment was as low 26.5 kilohertz, with a period 750,000 times longer than the temporal variation, or "jitter," of the flashes.

Perhaps the most astounding feature, however, is the energy of the photons. Putterman and Barber found that the spectrum of the light extends far into the ultraviolet, to wavelengths below 1,900 angstroms, or corresponding photon energies above 6 electron-volts (eV). By contrast, the extremely diffuse energy of the sound field is about 10^{-11} eV/atom, yielding an amplification factor of twelve orders of magnitude, making the collapsing bubbles "the greatest amplifier in the world" according to Putterman. That so much energy can be concentrated in so small a volume is the result of the collapsing bubble walls, whose velocities exceed the local speed

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Miscellaneous Soundings

Concert hall survey update

The formation of the Concert Hall Research Group, a consortium of professionals interested in concert hall acoustics, was reported in the Summer 1992 issue of *Echoes*. At present, three teams of researchers have made acoustical measurements at similar source and receiver locations in nine concert halls in the northeastern U.S.

The teams are led by John Bradley of the National Research Council of Canada, Anders Gade from the Danish Technical University, and Gary Siebein from the University of Florida. Measurements to date have been taken with the halls unoccupied, although measurements in occupied halls are expected in the next phase of the survey. The three teams have made considerable progress toward consensus on detailed methods of room measurements, especially with respect to the measurement of impulse responses.

The survey teams will present several papers on the results of their work in the special sessions on Concert Hall Acoustics at the Spring meeting of the ASA in Ottawa. These sessions, which were organized by John Bradley, will also include invited papers discussing recent work by researchers from around the world, covering recent advances in concert hall acoustics design, measurement, subjective qualities, and analysis. Other topics include the four-microphone technique, IACC measures, binaural measurement studies, and the measurement of occupied halls.

Gary Siebein, University of Florida

Office of Naval Research structural acoustics review

Each year the Office of Naval Research sponsors a review at which grantees present their most recent findings. This year's review took place in Orlando, Florida, hosted by the Naval Research Laboratory and presided over by ONR program managers Phillip Abraham, Geoffrey Main, and Kam Ng. The categories of presentations were: Basic research in structural acoustics, numerical methods, small scale model experiments, internal structures modeling, methods of transduction, active control, and flow induced noise.

Anyone interested in receiving a packet of information including the names and affiliations of the authors and the titles of their papers should contact: Dr. David Feit, Code 7024, Carderock Div., Naval Surface Warfare Center, Bethesda, MD 20084-5000.

Sabine Centennial

ASA celebrates Sabine Centennial

June 5-7, 1994 will be devoted to the life and work of Wallace Clement Sabine. The Acoustical Society of America will hold a number of activities in honor of the world's first and most famous acoustician just prior to its semi-annual meeting in Cambridge, MA.

Approximately 100 years ago (actually in 1895) Sabine was given the job of fixing the deplorable acoustics of the lecture room in Harvard's newly constructed Fogg Art Museum. This arduous task marked the beginning of his brilliant contributions to the field of acoustics.

The celebration is being jointly sponsored by the ASA, the National Council of Acoustical Consultants, the Audio Engineering Society, and the Institute of Noise Control Engineering.

The festivities will include a dinner, attendance at a performance of the Boston Pops, tours of parts of MIT, Harvard, and the Jefferson Laboratory, musical experiments, and talks by Sabine family as well as ASA members. For example, Leo Beranek will give a speech on "Sabine at Harvard" and John Kopec will discuss "Sabine at Riverbank." John's book, *The Sabines at Riverbank,* is due to be published in time for the celebration. One of the highlights of the celebration will be a benefit concert for the ASA of the Tokyo String Quartet on Monday, June 6th.

Miscellaneous Soundings

Speech, Music, and Allied Signal Processing in India

Uwe J. Hansen of Indiana State University's physics department and Chair of ASA's Technical Committee on Musical Acoustics was an invited participant in the International Workshop on Recent Trends in Speech, Music, and Allied Signal Processing. The workshop, held in Varanasi, India, 28-30 December 1992, was organized by the Acoustical Society of India (Calcutta Chapter), among other professional and academic groups. Participants came from France, India, and the U.S.

Speech related topics included:

- Acoustic-phonetic decoding
- Human-machine dialogues
- Speech perception by children
- Vowel perception through formants
- Automatic segmentation and recognition of vowels using shape analysis
- Phonetics of vowel formants in the Assamese language

The Music segment included presentations on:

- Perceptual measures of tonal and melodic structures in music; Classifying "Dholak" (Indian drum) strokes on their acoustic characteristics
- Neural net modeling of the perceptual learning of Rag structure
- Computers and Hindustani music
- Mode studies in percussion instruments (by U. Hansen and T. Rossing)
- Scope of computer-sided transcription for Indian classical music
- Synthesis of singing

During an informal summary session, particular concern was expressed for the need to reform educational curricula to include acoustics. For further information about the conference and papers, contact Dr. Uwe Hansen (812) 237-2044.

"Surely you were aware when you accepted the position, Professor, that it was publish or perish."

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Wallace Clement Sabine: A brief history

Born in Columbus, Ohio in 1868, Wallace Clement Sabine graduated from Ohio State University at the age of 18 and enrolled in Harvard University that same year for graduate studies in physics. He was appointed Instructor in Physics in 1890 and was made Assistant Professor at the age of 27, with a salary of $2,000 per year.

Sabine's entry into acoustics was not planned. In 1885, Harvard dedicated the original building of the Fogg Art Museum (no longer standing). The acoustics of the building's main feature, the lecture hall, were a disaster and its use had to be abandoned. President Charles W. Eliot approached the Physics Department for help and was referred by the Chairman to Wallace Sabine. Sabine's colleagues in the Physics Department looked upon his new assignment as a grim joke, but the adventure actually appealed to him more than his other current options.

WALLACE CLEMENT SABINE, 1869-1919
[Photo courtesy AIP Emilio Segrè Visual Archives]

Before 1895, no text in the Western world gave any definite guidance related to architectural acoustics. Sabine set himself the task of coaxing from science a logical answer to the age-old mystery of why the acoustics are good in some rooms and bad in others.

For three years he isolated himself from his colleagues, except to teach the classes assigned to him. To avoid interference from street noise, he worked until dawn for three nights a week, usually with the help of two laboratory assistants.

The intractable acoustics kept the Fogg Lecture Hall out of service until 1898. Sabine recognized that too much reverberation in a hall makes speech conversation difficult. He also observed that carpets and draperies reduce reverberation.

With the University's permission and a promise that he would return all to normal by class-time each morning, he and his assistants dragged hundreds of seat cushions from the nearby Sanders Theater to the Fogg after midnight and returned them by morning.

Using organ pipes as his source of sound, he would excite the room at a mid-frequency tone of 512 Hz and, from the instant of shutting off the sound, he would measure the time it took for it to decay to inaudibility. His measuring instruments were his ears and a stopwatch.

From this study and measurements in other lecture halls, he derived the famous Sabine reverberation equation. The equation permits the calculation of reverberation time in a room as dependent upon cubic volume and the total amount of sound absorbing materials in the room.

Based on his success in improving the Fogg Lecture Hall, the architects McKim, Mead and White of New York engaged him as acoustical consultant for the new Symphony Hall in Boston. Sabine's contribution was to prevent them from adopting a design, already planned, that would have been disastrous. Instead, the architects decided largely to duplicate the old Music Hall, the only change being the addition of a stage house so that the orchestra was no longer seated on a stage where the front rows of the main floor are now located. His equation validated this solution. History has proven it one of the best concert halls in the world.

"Sabine set himself the task of coaxing from science a logical answer to the age-old mystery of why the acoustics are good in some rooms and bad in others."

Later, Sabine consulted in the designs of the New England Conservatory of Music, the Hall of the Rhode Island House of Representatives, a lecture room at the Metropolitan Museum of Art, the Century Theater in New York, the Harris Theater in Minneapolis, the Old South Meeting House in Boston, and many other important rooms.

Though he had become the principal acoustical consultant in the U.S., Sabine never received an earned doctorate. When asked why not, he responded, "When the proper time came for me to do so, I should have been my own examiner."

In January 1919, after spending much of the preceding two years in Washington and overseas in connection with the war effort, he died prematurely of cancer, leaving a wife and daughter. His work stands as solidly today as ever.

Leo Beranek
Cambridge, Massachusetts

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of sound in the fluid and launch shock waves of their own.

These tremendous photon energies imply bubble collapse temperatures of tens of thousands of degrees Celsius, exceeding even the surface temperature of the sun, and demonstrate a strong but as yet unexplained inverse dependence of the collapse temperature on ambient liquid temperature.

It had been known for years that collapsing bubbles generate temperatures hot enough to break down complex molecules, or even rip apart water molecules into H+ and OH- components. The OH- components, called hydroxyl radicals, are highly reactive and combine within a few nanoseconds with whatever molecules are nearby. These radicals have been measured by several investigators and implicated in the alteration of the genetic code of biological cells whose DNA encountered them. The result is increased cell mutation in the cells that survive, mutation that could conceivably lead to cell defects such as cancer.

Charles Church, also at NCPA at that time, showed via a computational model that x-rays, which could also alter the DNA of cells, might be expected from violent bubble collapse. Both hydroxyl radical production and sonoluminescence of x-rays could result from the high temperatures in the "hot spot" that the center of the collapsing bubble becomes, but no estimates for the temperatures approached the measured values of Putterman and Barber.

Ken Susslick at the University of Illinois has studied the sonochemistry of acoustic cavitation, and has shown that the high local temperatures and rapid cooling rates accompanying the bubble's rebound produce unique chemical reactions. These reactions include the formation of unusual compounds that could be formed in no other way. The bubble motion and high temperatures can also agglomerate, heat, and remove the oxide layers of metal powders used in catalytic reactions, thus exposing more surface area of the powder grains and accelerating the chemical reactions desired.

While increased reactivities of greater than factors of 100,000 are exciting to chemical engineers, it is the physicists who may receive the greatest benefit of this research. Unlocking the secrets of sonoluminescence may lead to fast optical computers or have ramifications for controlled plasma fusion, which requires sufficient heat and temperature for hydrogen atoms to combine and release nuclear energy. Understanding the molecular physics governing how fluid motion accepts diffuse sound energy and delivers it to subatomic particles may yield insights into new physical processes that may be present. Only time and hard work will determine the ultimate benefits of making light from sound.

Erich Carr Everbach, Ph.D., is an Assistant Professor of Engineering at Swarthmore College and an Adjunct Professor of Electrical Engineering at the University of Rochester. He was a Hunt Fellow of the ASA (1989-90), investigating the role of acoustic cavitation in the lithotripsy of gallstones. Recently he was awarded an NSF Presidential Faculty Fellowship to support his research in nonlinear dynamics and shockwave propagation.

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