size varied, demonstrate unambiguously a decrease in target strength with increasing event size, and the rate of decrease matches theoretical expectation (K. R. Housen, Boeing Corporation). Code simulations of oblique collisions among asteroids also quantified the transfer of angular momentum in larger scale collisions in the gravity regime (as opposed to the strength regime, which can be measured in the laboratory) (S. G. Love, California Institute of Technology). Angular-momentum transfer was found to be quite inefficient (compared with laboratory-scale experiments) because so much is carried away in forward-moving ejecta. The ultimate control of the spin evolution of the asteroids, as an ensemble, turns out to be their bulk densities.

It also turns out that the density, or more specifically, the porosity, of desert sand accounts for some remarkable aspects of the Wabar craters, which were indeed found and systematically surveyed by Shoemaker and company. Modest in size (the largest being ≈120 m across), the craters turn out, despite earlier reports, to have not formed in bedrock. Rather, the floors and rims are lined with chunks of black and white impact glass and hunks of shock-compressed sand metamorphosed to firm rock. These impacts were preserved in the sands of time entirely because this "instant rock" resisted erosion. Similar shock-welding no doubt occurs in the surface regolith and soil layers of the moon and other planets and satellites. Finally, preliminary thermoluminescence dating of sand buried beneath the crater rim ejecta gives a formation age for the craters, reducing a previous value of ~6500 years before present by an order of magnitude. So rather than forming in prehistory, the rain of Wabar iron could have been viewed by descendants of the Prophet. This is the real lesson of impact studies, that the extreme is neither unusual nor infrequent.

References

1. St. J. B. Philby, *The Empty Quarter* (Holt, New York, 1933).
2. G. Ryder, D. Fastovsky, S. Gartner, Eds., *Geol. Soc. Am. Spec. Pap. 307* (1996).
3. B. Corner, W. U. Reimold, D. Brandt, C. Koeberl, *Earth Planet. Sci. Lett.* **146**, 351 (1997).
4. M. R. Rampino and B. R. Haggerty, in (*2*), pp. 11–30.
5. D. R. Lowe, G. R. Byerly, F. Asaro, F. J. Kyte, *Science* **245**, 959 (1986).
6. E. S. Cheney, *Precambrian Res.* **79**, 3 (1996).
7. J. D. O'Keefe and T. J. Ahrens, *J. Geophys. Res.* **98**, 17011 (1993).
8. E. M. Shoemaker, M. S. Robinson, E. M. Eliason, *Science* **266**, 1851 (1994).
9. J. S. Alexopoulos and W. B. McKinnon, *Geol. Soc. Am. Spec. Pap. 293* (1994), pp. 178–198.
10. R. A. F. Grieve and M. J. Cintala, *Meteoritics* **27**, 526 (1992); B. A. Ivanov and V. N. Kostuchenko, *Lunar Planet. Sci.* **XXVIII**, 631 (1997).
11. H. J. Melosh, *Impact Cratering: A Geologic Process* (Oxford, New York, 1989), chap. 11.
12. H. J. Melosh, E. V. Ryan, E. Asphaug, *J. Geophys. Res.* **97**, 14735 (1992); W. Benz, E. Asphaug, E. V. Ryan, *Planet. Space Sci.* **42**, 1053 (1994).
13. K. R. Housen and K. A. Holsapple, *Icarus* **84**, 226 (1990); K. A. Holasapple, *Planet. Space Sci.* **42**, 1067 (1994).
14. J. D. O'Keefe and T. J. Ahrens, *Lunar Planet. Sci.* **XXVIII**, 1043 (1997).

SONOLUMINESCENCE

Shocking Revelations

Lawrence A. Crum and Thomas J. Matula

In single-bubble sonoluminescence (SBSL), a small gas bubble that has been acoustically levitated in a liquid and driven into large amplitude volume oscillations by the sound field, radiates visible light each and every acoustic cycle (*1*). These emissions are extremely short in duration (<50 ps), and the spectral content of the light suggests that the temperature of the gas that gives rise to these emissions may be much hotter than the surface of the sun (~7000°C), may even be as high as a million degrees, and could potentially lead to thermonuclear fusion. On page 1398 of this issue, Moss *et al.* (*2*) present the results of their application of the tools of fusion research—large computer simulations of inertially confined plasmas—to uncover some of the physics of sonoluminescence.

Previously, Hiller *et al.* (*3*) reported that small amounts of noble-gas doping could greatly influence the light output of SBSL, and an accompanying Perspective (*4*) described how much was still unknown about this intriguing phenomenon. Since that time, there have been several additional articles published offering more experimental data and theories about the mechanism of light emission.

Eberlein (*5*) extended the original suggestion of Schwinger (*6*) that SBSL was a modified version of the dynamic Casimir effect and proposed that it was the first macroscopic demonstration of quantum vacuum radiation. In this scenario, the rapidly decelerating dielectric interface interacts with the quantum vacuum field, and photons are emitted. This theory has been challenged by a number of investigators (*7*) but was considered one of the top 20 physics stories of 1996. Bernstein and Zakin (*8*) have proposed that the origin of sonoluminescence arises from the emissions of electrons confined in small voids within the dense fluid during the final stages of bubble collapse. Lepoint *et al.* (*9*) have explained SBSL on the basis of an electrical discharge theory in which numerous small, charged liquid jets penetrate the interior of the bubble during bubble collapse. The tips of these charged jets produce a strong enough field that electrons are emitted and produce light through collisions (bremsstrahlung). Prosperetti (*10*) suggests that this light emission occurs not by electrical discharge, but when the high-speed jet strikes the opposing wall of the bubble, light is produced by a form of fractoluminescence.

The most popular theory at the moment appears to be the one originally proposed by Jarman (*11*) in the 1960s, in which the rapidly moving bubble interface launches an imploding shock wave into the gas contained in the interior (see figure). This imploding–shock-wave model was examined by a number of investigators (*12*), who used various formulations for the bubble and shock-wave dynamics and the equation of state for the gas. Predictions of temperatures in excess of several million degrees were made. Of course, the imploding shock theory assumes that the collapsing bubble remains symmetrical long enough to launch a shock wave, a feature challenged by some researchers (*10, 13*). There are a number of other theories besides these, and they all purport to explain at least some of the existing experimental observations.

The experimentalists have also made a number of amazing discoveries. For example, Young *et al.* (*14*) exposed a sonoluminescing bubble to a high magnetic field and found that they could double the light intensity; in addition, they were able to increase the acoustic pressure required for light emission to a factor of two higher than that required at zero magnetic field. In an experiment in which SBSL was compared with multiple-bubble sonoluminescence (MBSL) (in which a field of bubbles created by cavitation, rather than a single bubble, produces light), Matula *et al.* (*15*) demonstrated that the spectrum of MBSL contained emission bands that were characteristic of the liquid, but these bands were completely absent for

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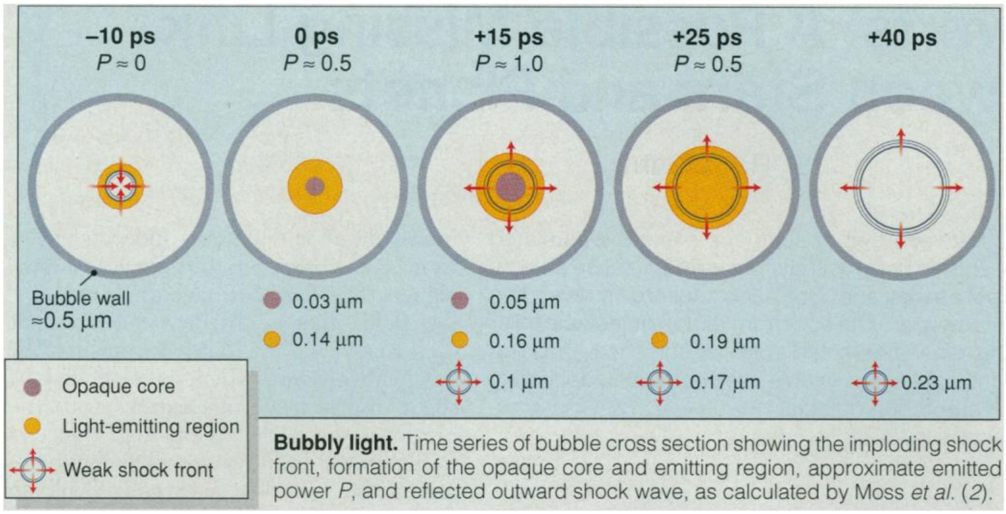

Bubbly light. Time series of bubble cross section showing the imploding shock front, formation of the opaque core and emitting region, approximate emitted power *P*, and reflected outward shock wave, as calculated by Moss *et al.* (*2*).

SBSL in the same liquid. Crum (*16*) suggested that MBSL and SBSL were completely different phenomena; however, in a second experiment, Matula *et al.* (*17*) demonstrated that the optical pulse widths of SBSL and MBSL appeared to be similar.

When SBSL was examined in ordinary water and heavy water with the gas containing either hydrogen and deuterium (*18*), it was apparently observed that the spectrum was more indicative of the contents of the liquid rather than that of the dissolved gas. Recently, using a femtosecond laser, Weninger *et al.* (*19*) discovered that near the final stages of collapse, the bubble interface moves at a velocity near Mach 4 (measured with respect to the ambient conditions contained within the bubble). This rapidly moving interface suggests that shock waves within the gas are a likely product of the imploding bubbles. Because the bubble is assumed to be spherical, it was expected that the light emitted from the bubble would be isotropic, without any preferred direction in space. However, Weninger *et al.* (*20*) presented evidence that under certain conditions, the emission had a dipole pattern, suggesting the presence of asymmetrical bubble shapes and other possibilities. Longuet-Higgins and Oguz (*13*) have studied the collapse of a bubble that is acoustically levitated within a liquid and concluded that asymmetrical collapse is more likely, if not required. However, when Matula examined sonoluminescence in NASA's flying parabolic trajectories, he was unable to observe any increase in the maximum sonoluminescence intensity during periods of microgravity over that observed in periods of hypergravity; presumably, a bubble in microgravity would not have the periodic vertical oscillation that occurs for an acoustically levitated bubble under the influence of buoyancy (gravity) and thus limiting the development of asymmetrical collapses.

The remarkable effect of noble-gas doping reported over 2 years ago has eluded explanation until Lohse *et al.* (*21*) suggested that the sonoluminescing bubble was actually a small chemical reaction chamber and that the nitrogen and oxygen components of air were converted into reactive molecules that were absorbed within the liquid, leaving only the noble gas behind. Currently, there is no (published) experimental confirmation of this exciting hypothesis.

Thus, even though there has been an intense amount of research effort in this area, there have been more questions raised than answers found over the past 2-1/2 years. In their present work, Moss *et al.* (*2*) find that a shock wave is produced in the gas contained within the collapsing bubble and apply the numerical codes of inertial confinement fusion (with implicit and explicit hydrodynamics) to an analysis of this collapse. These powerful codes, complete with a state-of-the-art equation of state for the gas within the bubble, including plasma thermal conduction, provide the most rigorous study to date of the imploding–shock-wave model. These calculations are consistent with experimentally measured acoustic emissions from SBSL (*22*). [There are still some incomplete areas; for example, mass diffusion is not included, nor is heat transfer before ionization, a phenomenon that Szeri (*23*) believes is very important.] Moss *et al.* find that when nitrogen is examined as the gas contained within the bubble, the hot gas looks a bit like our own sun. Even though the temperature of the gas contained within the imploded core of the gas is near a million degrees, there is considerable opacity seen by the photons, and the spectrum is determined mostly by the surface of the core, which is only a cool 90,000°C. When they compare their emission intensity of nitrogen with the measured spectrum of air, they find that their calculated intensity is a factor of about 25 times too small, but it agrees with the experimental data for N_2 SBSL. If they assume that the gas is really argon, then they get about the right answer! Thus, the calculations of Moss *et al.* would support the theory of Lohse *et al.* (*21*) who assumed that the air is quickly replaced by argon.

An interesting observation of Moss *et al.* is that a small increase in the value of the maximum radius results in a large increase in the temperature of the imploded gas, a result that seems to have some experimental confirmation (*24*). Because it has already been demonstrated that small changes in the driving wave form can "boost" the intensity of sonoluminescence (*25*), and because the calculations of Moss *et al.* suggest that the temperature within the interior of the imploded core may already be near a million degrees, it poses the exciting possibility that ways of boosting the maximum radius significantly might lead to thermonuclear fusion within the bubble (*26*).

References

1. D. F. Gaitan and L. A. Crum, in *Frontiers of Nonlinear Acoustics*, M. Hamilton and D. T. Blackstock, Eds. (Elsevier, New York, 1990), pp. 459–463; B. P. Barber and S. J. Putterman, *Nature* **352**, 318 (1991); D. F. Gaitan, L. A. Crum, R. A. Roy, C. C. Church, *J. Acoust. Soc. Am.* **91**, 3166 (1992); L. A. Crum, *Phys. Today* **47**, 22 (September 1994); S. J. Putterman, *Sci. Am.* **272**, 46 (February 1995).
2. W. C. Moss, D. B. Clarke, D. A. Young, *Science* **276**, 1398 (1997).
3. R. Hiller, K. Weninger, S. J. Putterman, B. P. Barber, *ibid.* **266**, 248 (1994).
4. L. A. Crum and R. A. Roy, *ibid.*, p. 233.
5. C. Eberlein, *Phys. Rev. A* **53**, 2772 (1996).
6. J. Schwinger, *Proc. Natl. Acad. Sci. U.S.A.* **89**, 4091 (1992); *ibid.* **91**, 6473 (1994).
7. N. Garcia and A. P. Levanyuk, *Phys Rev. Lett.* **78**, 2268 (1997); A. Lambrecht, M. Jaekel, S. Reynaud, *ibid.* p. 2267.
8. L. S. Bernstein and M. R. Zakin, *J. Phys. Chem.* **99**, 14619 (1995).
9. T. Lepoint, D. De Pauw, F. Lepoint-Mullie, M. Goldman, A. Goldman, *J. Acoust. Soc. Am.* **101**, 2012 (1997).
10. A. Prosperetti, *ibid.*, p. 2003.
11. P. D. Jarman, *ibid.*, **32**, 1459 (1960).
12. C. C. Wu and P. H. Roberts, *Phys. Rev. Lett.* **70**, 3424 (1993); H. P. Greenspan and A. Nadim, *Phys. Fluids A* **5**, 1065 (1993); W. C. Moss, D. B. Clarke, J. W. White, D. A. Young, *ibid.* **6**, 2979 (1994).
13. M. S. Longuet-Higgins and H. Oguz, *J. Fluid Mech.* **290,** 183 (1995).
14. J. B. Young, W. Kang, T. Schmiedel, *J. Acoust. Soc. Am.* **100**, 2718 (1996).
15. T. J. Matula, R. A. Roy, P. D. Mourad, W. B. McNamara, K. S. Suslick, *Phys. Rev. Lett.* **75**, 2602 (1995).
16. L. A. Crum, *J. Acoust. Soc. Am.* **95**, 559 (1994).
17. T. J. Matula, R. A. Roy, P. D. Mourad, *ibid.* **101**, 1994 (1997).
18. R. Hiller and S. J. Putterman, *Phys. Rev. Lett.* **75**, 3549 (1995); *ibid.* **77**, 2345 (1996).
19. K. R. Weninger, B. P. Barber, S. J. Putterman, *ibid.* **78**, 1799 (1997).
20. ———, *ibid.* **78**, 1799 (1997).
21. D. Lohse, M. P. Brenner, T. F. Dupont, S. Hilgenfeldt, B. Johnston, *ibid.* **78**, 1359 (1997).
22. I. M. Hallaj, T. J. Matula, R. A. Roy, L. A. Crum, *J. Acoust. Soc. Am.* **100**, 2717 (1996).
23. V. K. Vuong and A. J. Szeri, *Phys. Fluids* **8**, 2354 (1996).
24. B. P. Barber, K. Weninger, R. Lofstedt, S. J. Putterman, *Phys. Rev. Lett.* **74**, 5256 (1995).
25. R. Mettin, J. Holzfuss, W. Lauterborn, *Fortschr. Akust.—DAGA* **95**, 1145 (1995).
26. W. C. Moss, D. B. Clarke, J. W. White, D. A. Young, *Phys. Lett. A* **211**, 69 (1996).