participants indicated that the theory is still far from being complete.

The conference in Calcutta was probably the first devoted to a thorough discussion of black holes as real astronomical objects from all perspectives. The limited number of participants, each a real expert in the field, made possible a detailed presentation (*4*) of observational data and a broad discussion in all topics connected with black holes.

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**SONOLUMINESCENCE**

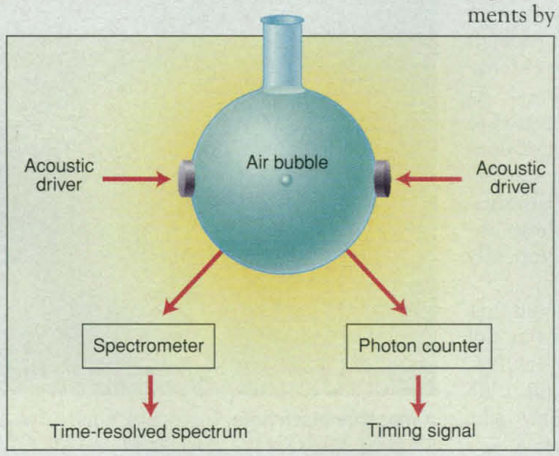
# That Flashing Sound


Harold Metcalf


Sonoluminescence is the mysterious and fascinating phenomenon of ultrashort flashes of light emitted during the catastrophic collapse of a gas bubble caused by an acoustic wave. In some sense, it is the conversion of sound into light. Although the phenomenon was observed as many as 60 years ago (*1*), it was not until 1990 that sonoluminescence was produced in a single isolated bubble (*2*) and in 1991 that serious studies of it first appeared in the literature (*3*). Now Hiller *et al.* have carried out a precise and careful measurement of the temporal properties of this luminescence (*4*), further narrowing the range of models to explain the phenomenon.

"Phenomenon" is an appropriate description of sonoluminescence because there is very little physical understanding, even in the face of an overwhelming body of experimental information. Some simple considerations are instructive: Measurements have shown that typical bubbles have an equilibrium radius of ~5 mm at standard temperature and pressure, and that during the acoustic cycle, the bubble expands to ~40 mm and then rapidly collapses to a minimum radius of ~0.8 mm. Thus, the gas is enormously compressed, suggesting temperatures as high as $\sim 5 \times 10^4$ K or ~4 eV, enough to produce significant ionization and plasma conditions. However, the ideal gas behavior seems to be the least violent scenario for the collapse; the far-from-equilibrium conditions that prevail are much more severe.

Experiments are typically done in an approximately spherical 100-ml flask filled with distilled and carefully degassed water (see figure). The acoustic excitation is provided by one or more piezo-electric transducers fed by a resonant ~25-kHz circuit. Except for the oscilloscope, the equipment costs a few hundred dollars and fits in a coffee can. There are extremely befuddling criteria for the dissolved gas: pure $N_2$ or $O_2$ do not work, nor does any mixture of them. The critical ingredient seems to be rare gases, but only in the 0.5 to 2% concentration range. Impurities of many solutes, for example, alcohols, at only a few micromolar concentration completely quench sonoluminescence.




**Bright lights, big sounds.** Highly schematic illustration of the sonoluminescence experiment of Hiller *et al.* (*4*). Light from the acoustic chamber (about 6 cm in diameter) is measured by a photon-counting detector and spectrally analyzed with a photon-correlation apparatus.

The total light output of a flash is $\sim 10^{-12}$ J, and the spectral density is consistent with a blackbody spectrum near $10^5$ K. Because the flash repetition rate is ~25 kHz, the appearance to a dark-adapted observer ~50 cm away is that of a fifth magnitude star, and thus, sonoluminescence is readily observed with the naked eye. The flash duration $\tau$ is less than 50 ps. In fact, there is no known photodetection system fast enough to measure it directly, and some detector manufacturers use sonoluminescence to calibrate the time resolution of their products.

The new results from the leading group in the study of sonoluminescence of Hiller *et al.* at UCLA (*4*) have extended the pioneering work in photon correlation measurements by Gompf *et al.* (*5*). In a series of careful experiments using time correlations of photoelectrons from separated detectors, Hiller *et al.* have found that $\tau$ can be as short as 35 ps and depends strongly on the dissolved gases and the temperature. They used a spectrometer in the light path to one of the detectors to get wavelength as well as time discrimination (correcting for the extra travel time in the spectrometer). One of their most significant results was that $\tau$ is the same to within "a few picoseconds" for all emitted wavelengths, suggesting that a plasma produced in a catastrophic event such as a collapsing shock wave is the most likely source of the light. By contrast, any heating mechanism that produced blackbody radiation would show a longer flash for the longer wavelengths that are produced as the gas heats up and cools down. This pulse is so short that all of the light is still in the flask after the source has shut off.

The coherence character of the emitted light is unknown, and its investigation may help to elucidate the emission mechanism. Indeed, studies of the second order correlation coefficient of the emitted light are important for future research in sonoluminescence and is under way in my laboratory (*6*). The angular dependence of such intensity interference measurements can be used to determine the size of the light-emitting volume. If such a measurement showed this volume was smaller than that of the bubble itself, it could provide confirming evidence for the shock-wave hypothesis. At present, there is no evidence that the light comes from the full bubble volume.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Needless to say, there is a much larger litany of phenomenological information about sonoluminescence than given above, and no simple theory about the origin of the light, much less its spectral and temporal characteristics, has been given. There are ardent proponents of an incredibly diverse array of speculations about sonoluminescence, many of them supported by significant arguments or detailed calculations. An abbreviated list contains not only the obvious blackbody, shock waves, bremsstrahlung, and subtle collision effects, but also includes more exotic effects that derive from quantum electrodynamics. These recent experiments provide support for the most violent of these mechanisms simply because it seems that everything happens at once. What remains totally mysterious, however, is why there is such strong dependence on the gas mixture and the choice of liquids, and why such violent events are so strongly dependent on seemingly mild conditions such as the initial water temperature.

The entire apparatus is extraordinarily simple and low-cost for research at the frontiers of physics. Thus, it is ideal for undergraduate students who learn about electrical and acoustical resonances, impedance matching, normal modes, transducers and detectors for ultrasound, and a host of related topics that can lead to an interesting study of "flask spectroscopy."

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**BOTANY**

# Plants See the Blue Light

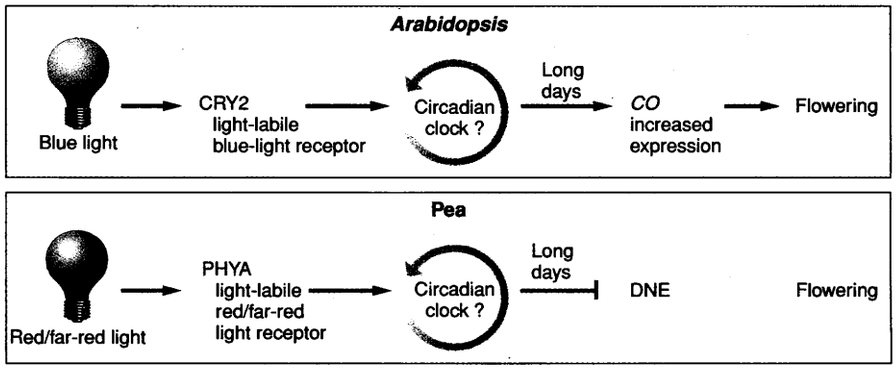

Paula Suárez-López and George Coupland


As day lengths increase in the spring, many plants respond by flowering. Others—such as one variety of tobacco that flowers in winter—flower when days get shorter (*1*). Day length is "seen" by a light-sensitive molecule in the leaf, phytochrome, which can sense red and far-red light (*2*). Indeed, mutations affecting one form of phytochrome, phytochrome A (PHYA), prevent the photoperiod response in the pea plant (*3*). However, *phyA* mutations only weakly affected photoperiodic responses in *Arabidopsis* (*4*), a plant widely used by researchers. On page 1360 of this issue, Guo *et al.* now show that *Arabidopsis* senses photoperiod through a different molecule, the blue-light receptor cryptochrome 2 (CRY2) (*5*).

Flowering of *Arabidopsis* is promoted by long photoperiods and delayed by short ones. Among the large number of mutations that either delay or promote flowering are those that decrease or abolish the response to photoperiod. For example, a group of late-flowering mutants, including two called *co* and *fha*, flower later than wild-type plants only under long days; the underlying mutations likely occur in a genetic pathway that triggers flowering when days get longer (*6*). Messenger RNA from the CO gene—proposed to encode a transcription factor—is more abundant in wild-type plants grown under long days than in plants grown under short days (*7*), and expression of the gene from a strong viral promoter causes day length–insensitive early flowering (*8*). These observations suggest that CO is transcriptionally regulated by daylength and in turn triggers flowering. In *Arabidopsis*, blue and far-red light promote flowering, leading to the suggestion that PHYA and a blue-light receptor trigger flowering (*9*). Guo *et al.* now show that the *FHA* gene encodes CRY2, a receptor for blue light recognized by its similarity to the blue-light receptor cryptochrome 1 (*cry1*) (*10*). Under long days *cry2* mutants show delayed flowering and reduced expression of CO, whereas overexpression of *CRY2* accelerates flowering and causes increased expression of CO under short days. This is consistent with the idea that *FHA* acts before CO in the long-day promotion pathway and is required for increased expression of CO under long days. There is about three times as much CO mRNA in wild-type plants as in the cry2 mutant, and about three times as much in wild-type plants under long days compared with those under short days. Such small changes in CO mRNA abundance might well be sufficient to affect flowering time, because increasing the dosage of the gene by introducing extra copies could accelerate flowering, and heterozygotes carrying one mutant and one wild-type copy of the gene flowered later than wild type (*7*).

Guo *et al.* also proposed that CRY2 promotes flowering by repressing the inhibition of flowering caused by the red and far-red light receptor phytochrome B (PHYB), on the basis of the behavior of *cry2* and *phyB* mutants under different light qualities. Guo *et al.* suggest that CRY2 and PHYB act antagonistically to regulate flowering time. The CRY2 protein accumulates in plants growing in darkness but is unstable when plants are exposed to light (*10*), while PHYB is light stable (*11*), so for most of the photoperiod CRY2 would not be present to antagonize the repression caused by PHYB. Further genetic analysis should make the interactions between CRY2 and PHYB clearer.

The function of CRY2 may be aug-




**Flowering time.** Both *Arabidopsis* and pea flower in response to long days. This process is disrupted by mutations in genes encoding light-labile photoreceptors: CRY2 in *Arabidopsis* (*5*) and PHYA in pea (*3*). CRY2 promotes flowering through the up-regulation of the *CO* gene, whereas PHYA in pea acts by repressing the inhibitor of flowering, DNE. In both species the circadian clock might act as a timekeeper to measure day length.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