RESEARCH: ASTROPHYSICS

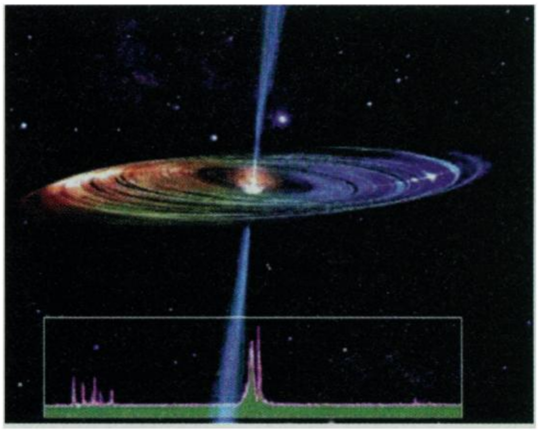
# At the Border of Eternity

G. S. Bisnovatyi-Kogan

The modern epoch of great astronomical discoveries began in 1962 with x-ray observations of the sky (*1*), followed by observations of quasars, microwave background radiation, neutron stars as pulsars and x-ray sources, and gamma ray bursts (*2*). Then came hints of the most intriguing objects in the universe: black holes. To be more precise, the first indications for the existence of black holes were obtained in 1972 from the UHURU satellite x-ray observations (*3*) of Cyg X-1, a binary system in which the mass of the compact star exceeds the limiting mass of a stable superdense neutron star (about three solar masses). At this mass, the star should be compressed to the state of a black hole. At a recent conference (*4*) in Calcutta, new data from x-ray, ultraviolet, optical, and radio observations gave convincing proof of these objects, which were predicted theoretically 60 years ago (*5*).

As long ago as 1796, Laplace noted that light cannot leave a star when its free-fall velocity, a function of the star's mass and radius, is larger than the speed of light. One can calculate a radius within which light cannot escape, but it also represents a border to another world, which can never be observed from outside. A hypothetical space explorer who tried to reach this so-called event horizon might do so, but owing to time dilation, a short trip into the black hole would correspond to an eternity for outsiders, and the possible death of our universe. Modern theoretical prediction of the existence of black holes is mainly connected with the names of Einstein, Chandrasekhar, and J. Oppenheimer (*5*).

So far, black holes can be observed only by looking for radiation from the gas surrounding it. As the gas moves into the black hole, its thermal and kinetic energy is increased by the gravitational black hole. When we find a compact object that exceeds the limiting mass, and if we believe in general relativity (which up to now has no contradictions with any astronomical observations and physical experiments), we may confidently say we have discovered a black hole. In about 40 cases, the existence of a black hole has been established by observations in different spectral regions (*6*, *7*). About three-quarters of them are supermassive objects—which each contain millions and billions of solar masses and radiate as a result of an accretion disk rotating around a central black hole—surrounded by dense stellar clusters, in which the number density of stars has a strong central concentration because of the strong gravity of a black hole.



**A massive black hole.** This one is found in the center of the spiral galaxy M101 (also known as NGC4258) in the constellation Canes Venatici. Maser emissions from water vapor in the disk (spectrum at bottom) enable us to infer its existence. In addition, the distance to the galaxy has been measured directly to be 6.4 Mpc (21 million light years) using the acceleration of the maser. This new method will help reveal the larger structure of the universe. [Courtesy of M. Inoue, National Astronomical Observatory, Japan]

At the conference, L. Ho (Harvard University) reviewed (i) optical and ultraviolet observations from the Hubble Space Telescope that gave estimates for black hole masses from measurements of stellar and gas kinematics, and (ii) x-ray observations from the Japanese satellite ASCA. The latter had observed broad K$\alpha$ emission lines of iron, with a line width corresponding to one-third of the speed of light, which could only be produced in the inner regions of accretion disks around supermassive black holes. Gas around a black hole collects into a disk because of its large angular momentum and centrifugal forces, which prevent the gas from falling directly into the black hole, inducing it to rotate around instead. The most precise measurements of gas kinematics around a supermassive black hole came from water mega maser radio observations in the nucleus of the galaxy NGC 4258 (see figure) and two other galactic nuclei, which were presented by Miyoshi (National Astronomical Observatory, Japan).

Inside our galaxy, proof of the existence of a black hole came from measurements of the velocity curve of an optical star paired with a compact object, observed as an x-ray source (*6*, *8*). These measurements made it possible to obtain strict limits for the mass of the compact object from Kepler's laws, and to claim the discovery of a black hole if the lower boundary exceeds the limiting mass. For Cyg X-1, the lower mass limit could not be obtained absolutely, owing to the orbital orientation, but in the soft x-ray nova A0620-00, this limit was for the first time conclusively found to be larger than the limiting mass. Since then, careful optical measurements of soft x-ray novae in their quiescent state have given the most convincing evidence for the existence of stellar-mass black holes inside our galaxy. A review of multiwavelength observations of galactic black holes was given by C. Haswell (University of Sussex, United Kingdom), and x-ray observations of these objects were presented by participants from Germany, India, Japan, and Russia. Optical observations from some objects with suspected supermassive black holes were presented by Finnish astronomers (talks of P. Agrawal *et al.*).

The flow of convincing observational results has advanced the theory of accretion disks around black holes, which in its "standard" simplified variant was created more than 25 years ago (*9*). Observations have shown that most of the radiation comes from regions at radial distances equal to several times the event horizon, where the radial motion of matter, not included in the standard variant, is very important. A comparatively cold accretion disk should be surrounded by hot "coronal" gas. Different theoretical models describing the structure of accretion disks around black holes with radial motion and energy transport along the radius (advective accretion flows), along with different models describing spectra formation that fit observations, were presented in the talk of the host and organizer of the conference, Chakrabarti (Bose National Centre, India), and in many other talks of the participants from China, India, Italy, South Korea, Mexico, Poland, Russia, and the United States (talks of Bisnovatyi-Kogan *et al.*). These presentations gave an exhaustive picture of theoretical efforts, and the debate, sometimes hot, between

The author is at the Space Research Institute, Moscow 117810, Russia. E-mail: gkogan@mx.iki.rssi.ru

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.


**References and Notes**

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**SONOLUMINESCENCE**

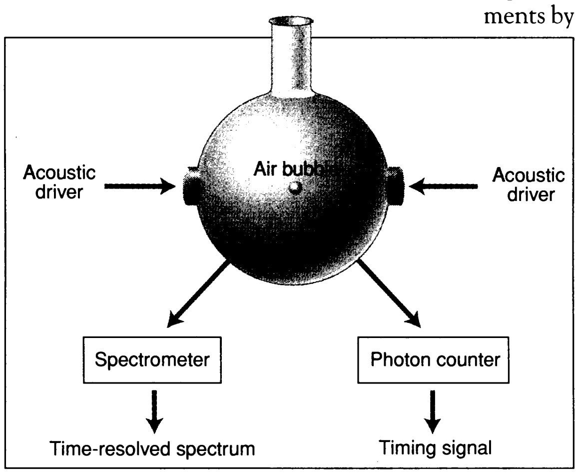
# That Flashing Sound


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.


The author is in the Physics and Astronomy Department, State University of New York, Stony Brook, NY 11794–3800, USA. E-mail: hmetcalf@ccmail.sunysb.edu