Camera Lucida: A Three-Dimensional Sonochemical Observatory

Evelina Domnitch and Dmitry Gelfand

ABSTRACT

Camera Lucida is an interactive "sonic observatory" that directly converts sound waves into light by employing a phenomenon called sonoluminescence. The project was conceived both as an artwork and as a musical instrument that allows its player to see and shape sounds while moving through space.

> *If we now envisage the more technical side of a possible future, it is very likely that the artist, tired of the cult for oils in painting, will find himself completely abandoning this five-hundred-year-old process, which restricts his freedom of expression by its academic ties.*
>
> *Other techniques have already appeared recently and we can foresee that just as the invention of new musical instruments changes the whole sensibility of an era, the phenomenon of light can, due to current scientific progress, among other things, become the new tool for the new artist.*
>
> —Marcel Duchamp [1]

Is it possible to create a sonic rainbow? Is it possible to translate the wave behaviors of sound into those of light? Is it possible to render sound visible and allow a musician to work with the shape of sonic currents?

Since Ernst Chladni's late–18th-century experiments with vibrating plates, much territory has been covered in the field of acoustic observation. However, there have been very few attempts at a 3D and non-virtual visualization of the movement of sound events through space, especially the kind of space that exists outside the anechoic confines of an acoustic laboratory. The entropic, omni-directional network of merging and diverging sonic fronts that characterizes almost any unbridled sound environment can be rendered visible only when aesthetic ends supersede the scientific pursuit of precise test results.

In order to visually register the customarily invisible dynamics of sound waves without introducing a simulation mechanism such as a recording/playback medium or a computer interface, one must tap into the delicate juncture between the sensorially separated bandwidths of light and sound. The *Camera Lucida* (light chamber) observatory allows one to directly convert sound waves into light by employing a phenomenon called *sonoluminescence*.

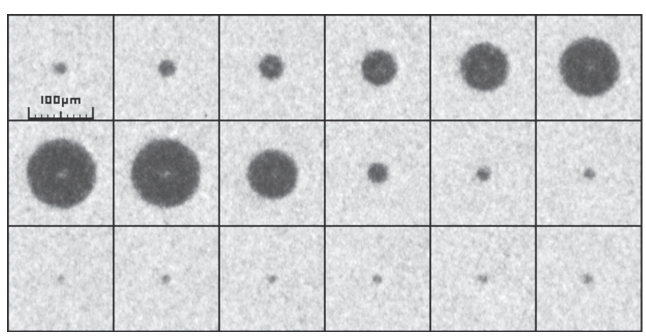
THE ENIGMA OF SONOLUMINESCENCE

Like x-rays and radioactivity, sonoluminescence was discovered while its discoverers were looking for something else. In 1929, H. Frenzel and H. Schultes witnessed the appearance of luminescence when an oxygen gas was dissolved in water and a sufficiently strong ultrasonic signal irradiated the liquid. To confirm their observations, they exposed a photographic plate with traces of the light induced by acoustic waves. The luminescence emanates from collapsing gas bubbles during a process called acoustic cavitation (Fig. 1) and indicates the momentary creation (in the space of 10^{-10} seconds per sound field cycle) of very high temperatures (about 5,000 degrees Kelvin) such as are found on the surface of the sun. Cavitation refers to the formation, growth and implosive collapse of bubbles in a liquid.

> Bubbles in liquids can be formed in various ways. They may come off the walls of liquids oversaturated with gas, as in beer or champagne. These are "soft" bubbles. But they can also be forced to appear by tearing the liquid with brute force (ultrasound for example). This type of bubble formation is called cavitation, and the bubbles are termed *cavitation bubbles,* because they are essentially empty, i.e., just cavities [2].

After an empty bubble implodes under the pressure of the surrounding liquid, its deflated skin may fill with vapor or gas and become a soft bubble. It is at this microtemporal juncture that the normally dispersed energy of a sonic vibration can become intensely focused inside the bubble, thereby compressing its gaseous contents to the point of luminescence. Sonic

Fig. 1. Photographic series of a trapped sonoluminescing bubble driven at 21.4 kHz. (Photo © Reinhard Geisler) The bubble dynamics are represented at an interframe time of approximately 2.5 microseconds.



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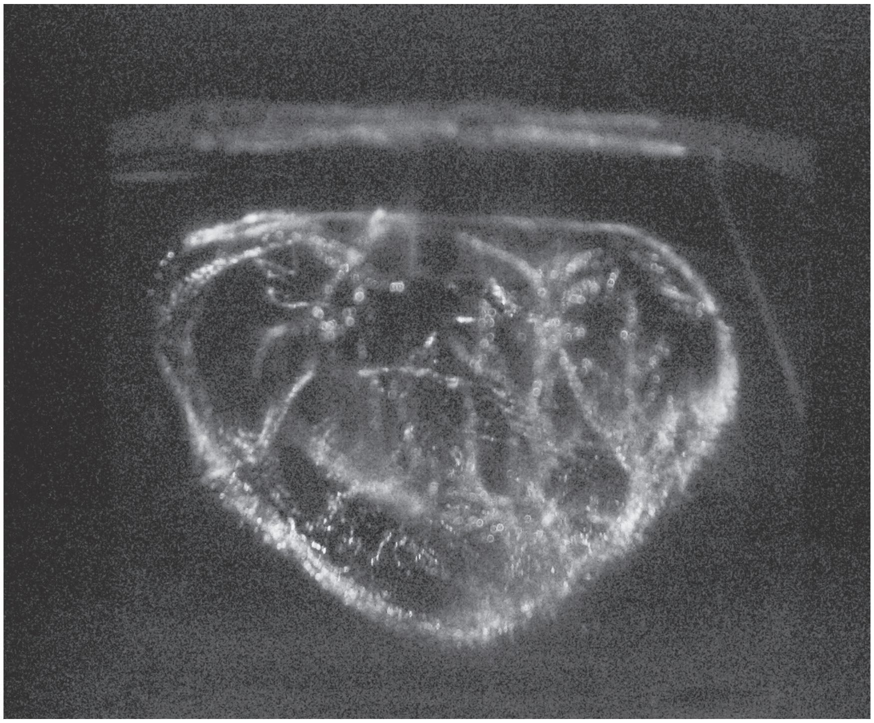


Fig. 2. ***Mongolfière Figures*****: Parachute-like sonoluminescent formation within xenon-infused sulphuric acid irradiated by a 140 kHz signal, emanating from a titanium horn transducer. (Photo © Evelina Domnitch and Dmitry Gelfand)**

oscillations of a particularly high magnitude may also cause a bubble to collapse so quickly and severely that it shatters into tiny fractions. Although an entirely new science of *sonochemistry* recently has developed in order to decipher the dynamics of acoustic cavitation, "the sequence of chemical events occurring between the mechanical release of energy associated with the collapse of bubbles and the [resultant] photonic emissions still remains predominantly unknown" [3].

A widely supported model of sonoluminescence is the hot spot theory, which postulates that the energy fueling the initial expansion and formation of a near-vacuum within a cavitation bubble is squeezed into a sweltering plasma core upon the bubble's implosion, which occurs at over four times the speed of sound. The primary impetus for this interpretation is the fact that the emission of light occurs at the point when the bubble has reached its minimal detectable size.

> The compression of cavities when they implode in irradiated liquids is so rapid that little heat can escape from the cavity during collapse. The surrounding liquid, however, is still cold and will quickly quench the heated cavity. Thus, one generates a short-lived, localized hot spot in an otherwise cold liquid [4].

The hot spot theory also concludes that the high pressure arising during the bubble's swift implosion (several thousand atmospheres) incites explosive shockwave synthesis in solid matter.

In terms of duration, pressure and energy per molecule, ultrasonic irradiation behaves in a vastly different manner from traditional energy sources such as heat, light or ionizing radiation. Because of the rapidity of tremendous oscillations in heat and pressure caused by cavitation bubble collapse, ultrasound offers a highly efficient means by which to synthesize, at the nanoscale, matter such as metals, alloys, carbides, oxides and colloids. A sonochemical preparation of biomaterials, best exemplified by protein microspheres, is also being researched.

> Using high intensity ultrasound and simple protein solutions, a remarkably easy method to make both air-filled microbubbles and nonaqueous liquid-filled microcapsules has been developed. These microspheres are stable for months, and being slightly smaller than erythrocytes, can be intravenously injected to pass unimpeded through the circulatory system [5].

While numerous practical applications of sonochemistry are flourishing, and a rough chronospatial hypothesis of acoustic cavitation has reached some degree of consensus, scientists are still incapable of determining the precise increase in temperature within a cavitation bubble and the speed at which it occurs. As with all other behaviors transpiring in nanospace at nanospeeds, one is precisely limited by one's instruments of measurement. Yonder lies the philosopher's and the artist's dominion, where the imperceptible and inconceivable serve to disentangle one's imagination from the burden of finitude.

Preliminary Experiments

The *Camera Lucida* project began as a speculative reverie on observing sound waves with the naked eye. The idea of using a gas that would luminesce when irradiated by sound converted into voltage was very appealing to us. However, as soon as we came upon the phenomenon of sonoluminescence, it became quite clear that we had struck virgin soil. Though imbued with excitement and great potential, this path was riddled with obstacles: most of the physicists, chemists and sound engineers we consulted predicted that our project was destined to fail or that the effects would be barely perceptible to the naked eye.

Nonetheless, after two years of hypothetical wanderings through the thick woods of latter-day acoustics, optics and fluid dynamics, we finally donned our sonochemical cloaks in Japan, via an invitation from the Institute of Advanced Media Arts and Sciences (IAMAS). On the outskirts of the old samurai town of Nagoya, at the freshly erected "Palace" of Advanced Industrial Science and Technology (AIST) crowned by a fountain filled with titanium dioxide spheres, we attended the 11th Annual Meeting of the Japan Society of Sonochemistry. It was there that we befriended Werner Lauterborn, director of the Drittes Physikalisches Institut of the University of Göttingen, Germany. Because most of the presentations were in Japanese, we decided along with Lauterborn to skip some of them in favor of a six-hour dithyramb about the "2 or at most 3 laws that govern the cosmos" (in Lauterborn's words).

By the end of our discourse, having distilled the quintessence of our sonochemical observatory project, Lauterborn advised us to contact Thierry Lepoint, who had allegedly attained the brightest sonoluminescence visible to the naked eye.

Sonoluminescence is usually barely visible, even after one's eyes have become acclimated to total darkness. Lepoint's experiments with xenon-infused sulfuric acid (H_2SO_4) irradiated by a 140-kHz signal emanating from a titanium horn transducer were said to procure sonoluminescence that could be witnessed in broad daylight. Furthermore, by minimizing the distance between the transducer, which projects the ultrasound downward, and the surface at the bottom of the resonating chamber, one could observe *Mongolfière Figures*: parachute-like formations named after two French brothers who designed ostentatiously shaped hot-air balloons in the 19th century (Fig. 2). As soon as Lepoint sent us all the specifications, we combined our efforts with a devout group of sonochemists from AIST, Y. Iida, T. Tuziuti, K. Yasui and T. Kozuka, and began conducting a series of experiments unprecedented in Japan, prodding the mysterious phenomenon of sonoluminescence.

Although our initial experiment was successful in terms of brightness, we were not able to create any Mongolfière Figures, even after numerous recalibrations. The transducer detonated a fiery jet of xenon plasma, which was magnificent in and of itself but in no way alluded to the undulating sound environment within the resonator. An experiment with luminol and ammonium sulfate followed, which conjured a silken and subtly hypnotic sonoluminescence: slightly wavering parallel lines of light, corresponding to the troughs of the sound waves (Fig. 3). While we were quite impressed by the opto-acoustic cohesion, we deemed this representation far too static and continued seeking a way to observe a full range of sonic dynamics.

We decided to re-enact the xenon-infused sulfuric acid experiment, but with added parameters. A chamber with six transducers was engineered, which received its input from a humanly audible sound composition, synchronously modulating into the ultrasonic register (much like the manner in which mobile telephones permit the human voice to be non-linearly hoisted by a high frequency signal that carries it into outer space). In spite of our efforts, we obtained the same result as before, except that now there were six plasmic jets.

After many frustrating hours of delicately tuning the frequency and amplitude modulation, an altogether different spectacle suddenly emerged: the unidirectional jets of luminescing bubbles started to swirl and rip apart into trembling, gelatinous vortices, simultaneously forming periodically exteriorized rings. The entire chamber was permeated by colliding and interweaving spirals of light, the quantity of which no longer corresponded to the number of transducers. Although we could distinguish certain recurring patterns of luminescence, the overall environment was tremendously varied both in form and light intensity. The correspondence of these variations to the audible sound composition was inexplicable yet starkly apparent. We realized afterward that we had inadvertently ignored the amplifier's bleeding voltage meters used to indicate threshold amplitude levels, and that we had triggered a high-pressure thermo-acoustic wind. We named this phenomenon "xenon wind" (Fig. 3 and Color Plate B No. 2). At last, we were ready to begin the construction of *Camera Lucida*.

Fig. 3. Six-channel *Camera Lucida* prototype: A 20–10-kHz signal irradiates a solution of luminol and ammonium sulfate, resulting in parallel lines of sonoluminescence corresponding to the troughs of the sound waves. (Photo © Chunichi Shimbun)

Materialization and Operation

With the invaluable help of Honda Electronics, our assorted prototypes and preconceptions were forged into a singular apparatus that is described below.

A transparent chamber (Fig. 4) is filled with a gas-infused liquid. Eight ultrasonic transducers, attached to the walls of the chamber, generate arrays of frequencies that are made visible while traveling through the chemical medium owing to fluctuating cycles of sonoluminescence and pressure currents forming along the sound paths.

The observatory's sound source is an interactive musical composition, the audible spectrum of which, propagating within the exhibition space via eight channels, is modulated in real time into the ultrasonic register, analogously propagating via eight ultrasonic transducers within the transparent chamber (Fig. 5). By playing the composition, the viewer/performer is able to activate a vast range of simultaneous as well as isolated sonoluminescent behaviors. The user is also able to change the directionality of the ultrasonic transducers in order to closely explore interference patterns and Doppler effects.

In addition to the translation of the humanly audible sound composition into the ultrasonic environment of the observatory, a simultaneous reverse translation is generated by placing a hydrophone (an underwater microphone that is sensitive to ultrasonic frequencies) inside the chamber: the discrete parameters of the acoustics within the chemical medium effect the behavior of the sonorities within the exhibition space. As such, the interactive musical composition serves not only as a means of activating the observatory but also as a large-scale model of the observatory's uncanny acoustic dynamics.

The Sonoluminescent Universe

While probing nature's inherent capacity to transform sound into light, one necessarily encounters a great many cosmogonical implications. It is revealed in the Vedas that sound is the Creator, *Nada Brahma*, the vibrational energy that pervades all things [6]. After Brahma meditated for a thousand god-years in the directionless, dark, primeval ether, the sound of Krishna's flute entered his eight ears (the earliest promulgation of the musical octave was in India, predating Pythagoras's allegedly Egyptian

Fig. 4. Transparent chamber (60-×-40-×-30 cm) with eight ultrasonic transducers custom-designed by Honda Electronics: four on the sides and four at the bottom. (Photo © Evelina Domnitch and Dmitry Gelfand)

and/or Chinese resources). When Brahma repeated the sound with his voice (*aum* or *om),* the quiescent particles comprising the ether began to heterogenize and were thereupon cast out from the darkness.

> To some such laws the ancient Philosophers seem to have alluded when they called God Harmony and signified his actuating matter harmonically by the God Pan's playing upon a Pipe and attributing music to the spheres made the distances and motions of the heavenly bodies harmonical [7].

The structure of the cosmos was triggered by a fundamental frequency, followed by overtones upon overtones, cascading omni-directionally into increasingly diversified oscillations, from the 92 periodic elements to the resonant frequencies of one's bodily organs. Everything is made out of ceaselessly regenerative wave systems—any level of stasis is just a sensorial illusion generated by gaps in scale between inner and outer space-time. Not for an instant is any particle left unturned in the wake of cosmic renovation. Since energy/mass cannot be destroyed; it must undergo constant, pattern-yielding metakinesis. Consequently, certain harmonic patterns, for example the Fibonacci sequence, can propagate across the entirety of energy spectra from the sonic to the electromagnetic to the gravitational register.

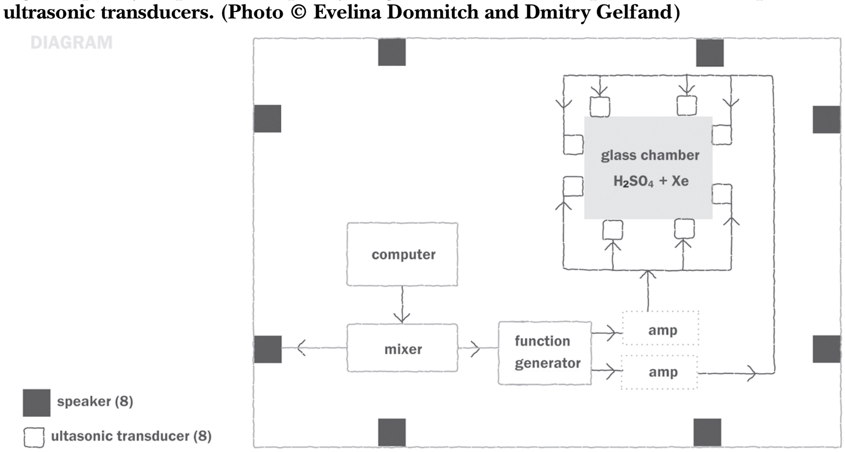
One of the earliest dated sources of the Chinese musical system, a text known as *Lüi* (Lü Bu-Wei, 3rd century BC), conveyed a system based on 12 sounds generated by 12 pitch pipes, whose length is calculated in the relation of exponentially progressing powers of 2 and 3 [8]. Each of the 12 sounds corresponds to a vibratory artifact stemming from a particular period in cosmic history. The first pitch, *Huang Zhong,* characterizes the embryonic stage, when the entire mass of beings starts wriggling like earthworms. The second pitch, *Tai Cu,* corresponds to the striking of a bell, which forced the light, buried among the primal entities, to come out from stagnation.

According to contemporary astrophysical mythology, the early universe was so dense and torrid that photons remained glued to subatomic particles, together constituting acoustically modulating plasma. At a pivotal moment, the temperature dropped below 3,000° Kelvin, allowing the photons to decouple from electrons, protons and neutrons, which in turn assembled into the first atoms (hydrogen), marking the birth of matter. Meanwhile, the emancipated light journeyed across the universe as it expanded and cooled, comprising the Cosmic Microwave Background (CMB) that one may currently perceive by means of radiotelescopy or by the small level of noise it generates on one's television set.

When it was discovered in the 1960s, this cosmic noise floor was found to be remarkably uniform across the sky. It was not until 1992 that the Cosmic Background Explorer (COBE) satellite discovered thermo-acoustic ripples constituting an entire hundred-thousandth of the otherwise homogenous flow of faint microwaves. Thermal maps of the cosmic background radiation provide one with a cursory glance of the Universe before it flowered into a mosaic of reticulate inhomogeneities. The temperature wrinkles accountable for the new cosmography denote tiny density fluctuations during the particle evolution of the *prima materia.* These wrinkles were gradually magnified by gravitational attraction into familiar morphologies such as stars, galaxies and galactic clusters. "Gravity and sonic motion have worked together to raise the radiation temperature in the troughs and lower the temperature at the peaks [of the fundamental sound wave and its overtones]" [9].

Recent experiments, notably the Boomerang and Maxima projects [10], have revealed extremely sharp perturbations in the CMB, precisely indicative of

Fig. 5. *Camera Lucida* configuration: the sound composition is an 8-channel Max patch that is sent from a computer to a mixer and then to eight self-amplified loudspeakers and a multi-channel function generator, which modulates the humanly audible signal and sends it to two high-frequency amplifiers (frequency range: 9kHz–250kHz; output: 1500 W) that power 8 ultrasonic transducers. (Photo © Evelina Domnitch and Dmitry Gelfand)



the resonant acoustic phenomena long awaited by cosmologists. “The early universe is full of sound waves compressing and rarefying matter and light, much like sound waves compress and rarefy air inside a flute or trumpet,” said Boomerang team leader Paolo de Bernardis. “For the first time the new data show clearly the harmonics of these waves” [11].

Regardless of the contrasting methods used by cosmologists both now and in antiquity, the conclusions and allegories are surprisingly similar: sound is a creative and transformative impetus, responsible for shaping the evolution of matter/energy. It seems that the “elucidation” of the harmonic phenomena underlying sonic as well as electromagnetic vibration can unveil the mysteries enshrouding the birth of the universe.

Ocular Tuning

There are very ancient traditions scrutinizing the connections between light, sound and color. From Indian and Chinese to Egyptian resources, Pythagoras collected substantial data during his Eastern travels, uncovering the correlation between the musical octave and the spectrum of hues comprising the humanly visible portion of electromagnetic radiation. It was not until Isaac Newton, however, that the speculations of the Pythagorean school evolved into a pronounced theory. Newton proposed that the light spectrum is “proportional to the Seven Musical Tones [the diatonic scale] or Intervals of the eight Sounds” [12]. Historical evidence later arose alluding to the fact that it was his assistant, endowed with better eyesight, who identified the striations of the sunlight spectrum refracted by a prism, but it was certainly Newton who had instructed him to make seven divisions. As a result of this decision, most people today believe unthinkingly that the rainbow is composed of seven colors, called red, orange, yellow, green, blue, indigo and violet.

Soon thereafter, Newton distilled a far more subtle musical dimension of the spectrum. By pressing together two pieces of glass, one curved like a lens and one flat, forming a gap that enlarges with distance from the contact point, colored rings (“Newton’s Rings”) appear, due to the resultant light wave interference. When he calculated the spaces between rings—spaces on the order of a ten-thousandth of an inch—he found that they were proportioned as the cube roots of the squares of the Pythagorean string lengths that would have given the corresponding intervals. It was through this discovery that he later calculated the wavelengths of light.

Newton’s color research strongly inspired many artists and musicians—among the most exemplary of which was one of his contemporaries, Louis-Bertrand Castel, who spent 40 years of his life building a color-projecting harpsichord: “By moving the fingers as on an ordinary harpsichord, the movement of the keys makes the colors appear with their combinations and their chords” [13]. Several hundred years later, the advent of electrically harnessed light opened far more elaborate possibilities for color projection, such as Wallace Rimington’s Color Organ, which accompanied the 1915 New York premiere of Scriabin’s *Prometheus* symphony. Having notated precise color indications in the score, the composer held that each tonal mode corresponded to a particular shade of color and each modulation to a nuance of that shade. Scriabin requested that everyone in the audience wear white clothing so that the projected colors would reflect off their bodies and thus saturate the entire hall. In the 1920s and 1930s, the 18th century’s color intonators were majestically reborn in the hands of various artist/animators, such as Oskar Fischinger and Charles Dockum, whose MobilColor and Lumia had been created during the course of a rivalry between the Museum of Modern Art and the Guggenheim Museum to acquire the superlative light organ. In the 1950s and 1960s, the Kinetic Art movement gave rise to even more elaborate acousto-optic instruments. Much like the vast collective of their predecessors, however, the interpolation of sound into light was more often than not the result of arbitrary suppositions.

The Art of Science

> *After a certain high level of technical skill is achieved, science and art tend to coalesce in aesthetics, plasticity, and form. The greatest scientists are always artists as well.*
>
> —Albert Einstein [14]

The phenomenon in physics known as chaos represents the non-linear behavior of a system that is irregular and unpredictable but that is nonetheless governed by deterministic laws. The augmentation of the chaotic propensity of a system makes it ostensibly more difficult to study its laws. This is, however, a common scientific practice, because quite often, it is impossible to discern, let alone quantify, the constituent forces of a system without strategically increasing its instability. In order to fully embrace the forces composing sonoluminescence, we decided that the *Camera Lucida* must be constructed as a finely tunable musical instrument, and this could only be accomplished by introducing several new layers of instability to the sonochemical process. The first layer of instability arises from the modulation of an ultrasonic signal by an audible one. The second layer is a multi-channel, multi-directional resonating chamber (in contrast to the customary single channel, single transducer systems), permitting one to regulate the degrees of chaos (thus introducing an additional dimension of chance).

Although we may not yet be able to unveil the precise laws governing sonoluminescence, with the help of innovative technologies, one can interact with these laws and perhaps eventually elucidate the unforeseen workings of nature. “Despite all its success, there is still much that goes on in nature that seems more complex and sophisticated than anything technology has ever been able to produce” [15]. Technology and art need not strive to imitate nature, but instead to participate in its multifarious unfolding. Conceived as both a work of art/nature and a scientific research tool, the *Camera Lucida* project seeks to blur the discrepancy between such definitions of intent.

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16. "As ultrasound passes through a liquid, the expansion cycles exert negative pressure on the liquid, pulling the molecules away from one another. If the ultrasound is sufficiently intense, the expansion cycle can create cavities in the liquid. This will occur when the negative pressure exceeds the local tensile strength of the liquid, which varies according to the type and purity of liquid. (Tensile strength is the maximum stress that a material can withstand from a stretching load without tearing.) Normally, cavitation is a nucleated process; that is, it occurs at preexisting weak points in the liquid, such as gas-filled crevices in suspended particulate matter or transient microbubbles from prior cavitation events. Most liquids are sufficiently contaminated by small particles that cavitation can be readily initiated at moderate negative pressures. Once formed, small gas bubbles irradiated with ultrasound will absorb energy from the sound waves and grow. Cavity growth depends on the intensity of the sound." Suslick [4] pp. 140–141.

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Glossary

acoustic cavitation—the formation, growth and implosive collapse of bubbles in a liquid irradiated by ultrasound [16].

hot spot theory—postulates that the rapid compression of gas inside of a collapsing cavitation bubble results in a short-lived localized hot spot.

sonochemistry—the study of the chemical effects of acoustic cavitation.

sonoluminescence—light emission during the collapse of a cavitation bubble.

thermo-acoustic ripples—term used in contemporary cosmology to signify density fluctuations in the early universe. "As in the air, a small disturbance in gas density would have propagated as a sound wave, a train of slight compressions and rarefactions. The compressions heated the gas and the rarefactions cooled it, so any disturbance in the early universe resulted in a shifting pattern of temperature fluctuations" [17].

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Since 1998, Evelina Domnitch, born in Minsk, Belarus, and Dmitry Gelfand, born in St. Petersburg, Russia, have been collaboratively developing interdisciplinary artworks that integrate chemi-physical experimentation with optics and computer science. The primary impetus of their installations is the study of wave phenomena. Their works have been exhibited internationally.