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Sonoluminescence and the acoustic cavitation
ソノルミネセンスと音響キャビテーション

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1. Introduction

The irradiation of a liquid with a high-intensity ultrasound causes acoustic cavitation, i. e., the formation and oscillation of bubbles. Sonoluminescence (SL) originates from the high temperature and high pressure conditions resulted from the intense compression of gas and vapor within the collapsing bubbles. The acoustic cavitation and its application to sonochemistry have been studied since the famous work by Wood and Loomis in 1927 [1]. Frenkel and Schultes discovered a faint luminescence accompanied the fogging of a photographic plate immersed in a water bath which was subjected to a high intensity ultrasound [2]. The term "sonoluminescence" was named by Harvey [3], who explained that the luminescence was caused by electrical discharge at the collapse of charged bubbles. Several theories have been proposed for the mechanism explaining the SL emission, including the electrical microdischarge theory, the mechanochemical theory, the triboluminescent theory, the chemiluminescent theory, the hot spot theory, the shock wave theory, and so on. In the present stage, the hot spot theory is widely accepted. Due to the quasi-adiabatic process of bubble oscillation, high temperature and high pressure conditions inside the bubble are realized. These conditions produce ionization of rare-gas molecules, resulting in bremsstrahlung.

Dynamics of acoustic cavitation bubbles has been extensively investigated. Equations governing the spherical oscillation of a single bubble are the Rayleigh-Plesset equation. Acoustic field-bubble and bubble-bubble interactions are described by the primary and secondary Bjerknes forces. The intensity of multibubble SL (MBSL) is greatly affected by the bubble dynamics which depends on acoustic frequency and pressure. This review presents recent studies on MBSL in relation to bubble dynamics.

2. History of acoustic bubbles

Firstly, we consider a process from bubble generation to light emission. Bubble nuclei adhered to dust in a liquid or to a container wall, grow into small bubbles by the rectified diffusion of gas dissolved in the liquid under acoustic pressure. These bubbles are denoted as "growing bubbles" in Fig. 1. Some growing bubbles may dissolve in the liquid because of surface tension, and other bubbles may further grow into "collapsing bubbles," which oscillate violently. Note that "collapsing" does not necessarily mean bubble extinction. The collapsing bubble may cause nonspherical oscillation because of its strong nonlinearity. This leads to fragmentation into small daughter bubbles. The collapsing bubbles may cause each other to coalesce via the second Bjerknes force, and sometimes form a bubble cluster. The conditions inside the collapsing bubble are high temperature and high pressure, which may produce light emission and OH radical production through the decomposition of water molecules. OH radicals transfer through the liquid/bubble interface and interact with foreign molecules surrounding the bubble. Oscillations of the bubble wall produce pressure waves propagating in a liquid (acoustic emission). Most of the kinetic energy of the bubble oscillations is transformed into the energy of acoustic emission.

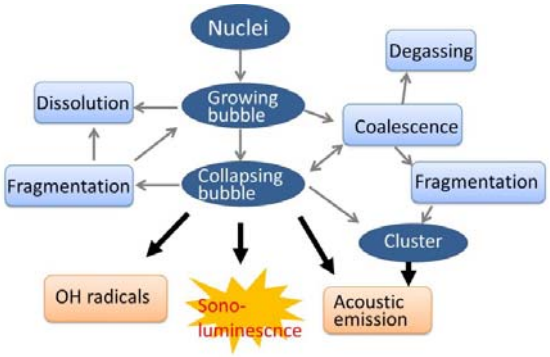

Fig. 1. History of acoustic bubbles

3. MBSL from alkali-metal salt solutions

SL from an aqueous solution of alkali-metal salt such as NaCl or KCl exhibits a line emission of alkali-metal atom. To realize Na emission of D lines at 589.0 and 589.6 nm, Na^+ ions dissolved in water must be reduced at some location. The site of Na emission has long been discussed. There are two possibilities of the origin: the gas phase inside the bubbles or the hot liquid phase at liquid/bubble interface. Sunartio et al. [4] directly compared the

spatial distribution of MBSL from aqueous solutions containing Na^+ with that of sonochemical luminescence from luminol solutions. From spatial similarities, they concluded that the Na emission come from sonochemically active bubbles, which differ from sonoluminescing bubbles. Choi et al. [5] suggested the gas phase origin on the basis of the result that the Na line broadened upon the addition of small amount of ethanol. Hayashi and Choi [6] observed the dissolved-gas dependence of K line shape, suggesting that K line includes two components. They estimated the temperature and pressure at the occurrence of K emission to be 3480 K and 585 atm, respectively. Figure 2 shows the spatial distribution and spectrum of SL from 4 M-NaCl solution at 145 kHz and the acoustic power of 15 W saturated with Kr. The spectrum exhibits continuum emission, OH radical emission at 310 nm, and Na emission that is asymmetrically broadened to the red side. A blue satellite peak at 558 nm accompanied the Na emission. The SL image clearly demonstrates the different distribution of the continuum and Na emission, indicating that both emissions come from different bubble population. The detailed studies showed that Na emission consists of a broad-linewidth component and narrow-linewidth component [7]. The broad component and blue satellite peak originate from van der Waals molecules composed of Na and rare gas. The narrow component was predicted to occur under temperature conditions at bubble collapse higher than that for the broad component.

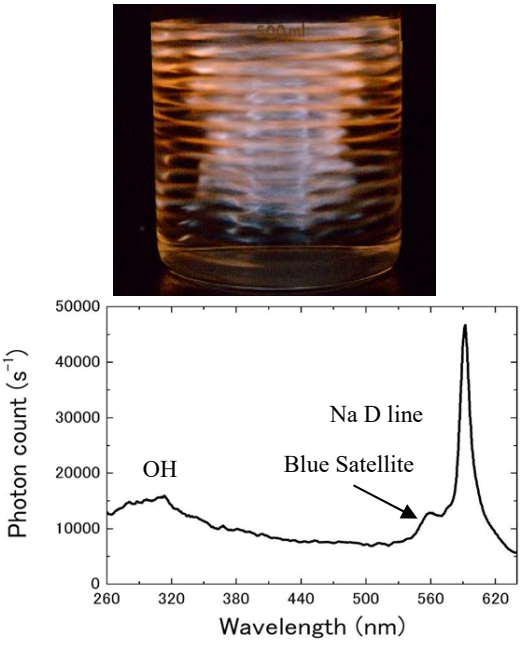

Fig.2. Sonoluminescence from 4 M-NaCl solution in a cylindrical container at 145 kHz and 15 W (upper), and its spectrum (lower).

4. Bubble dynamics

Sound field-bubble and bubble-bubble interactions give rise to various aspects of bubble dynamics according to acoustic frequency and pressure, which may affect the SL intensity. Figure 3 shows high-speed images of typical types of collective bubble dynamics. Figure 3(a) represents a bubble double layer (jelly fish), a kind of bubble cluster, which is frequently observed at around 30 kHz in a standing wave field. The bubble filaments, as shown in Fig. 3(b), form a kind of a web with a center located at the pressure antinode, which were captured at 82.4 kHz and 11 W. The bubbles in (b) translate in the direction denoted by arrows with repeating bubble coalescence and fragmentation. When the acoustic power was increased up to 20 W, bubble dynamics substantially changed to a cluster (cloud) as shown in Fig. 3(c) [8]. This cluster moves around with emitting large audible noise. The occurrence of bubble clusters causes a sudden reduction in the SL intensity.

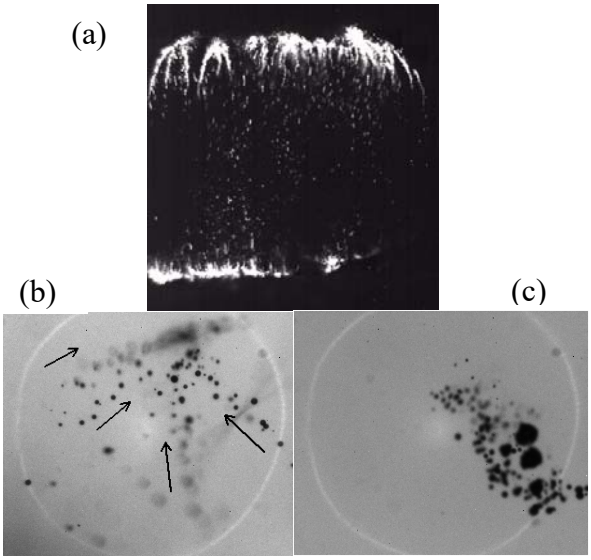

Fig.3. (a) Laser light scattering image of Bubble double layer observed at 25.7 kHz and 13W. (b) Shadowgraph of streaming bubbles at 82.4 kHz and 11W. (c) Shadowgraph of bubble cluster at 82.4 kHz and 20 W. Exposure time is 1 μs for (b) and (c)

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