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Two-component radiation model of the sonoluminescing bubble

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Based on the experimental data from Weninger, Putterman, and Barber, Phys. Rev. E **54**, R2205 (1996), we offer an alternative interpretation of their experimental results. A model of sonoluminescing bubble which demonstrates that the electromagnetic radiation originates from two sources: the isotropic black body or bremsstrahlung emitting core and dipole radiation-emitting shell of accelerated electrons driven by the liquid-bubble interface is outlined. [S1063-651X(97)50712-4]

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Theoretical explanation of sonoluminescence has been a long standing puzzle since 1934, when it was observed for the first time [1]. The most viable theoretical models of the phenomenon are based on the so called shock wave model [2], which clarifies certain characteristic features of the effect. However, this model is constrained by the assumption of the spherical symmetry of the bubble during all stages of its collapse.

However, recent pioneering experimental studies [3] convincingly showed the existence of an emission component with dipole angular distribution of intensity, which strongly suggests the presence of some kind of nonspherical dynamics of the bubble.

Angular dependence in the intensity of sonoluminescence can be described by the following correlation [3]:

$$\Delta Q_{AB}(\theta_{AB}) = \frac{1}{\overline{Q_A}\,\overline{Q_B}} \langle [Q_A(i) - \overline{Q_A}][Q_B(i) - \overline{Q_B}] \rangle_i, \quad (1)$$

where θ_{AB} is the angle formed by the photomultiplier tubes A and B and the bubble that is positioned at the vertex. $Q_A(i)$ is the total charge recorded in the detector A on the ith flash, $\overline{Q_A}$ is the running average of $Q_A(i)$, and $\langle\ \rangle_i$ denotes an average over i. Major experimental results obtained by the authors of Ref. [3] are as follows:

(i) Detection of two light emission components with isotropic and dipole angular distribution through the measurement of $\Delta Q_{AB}(\theta_{AB})$.

(ii) Finding of qualitatively different physical states of the sonoluminescing bubble in which the two emission components have a different share in total light intensity.

(iii) Measurement of intensity fluctuations in the different physical states of the sonoluminescing bubble.

(iv) Measurement of the correlation ΔQ_{AB} given by Eq. (1) as a function of time delay Δt between acquisitions in detectors A and B.

The authors of Ref. [3] interpreted their experimental results (the presence of the dipole emission component) as due to the refraction of light by the nonspherical bubble wall, i.e., liquid-bubble interface. Their major argument was that red light ($\lambda > 500$ nm) showed no angular correlation, whereas blue light (260 nm $< \lambda <$ 380 nm) was significantly correlated. This experimental fact was interpreted [3] as dominance of diffraction over refraction in the case of long wavelength (since the radius of bubble is about the same size as red light wavelength), and vice versa in the case of short wavelength (blue light). Below we show that these novel experimental facts can be explained in an alternative way and outline fundamentals of the two component model.

An explanation of the presence of the dipole component in terms of the light refraction from the nonspherical liquid-bubble interface [3] implies that the primary isotropic core emission comes from a point source that is more likely to be either the black body radiation coming from the contents of the bubble which was heated up by the implosion [4], or bremsstrahlung emitted from the air after it has been ionized by shock compression [2]. Furthermore, light from this point source is refracted from the nonspherical liquid-bubble interface, which results in a dipole angular distribution of the detected light [3]. However, it is reasonable to assume that the angularly correlated component primarily has a dipole origin itself. Preliminary numerical simulations showed that liquid-bubble interface achieves substantial accelerations at the final stages of the collapse. The measure of the latter physical quantity could be $\ddot{R}(t)$ (second derivative of the radius with respect to time) calculated from the Rayleigh-Plesset equation, which even in *adiabatic* calculation acquires values $\sim 10^{16}$ m/sec^2. A similar result yields a rougher estimate: $a \sim \Delta v/\Delta t \sim 2v/\Delta t$, where v is the maximal velocity acquired during the collapse (~ 5 km/sec) and Δt is the time scale of the radius turnaround ($\sim$ psec). The free electrons that come from ionization of the air will be easily dragged by the liquid-bubble interface since they have small inertia. One could safely assume that typical accelerations of the free electrons dragged by the liquid-bubble interface will be order of the $\ddot{R}(t)$. It is well known that accelerated, charged particles moving with nonrelativistic velocities (which is apparently the case for particles within the sonoluminescing bubble) emit dipole radiation. However, a *spherical* shell of electrons driven by liquid-bubble interface will not emit dipole radiation, since the dipole moment

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of such configuration is zero (unless the electrons are nonuniformly distributed on the interface, which is quite improbable). Previous experimental studies (involving light scattering techniques along with relevant Mie-scattering algorithms) suggest that the bubble remains spherically symmetric until the final stages of the collapse and only then (presumably on the psec time-scale) it becomes distorted by ''shape'' instabilities [4]. Therefore, at this very instance of time, dipole moment of the system suddenly becomes nonzero, thus allowing dipole radiation to take place.

It is important to note that the two component model in which the dipole component originates from the dipole emission of shell of electrons dragged by liquid-bubble interface is consistent with the experimental fact [3] that the red light has no angular correlation, whereas blue light shows significant angular correlation. It is known that the spectral resolution of the intensity of dipole radiation is given by [5]

$$dE_{\omega}=\frac{4\omega^4}{3c^3}|\mathbf{d}_{\omega}|^2\frac{d\omega}{2\pi}\propto\omega^4. \tag{2}$$

Therefore, since the intensity of the dipole radiation strongly depends on frequency [via Eq. (2)] for low frequencies (red light) intensity of dipole radiation is overwhelmed by the isotropic core (black body or bremsstrahlung) emission, whereas in the case of high frequencies (blue light) dipole radiation is more pronounced.

As we mentioned above yet another significant experimental result of Ref. [3] is the measurement of the angle dependent correlation ΔQ_{AB} (see Ref. [3] for details) as a function of a time delay Δt between acquisitions in photomultiplier tubes A and B. This data is important because it provides a clue to determining a source of dipole component. In particular, it has been shown [3] that angle dependent correlation $\Delta Q_{AB}(\Delta t)$ reveals a long time delay, which indicates that dipole component is due to the peculiarities of hydrodynamic motion. After excluding various possibilities the authors of Ref. [3] concluded that the most viable mechanism is refraction of light by a *nonspherical* liquid-bubble interface. Therefore, nonsphericity of the bubble plays a key role in their scenario. However, this argument would also perfectly fit our alternative interpertation of the experimental data, because this is the nonsphericity of the bubble that makes the dipole moment of the shell of electrons driven by the liquid-bubble interface nonzero, thus allowing the system to emit dipole radiation.

It is also important to address issue of the intensity fluctuations. In Ref. [3] it was established that sonoluminescent states where the dipole component dominates isotropic component exhibit very large fluctuations in emission intensity. Sonoluminescing states with fractions of dipole components of 6 parts per thousand peak to peak are characterized by intensity fluctuations that are over a factor of 10 greater than states with dipole components of about 1 part per thousand or less. A clue to the explanation of this effect could lay in nonsphericity of the bubble at the instance of light emission. A sonoluminescing state with high fraction of dipole component is achieved when there are large deviations from spherical shape of the bubble. Because of this process is chaotic (since it draws its orgin from some kind of hydrodymic instability) and the position of the photomultiplier tube is fixed this results in large fluctuations of intensity. This explanation is equally valid for the refraction model [3] and our two component model, since in both of them cause of dipole emission ultimately is nonsphericity of the bubble.

While mentioning the isotropic core emission above, we referred to the black body and bremsstrahlung radiation in an equal manner. However, as we shall see below, thanks to the discovery of the two different sonoluminescing states [3] with no (small) and dominant dipole components, futher experimental measurements of the sonoluminescing flash duration could discriminate between black body and bremsstrahlung emission mechanisms as well as between the refraction model [3] and our two component model. As it was emphasized in Ref. [4] black body radiation model predicts that the duration of the sonoluminescence light flash should be order of tens of nsec because the temperature of the contents of the bubble is order of 2000 K and larger for a time span over 20 nsec. On the other hand, detailed numerical simulations of the shock wave model based on the bremsstrahlung emission assumption confirms tens of psec duration flash [2]. The refraction model [3], which explains the presence of a dipole component in certain sonoluminescing states, apparently will never predict change in the duration of the light flash, since the light is simply refracted from a nonspherical liquid-bubble interface. However, in our two component model this is possible because the dipole component has a different origin, dipole radiation of the accelerated electrons driven by the liquid-bubble interface. A sonoluminescing state in which the dipole component is dominant and the core black body emission is assumed deserves particular attention, because in this case our two component model predicts different light flash duration. Dominance of the dipole component in our model means that the core isotropic component (black body radiation) has very low intensity and all detected light comes from the dipole radiation of shell of electrons driven by the liquid-bubble interface. As we mentioned above, dipole emission of such configuration is possible when the bubble loses spherical shape (when the dipole moment suddenly becomes nonzero), which happens at the very final stages of the collapse, presumably on the psec timescale. Apparently, in this case, the light refraction model [3] would still predict a tens of nsec duration flash since the primary (and the only) emission source is the isotropic black body radiation, and of course, refraction cannot change the duration of the light flash itself. The authors of Ref. [3] established both of the states [with no (small) and dominant dipole components] exhibit the same flash to flash synchronicity. However, they have not presented measurements for the duration of the light flash in both cases. This is important, because under the assumption of black body core emission it would allow one to discriminate between the refraction model and our model. In the case of the sonoluminescing state with no (small) dipole component, both models would predict the same duration of the light flash which would be order of tens of nsec, since in both cases emission comes from the isotropic black body source, which has a relatively large time scale [4]. Whereas, in the case of sonoluminescing state with dominant dipole component our model would predict short (tens of psec) light flashes and refraction model would still predict long (tens on nsec) flashes. On the other hand, assuming that isotropic core

TABLE I. Predicted durations and intensities of the sonoluminescing flash by the refraction and two component models under the assumption of the black body and bremsstrahlung core emission mechanisms, respectively.

Core emission	SL state	Dipole emission model	Flash duration	Flash intensity
Black body	no (small) dipole	refraction	tens of nsec	tens of mW
		two component	tens of nsec	tens of mW
	dominant dipole	refraction	tens of nsec	tens of mW
		two component	tens of psec	$\ll$ tens of mW
Bremsstralung	no (small) dipole	refraction	tens of psec	tens of mW
		two component	tens of psec	tens of mW
	dominant dipole	refraction	tens of psec	tens of mW
		two component	tens of psec	$\ll$ tens of mW

emission is of bremsstrahlung type, both the refraction [3] and two component model predict the same flash durations tens of psec. I ought to remark that in the literature the duration of light flash is claimed to be tens of psec. To the best knowledege of the author, the source reference for this information is Ref. [6]. However, awareness of the existence of the dipole component emerged from later experimental studies presented in Ref. [3]. Therefore, *a priori* it is unclear whether measured duration of the flash tens of psec [6] was for the state with the dominant dipole component or with the small one. To clarify this point further experimental studies are necessary.

Finally, we conclude with an estimate of the peak power of the sonoluminescence radiation based on the assumption that all the light comes from the dipole radiation of the shell of electrons dragged by the liquid-bubble interface (dominant dipole state). The typical value of the peak power is of the order of tens of mW [2,7]. We know that the total power of dipole radiation of a system of accelerated electrons emitted in every direction is [5]

$$I=\frac{2}{3c^3}\ddot{\mathbf{d}}^2, \tag{3}$$

where $\ddot{\mathbf{d}}\equiv\Sigma e\ddot{\mathbf{r}}$ denotes the second derivative of the total dipole moment with respect to time ($\mathbf{r}$ stands for a radius vector of a particular electron). Apparently, it is impossible to estimate I unless angular distribution and the acceleration of every electron on the nonspherical shell is known. However, let us assume that we have system of N electrons moving with plausible acceleration value $a\sim10^{16}$ m/sec^2 in the same direction (here we mention that there are models that propose the formation of a highly supersonic jet at the final stages of the collapse; see further Refs. [13,14] in Ref. [3]). To estimate N we can use the equation of state of a perfect gas $N=P_0V_0/(k_BT_0)=P_0 4\pi R_0^3/3/(k_BT_0)$, assuming full ionization at the final stage of the collapse. Putting plausible values for ambient radius $R_0=10$ μm, ambient pressure $P_0=1$ atm, and temperature $T_0=300$ K, we obtain $N\approx10^{11}$. This results in $I=2(eaN)^2/(3c^3)=6\times10^{-7}$ mW of peak power of sonoluminescing flash. We remark here that, say, $N=5\times10^{14}$ would yield a reasonable power output, tens of mW. This result could serve as a crucial test for our model. If further experimental studies will reveal that flash intensity in the sonoluminescing state with dominant dipole component is the same as in the case of dominant isotropic component, our model would be ruled out. That is, dipole (as opposed to refraction) radiation cannot appear in sonoluminescence, unless there is some other mechanism that could produce more accelerated electrons, such as the creation of free, accelerated electrons via ionization of ambient water molecules when they are hit by the jet. Because of this uncertainty, in principle, sonoluminescing flash intensities in the dominant dipole state predicted by our model cannot be regarded as sufficiently robust.

As it was argued above, present experimental data allows alternative interpretation. Therefore, it is important to perform new experimental measurements of the light flash duration and intensity in the two sonoluminescing states with dominant and no (small) dipole components in order to discriminate between the refraction model [3] and our two component model, as well as between black body and bremsstrahlung emission mechanisms. Table I, where we present anticipated durations and intensities of the sonoluminescing flash by the refraction [3] and our two component models under the assumption of the black body and bremsstrahlung core emission mechanisms, summarizes specific predictions of the models.

[1] H. Frenzel and H. Schultes, Z. Phys. Chem. Abt. B **27**, 421 (1934).
[2] C. C. Wu and P. H. Roberts, Phys. Rev. Lett. **70**, 3424 (1993).
[3] K. Weninger, S. J. Putterman, and B. P. Barber, Phys. Rev. E **54**, R2205 (1996).
[4] L. A. Crum, Phys. Today **47** (9), 22 (1994).
[5] L.D. Landau and E.M. Lifshitz, *The Classical Theory of Fields* (Pergamon Press, New York, 1975).
[6] B. P. Barber, R. Hiller, K. Arisaka, H. Fetterman, and S. J. Putterman, J. Acoust. Soc. Am. **91**, 3061 (1992).
[7] B. P. Barber, R. Hiller, R. Löfstedt, S. J. Putterman, and K. Weninger, Phys. Rep. **281**, 65 (1997).