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Acoustical Properties of Plankton

D. A. Selivanovsky(1), P. A. Stunzhas(2), I. N. Didenkulov(1)

(1) Institute of Applied Physics, 46 Ulyanov str., Nizhny Novgorod, 603600, Russia
e-mail: dimus@appl.sci-nnov.ru

(2) Shirshov's Institute of Oceanology, Moscow, 117851, Russia

Plankton is distributed in all oceans and seas, and therefore its acoustic properties can be essential for underwater acoustics. A sound scattering cross section of plankton can increase due to gas cavities associated with plankton cells. Such gas cavities has been found in many kinds of phyto- and zoo- plankton. The present paper gives results of investigation of plankton gas cavities with different methods. It was found in particular that sound velocity in phytoplankton suspensions varies both up and down compared to the sound velocity in pure water. A response of phyto- and zoo- plankton on compression and decompression is studied. It was found that species of euphausiids having long range vertical daily migration use bubbles (swimbladders) to control their buoyancy, while species living without long vertical migration do not have swimbladders.

1. Introduction

The acoustic significance of plankton was discussed many times. Having density and compressibility of the matter very closed to water small plankton cells can not influence strongly on sound. But it can be possible if one suggest that there are gas bubbles associated with cells. The existence in phytoplankton cells gas cavities was supposed earlier by Bogorov on the basis of general concept on vital activity [1]. This was also mentioned in [2] with the reference to R. Meister's data [3]. However direct observations of gas bubbles in phytoplankton are hardly possible. For example, sizes of gas vacuoles of alive cells may be less than resolution of an optical microscope, while in cells fixed for an electron microscope gas cavities may disappear for the preparation of the specimen. The ability of phytoplankton to cause dispersion of sound velocity was also discussed, but this phenomenon has not been investigated well so far. In this work detection of gas bubbles in marine phytoplankton is studied by various physical methods and sound velocity dispersion in plankton solutions is investigated.

Another interesting problem is the physical adaptation mechanisms and their acoustic consequences for phyto- and especially zooplankton in response to great pressure changes during vertical daily migrations. There are numerous mentions on the influence of changes of the pressure in the media on plankton [4-9]. Two aspects of this problem are of interest: changes of behaviour or state of objects and changes in their acoustical properties - scattering cross section. Usually an ability of plankton organisms to survive at high pressure is studied and used range of pressure is correspond to the maximum depths of immersion of plankton [10]. However, it is obvious that just near the surface of the ocean all organisms experience the most considerable relative changes of pressure during migration. Plankton organisms which have gas cavities may response on strong relative change of pressure in a specific way. In this paper results of acoustic backscattering measurements and observations of some plankton organisms under changing pressure are also described.

2. Gas cavities in phytoplankton

Experiments on diagnostics of gas cavities in phytoplankton were undertaken by measurements: (1) acoustic reverberation, (2) static compressibility, (3) excess of volume during alga bloom, (4) the dispersion of sound velocity in phytoplankton solution. Experiments were carried out in the laboratory with the collections of marine algae and also in situ in tropical Atlantic totally for 32 species of phytocells.

2.1. Experiments

1. Ultrasonic reverberation measurements were done simultaneously with the compressibility measurements. It was supposed that gas bubbles in phytoplankton cells remarkably increases the level of reverberation of the medium. Further, any changes in bubble size during compression/decompression produce corresponding changes of the reverberation level. The experimental setup consisted of a flask filled in with alga solution. Special 6.5 MHz sonar having pulse duration of 10 mcs was installed inside the flask. Sensitivity of the sonar allowed one to measure the volume backscattering coefficient of value above $5 \cdot 10^{-9}$ mm^{-1} [11]. Acoustic backscattering cross sections of cells were calculated from the coefficient of volume scattering and the concentration of cells.

2. Static compressibility was measured with the same flask and the reference one filled in with just water. It was considered that an excess of compressibility of algae solution compared to pure water is due to presence of gas cavities, and their volume change is inverse proportional to the pressure [12,13]. The volume of gas cavities was also calculated from the data. To eliminate possible error caused by photosynthesis oxygen output into water oxygen absorber - sodium sulphite in amount of 0.04 g/l was added.

3. Excess of volume of alga solution compared to the reference one taking into account photosynthesis reaction was measured. In the first approximation the reaction can be accounted as follows [14]:

$$CO_2 + H_2O \xrightarrow{h\nu} CH_2O + O_2$$

with corresponding molar volumes of reagents as

$$33.4 + 18 < 28.4 + 32 \text{ (cm}^3\text{/mole)}.$$

4. Dispersion of sound velocity may be expected for phytoplankton solution if alga cells contain gas cavities. It is known that sound velocity in bubbly liquids decreases below the bubble resonance frequency. In experiments sound velocity was measured at two distinctly different frequencies, *i.e.* 7.5 MHz and 0.75 MHz. It was supposed that resonance frequencies of phytoplankton cavities are inside this range, and therefore the ratio of sound velocities $\chi = c(7.5\,\text{Mhz})/c(0.75\,\text{MHz}) > 1$. Two sound velocity gauges working at these two frequencies allowed to make measurements with relative accuracy $\Delta c / c \approx 3 \cdot 10^{-6}$. The sensitivity of the method was enough to detect bubbles with the total void fraction of $\beta \approx 3 \cdot 10^{-10}$, that corresponds, for example, to bubble concentration of 100 ml^{-1} having radius of 1mcm. Measurements were made in monocultures of phytoplankton and in pure water. Some of measurements were done in situ from the ship. Simultaneously the temperature of medium was measured with the accuracy of $3 \cdot 10^{-3}$ °C. Also, the concentration of phytoplankton biomass was estimated through the synchronous measurements with a flow fluorimeter and with a sensors of dissolved oxygen [15]. However, experiments showed that the ratio χ can be both larger and lower than one. Hence, additional investigation of sound velocity dispersion was done by phase and the resonance methods in the frequency range 200Hz - 11 MHz [16-18]. In the phase method glass tubes with acoustic transducers at both ends were used. Sound velocity was estimated by measurements of frequencies, which produce the same phase at the receiving transducer as at the emitting one. In the resonance method resonance frequencies of alga solution in a vertical glass tube with a transducer at the bottom were measured. The relative accuracy of measurements was 10^{-5}.

2.2. Results

Investigations with the methods 1, 2, and 3 indicated that there are gas cavities in all examined species of phytoplankton cells [19].

Measured values of the backscattering cross section for different phytoplankton cells were found to be 1-2 orders larger compared to the theoretically estimated ones. Theoretical estimations were done with the Rayleigh formula for small scatterers [20]. The average density of cells was used to be about 1.1 of the water density and the compressibility is equal to that of water. The excess of scattering cross section can be explained by existing of gas bubbles associated with cells. The sizes of the gas vacuoles were evaluated on the assumption that they are free spherical gas bubbles, having the Q-factor $Q \approx 5$. It was found that under additional 0.1-0.5 atm compression the backscattering coefficient from some species of cells decreases drastically to values closed to theoretically estimated for cell without bubbles. Such a drop of the reverberation level is irreversible for *Platymonas viridis*, *Dunaliella salina*, *Phaeodactilum tricornutum* and some other algae. Their initial reverberation level was recovered after few hours and can be dropped again by a new compression. For other kinds of algae the scattering cross section was changed elastically up to pressure of +5 atm (*Prorocentrum micans*, *Peridinium triquetrum*, *Olisthodiscus luteus* and some others). Their scattering cross section recovered just after the compression was removed - the response which is similar to a free bubble.

Compressibility measurements also showed the existence of gas cavities in phytoplankton and their sizes were estimated. Two types of cavities were also found: with elastic and irreversible response to the external pressure.

Measurements of the excess of volume of blooming algae were done for a few days with each of phytoplankton solution to obtain as large as possible increase of volume, the concentration of cells, and the content of oxygen in solution.

Volumes of gas bubbles associated with cells of different kinds of algae estimated from all of these measurements are shown in the Table I.

Table I. Volumes of gas cavities in alga cells, measured by different methods.

Alga Species (Volume of Cells, mcm^3)	Volume of gas cavity (mcm^3)		
	Reverbe-ration method	Compres-sibility method	Volume excess method
P. micans ($1.4 \cdot 10^5$)	0.6-1.4	5000	100-600
P. triguetrum ($5 \cdot 10^4$)	0.4-0.7	5-10	7-100
O. lateus ($6 \cdot 10^2$)	0.2-0.5	300-700	10-60
P. viridis ($2.5 \cdot 10^2$)	0.04-0.4	10-40	3-15
D. salina ($1.5 \cdot 10^2$)	0.1-0.4	5-100	10-30
P. tricornutum (20)	0.01-0.06	2-10	2-8

Laboratory measurements of sound velocity in alga solutions revealed the anticipated effect only for one species, *i.e. D. salina*. In this case the ratio $\chi > 1$ and $\chi \to 1$ under compression. This effect obviously confirms the existence of gas cavities associated with *D. salina* cells.

However, in sea measurements it was found that χ can be both smaller and larger 1. It was also observed that sound velocity at both frequencies fluctuates but in average is larger that the sound velocity of pure water. The excess of sound speed was found to depend on the concentration of cells approximately as $\Delta c \sim n^{1/3}$. Measurements with the phase and the resonance methods showed complicated (broken) dependence of sound velocity in alga solutions on frequency. It was observed both increased and decreased sound velocities relatively to the sound speed in pure water at the same temperature. The maximum relative excess of sound velocity was about $\Delta c / c \sim 10^{-3}$.

3. Zooplankton buoyancy mechanism

The investigations of euphausiids were stimulated by the work of J. Mauchline [8], where the interesting peculiarity of migration of some of sound scattering layers was observed. It was shown that euphausiids decrease their vertical velocity as they approach to the ocean surface at night time migration. This feature evidently breaks the known data that at the time of twilight rising euphausiids follow for a certain level of underwater illumination [21]. The curve of rising velocity looks similar to the well known decompression rule for divers. This fact may be due to the necessity of the decompression of euphausiids in the layer where pressure drops relatively rapidly. In such a case one may suggest that euphausiids must use some volume of gas as their buoyancy mechanism and maybe for breathing. Therefore, our work was aimed to study adaptation of euphausiids to changing pressure.

3.1. Experiments

Observations of zooplankton objects were carried out visually and with a 6.5MHz sonar. Samples of zooplankton were put in the glass flask where the pressure can be changed with a compressed helium. The flask was a vertical glass cylinder of three litre volume and 450 mm height. Sonar antenna having directivity pattern of 5° was installed into the neck of the flask. The beam of the sonar was directed vertically down along the axis of the vessel. Experiments were carried in dark conditions, but for visual observations the flask was illuminated from the bottom by the narrow vertical beam of red light.

The observations of euphausiids were made at night time. They were caught by the locking net (total area - $0.5m^2$, cells - 750mcm) of their feeding at thermocline horizons (20-40m). Alive krill (crayfishers) of certain species were chosen and put by siphon into a flask where the pressure was increased up to that at the horizon of catching. During this procedure krill had no contact with air. One hour later the level of pressure was decreased to the atmosphere pressure. In some cases pressure was dropped rapidly, in others was decreased step by step for three stages. The duration of each stage was two-three times longer than the following stage. Behaviour of zooplankton was qualified by their "activity", which was quantitatively estimated by frequency of their appearing in the beam of sonar and the beam of red light source [22].

3.2. Results

Totally 12 experiments on compression-decompression of euphausiids were performed. Four species were studied: *E. gibboides*, *E. tenera*, *E. americana* and *E. pseudogibba*. The first three species have large range vertical daily migrations - up to 300-500 meters. Migration range of the latter one is very small compared to the first ones.

After being placed into the flask small crayfishers of the first three species were rather mobile under increased pressure, which corresponded to the pressure at the depth of their catching. They moved with velocities of about 0.3m/s. After the pressure drop to the normal value the crayfishers of the first three species were observed to have a shock: all of them concentrated on the bottom of the flask and were practically immovable for 20-45 minutes (the frequency of their appearance in the sound or the light beams decreased by 4-6 times). Then, the crayfishers became active again and concentrated in the upper part of the flask for the period from 45-70 minutes to 2-4 hours after the moment of decompression. Their mobility gradually decreased and after this period of time all of them were found died.

The crayfishers *E. pseudogibba* remained equally mobile during the pressure variation and remained alive. The crayfishers of the first three species remained also alive if these was no decompression or it was performed step by step. No changes of the scattering cross sections of crayfishes due to the pressure variations were measured.

4. Conclusions

Thus, investigation conducted with different methods obviously shows that phytoplankton cells contain gas cavities (vacuoles). In spite of the fairly large dispersion in volumes of the cavities, estimated by different methods (Table I) it can be seen that larger cells have larger vacuoles. But relative volumes of cavities compared to the volume of cells are larger for smaller cells. This suggests that to some extent, the main function of gas vacuoles is to maintain neutral buoyancy.

Results of investigation of zooplankton show that long-range vertically migrating species of euphausiids (*E. gibboides*, *E. tenera*, *E. americana*) can use gas bubbles (swimbladder) to control their buoyancy that is similar to fishes. No migrating species (*E. pseudogibba*) do not contain any swimbladders. The scattering cross sections of all of these species are derived mainly by mechanical properties of their bodies and are not essentially influenced by their swimbladders.

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