Background Light Measurements in the Deep Ocean.

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Summary. — Ambient light intensities in the ocean at depths between 1500 m and 4700 m near Hawaii Island were measured around the one photoelectron level with 5" diameter hemispherical photomultipliers. Measurements of count rates above variable thresholds were carried out in ship-suspended and bottom-tethered configurations. The ship-suspended rates show considerable fluctuation and their mean value decreases with depth approximately as $\exp[-x(m)/877]$. The bottom-tethered rates are about an order of magnitude lower than the ship-suspended rates and show little fluctuation. The calibration of our instrument indicates an absolute flux at 4700 m depth based on the bottom-tethered measurement of 218^{+20}_{-40} photons/cm$^2\cdot$s, which is consistent with calculated intensities due to β-decay electrons from ^{40}K. The difference in the two cases is attributed to bioluminescence due to environmental stimulation.

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1. – Introduction.

The deep ocean environment may be an excellent location for the study of high-energy cosmic-ray muons and neutrinos. Great depths provide a good shield against low-energy cosmic-ray muons, and the vast quantities of sea-water can supply sufficient target material to detect interactions of very-high-energy neutrinos. Actually, a very large deep underwater muon and neutrino detector (DUMAND) has been proposed (1) and intensive feasibility studies have been performed. In the DUMAND project, very-high-energy muons and neutrinos are detected via the Čerenkov light emitted from secondary particles produced in their interactions within the sea-water. However, even under deep ocean conditions there are some natural background light sources Čerenkov light generated by radio isotopes dissolved in sea-water (mainly ^{40}K) and bioluminescent light of ocean inhabitants are considered to be the main light sources. The former component can be estimated from the data of salinity of the sea-water and the energy loss of energetic electrons from ^{40}K, while little is known about the bioluminescence under deep ocean conditions.

Recently, BRADNER *et al.* measured the light intensity in deep ocean near Hawaii Island using a telemetering transient recorder (2). They observed stimulated bioluminescence in the wake of the instrument. At the same region we performed background light measurements using a variable-threshold sensor. We used two different deployments, a ship suspended and a bottom tethered, and we have compared these two sets of data.

2. – Apparatus.

The instrument is self-contained and powered by dry batteries. We used two 5″ ∅ hemispherical photomultipliers (PMTs) (Hamamatsu type *R*1391) mounted side by side in a glass housing of 17″ ∅ (Benthos deep sea glass sphere) as shown in fig. 1. The space between PMTs and glass wall is filled with a transparent silicon jell to provide good optical contact. The high-voltage power supplies and amplifiers for the PMTs are also mounted in the glass housing.

(1) The INTERNATIONAL DUMAND COLLABORATION: *Proposal to Construct a Deep-Ocean Laboratory for the Study of High-Energy Neutrino Astrophysics, Cosmic Rays and Neutrino Interaction, November 10, 1982.*

(2) H. BRADNER, M. BARTLETT, G. BLACKINTON, J. CLEM, J. LEARNED, A. LEWITUS, S. MATSUNO, D. O'CONNOR, C. ROOS, J. WATERS, M. WEBSTER and M. YARBROUGH: *Bioluminescent light profile in the deep ocean near Hawaii*, to be published in *Nature (London)*.

The output signals from the PMTs are transmitted through cables to the data-taking circuit contained in a separate metal housing. The cylindrical electronics housing is made of stainless steel and has an inner diameter of 87 mm and length of 850 mm.

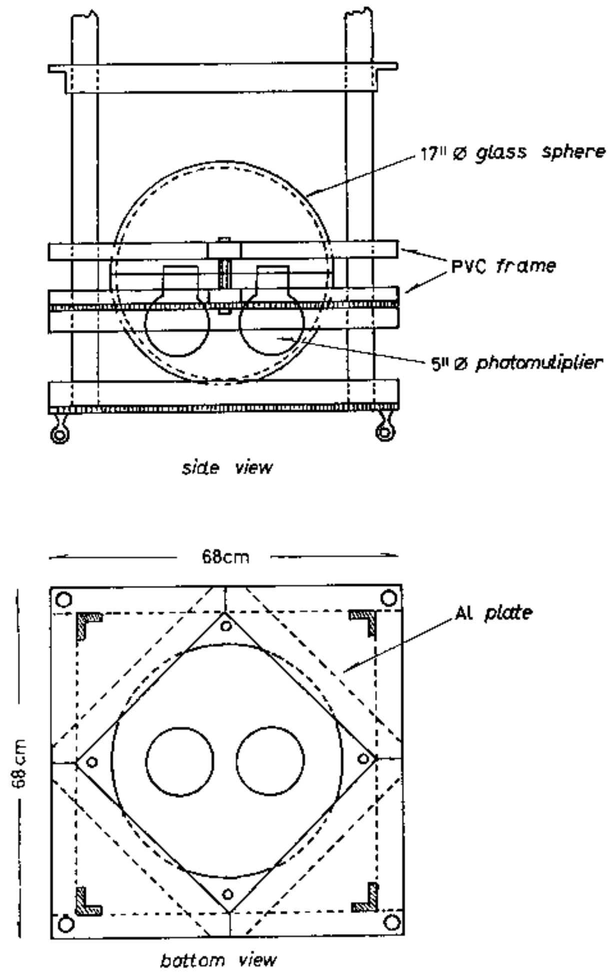

Fig. 1. – Construction of light sensor. Two 5" ⌀ photomultiplier tubes are mounted side by side in a deep sea glass sphere.

Figure 2 shows a schematic block-diagram of the data acquisition system. The output signals from the PMTs are differentiated with time constants of 0.24 μs and amplified with a gain of 100. The number of pulses exceeding a preset discriminator level is counted by a 16-bit counter. Signals coincident within 200 ns from the two PMTs are also counted. The discriminator level

TABLE I. – *Data-taking scheme* (initial wait time 32 min).

Channel number	Gate time (s)			Cycle number	Subtotal time (s)	Number of data
4	0.01	0.1	1.0	10	11.1	30
6						
7						
8						
9	0.02	0.2	1.0	10	12.2	30
10						
11						
12						
14	0.03	0.3	1.0	10	13.3	30
16						
18						
20						
22	0.05	1.0		10	10.5	20
24						
28						
32	0.1	2.0		5	10.5	10
36						
40						
44	0.2	3.0		5	16.5	10
48						
56	0.3	5.0		5	26.5	10
64						
100	10			5	50.0	5
				total	344.4	145

and the gate time are automatically changed under control of a microprocessor following a program stored in the ROM. There are 23 sampling steps of the discriminator level ranging from 32 mV to 800 mV, which cover the signal region from 1 to 10 photoelectrons. The gate time is selected for each threshold between 10 ms and 10 s in order to smooth out statistical fluctuations. One run consists of measurements repeated 10 times for low threshold and 5 times for higher threshold. The running time at a fixed depth is about 5.7 min. Table I shows details of the data taking program, where ch. 1 corresponds to 8 mV at the input of the discriminator. The program requires an initial wait time of 32 min before data taking to permit stabilization of the PMTs.

Electronics including PMTs are activated by a timer. The number of signal counts together with channel number and gate time are stored in a microcassette recorder and these data are analysed after recovery of the instrument. The memory capacity of the microcassette recorder is 25000 bits, which enables us to take 2500 data points in one experimental run.

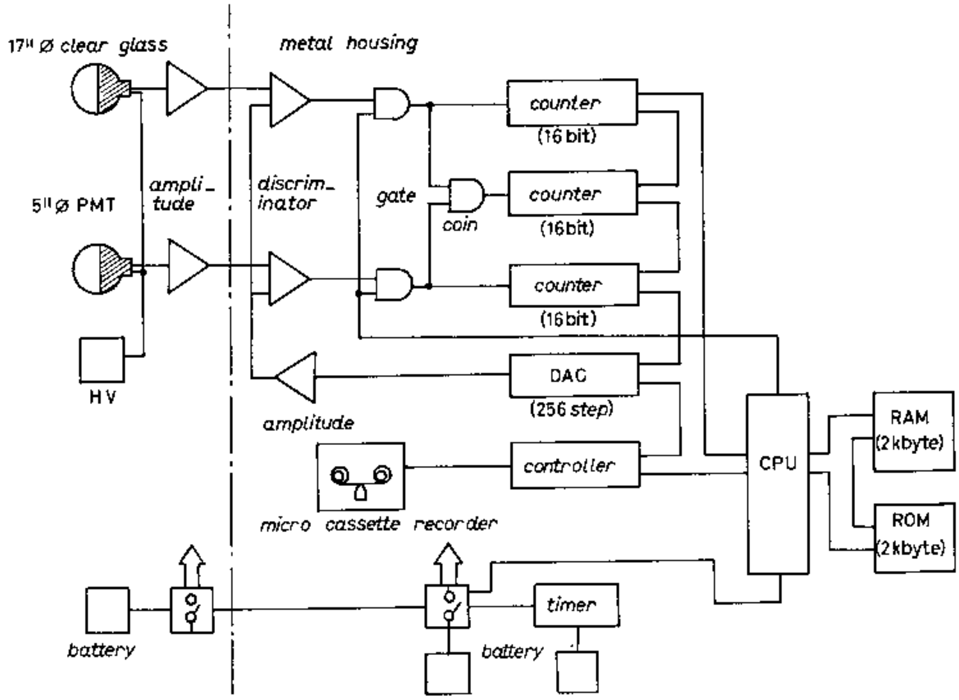

Fig. 2. – Block diagram of data-taking circuit.

3. – Results.

Measurements were done on a cruise with the University of Hawaii's research vessel Kana Keoki, August 24-26 1984 at the DUMAND site, 30 km off Keahole point of the Big Island of Hawaii. First, the instrument was lowered down to 4500 m at a speed of 30 m/min, suspended by a wire. After staying 45 min at 4500 m, the instrument was wound up with a rate of 50 m/min stopping every 1000 m. The data-taking scheme was programmed such that data were taken while stopping at the depth of 4500, 3500, 2500 and 1500 m. Next, the instrument was permitted to free fall to the sea floor of 4800 m depth. The sensor was mounted 100 m above the mooring which included timed and acoustically triggerable releases. Flotation was attached to the instrument package and a buoy with radio beacons and strobe lights was attached 50 m above. The data-taking program was the same as for the first case except for the fact that measurements were repeated four times at the same depth. Both the deployments were carried out at night. The sensor housing was always covered with a black cap, which was removed just after the sensor was lowered below the water surface.

In fig. 3 count rates *vs.* time interval of observation are plotted. The data

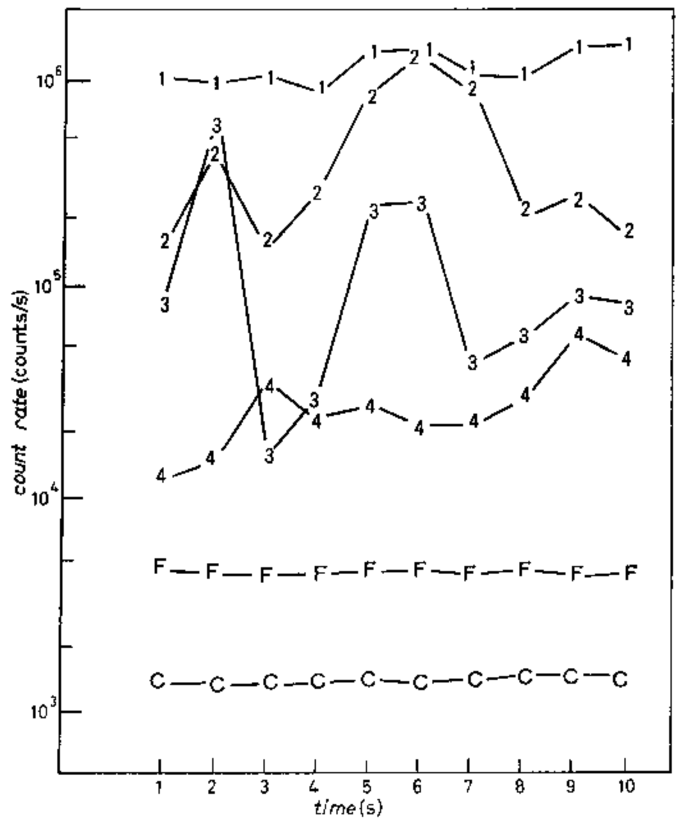

Fig. 3. – Time variation of count rate. Ship-suspended data at different depths and bottom-tethered data are shown together with laboratory rates at 3 °C. 1:1500 m; 2:2500 m; 3:3500 m; 4:4500 m; F: free fall; C: dark noise data at 3 °C.

is for PMT No. 1 and the threshold voltage is 320 mV. Data points marked 1, 2, 3 and 4 are for the ship-suspended case and each corresponds to count rates at the depth of 1500, 2500, 3500 and 4500 m, respectively. Data with mark F is for the bottom-tethered experiments. In fig. 3 we also plotted dark noise data, with mark C, measured in the laboratory at 3 °C. From fig. 3 we can see clear differences in count rates depending upon the methods of deployment. The ship-suspended rates change with time very much except for case 1, where count rates are too high to be fully resolved. In contrast, the bottom-tethered rates are comparatively stable and their absolute rates are about an order of magnitude lower than the ship-suspended ones. The data for PMT No. 2 shows almost the same behaviour as PMT No. 1.

Figure 4 shows the integral pulse height spectra observed by PMT No. 1. Symbols 1, 2, 3, 4, F and C are same as in fig. 3. The ship-suspended data fluctuate very much and show a complicated behavior, whereas the bottom-tethered spectrum is rather smooth. From fig. 4 we can see that the free-fall

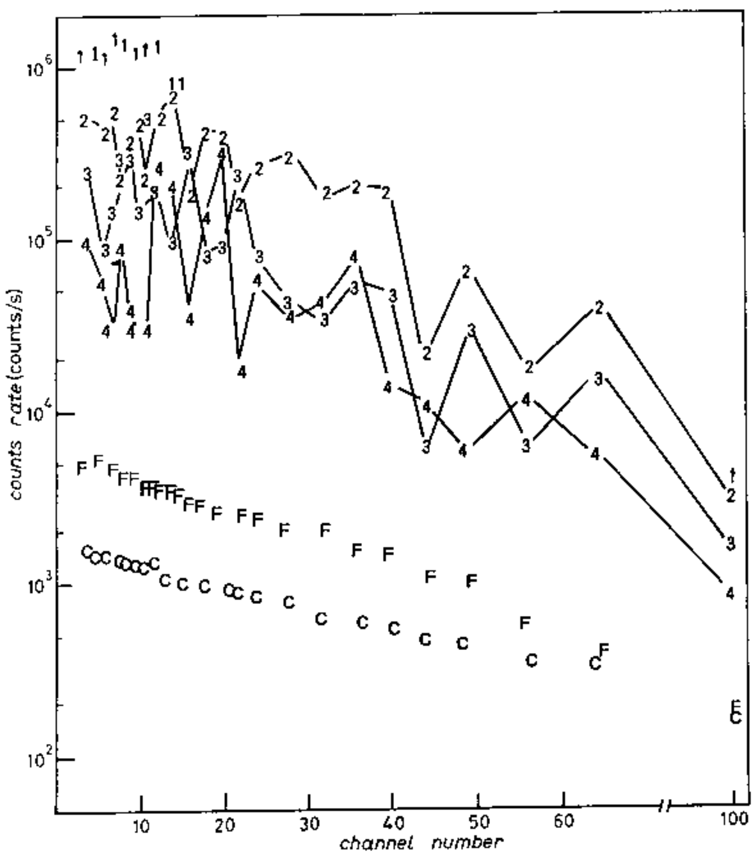

Fig. 4. – Pulse height spectrum of background light. Symbols 1, 2, 3, 4, F and C are the same as in fig. 3.

count rate (F) converges to that of laboratory rate (C) in the highest channels. This result indicates that signals of F come from very weak sources.

Though the time variation of the bottom-tethered rates are weak compared to the ship-suspended case, we do observe some time spikes in the bottom-tethered data. Such signals appear in both PMTs. Figure 5 shows examples of the time structure of the spike signals. It appears as if their time structure could be expressed by an exponential function with a time constant of $(0.3\div1.0)$ s. The observed frequencies and time structures seem to coincide with the expected signals (3) in deep quiescent ocean basins. In the case of the ship-suspended method, the signal rates are too high for any time structure analysis given such a long time constant.

(3) J. R. Losee: *Bioluminescence in the deep ocean*, in *Proceedings of the 1980 DUMAND Signal Processing Workshop* (1980), p. 9.

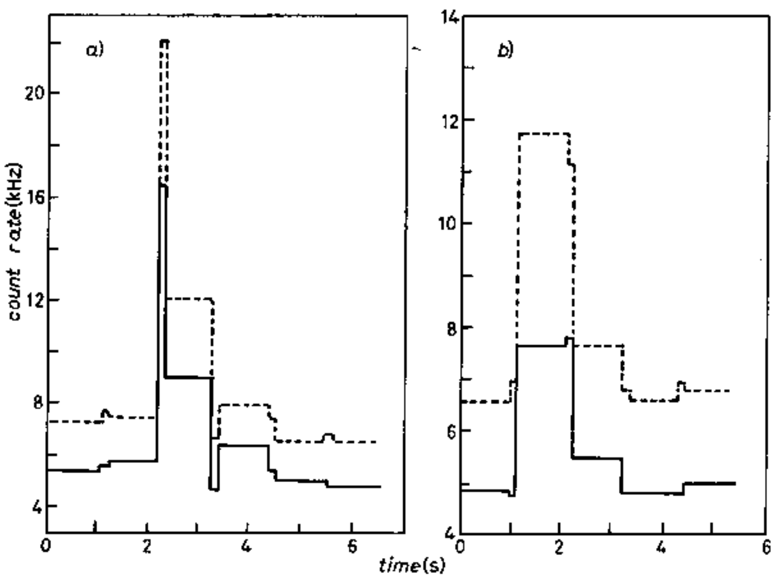

Fig. 5. – Examples of time structure of spike signals. Similar patterns are observed in individual photomultipliers. — — — PMT No. 2, ——— PMT No. 1. *a*) Channel 6, cycle No. 1; *b*) channel 6, cycle No. 4.

To estimate the absolute flux of the measured background light, we calibrated the detection power of our optical sensor ([4]). Using a large water tank and a calibrated photodiode, we found the following calibration constants for a discriminator threshold of 32 mV (ch. 4);

$$I \text{ (photons/cm}^2\cdot\text{s)} = \text{(count rate)}/17.4 \qquad \text{for PMT-1},$$

$$I \text{ (photons/cm}^2\cdot\text{s)} = \text{(count rate)}/28.8 \qquad \text{for PMT-2}.$$

Here, the averaged wave-length of the photon spectrum used in the calibration is 484 nm and its width is about 100 nm. (This spectrum roughly simulates that of Čerenkov radiation with the transparency of sea-water at the DUMAND site.)

The photon fluxes observed by the two PMTs No. 1 and No. 2 agree very well for all depths. Figure 6 shows the light intensity measured by the two PMTs *vs.* depth. Because the count rates of the ship-suspended case fluctuate largely, we plotted the median value in fig. 6. The light intensity curve can

([4]) T. Aoki, S. Matsuno, Y. Ohashi, A. Okada, B. O'Connor and M. Webster: *Calibration of a light sensor for background measurements in deep ocean*, ICR-Report-124-85-5.

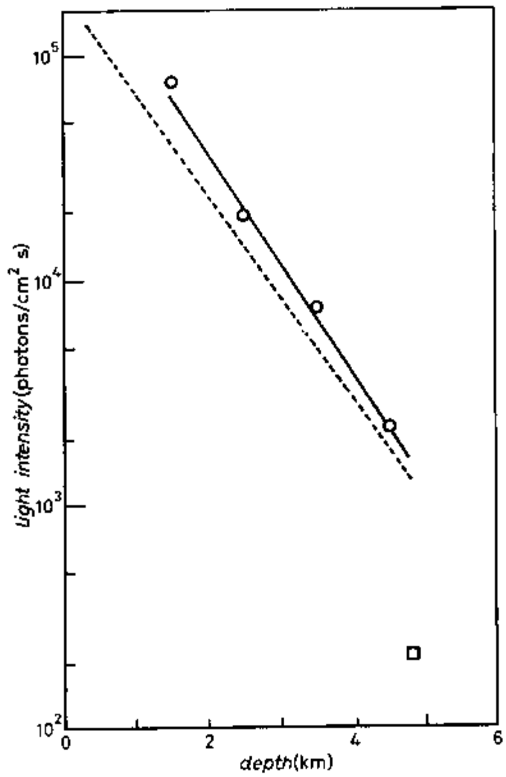

Fig. 6. – Background light flux *vs.* depth. The ship-suspended data (○) fit the solid line, which is expressed as $I = 3.72\cdot10^5 \exp[-x(m)/877]$ quanta/cm$^2\cdot$s. The dotted line indicates the result given by BRADNER *et al.* (2), for $I = 2.008\cdot10^5 \exp[-x(m)/960]$. □ free-fall present data.

be expressed as a function of depth x as

$$I = 3.72\cdot10^5 \exp[-x(m)/877] \text{ quanta/cm}^2\cdot\text{s},$$

which is quite similar to

$$I = 2.008\cdot10^5 \exp[-x(m)/960] \text{ quanta/cm}^2\cdot\text{s},$$

given by BRADNER *et al.* (2).

4. – Discussions.

What is the origin of the differences in data sets for the two deployments? There are several reports (2,3) on the observation of extensive bioluminescence in the deep ocean. The time dependence and depth dependence of our data also suggest it to be due to bioluminescence. It is well known that luminous species easily respond to physical or chemical stimulation. For the case of the ship-suspended runs, the environment of inhabitants can be agitated by the motion of the instrument. Though the winch operation was stopped while the measurements were taken, the ship motion was always transmitted to the instrument through the wire. Under these circumstances it is quite natural that the light intensity due to bioluminescence changes greatly with time. Further, it is known that the planktonic biomass y can be expressed by the equation $y = a \cdot \exp[-kx]$, where x is the depth ([5]). The coefficients a and k change from place to place depending upon the abundance of organisms in the productive surface layer. Our data on the depth dependence of the light intensity shows a similar behavior, which suggests that the photon flux data may reflect the amounts of organisms in the environment.

The mean value of the bottom-tethered flux is $218^{+20}_{-80}\,\text{cm}^{-2}\,\text{s}^{-1}$. For the bottom-tethered case, the stimulation of luminous species is very weak. The contribution of noticeable spike signals, which are considered to be due to such species, is only 6% of the total count rate. Several authors ([6,7]) have calculated the photon flux due to Čerenkov light emitted by β-decay electrons from ^{40}K. Their results scatter around 150 photons $\text{cm}^{-2}\,\text{s}^{-1}$. Considering the uncertainties of the energy loss process, light attenuation length and sensor detection efficiency assumed in the calculation, as well as the possible deviation of the wave-length spectrum used in our calibration from the true one, the expected value and our observed one are consistent with each other. Also, because Čerenkov light from individual ^{40}K decays is quite feeble (typically ~ 40 photons), this light will appear to the PMT as a single-photon source ([7]). Our analysis of the pulse height spectra shows that the bottom-tethered data does not contain large signals. From these results we conclude the main light source for the bottom tethered exposure is ^{40}K. The count rate stability with time similarly favours the above conclusion.

In summary, we have confirmed that there is a substantial amount of stimulable bioluminescence throughout the water column in an abyssal region West of Hawaii. The average intensity of the bioluminescence falls off exponentially with depth. We find, however, that a bottom-tethered instrument at 4.8 km depth sees light levels that are steady and largely attributable to ^{40}K decays.

([5]) M. E. Vinogradov: *Vertical Distribution of the Oceanic Zooplankton* (Wiener Bindery, Jerusalem, 1970).

([6]) A. Roberts: *Potassium 40 in the ocean, and how to live with it*, in *DUMAND 1978*, Vol. 1 (1978), p. 139; J. G. Learned: *Trigger rate considerations for the 1978 DUMAND summer study model array*, *DUMAND 1978*, Vol. 1 (1978), p. 147.

([7]) B. D. Geelhood: *Impact of ^{40}K on DUMAND Unwanted Light in the Ocean*, in *Proceedings of the 1980 DUMAND Signal Processing Workshop* (1982), p. 30.

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● RIASSUNTO (*)

Sono state misurate le intensità di luce ambiente nell'oceano a profondità tra 1500 m e 4700 m vicino alle isole Hawaii intorno al livello ad un fotoelettrone con fotomoltiplicatori emisferici di 5" di diametro. Sono state effettuate le misure delle frequenze di conteggio oltre alle soglie delle variabili in configurazioni appese alla nave e ancorate al fondo. Le frequenze delle configurazioni appese alla nave mostrano una fluttuazione considerevole e il loro valore medio decresce con la profondità come $\exp[-x(m)/877]$. Le frequenze delle configurazioni ancorate al fondo sono circa di un ordine di grandezza inferiore di quelle delle configurazioni appese alla nave e mostrano una piccola fluttuazione. La calibrazione del nostro strumento indica un flusso assoluto a 4700 m di profondità basato sulla misura delle configurazioni ancorate al fondo di 218^{+20}_{-80} fotoni/cm$^2\cdot$s, che è consistente con le intensità calcolate dovute al decadimento β degli elettroni da ^{40}K. Si attribuisce la differenza nei due casi alla bioluminescenza dovuta alla stimolazione ambientale.

(*) *Traduzione a cura della Redazione.*

Измерения фонового свечения в океане на больших глубинах.

Резюме (*). — Измеряются интенсивности свечения окружающей среды в океане на глубинах от 1500 м до 4700 м вблизи Гавайских островов с помощью 5-дюймовых полусферических фотоумножителей. Измерения скоростей счета выше изменяющихся порогов были проведены в случае подвешенном на корабле и в случае прикрепления ко дну. Интенсивности счета в подвешенном состоянии обнаруживают значительные флуктуации и их средняя величина уменьшается с глубиной приблизительно как $\exp[-x(m)/877]$. Интенсивности счета в случае прикрепления ко дну примерно на порядок меньше интенсивностей в подвешенном состоянии и обнаруживают малые флуктуации. Градуировка нашей аппаратуры дает на основе измерений в случае прикрепления ко дну величину абсолютного потока на глубине 4700 м, равную 218^{+20}_{-80} фотонов/см^{2}с, которая согласуется с вычисленными интенсивностями, обусловленными электронами β-распада от ^{40}K. Различия, обнаруженные в двух случаях, приписываются биолюминесценции, связанной с возбуждением окружающей среды.

(*) *Переведено редакцией.*