3. *Luminous Phenomena Accompanying Destructive Sea-Waves (Tunami).*

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(Read June 20, 1933.—Received Nov. 30, 1933.)

1. Introduction.

On the occasion of the destructive sea-waves (tunami) which devastated a number of towns and villages situated along the coast of Sanriku on 3 March, 1933, Mr. K. Musya of our Institute made an extensive study of the luminous phenomena which are reported to have been observed in many places at the time of invasion of sea-waves. Among the different kinds of phenomena classified by Musya[1] there is a certain class which seems to deserve a special notice, i.e., a strong flash of light which is reported to have been emitted from the sea surface at a region lying near the mouth of the Bay of Kamaisi, Rikuzen. The testimonies from a number of reliable independent witnesses who happened to be at different places widely apart from each other at that time, agree almost indisputably to the effect that the origin of the light was situated somewhere near the mouth of the bay above named. An observer at Hunakosi which is about 20 km. to the north of Kamaisi saw a flash in the direction of Kamaisi which Musya could identify with those observed by the nearer observers.

The flash observed seems to have been much alike that of search-light of a man-of-war seen from a distance, though the descriptions of the witnesses in this respect are generally vague as are always the case in similar occasions.

According to the result of investigation by Musya, fire-brand, lightning, electric short-circuiting of power transmission line and the like could be safely excluded from among the possible cause of the luminosity at this place. The possibility of the atmospheric electric discharge pointed out by the present author[2] as due to the electro-

1) K. Musya, p. 87 of this No. of the Bulletin.
2) T. Terada, *Bull. Earthq. Res. Inst.*, 9 (1931), 225.

capillary phenomena connected with the disturbance of subterranean water, cannot be referred to in the present case, as the luminosity observed is said to have had its origin at, or near the surface of the sea. Nor, another possibility pointed out by Prof. T. Shimizu[3] could be applied here, as no conspicuous fault or fissure could be found or expected in the neighbourhood of the region in question. Among the remaining alternatives, the most probable one seems to be the assumption that the luminosity might have been caused by some luminous planktons, as already suggested by Musya and others. The question is whether the luminosity due to such a microscopic organism can attain such an intensity that it may illuminate the lower atmosphere to a degree comparable with searchlight.

For the quantitative discussion of the problem thus introduced the necessary data are utterly wanting. Especially, want is felt of the reliable data regarding the intensity of light emitted by a single individual of planktons which might have been responsible to the flash observed and also of the data as to the density distribution of such a plankton in the sea at the time of the sea-waves. We may, however, attempt some estimation at least for the possible range of magnitudes involved in the problem and thus get an idea as to the possible order of magnitude attainable due to the supposed cause.

2. The intensity of light due to sea water laden with luminous planktons.

Suppose that the sea water is laden uniformly with a kind of plankton, say *Noctiluca miliaris*, with the density n per cm^3. Let the intensity of light emitted by a single plankton be c in C.P.

Instead of considering the extinction of light in the water, assume for simplicity's sake that the light from the layer with the depth ζ from the surface is transmitted to the surface with no sensible absorption, while the light from the layer below the depth ζ is completely absorbed. In the case of parallel beam of light this effective depth ζ is equal to the depth h_0 which appears in the extinction formula:

$$J = J_0 e^{-\frac{h}{h_0}}.$$

The loss at the emergence from the surface may be put out of account in the present problem.

3) Not yet published, but read before the Meeting of Physico-Math. Soc. Jap. and briefly described in Musya's book "地震に伴ふ發光現象の研究及資料".

If the length and breadth of a rectangular area of the sea laden with excited planktons be a and b respectively, the total intensity of this luminous parallelopipedon, considered as a simple source illuminating the atmospheric layer at a height comparable with a or b, may be considered to be given by

$$I = nc\,\zeta\,ab.$$

3. Density of planktons.

The density distribution of the plankton at the time of the event is utterly unknown. According to personal informations kindly given to the author by the members of Imperial Fisheries Institute, it is not quite seldom that a cubic metre of sea water contains above 10^5 *Noctiluca*, i.e. $n=10^{-1}$/cc. In some case, the surface water contains this organism to such a density that the planktons are practically in contact with the neighbouring individuals.[4] If the distance between the individuals in such occasion be 1 mm., then we have $n=10^3$. This latter will, however, be an over-estimation if we assume that such an extreme density prevails uniformly down to a depth of several metres and in an area of several km^2. On the other hand, as we are attempting to explain a

4) See Sir Wm. HERDMAN: Founder of Oceanography (1923), 214 and 235; an estimation after the description of this book may give $n>1000$ per cc! Also, see Sir John MURRAY and Johan HJORT: The Depth of the Ocean (1912), 68. In p. 338, footnote of the latter book, there is a quotation from Challenger Expedition Report, showing that *Noctiluca* is more richly contained in Colder Stream (prevalent in Sanriku coast) than in warmer current. Under normal circumstances, *Noctiluca* is not abundunt in March in this very district, but there is, according to Mr. Musya, some evidence which seems to show a possibility of an abnormal prosperity of this plankton at the time of the earthquake, and also that such an exceptional growth of the organism might have had some connection with the occurrence of the earthquake. An investigation is now being made by Musya in this respect. It may be cited here that Mr. Y. SUYEHIRO, *Dôbutugaku-Zassi* (Zoological Magazine), 45 (1933), 245, remarked some remarkable anomaly in the quantity as well as in the quality of the planktons found in stomachs of sardines (*Sardina melanosticta*, Temmink and Schlegel) caught on the eve of the earthquake of March 3, 1933, i e. on the evening of March 2, in the sea near Misaki which is about 600 km. distant from the origin of earthquake of March 3. He also reports that a rare specimen of fish, *Nemichtys avocetta*, Jordan and Gilbert, which is generally caught at a depth greater than 300 fathoms, was caught at the beach near Odawara in the morning of March 3. These facts suggest us that some kinds of disturbance of gentler character might have ocurred in the sea bed near Sagami, at some sensible time before the advent of earthquake at the sea bed several hundred km. to the north. These fact are well worth notice and make a further serious study of the allied phenomena highly desirable.

luminosity observed which was exceptionally conspicuous at a certain place compared with other places, it will be reasonable to assume some value of n which may be considered to be an upper limit. In this respect $n=1$ may scarcely be an over-estimation, even if we assume this value for a depth of several metres and for an extent of several square km.

4. Luminous intensity of a single plankton.

Data regarding the order of magnitude of the intensity due to a single *Noctiluca* could not be found. According to the personal opinion of some experts, the intensity seems to be somewhat weaker than that of a single "senkô" (a kind of incense stick used commonly by Buddists). The intensity of the latter was previously estimated by the author and his collaborator[5] at 4.10^{-7} in C.P. In absence of any further data, we may provisionally assume $c=10^{-7}$.

On the other hand, according to the experience of some members of Imperial Fisheries Institute, it was once observed on board the training ship Unyô-maru in some part of the Okhotsk Sea that the luminosity of the luminous planktons all about the ship was so strong that newspaper could be read with ease on board the ship by the sheer light of the sea. Taking this testimony as reliable, a rough estimation can be made of the luminosity of the sea laden with these organisms.

Assume for simplicity's sake that the unit area of the sea surface at A (Fig. 1) emits the light of which the illumination at P at a distance ρ, per unit area perpendicular to ρ, is $c' \cos\theta/\rho^2$ where c' is the intensity of the unit area at A as the source. The total intensity of illumination for a horizontal plane at P will be

$$\int_0^\infty \frac{c' 2\pi r \cos^2\theta dr}{\rho^2} = \pi c'.$$

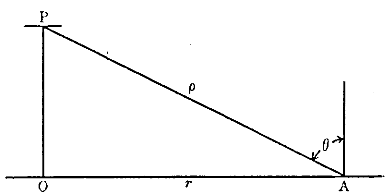

Fig. 1.

Since the extent of the luminous sea surface is limitted in actual case the above value must be multiplied by some factor less than unity. For the estimation of the order of magnitude this factor could be neglected.

On the other hand, our eyes well adapted to darkness are able to read newspaper at 1 m. from an ordinary candle, in which case the illumination is of the order of 10^{-4} C.P. at 1 cm. distance.

Experimenting with a number of "senkô," typographical units with

5) T. TERADA, *Bull. Earthq. Res. Inst.*, 9 (1931), 525.

the size commonly in use for scientific journals can be discerned at a distance of 1/2 cm. from a group of 10 senkôs, i.e. with the illumination $4.10^{-6}/(0.5)^2 = 1{\cdot}6.10^{-5}$ C.P. cm. Hence we may assume that the illumination of the newspaper on board Unyô-maru at the time in question as of this order and put $\pi c' = 10^{-5}$, i.e. $c' = 3.10^{-6}$. This is to be equated to $n\zeta c$ according to the definition previously given, so that

$$n\zeta c = c' = 3.10^{-6}.$$

If we take for instance $n = 0.1$ and $\zeta = 100$ cm., we have

$$c = 3.10^{-7},$$

which is just of the order of 1 senkô. This may, however, be considered as a kind of upper limit for the value of c when c means the actual candle power of a single organism. We must allow the possibility that c may be of the order of 10^{-8} as well.

5. Depth of the luminous layer of water.

The extinction coefficient of the sea water in the present case is also unknown. The value of h_0 in the formula

$$J = J_0 e^{-\frac{h}{h_0}}$$

is about 10 m. for the surface layer in the case of an example given in Krümmel's Ozeanographie, Vol. I (1907), p. 260 and 264. As, in the present case, we assume that the water is richly laden with planktons it will be plausible to assume h_0 somewhat less than the above example for Monaco. Thus, we take here $h_0 = 1$ m. or 100 cm.

6. Extent of luminous sea area.

As for the area of the sea surface excited to luminiscense we may be guided by the following considerations. Judging from the interval of time which is reported to have elapsed between the observation of the luminous flash at Kamaisi and the arrival of the sea-waves to the shore of the same place situated at the end of the bay, it may be assumed that the most intense flash was emitted when the front of the waves reached somewhere about the mouth of the bay. On entering the bay the bore-like character of the wave front will be enhanced and the turbulence of the surface water will be then and there made most violent, a condition which is favourable for exciting *Noctiluca* into a continuous and simultaneous luminosity. It is known[6] that the luminosity

6) Max VERWORN, Allgemeine Physiologie (Jena 1901), 405.

of a *Noctiluca* may be made continuous by an intermittent mechanical excitation and also that the luminosity thus excited gradually fades out.

The velocity of the waves may be assumed as 100 m/s. in the order of magnitude. If we assume that the luminosity may continue for 10 sec., then a strip of sea surface parallel to the wave front with a breadth of 1 km. will appear luminous, provided that this area is sufficiently laden with the planktons. Thus, we obtain for the breadth of the luminous area $b=1$ km.

On the other hand, the length a of this luminous area is naturally limitted by the breadth of the mouth of the bay. We may take for instance $a=5$ km. in the present case.

7. Total intensity of the luminous sea area.

The total candle power of the luminous sea area may now be calculated. Recapitulating the above estimations, we have

$$c=\alpha.10^{-7} \quad \text{where} \quad \alpha=1-0{\cdot}1,$$
$$\zeta=100\,\text{cm},$$
$$a=5\,\text{km, or } 5.10^5\,\text{cm},$$
$$b=1\,\text{km, or } 10^5\,\text{cm},$$
$$n=\beta/\text{cc}.$$

Thus for the total candle power, we obtain

$$C=nc\,\zeta\,ab=5\alpha\beta.10^5.$$

If $\alpha=1$ and $\beta=2$ we will have a million C.P.

Even if c be much less than here assumed, say $\alpha=0{\cdot}01$, it is not impossible that β may become 200, in which case the total intensity will be of the same magnitude.

According to a previous estimation, the full C.P. of a squadron may be regarded as 10^7 in the order of magnitude. The above result is therefore is of the order of a tenth or hundredth of this value. According to Dr. Y. Takenouti of Aeronautical Research Institute, who made some observations in this relation at the request of the author, the illumination of a single searchlight of a man-of-war situated near the mouth of the Bay of Tokyo may be clearly discerned from a distance of 35 km. from the ship, in a clear night.

It seems therefore of no wonder even if the light from the luminous planktons at the mouth of the Bay of Kamaisi might have been seen from a distance of some ten kms. from the spot, and it will be impossible that nobody could have taken notice of such a flash of light originating at a distance of only a few km.

For a more detailed discussion of the above problem it will be necessary to take account of the Tyndall effect of the atmosphere which could be made on the basis of Rayleigh's theory if we are provided with sufficient data as regards the extinction coefficient of the atmospher at the time of the event in question. We will refrain, however, to take a further step towards this direction, as we are here merely concerned with the demonstration of the possibility which may be realized under some favourable circumstances. It may happen that the lower atmosphere just above the sea surface laden with luminous planktons is rich in particles which scatters the light from below, while the atmosphere between the observer and the luminous spot is comparatively transparent. In such an extreme case, the Tyndall effect may rather enhance the effect of the luminous flash in the eyes of the observer.

It may be inquired why such a luminous flashes are not occasionally observed in ordinary days in absence of destructive sea-waves, if the coastal water of this region is frequented by such a swarm of luminous planktons. The question may be answered if we consider that the turbulent agitation of water due to the invasion of the bore-like front of the sea waves will be of exceptional violence which can never be attained by means of usual surface waves which are in the main of irrotational type of motion and, besides, affect merely the superficial layer of water in sensible degree. Thus, a *simultaneous* excitation of planktons over a wide area of sea surface may be expected only in a very rare occasion of violent sea-waves such as is here concerned. If the time interval during which a single individual emits light in ordinary occasion is $1/n$ of the period of intermittence of emission, where n is an integer,the integral effect of a swarm of such individuals will be $1/n$ of the effect obtained in the case of simultaneous emission which was estimated in the above. In the ordinary case, n is probably very large, say 100, 1000 or larger, whereas in the case of sea-waves n becomes 1 as already remarked.

Thus, we are dispensed with the necessity of making improbable assumption that the density of planktons happened to be unusually large just in the time of invasion of sea-waves.

In order to avoid misunderstanding it must be remarked that the above discussions were made merely to point out one of the possible cause which might have played some role in the luminous phenomenon observed. Though the above cause seems rather probable from various reasons which may be quoted from other quarters, we will attempt to enumerate other possible causes as well which might come into play under favourable conditions.

8. Possibility of electrical excitation of luminous planktons.

It is known[7] that *Noctiluca* may be electrically excited into luminiscence, though we are provided with no quantitative data as to the necessary magnitude of the electric current density in the water containing the planktons. In the present case there seems to be two causes which may give rise to an electric current in the sea water in the occasion of destructive sea waves.

(A) When the bore-like front of tsunami is in progress, the water just at the wave-front is set into translational motion of which the velocity may be compared with the wave velocity, since in this case the water at the front is rushing with the front itself. As this portion of water are moving in the terrestrial magnetic field, an electromotive force is induced in the direction perpendicular to the field. If we consider the vertical component of the magnitic field only, the e.m.f. is in the direction of the wave front, which holds in the special case when the waves are propagated in the direction of the magnetic meridian. We assume the latter case, as we are concerned here only with the estimation of the order of magnitude as usual.

If the vertical component be H_v and the velocity of water v then the e.m.f. is

$$E_1 = H_v v.$$

If the conductivity of the water be k, the current is

$$i_1 = H_v \, v \, k.$$

Putting $H_v = 0{\cdot}3$ gauss, $v = 100$ m/s or 10^4 cm/sec. and $k = 0{\cdot}03$ reciprocal ohm (for 35‰ salinity and 10°C.) we have

$$i_1 = 0{\cdot}09.10^{-5} \text{ amp., or approximately } 10^{-6} \text{ amp.}$$

Thus we may expect a current of about a micro-ampere per unit section of water.

(B) In a previous paper "On luminous phenomena accompanying earthquakes" the electromotive force was considered which may

7) MAX VERWORN, *loc. cit.*, 446.

arise due to the motion of subterranean water through rocky or earthy fissures under the gradient of hydrostatic pressure caused by earthquake. The rough estimation showed that a pressure difference of $p_0=3.10^{10}$ c.g.s. produces an e.m.f. $E_0=3{\cdot}3\,.\,10^6$ volts.

Referring to the annexed figure which schematically shows the profile of the front of a tunami, the pressure difference between C and D on the sea-bed is

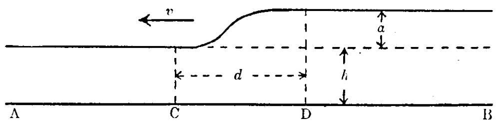

Fig. 2.

$$p=a\rho g,$$

where ρ is the density of water and g the gravity. The electromotive force E_2 between C and D will be given by

$$\frac{E_2}{E_0}=\frac{p}{p_0},$$

assuming the physical constants of the subterranean water to be equal to those in the previous paper. Taking the height of the wave $a=10$ m. and besides, $\rho=1$ and $g=10^3$ c.g.s. for rough estimation, we have $p=10^6$ and thus

$$E_2=1{\cdot}1\,.\,10^2 \text{ volts.}$$

The distribution of current density will depend on the configuration of the water mass as well as the distribution of conductivity in the ground. For a very rough estimation, however, we assume that the current flows uniformly in the portion of water with a depth h (Fig. 1) and the length d while the resistance of the ground is of a higher order of magnitude compared with the sea water. Even if the resistance of the ground be equal to that of the water, the resulting current will become half the value calculated by the above assumption. The actual maximum current will become somewhat greater than the uniform value obtained under the artificial assumption here made.

With the above assumption we obtain the total current I_2 taking the conductivity of water as k

$$I_2=\frac{Ehk}{d}.$$

Putting $h=30$ m. or 3.10^3 cm., $d=100$ m. or 10^4 cm. and $k=3.10^{-2}$ reciprocal ohm as before, we obtain finally for the total current through the water layer above considered. $I_2=0{\cdot}99$ or nearly 1 amp.

The current density

$$i_2 = 1{\cdot}1 \,.\, 10^2 \times 3.10^{-2}/10^4$$
$$= 3{\cdot}3 \,.\, 10^{-4} \text{ amp.}$$

Comparing the above two cases, (A) and (B), it will be seen that the latter alternative is more effective than the former under favourable conditions.

If the specific conductivity of some part of the body of the plankton be greater than that of the sea water, the current density may become large in that part especially when such a part be provided with a sharply pointed protuberance such as the tentacle or flagellum of *Noctiluca.* It is highly desirable that some of marine biologists will attempt a systematic investigation in these respects.

The above discussions are not made with the purpose of giving any definite answer to the question regarding the actual cause of the luminous phenomena which was observed at Kamaisi on March 3 of 1933, but merely with the purpose of pointing out a possibility which cannot be overlooked without a crucial study. It seems, however, that at least in some especially favourable circumstance some swarm of luminous plankton may give rise to a flash of light of the similar character as that which is reported to have been observed near Kamaisi at the time of tunami.

The main object of the present paper is to draw attention of seismologists, as well as of laymen in those districts where tunamis are of frequent occurrence, to this particular phenomenon which may be liable to be slighted and soon forgotten by scientists as trivial, or "incredible" according to their "common sense", which is a rather dangerous authority to be relied upon in such a case. On the other hand, if the reality of the phenomenon be established and the cause of the luminosity be elucidated, the flash of light may serve as a natural signal which may warn the inhabitants of the town at the end of the similar bay to take immediate flight before the arrival of the invading sea-waves which will arrive after a lapse of time nearly equal to one quarter of the natural period of oscillasion of the bay.

The best thanks of the author are due to Mr. K. Musya for the informations regarding the luminous phenomena, as well as to Messrs. Y. Suyehiro, H. Aikawa and M. Uda of the Imperial Fisheries Institute for the kind supply of the useful data and literatures regarding luminous planktons.

3. 津浪に伴ふ發光現象

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1933年3月3日の朝三陸沿岸を襲つた津浪に隨伴して種々の發光現象が觀察され，それに就ては詳細な武者金吉氏の調査の結果が本誌別項に報告される筈である．それ等の發光現象の中で，特に釜石灣口に近き海面から發せられたと思はるゝものに就きては，多數の目擊者の證言が大體に於て一致して居て，その實在性に關する疑が少ないやうである．然るに此の光は，電光，火災，送電線のショート，又山崩れの爲等によつて說明し難く，又地下裂罅の發生による放電や地下水移動による電位差に歸因する空中放電とも考へ難いので，殘る1つの可能性は發光プランクトンの群が津浪に因る海水擾亂の爲に一せいに刺戟されて同時に持續的發光をした爲ではないかといふことである．本篇はこの原因によつて凡そ如何なる程度の光を生じ得るかといふことを見積る爲に若干の假定に基いて概算した結果を述べたものである．その結果實際釜石で見られたやうな光がこの原因から生じても非常な不合理はないやうに思はれるのである．勿論當時さういふプランクトンの群が，その地方に居たといふ證據はないのであるが，他の可能性が考へられる迄は，この原因を1つの假說として提出することが出來るであらう．

尙，津浪の爲に海水が地球磁場內で動く爲に誘導される電流，又津浪による地下壓力傾度の爲に生ずる地下水移動に因る電動力と，これによる電流を概算し，プランクトンが此等電流により刺戟される可能性を論ずる際の參考として置いた．

津浪が灣口に到達したことを生物の發光によつて知ることが出來れば避難者の爲に1つの有效な信號として役立つであらうから，此種の現象の今後の研究は實用的見地からも決して閑却してはならないことゝ考へられる．