FURTHER STUDIES OF THE FIREFLY.

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UNDER the title "The Light of the Fire-fly"¹ the present writer, in conjunction with Dr. W. W. Coblentz, has described an investigation of the visible radiation of one variety of firefly (*Photinus Pyralis*). The chief difference between that investigation and preceding ones (for instance that of Professor Langley) lay in the application of photography with color-sensitive plates. By this means the difficulties imposed by the faint and intermittent character of the light were largely overcome. Measurements of energy distribution, practically impossible by visual means, were made, and the character and extent of the visible radiation were determined from photographic exposures which integrated the effect of the fire-fly's flashes during periods of several hours. The visible radiation was found to consist of a continuous band of yellow-green light extending from $.51\mu$ to $.67\mu$, with a maximum at $.57\mu$, the wave-length of maximum visual sensibility for high illuminations and likewise of maximum energy in the solar spectrum, as received through the atmosphere.

If this narrow band in the visible region of the spectrum constitutes the total radiation, it would appear that the fire-fly—as far as its radiated energy is concerned—is the most efficient of known illuminants. Its (radiant) efficiency was calculated to correspond to nearly fifty candles per watt, little short of what it would have been had the light been quite monochromatic of wave-length $.57\mu$.

The object of the present paper is to discuss more fully the grounds for believing the firefly's visible radiation to be its total radiation. Experiments in the infra-red and ultra-violet regions of the spectrum were recently made to investigate this important question and the results are here described.

¹Transactions of the Illuminating Engineering Society, October, 1909, p. 675. Also Bulletin of the Bureau of Standards, vol. 6, no. 3.

The only experiments heretofore made outside the visible region are those of Langley and Very, recorded in their memoir "The Cheapest Form of Light."¹ The bolometer measurements there described showed clearly the very small quantity of heat radiated by the insects, as compared with any artificial source, for a given quantity of light. These results are generally interpreted as showing that, aside from body heat, the visible radiation is the only radiation. Study of the paper referred to, however, shows that one possibility in the character of the radiation was not investigated, namely, that infra-red radiation of a quantity comparable with the visible may exist between the regions of visible and "body" radiation. In order that this deficiency in Langley's work may be clearly understood, his experiments will be briefly outlined, with his conclusions and with comments to indicate the reasons for believing a more conclusive test necessary.

It is first pointed out that there will be a certain amount of heat radiated, due to the body temperature of the insect. This heat, corresponding to a temperature below 50° C., will lie in the region of waves much longer than those ordinarily accompanying visible radiation in the production of light by high temperatures. This radiant heat will be distinguished from radiation other than body radiation by its inability to pass through glass, which is transparent to wave-lengths of less than 3μ . The body radiation may therefore be separated from that of shorter wave-length than 3μ by the interposition of a piece of glass. This obviates the necessity which would otherwise exist of forming a spectrum, with consequent great loss of light.

With the most sensitive bolometer at his command, Langley then made the following experiment. The radiation from an insect was allowed to fall on the bolometer surface. A small but real galvanometer deflection was obtained, representing the excess of total heat radiation from the insect over that from a metal plate at 25° C. used as the background. A sheet of glass was then interposed, *which cut off all the observed heat (i. e., there was no observed galvanometer deflection)*.

The next experiments were comparisons of the energy radiated

¹Smithsonian Miscel. Collections, no. 1258.

by the firefly and by a flame. A "nearly non-luminous Bunsen flame," much fainter than the insect, was compared with the latter. The total radiation from the insect gave one-fourth of a division deflection, the flame 177.5 divisions. The interposition of glass cut down the flame radiation to 14.5 divisions, still very much greater than the total radiation from the insect, for a smaller quantity of light. Subsequently measurable indications of insect radiation through the glass (shorter than 3μ) were obtained, and those showed that "flames whose intrinsic brilliancy is nearly comparable to that of a point below the middle of the candle flame, and whose total brilliancy is as exactly as possible comparable to that of the insect, give several hundred times the heat of the latter, even if we consider only that quality of heat which is found above 3μ ."

The point to which our particular attention should be directed here is this: In every case where the insect radiation above 3μ was allowed to fall upon the bolometer, *not only the infra-red but also the visible radiation was acting*. Hence, when the very small deflections were observed, the question was left entirely open as to whether they came from the visible radiation, or from some radiation between the limit of the visible spectrum (about $.75\mu$) and 3μ . The comparison with an equally luminous flame did not settle this question, for similar results would follow were there, for instance, a second emission band in the insect spectrum of equal strength between $.75\mu$ and 3μ . Data are lacking as to the exact energy distribution in this "nearly non-luminous flame," but it is quite safe to say that the energy in the infra-red region was so very much more than in the visible that the roughly qualitative measure of "several hundred times" would have applied equally well had there been firefly radiation of equal quantity to the visible, but lying between $.75\mu$ and 3μ . In other words, the test which was lacking was a measurement of the energy in the radiation from 3μ down, with and without a screen opaque to the *visible radiation*. Had there been marked deflection with the total radiation, measurable deflection with that from 3μ down, and none with the visible and that greater than 3μ eliminated, then the restriction of the radiation to the visible region and to body heat would have been

established. It should be noted that Langley did not specifically state the latter to be the case, his emphasis being laid more on the smallness of the heat radiation as compared with ordinary illuminants. In the diagram representing the firefly's radiation however, it is given as entirely in the visible region.

The firefly's actual efficiency as a light source is dependent to a large degree on the radiation being confined to the visible region. If there should be found infra-red of quantity comparable with the visible, the firefly, while still a very efficient source, would not be, as usually supposed, the example of an ideally efficient light produced by nature.

The chief interest in the study of the firefly lies perhaps in the possibility of producing light artificially by a similar process. The exact character of this light is therefore a matter of importance. It is important for us to know whether nature has produced merely a very efficient light or has produced the most efficient light possible. In the latter case we might conclude with some reason that a process of selection has been gone through and so that it is not beyond the realms of possibility that we may discover similar means of producing light, not so efficient, but more suitable to our use by virtue of the more pleasing color of the light obtained.

At the beginning of the present firefly season the writer did not have available facilities for repeating the very delicate bolometric work of Langley; therefore some other means of continuing the investigation was sought. In view of the extreme difficulty of making radiometric observations on the faint and intermittent light of the firefly, by far the best method for continuing the investigation of its radiation would be a photographic one, were such available. But the best color-sensitive plates at present known are sensitive only as far as the deep red. Another method which has been employed in the study of the infra-red spectrum occurred to the writer as a possible means of carrying the study of the firefly spectrum through part of the region between the visible and the body radiation. This is the phosphor-photographic method, employed by Draper, Lommel, Dahms and others. In brief, it consists of this: Phosphorescence, which is excited in various substance by exposure to short waves (blue, violet or ultra-violet),

is destroyed by exposure to longer waves (orange, red, infra-red). Thus, a surface of Balmain's paint or of Sidot blende, excited to phosphorescence and then exposed in a spectrograph, will have areas of reduced brightness wherever long wave energy has fallen upon it. If this surface is then laid on a photographic plate for a short period a permanent record is obtained on the plate after development.

In order to test the applicability of this method to the light of the firefly certain information had to be obtained as follows:

1. What phosphorescent substance combines the longest duration of phosphorescence with the greatest susceptibility to the extinguishing action of long waves?
2. What quantity of energy is necessary to produce extinction?
3. What is the spectral extent of this extinguishing action?
4. What is the relative response to extinguishing action in different parts of the spectrum?
5. What is the period after excitation during which extinction of phosphorescence is produced?
6. Is the extinguishing action integrative, *i. e.*, are a large number of short exposures (such as the flashes of the firefly) equivalent to a continuous exposure of the same total length?

The first question was answered by the choice of Sidot blende, phosphorescent zinc sulphide. This substance continues to glow sufficiently for photography for many hours after excitation, and exhibits the property of extinction by infra-red more strongly probably than any other known substance. A small quantity, prepared by Verneuil, was secured from Eimer and Amend and used throughout the investigation.

As to the quantity of energy necessary to produce the extinguishing action, no exact quantitative measurement was made. Such a measurement would have had no value without a knowledge of the quantity of energy radiated from the firefly. If, for instance, it were known that a ergs per second were radiated in the visible spectrum by the firefly, the problem would be to search for radiation of the same order of magnitude in the infra-red, and therefore a method to be applicable should be capable of detecting this quantity of energy. The visible radiation from the firefly being of

unknown quantity, this line of attack was not seriously considered. An idea of the high sensitiveness of the method was obtained from the rough observation that the light of an incandescent lamp through a ruby glass (absorbing the short waves which excite phosphorescence) at 10 cm. distance, sufficed to cause noticeable reduction of phosphorescence in a second.

The property of Sidot blende which made it suitable for this search for infra-red was learned upon the study of the spectral region in which extinction occurs. This region is not only in the infra-red but also in the visible, as far as the green. It follows then that the visible radiation of the insect should also extinguish phosphorescence. It was therefore thought that the test for the applicability of the method would be to determine whether the visible radiation of the firefly would cause reduction of phosphorescence. If so, then, provided the sensibility to extinction were of the same order of magnitude in the infra-red as in the visible, the method would be applicable. This led to investigation of questions 3 and 4.

The response to long-wave excitation has been found by Dahms and by Nichols and Merritt to extend from the green of the visible spectrum to 1.5μ . Part of the region in which we are interested would therefore be capable of investigation.

As to the relative response to extinguishing action in different parts of the spectrum, no suitable data were available. What is here required is the relative action at different wave-lengths for the same quantity of energy. The only quantitative determination of extinguishing action is that of Nichols and Merritt.¹ Using a Nernst glower as source, they took as a measure of extinguishing action the reciprocals of the relative times of decay of phosphorescence to a certain value with and without exposure to infra-red. Their measurements indicate a maximum of action in the infra-red of 1.3μ , with very slight action in the visible region and a minimum in the neighborhood of 1μ . As however the energy radiated by the Nernst glower is far greater in the infra-red than in the visible, the maximum of reducing action may be expected to lie to the shorter wave-length side of 1.3μ for an equal energy spectrum. In the absence of other data and of facilities for making a direct

¹PHYS. REV., Vol. 25, p. 380.

determination, it was decided to use the data of Nichols and Merritt, making a reduction to a normal spectrum from a knowledge of the energy distribution of the Nernst glower. The latter was obtained from a curve by Coblentz¹ which is for a glower near normal consumption, as the one used by Nichols and Merritt presumably was. A further correction was then made for the dispersion of the quartz prism which was used to form the spectrum of the Nernst. This was calculated from data given by Kayser.² The original curves (two different days) as given by Nichols and Merritt, and the reduced curves are given in Fig. 1 plotted to equality at $.7\mu$. No great accuracy can be claimed for the final curve, because of the indirect method of obtaining it. It shows however that the impression obtained from the original curves that the chief action is in the infra-red is apparently wrong, the real maximum of action lying at $.7\mu$ in the visible. The amount of action in the infra-red as far as 1.5μ appears however to be everywhere at least of the same order of magnitude as the action at $.57\mu$, the wave-length of the visible firefly radiation. If, therefore, reducing action could be obtained by the visible radiation, it would show that the method is available for detecting infra-red radiation down to 1.5μ .

Use of this data of Nichols and Merritt carries with it the assumption that their means of measuring sensibility to reducing action—by time of decay to a given value—is equivalent to a method

Fig. 1.

Extinguishing action of infra-red on the phosphorescence of sidot blende. I. Values obtained by Nichols and Merritt; II. Same corrected for energy distribution of Nernst glower; III. Further correction for prismatic dispersion.

¹Bulletin of Bureau of Standards, 4, p. 543.

²Handbuch der Spectroscopie, Vol. 4, p. 486.

measuring by quantities of energy. In other word, a small quantity of energy acting over a long period is equivalent to a large quantity over a short period. This assumption, which holds approximately for the photographic plate, was tested with a Sidot blende surface, by exposures of two, four and eight minutes in a quartz spectograph in which the slit openings for each exposure were inversely as the time of exposure. As nearly as could be judged, the photographed phosphorescence showed equal reducing action in all exposures. The use of the data as reduced appears therefore to be justified.

There is of course involved as well in using this data the assumption that the Sidot blendes used by Nichols and Merritt and in the present investigation are identical in their properties. This can be considered as probable, but could only be established by repeating their investigation.

The next question to be answered was the length of the period after excitation during which extinction of phosphorescence is produced. To test this a series of four holes was made in a metal plate, each hole covered with a photographic absorption screen of different density. A surface of Sidot blende, immediately after excitation by the light of a quartz mercury arc, was exposed for one minute through this plate to the radiation from an incandescent lamp with a ruby bulb at a distance of 25 cm. At intervals of one hour thereafter similar exposures were made on successively adjacent portions of the surface. After five such exposures the Sidot blende was left for an hour and then a photographic plate exposed upon it for two hours. This plate showed clearly that when the photographic exposure is made as long after excitation as six hours the extinguishing action due to infra-red exposure immediately after excitation is much less than that due to exposure after one hour, that the action is nearly uniform for about three hours, and that after three hours the effect again decreases. This was confirmed by further experiments. In order therefore to take the best advantage of the method, the Sidot blende should be excited some time before the exposure to infra-red, and the exposure to firefly light should not be continued (to advantage) longer than three hours.

The final question to be considered before actual work with fire-

flies was whether the phosphorescent Sidot blende acted toward a feeble and intermittent illumination as a photographic plate does; that is, will the action of the separate flashes be added? This is a question to be answered only by experiment, for it might well happen that a certain quantity of energy is necessary to start the extinguishing action, any quantity less than this having no effect. An artificial firefly was therefore constructed—a disc which could be rotated by a motor, the disc having a small opening near its circumference. A quartz spectrograph was set up and the slit and (incandescent lamp) light source adjusted to give by visual estimate about the intrinsic brightness of the firefly in the yellow. An exposure of two minutes was found sufficient to produce a reversed spectrum. The opening in the disc was then made 4° so that the exposure would be for one-ninetieth of the total time. Three hours of intermittent exposure through this disc would thus give a total exposure of two minutes. Such an exposure was therefore made, and on the same surface a continuous exposure of two minutes at the middle of the three-hour period. The resultant photograph showed as much action by the intermittent exposure as by the continuous one of the same total length, possibly more.

The result of these preliminary experiments was, therefore, to show the applicability of the method of phosphor-photography in detecting any firefly radiation down to 1.5μ , *provided* the visible radiation was strong enough to effect reversal. The method appears to be as suitable for firefly investigation in the infra-red as is the photographic method in the visible, granting that the conclusions hold which have been drawn as to relative sensibility to radiation of different wave-lengths.

The method having been tested, arrangements were made to try it on fireflies. This work had of necessity to be carried on in a more southern latitude than that of Cleveland, where the writer is situated, and where fireflies are small and scarce. The Physical Laboratory of the Johns Hopkins University was kindly placed at his disposal, and he spent several days there.

The first experiment consisted in exposing the phosphorescent surface (one-half hour after excitation) to the total light of the firefly. Two metal plates with 6 mm. diameter holes in their

centers were laid one over the other with a sheet of glass 1 mm. thick between. The lower plate was separated by a fraction of a millimeter from the Sidot blende.

An exposure of 20 minutes to the flashes of a single firefly was sufficient to produce observable reduction of phosphorescence. Exposure was discontinued after half an hour and a photograph was taken (Cramer Inst. Iso. plate) which showed with great clearness the reduction of the exposed area. This proved that sufficient energy was radiated by the firefly to render the method applicable. The time of exposure which sufficed showed too that the period of response to extinguishing action, about three hours, should be enough to detect a fractional part of the energy which produced the observed radiation.

The next experiment was to determine the location of this energy in the spectrum. A deep ruby glass, nearly opaque to the visible radiation but very transparent in infra-red, was substituted for the piece of clear glass. If the reduction of phosphorescence was caused chiefly or wholly by the visible radiation then there should be little or no reducing effect with the red glass. If on the contrary there is infra-red energy and if this is comparable in quantity to the visible radiation, reduction should occur even with the red glass.

Trial showed that an exposure of three hours and a half to firefly light through the red glass had no reducing effect that could be detected. Therefore it follows at once that there is no infra-red energy between 1.5μ and $.75\mu$ in quantity comparable with the visible radiation.

The visible and infra-red regions as far as 1.5μ having been covered by photography and phosphor-photography, attention was turned to another region of the spectrum, namely, the ultra-violet. The spectrogram obtained a year ago extended as far as $.38\mu$ and the shorter wave-length region was not investigated. Since then, however, R. W. Forsyth¹ reports finding ultra-violet radiation from luminescent bacteria, formerly considered as giving monochromatic green radiation. In view of this observation a search for short-wave energy in the radiation of the firefly seemed necessary.

¹Nature, 83, p. 7, 1910.

A small Fuess quartz spectrograph was employed, with Cramer spectrum plates. The dispersion in this instrument is such that the spectrum from $.6\mu$ to $.2\mu$ is about 4 cm. long, and with a quartz mercury arc photographic action is obtained as far as $.216\mu$. With a wide slit an exposure of an hour was made to firefly light. The resultant negative showed strong action at $.57\mu$, but no trace of action elsewhere. There is then no ultra-violet radiation of magnitude comparable with the visible.

These experiments therefore cover the spectrum from the extreme ultra-violet to the infra-red at 1.5μ . Between this point and the region opaque to glass lies an interval of 1.5μ , in which there may be radiated energy. It has been surmised that the outer skin of the insect is opaque to radiation of wave-length greater than 2μ and perhaps with the water contained to 1.5μ . Were this true it would follow that as far as the energy radiated from the insect is concerned the present investigation is sufficient to establish its restriction to the visible region and to "body heat." It was thought of interest to investigate the transmission of the abdominal horny skin of the firefly, and for this purpose a small piece of skin, about 1×3 mm. in size, was removed from an insect and laid upon a glass microscope slide. To the eye it appeared somewhat cloudy, but quite transparent in parts, of a pale yellow color by transmission. This was first investigated by the phosphor-photographic method, with a quartz spectrograph and found to be free from absorption bands, or noticeable difference in absorption as far as 1.5μ . Investigation was then continued with a bolometer. Needless to say, the bolometric sensibility requisite is far less than would be necessary for measuring the fireflies' light. A linear bolometer and mirror spectrometer furnished with a fluorite prism were available. With the assistance of Dr. C. F. Lorenz, the energy distribution from a Nernst glower, bare, the same through a piece of glass microscope slide, and finally the energy as transmitted by the piece of skin, mounted on the glass slide, were measured. The ratio of the last to the second set of values so obtained gave the transmission of the firefly's skin. Measurements were made both with the skin dry and with it wet. It proved in its natural thickness not to be opaque for waves longer than 1.5μ . On the contrary, the trans-

mission showed a gradual increase from the visible region to beyond 3μ , being for this piece about half as much again in the extreme infra-red as on the edge of the visible. This shows that there yet remains to be investigated the region from 1.5μ to 3μ .

At the conclusion of these experiments on the nature of firefly radiation, some experiments were made with a view to learning a little more about the process of light emission involved. Although these results were practically negative, they may be of some interest because they were carried out to test a different theory of the firefly light than those usually held.

The firefly radiation is commonly supposed to be produced by some chemical process, probably a slow oxidation, this process being largely under the control of the insect. On the other hand, true phosphorescent substances derive their light from some external source; they store up the energy, to reëmit after excitation has ceased. In view of the large amount of incident radiation and the small amount emitted, this process is probably very inefficient.

Some time ago in making experiments on the effect of heat on phosphorescent substances, the writer was struck with the similarity of the flash given out by heated Sidot blende to the flash of the firefly. If for example a small pile of Sidot blende is laid on a thin metal plate, excited, and allowed to decay to a dull glow, application of a Bunsen burner to the plate causes a vivid flash of phosphorescent light. This may be repeated several times. Might not the light of the firefly be true phosphorescence from a phosphorescent substance of slow decay, whose emission of light is stimulated by heat or oxygen, as is true of certain phosphorescent substances? In this case the emitted light would be stored-up solar energy absorbed during the day, and the process of light production would not necessarily be efficient at all.

It is true that this theory would call for a powerfully phosphorescent material, capable of storing up probably a larger quantity of energy than any known. Certain peculiarities of fireflies seemed nevertheless to fit in with this idea; such as the fact that they are most active shortly after sunset and that later they are apparently scarcer and less active. While no great confidence was felt in this theory, it was thought worth while to apply several of the charac-

teristic tests of phosphorescence to the firefly, such as the influence of ultra-violet and infra-red radiation, and confinement in the dark. Experiments of this particular kind have, with one exception, not previously been made, and might, if not confirming the theory, at least add to our knowledge of the firefly's light. The one exception is the influence of heat. Experiments are cited which show an increase of light emission in fireflies, glow-worms, and such creatures, when warmed. This is similar to the action of heat on true phosphorescence, but is as well what one would expect if heat acts merely as an irritant or stimulant.

As already stated, these experiments were practically negative. The only effect on the living insects of exposure to strong light (arc, Cooper-Hewitt mercury arc) was to cause them to entirely cease to glow for a few minutes after exposure and return to a dark room. Ordinarily, in the dark, there are two small spots which emit a dull glow continuously independent of the characteristic flashing. Exposure to strong light extinguished these, as well as causing the flashes to cease. After a short interval of waiting and upon vigorous shaking the insects again glowed and flashed. Their response to light would therefore indicate control and apparent appreciation on their part that their own light is unnecessary under these circumstances. Ultra-violet (from an iron arc) and infra-red radiation (carbon arc and ruby glass) produced no visible effect on the living insects.

Two batches of insects were placed in glass vessels, furnished with moist grass and leaves and covered with wire screen. One vessel was kept in a dark room for twenty-four hours, the other kept in a light room where sunlight fell upon it during the afternoon. In the evening both lots were examined. There appeared to be no difference in their behavior. Both were less active than freshly caught insects, but the ones confined in darkness responded to shaking quite as well as the ones which had enjoyed the daylight. There was, therefore, no indication that previous exposure to light is necessary to enable the firefly to emit light.

Finally some of the abdominal material was spread on a glass and different parts of it exposed to the light of a bare carbon arc, to the arc light through a deep red glass and through a cyan blue

glass. Long exposure failed to show the slightest effect. Apparently, therefore, the only effect on the luminescent material of exposure to light is to be found in the living insects. In these the light is discontinued by some voluntary process or nervous reflex.

The results of this further study of the firefly may be here summarized: The spectrum of the firefly radiation has been studied from the ultra-violet at $.2\mu$ to the infra-red at 1.5μ . Photography was employed for the ultra-violet and visible regions, the extinction of phosphorescence for the infra-red. The only radiation found is the band at $.57\mu$ previously investigated. Apparently none of the same order of magnitude exists elsewhere in the region studied. The abdominal skin of the insect being here shown to be transparent certainly as far as 3μ , there remains for investigation the interval from 1.5μ to 3μ , if we agree to call all beyond 3μ "body heat." That all beyond 3μ is merely low temperature radiation still of course lacks experimental proof. The light of the firefly has been investigated for the properties of true phosphorescence, and found to respond to none of the characteristic tests, such as dependence upon previous exposure to light or extinction by long waves. The light appears to be under the control of the insect.

In conclusion it may be remarked that obviously the most satisfactory method of studying the whole region between body heat and visible radiation would be by a method sensitive to the whole interval. Probably more sensitive bolometers than that of Langley may now be constructed, and the measurements in question made. The opportunity, however, presented itself to try out the phosphor-photographic method as a means of detecting very faint radiation. It has proved well suited to that purpose, and, possessing the valuable integrating property of the photographic plate, is perhaps better adapted, within its range of sensitiveness, to detecting faint radiation than any radiometric method. More confidence may be felt in its failure to give evidence of infra-red radiation than in the failure of the bolometer of Langley, since the latter was practically incapable of detecting the visible radiation to which the phosphor-photographic method is sensitive to nearly the same degree as to infra-red.

The results of the present investigation may be said to render

still more probable the belief that the firefly produces only visible radiation, of high efficiency. There is no evidence that the light is due to anything other than a true production of light by some bio-chemical process, which, as Langley remarks, "we know nothing to prevent our successfully imitating."

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