HEAT RAYS OF GREAT WAVE LENGTH.

BY HEINRICH RUBENS AND E. F. NICHOLS.

SINCE we have become accustomed to think of waves of electrical energy and light waves as forming component parts of a common spectrum, the attempt has often been made to extend our knowledge over the wide region which has separated the two phenomena, and to bring them closer together, either by cutting down the wave length of electrical oscillations — which, through the remarkable experiments of Righi[1] and later of Lebedew,[2] have been reduced to $\frac{1}{100}$ of the shortest waves measured by Hertz — or by the discovery and measurement of longer heat waves. In this direction no noticeable progress has been made since Langley's well-known experiments in 1886. On the contrary, since the determination of the dispersion of rock salt by Paschen[3] and one of the present writers,[4] it has been necessary to modify Langley's[5] estimate very considerably, so that the longest heat waves previously observed can scarcely have exceeded 0.015 mm., or about twenty-five times the wave length of sodium light. The farthest limit of exact measurement reached by Paschen,[6] in his determination of the dispersion of fluorite, was at 0.00943 mm., or approximately sixteen times the wave length of sodium light. The great difficulty which accompanies the study of infra-red waves of great wave length is that these rays form only the minutest part of the total energy emitted by the flame or incandescent body used as a source. Consequently, if their properties are to be studied, these waves must be separated from others which completely overlap and conceal them.

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[1] A. Righi, Rendiconti Acc. d. Lincei (5), 2, 505 (1893).
[2] P. N. Lebedew, Wied. Ann., 56, 1 (1895).
[3] F. Paschen, Wied. Ann., 53, 337 (1894).
[4] H. Rubens, Wied. Ann., 54, 476 (1895).
[5] S. P. Langley, Ann. de Chim. et de Phys. (6), 9, 433 (1886).
[6] F. Paschen, Wied. Ann., 53, 301 (1894).

To accomplish this end a prism of either rock salt or fluorite has commonly served.

The heat spectrum formed by a fluorite prism, because of absorption, contains no waves which exceed 0.01 mm. in length, while that from a rock-salt prism contains these waves and still longer ones in measurable quantity. That the diathermacy of this substance is by no means without limit, was conclusively shown by Gustav Magnus[1] twenty-six years ago, when he discovered that a rock-salt plate 5 mm. thick transmitted only about one-third of the energy emitted by a rock-salt crystal heated to a temperature of 150°.

The loss of energy due to the selective absorption of a prism is indeed avoided in the grating, but this escape is cumbered with disadvantages even more formidable; for not only are the diffraction spectra very weak in energy, but they overlap in such a way that it is almost impossible to separate them.

The new dispersion theories, however, suggest a method, by the use of which, unassisted by either prism or grating, homogeneous rays of great wave length may be obtained, and in sufficient quantity to make the determination of their properties and wave length possible. Helmholtz' dispersion theory, based on the laws of electromagnetic resonance, and that of Ketteler, based on the theory of elasticity, both lead to the same final equation which was shown in an earlier study by one of the present writers[2] to be in close agreement with the observed facts. In a region of the spectrum where there is little or no absorption, the formula common to both hypotheses is

$$n^2 = b^2 + \frac{M_1}{\lambda^2 - \lambda_1^2} - \frac{M_2}{\lambda_2^2 - \lambda^2},$$

in which n is the index of refraction corresponding to the wave length λ, and λ_1, λ_2, are wave lengths approximately in the middle of the two neighboring absorption bands, one in the ultra-violet and the other in the infra-red. b^2, M_1, and M_2 are other constants characteristic of the substance.

Theoretically, the absorption in the region of these two bands

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[1] G. Magnus, Pogg. Ann., 139, 445 (1870).

[2] H. Rubens, Wied. Ann., 53, 267 (1894), and Wied. Ann., 54, 476 (1895).

near λ_1 and λ_2 is very heavy, approaching the absorption of a metal for light rays; for a weaker absorption could not influence the dispersion. As absorption in this degree is necessarily accompanied by a metallic reflection, the wave lengths corresponding to the absorption band in any substance would appear magnified out of all due proportion in the spectrum of rays reflected from it. Suppose, for example, that within the region covered by the absorption band the reflection be twenty to thirty times as great as in other parts of the spectrum; as was shown by one of the present writers[1] to be the case in the reflection of quartz near wave length 0.0085 mm.; then in the spectrum of rays after three reflections from the substance, these waves would lose comparatively little in intensity, while the intensity of waves lying on either side would be brought down in the ratio of $(20)^3$ or $(30)^3$ to 1; *i.e.* as 8000 or 27000 to 1. If, further, a source of energy be chosen which emits these waves advantageously[2] — as will necessarily be the case if the body heated is of the same substance as the reflectors — the spectrum after three reflections will contain, in measurable quantity, only the wave lengths sought.

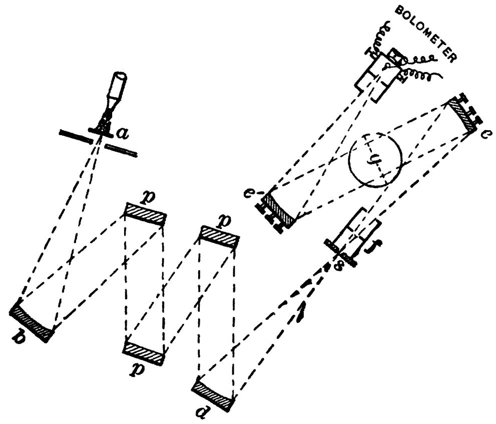

Fig. 1.

From the foregoing considerations the arrangement of apparatus shown in Fig. 1 will be easily understood. In the figure *a*,

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[1] E. F. Nichols, PHYSICAL REVIEW, Vol. IV. p. 297; Berichte d. Berl. Acad., Nov. 5, 1896.

[2] From "advantageously" it is not to be inferred that the greater part of the rays emitted by the source chosen shall correspond to the wave length of the absorption band, but rather that the emission of these rays in proportion to others shall be greater than from an ideal black body heated to the same temperature. In the case of glowing fluorite powder, for example, the wave lengths emitted which correspond to that region of absorption showing metallic reflection form only the smallest portion of the total energy. Still the ratio is larger than would be gained by using another powder in its place.

the source of energy, was a bit of platinum foil 15 × 15 mm., coated with the substance to be studied, and heated from behind by a blast lamp. A concave silver mirror at *b* reflected a bundle of parallel rays, which afterward underwent three successive reflections from the surface *p* of the substance in question. By means of the second concave silver mirror at *d*, the rays were brought to focus on the slit of a reflecting spectrometer. A transmission grating made of wires $\frac{1}{5}$ mm. thick could be placed at will on the spectrometer table at *g*, in the path of the rays, for the purpose of wave-length determination. To obtain a sufficiently sensitive bolometer, it was necessary to work with a galvanometer of the highest efficiency. As such the "Panzer Galvanometer," recently designed by Dr. du Bois and one of the present writers, gave most satisfactory results, and kept a very constant zero point, so that in spite of the magnetic disturbances occasioned by the Berlin street traffic, it was possible to recognize with certainty temperature differences of 0°.00001 of the exposed bolometer. The slit width chosen for experiments — equal to that of the bolometer — was 3.6 mm., which corresponded to an angular width of 0° 20′ on the spectrometer circle. The bolometer first tried consisted of thirteen strips of iron 0.25 mm. wide by 0.005 mm. thick, which, because of its large resistance and high temperature coefficient, had proved very sensitive in previous work. This instrument was replaced later by a platinum bolometer; for it was discovered that the layer of lampblack with which it was coated did not absorb more than about 5 per cent of the rays obtained from fluorite. The new instrument — supplied us through the kindness of President Kohlrausch — consisted of five strips of platinum $\frac{1}{2}$ mm. wide by 0.001 mm. thick, and was constructed in accordance with the design of Lummer and Kurlbaum.[1] The absorbing layer was in this case a coating of platinum black, deposited electrolytically. This instrument, although less sensitive for waves of shorter wave length, gave deflections twice as large as the earlier one for the long rays resulting from three reflections on fluorite. It thus appears that platinum black possesses an absorption covering a much wider region than lampblack, which fact has been shown

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[1] O. Lummer and F. Kurlbaum, Wied. Ann., 46, 204 (1892).

in a different way by the experiments of Lummer and Kurlbaum.

By the foregoing method, the two substances quartz and fluorite have already been studied. For both of these substances the constants in the Ketteler-Helmholz equation had been computed from direct observations of refractive indices, pushed as far into the infra-red as the absorption in each case permitted. From Paschen's[1] computation for fluorite, the middle of the infra-red absorption band was predicted at wave length 0.03 mm. Similar computation, by one of the present writers,[2] placed the band in quartz at wave length 0.01 mm. The peculiar relation of these constants to the remaining quantities which enter into the equation renders the correct placing of such a band somewhat uncertain; for, although its existence influences the dispersion in the observed region markedly, its exact position plays a comparatively minor rôle. From the theory, therefore, after three reflections from quartz, or from fluorite, only rays in the neighborhood of either 0.01 mm. or 0.03 mm. wave length should remain, and the

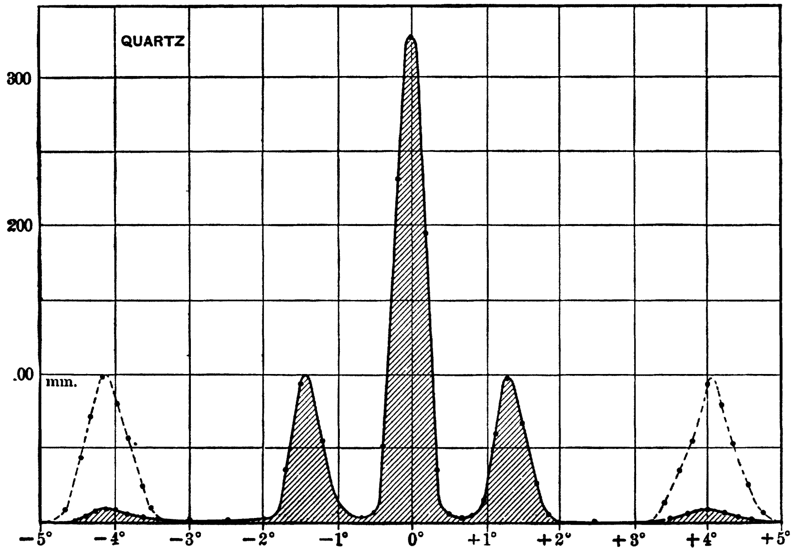

Fig. 2.

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[1] F. Paschen, Wied. Ann., 53, 812 (1894).

[2] H. Rubens, *l.c.*

experiments have proved, in the main, the correctness of the reasoning.

In Figs. 2 and 3, two series of observations, one on fluorite and the other on quartz, are shown graphically. The ordinates give the galvanometer deflections, and the abscissæ the corresponding readings of the circle of the spectrometer, which characterize the position of the bolometer in the spectrum.[1] In both figures, the central image stands out plainly, and symmetrically on either hand the diffraction images of the first order. In the case of quartz, the images of the third order are also easily recognized.[2] The grating constant, which was unusually large, was optically determined by the position of the diffraction images of the sodium line out to the image of the twenty-third order, which gave a constant 0.37165 mm. Measured on the dividing engine, the constant was 0.37167 mm.; 1° deviation, therefore, indicated a wave length of 0.0065 mm. approximately.

Experiment with Quartz.

The three reflecting surfaces in this case were from two prisms and a plate, all cut perpendicular to the optic axis of the crystal. The deviation of the maximum point of the diffraction image of the first order from the middle of the central image was 1° 22′, and that of the third order 4° 6′. The mean wave length of the observed rays thus computed gave in the one case 0.00887 mm., in the other 0.00882 mm. The agreement between the two values lies wholly within the probable error, and furnishes, at the same time, a valuable check upon the accuracy of the grating to a deviation of 4°.

In consequence of the wide slit and the equally wide bolometer used, it is impossible to draw conclusions concerning the distribution of energy in the diffraction image itself; but the fact that

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[1] In Fig. 3, which gives graphically the series of observations made with fluorite, the scale of ordinates chosen is ten times as great as that in Fig. 2, which shows a similar series with quartz.

[2] In order to show more plainly the position of the maxima in the spectra of the third order, the ordinates corresponding to the galvanometer deflections were multiplied by ten, which gave rise to the dotted-line curves. Because of the peculiar construction of the grating, the spectra of the 2d, 4th, 6th, ... orders are wanting.

the image of the third order appears little or no wider than that of the first, shows that the rays must be fairly homogeneous, and can scarcely comprise a wave-length difference greater than 10 per cent. Using a bit of platinum foil coated with iron oxide at a temperature of about 1000° as a source, it was easy with the arrangement of apparatus described to effect a heating of the bolometer of 0°.02, which corresponded to a deflection of about 2 m. The properties of rays of equal wave length have long been known, as it is possible to obtain them in measurable intensity in the spectrum of a rock-salt, or even fluorite, prism.

Experiment with Fluorite.

The rays emitted by an incandescent platinum foil coated with fluorite powder after three reflections from fluorite retain scarcely more than 0.001 of their initial energy.

This remnant, when undispersed, was capable of raising the bolometer temperature about $\frac{1}{800}^{\circ}$ (120 mm. deflection), and the greatest patience and care were necessary, with this small quantity of energy, to establish the exact position of the maxima in the images of the first order lying on either side of the center.

In Fig. 3, which represents one of the several series of observations for this purpose, it is seen that the maximum energy in the diffraction spectrum of the first order lies 3° 45′ from the middle of the central image, which corresponds to a wave length of 0.0244 mm. The mean wave length resulting from other series varied from 0.024 mm. to 0.025 mm.

Heat rays of $\frac{1}{40}$ mm. wave length show in many respects quite different properties from those previously studied, which lie much nearer the visible spectrum. They are, for example, completely absorbed by a fluorite plate 2 mm. thick. A rock-salt plate 5 mm. thick lets through only about 3 per cent and an equally thick silvite plate about 5 per cent. In fact, after considerable searching we have not yet succeeded in finding a substance as diathermous for these rays as fluorite is for infra-red rays to a wave length of 0.007 mm.

The least absorbent substance so far discovered is vitreous chloride of silver in the form of thin plates, which Schultze-Sellack,[1] in the year 1870, showed to be more and more diathermous the greater the wave length of the incident rays. A plate of chloride of silver 0.5 mm. transmitted about 70 per cent of the incident rays, while a plate 2½ mm. thick absorbed 75 per cent of the remaining energy.

To study the optical behavior of lampblack in this region, a plate of chloride of silver, the absorption of which had been earlier determined, was blackened in the smoke of a candle until it was completely opaque to the sun's rays, and the absorption again measured, with the surprising result that the increase did not exceed 5 per cent, which shows that lampblack cannot be considered a black body for these rays.

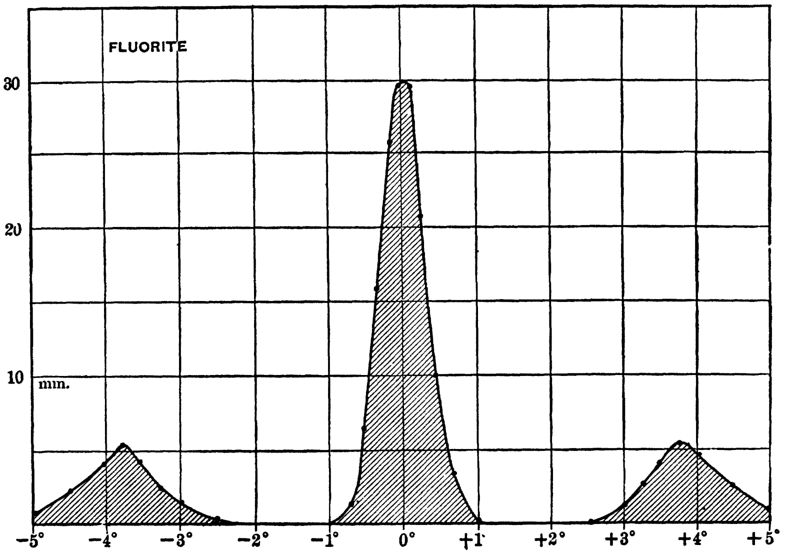

Fig. 3.

It appeared, further, of interest to find out whether these waves were destructively absorbed by water vapor and carbon dioxide gas, as is the case with shorter heat waves. To this purpose a blast of carbon dioxide gas and dry air were alternately blown into the collimator (Fig. 1, *f*) of the spectrometer, but no corresponding

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[1] C. Schultze-Sellack, Pogg. Ann., 139, 182 (1870).

changes were perceived in the intensity of the rays. The same experiment was tried with water vapor with like result. If either absorb in this region the action must be very weak.

If the numbers obtained from the foregoing experiments for the mean wave length of the rays resulting from three reflections on quartz, and on fluorite, be compared with the values computed from the Ketteler-Helmholtz dispersion formula for the middle of the absorption bands in each case, the observed value for quartz is 10 per cent less than the computed, and for fluorite 20 per cent. This may perhaps be accounted for by the inaccuracies unavoidable in the computed values, but there may be errors affecting the experimental values as well. For example, nothing is so far known of the relation between the absorption of the platinum black, with which the bolometer was coated, and the wave length. In case the absorption decreases as the wave length increases, which is by no means unlikely, the same quantities of energy would give rise to smaller and smaller deflections of the galvanometer as the wave length increased. This would obviously cause a displacement of the true maximum toward shorter wave lengths. Further, the curve which represents the distribution of energy of a black body when heated first rises as the wave length increases, reaches a maximum, and then sinks asymptotic to zero. The maximum of the energy curve of the source used lies certainly at a wave length much shorter than those here considered; consequently within the absorption band the longer waves are again at a disadvantage compared with the shorter ones.

In any case, one is justified in regarding the agreement between the observed and computed wave lengths as close enough to confirm the utility of the theories involved.

In addition to the experiments with quartz and fluorite, similar trials were made with rock salt and sylvite, which, according to the course of their dispersions in the region where it has been studied, should, after multiple reflection, give rays very considerably longer than those here recorded; but we have not yet succeeded in getting sufficiently faultless surfaces of these substances to make the experiments successful. We still hope, however, to overcome these difficulties, and to refine the present method until we are in position to study waves of much greater wave length ; and, further, to obtain a much higher degree of sensitiveness by substituting the improved radiometer[1] for the present bolometer.

Before closing, it will be of interest to call attention to the fact that, in respect to wave lengths, the rays corresponding to the infra-red absorption band in fluorite lie almost exactly midway between the shortest ultra-violet rays observed by Schumann[2] ($\lambda = 0.0001$ mm.) and the 6 mm. electrical waves of Lebedew, when the interval is reckoned according to octaves, as is customary in acoustics. On the other hand, if the spectrum be laid out according to uniformly increasing wave lengths, the space between the longest heat waves and the shortest electrical waves is 240 times greater than the length of the whole ultra-violet, visible, and infra-red spectrum taken together, and if reckoned according to the uniformly increasing number of oscillations is 250 times smaller than the combined ultra-violet, visible, and infra-red spectrum.

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[1] E. F. Nichols, *l.c.*

[2] V. Schumann, Wiener Acad. Ber., 102, 415, and 625 (1893).