

THE
PHYSICAL REVIEW.

THE VISIBLE RADIATION FROM CARBON. II.

BY EDWARD L. NICHOLS.

SPECTRO-PHOTOMETRIC OBSERVATIONS.

IT was my expectation, in planning this research that whatever might prove true as to the character of the radiation from gray carbon, the distribution of energy in the spectrum black carbon would change in such a manner with increasing incandescence as to become nearly or quite identical with that of the various luminous gas flames at temperatures corresponding to the temperature of the glowing carbon in those flames. I had also hoped, among other things, to be able to bring about a degree of incandescence approaching that of the acetylene flame itself, before the usefulness of the thermo-element as a means of measuring the temperature failed because of the melting of the platinum wire, and in this way to obtain a check upon my previous measurements of that flame, and at the same time to be able to determine the temperature of any given luminous flame in which the incandescent material consists of carbon particles by ascertaining the temperature of the carbon rod for which its surface had a spectrum corresponding in distribution of energy to that of the flame.

It will be seen from inspection of the curves to be discussed in a subsequent paragraph that this expectation was far from being realized, and that the distribution of energy in the spectrum of the carbon rod instead of approaching that of the acetylene flame as the temperature of the rod increased took on an entirely unexpected

character. Even at low temperatures, that is to say up to about 1100° the change in the spectrum was not of the comparatively simple character which had been anticipated, and shortly after passing the temperature of 1100° a very surprising complication in the results arose. The energy in the yellow of the spectrum, which from the beginning had been increasing at a relatively more rapid rate than either in the red or at the blue end, became so great as to give to the distribution curve a form entirely contrary to expectation.

I was very slow to believe in the integrity of these results and nearly a year was spent in repetitions of the measurements before I could convince myself that the phenomenon was a genuine one. Measurements taken upon a great number of different rods and at different times showed the same result, however, and I was finally forced to the conclusion that the radiation from the carbon rods showed a much more complicated law of distribution than had been anticipated, and that a sort of selective radiation occurred such as to render the establishing of any simple relationship between the curve of distribution and temperature out of the question.

The hope of being able to make direct temperature measurements up to the melting point of platinum was also disappointed. While the carbon rods at comparatively low temperatures showed a fair degree of stability under the action of the current, they appeared to undergo a decided change of behavior at about 1500° and before that temperature a rather rapid disintegration, showing itself by a change of resistance, manifested itself. This effect appeared to be similar to that which shortens the life of the filaments of incandescent lamps. It appeared also that at these high temperatures, the carbon tends to combine with the metals of the thermo-element affecting the electromotive force very much as the vapors in a furnace have been found to do. The thermo-elements inserted in the rod begin, in consequence of this action, to fail of their purpose. It was found that after exposure to temperatures much above 1400° , the electromotive force corresponding to even lower temperatures was considerably below the normal. I was consequently compelled to abandon the attempt to measure directly temperatures above this point, although it was possible to bring the rods to a higher degree

of incandescence for a length of time sufficient to perform the spectro-photometric observations. In order to obtain at least an approximate estimate of these high temperatures, I made use of the fall of potential between the terminals of the rod, and also of the current of the heating circuit, and by extending these curves which, throughout the range of measured temperatures were found to be nearly straight, to the higher temperatures which I wished to estimate, to obtain some idea, even if not an exact one, of the latter.

In expressing the results of the photometric measurements already described, I have made use of two forms of curve. One set of curves, in accordance with the nomenclature proposed in my original paper on the visible radiation from platinum, and later adopted by Paschen¹ and other writers, I may designate *isotherms*. These curves give, in terms of the corresponding wave-lengths of the comparison source (in this case the acetylene flame), the relative distribution of energy in the visible radiation from carbon rods. The other curves, which I have termed *isochroms*, indicate the rise in the energy of any particular wave-length of the visible spectrum, with increase of temperature. Each of these curves, taken by itself, is entirely independent of the nature of the light of the comparison source but the absolute relation of such curves to one another can only be obtained when we know the distribution of energy in the spectrum of that source. By means of the isochroms, it is, however, possible even without this knowledge, to compare the rise in intensity of various wave-lengths of the spectrum with increasing temperature.

The set of curves shown in Fig. 7 are plotted directly from observations upon a black (untreated) carbon at temperatures ranging between 795° C. and 1055° C. In this diagram abscissæ are wave-lengths and ordinates are ratios of the brightness of the spectrum of the carbon rod in each region to that of the corresponding region in the spectrum of the acetylene flame. The data are given in Table I.

A noteworthy fact exhibited by means of these curves is the relatively rapid increase of intensity in the middle of the spectrum. In

¹ Paschen, Wiedemann's Annalen, LVIII., p. 455, 1896.

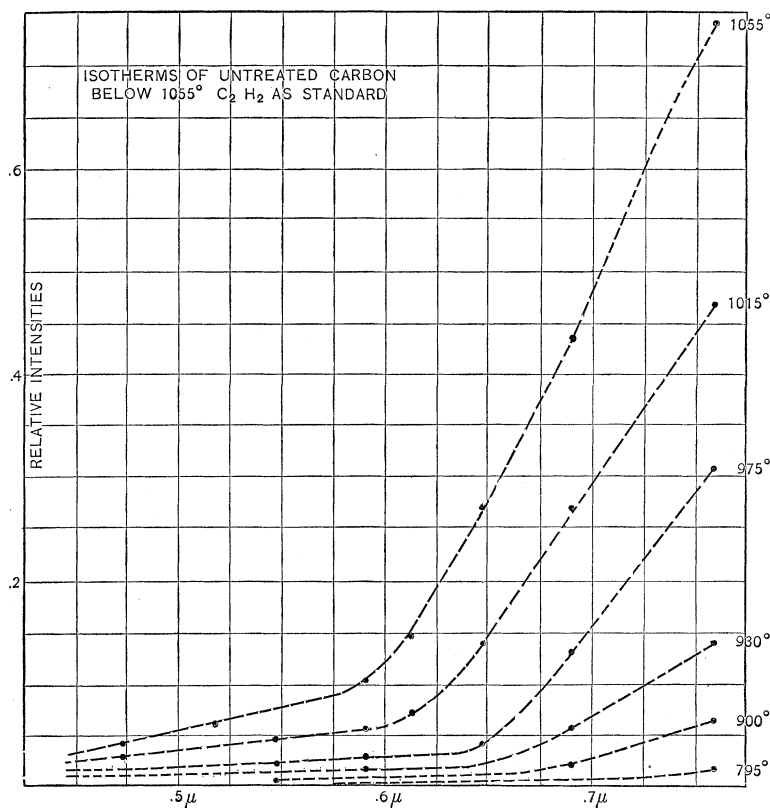


Fig. 7.

TABLE I.

Relative intensities of various regions in the spectrum of an untreated carbon rod; the intensity of the corresponding region in the spectrum of the acetylene flame being in such case taken as unity.

λ	Value of $\frac{\text{Intensity of Carbon}}{\text{Intensity of C}_2\text{H}_2}$ at Temperatures Given Below.					
	795°C.	900°C.	930°C.	975°C.	1015°C.	1055°C.
.760 μ	.018	.064	.140	.310	.466	.742
.690 μ	.007	.022	.057	.131	.270	.436
.647 μ	.005	.012	.022	.042	.128	.272
.613 μ					.072	.148
.589 μ	.003	.008	.017	.028	.067	.103
.548 μ			.013	.022	.046	
.518 μ			.011	.017		.058
.470 μ			.008	.014	.027	.041
.440 μ			.006	.012	.022	.030

passing from 930° to 1055° the brightness of wave-length $.76\mu$ increases 5.3 times; that of $.70\mu$, 7.2 times; that of $.60\mu$, 13.5 times

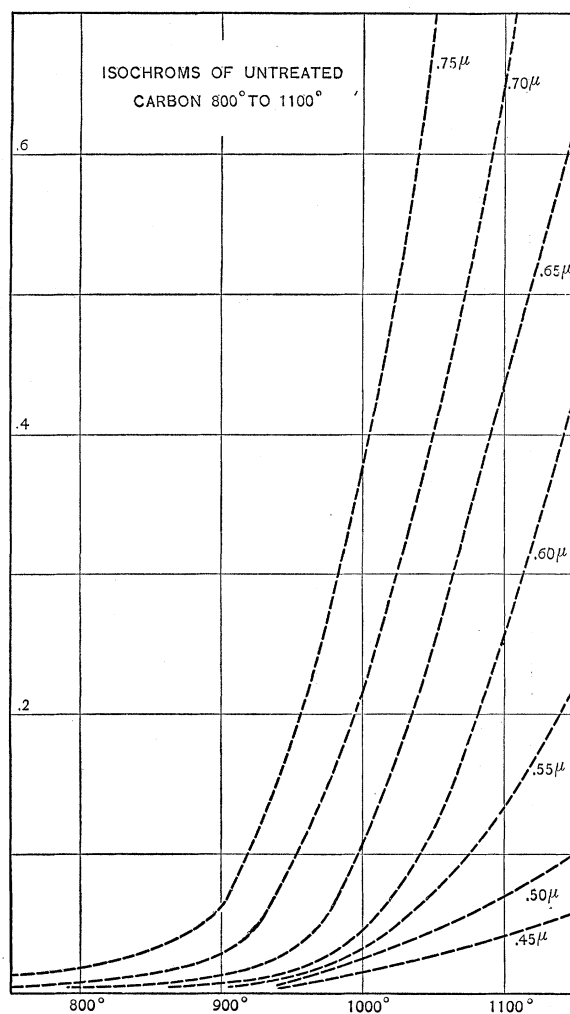


Fig. 8.

and that of $.50\mu$ only 9 times. We have here the beginnings of a process which becomes more marked in its effects as higher temperatures are attained.

From 1100° upwards it was found much more difficult to obtain satisfactory readings. The carbon rods which I had brought from Paris for this investigation would not stand prolonged heating and it was necessary to replace them frequently. In order to bring the

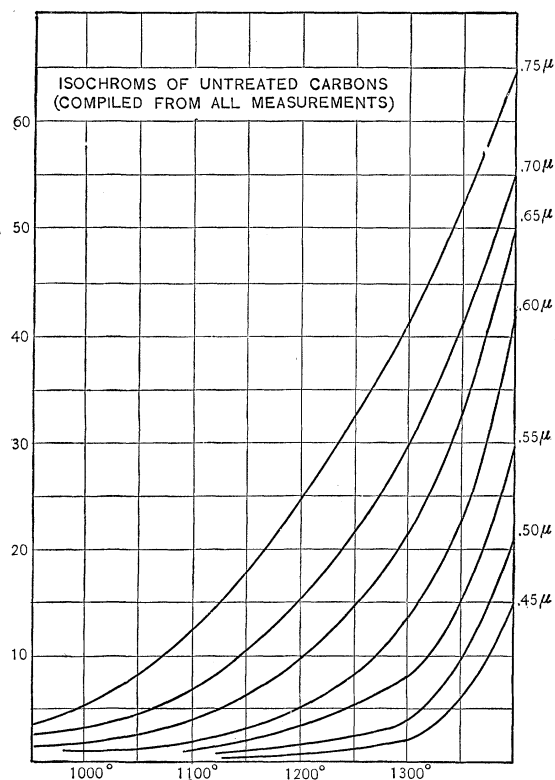


Fig. 9.

observations upon the various rods to a common scale, isochroms from the readings for each rod were plotted. The general character of these curves is shown in Fig. 8 in which the isochroms corresponding to the isotherms of Fig. 7 are given. From the ordinate at 1000° of the isochrom for $.6\mu$, which for convenience was taken as unity for the entire set a reduction factor was obtained by means of which all the curves for all the carbons were brought to the same scale. A new set of isochroms were then plotted for each of the

wave-lengths $.75\mu$, $.70\mu$, $.65\mu$, $.60\mu$, $.55\mu$, $.50\mu$ and $.45\mu$ in the drawings of which all the observations upon the rods were used. While this method did not bring the various sets of observations into perfect agreement, the results were sufficiently definite to indicate with a close degree of approximation the trend of these curves for temperatures up to 1400° . The result of this compilation for the wave-lengths just mentioned is shown graphically in Fig. 9. From these curves in turn, isotherms for the temperatures 900° , 1000° , 1100° , 1200° , 1300° and 1400° were plotted. These

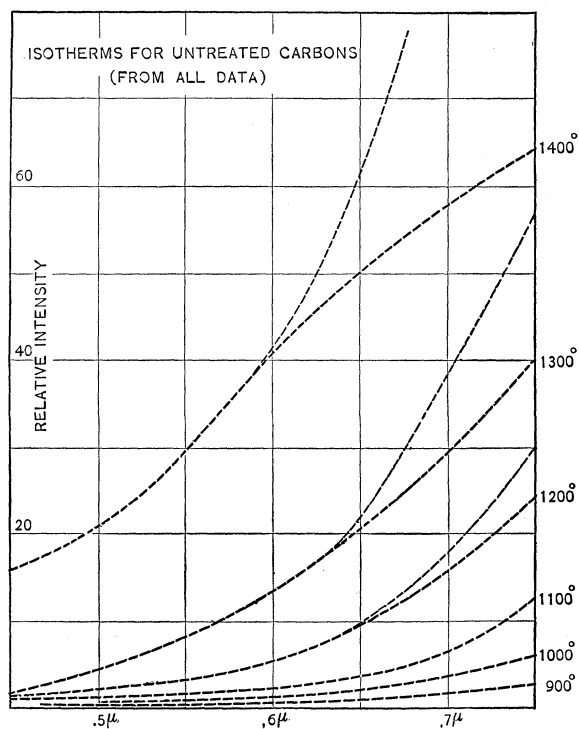


Fig. 10.

curves are given in Fig. 10. The numerical data are contained in Table II.

Had the law of increasing intensities throughout the spectrum with rising temperature been that anticipated at the beginning of

TABLE II.

Relative intensities of various regions in the spectrum of untreated carbon, compiled from all data; the brightness of the spectrum of the acetylene flame being taken as unity throughout and the intensity of the region .6 μ in the spectrum of carbon being taken as equal in brightness to that of the corresponding region in the flame spectrum when the temperature of the rod is 1000°C.

	Value of $\frac{\text{Intensity of Carbon}}{\text{Intensity of C}_2\text{H}_2}$ at Temperatures Given Below.					
λ	1400°C.	1300°C.	1200°C.	1100°C.	1000°C.	900°C.
.750 μ	64.4	40.4	24.2	11.9	5.2	2.3
.700 μ	58.2	29.7	15.6	6.0	3.2	1.6
.650 μ	50.3	21.0	9.8	3.4	1.7	0.8
.600 μ	40.7	13.6	5.3	2.1	1.0	0.5
.550 μ	29.7	8.2	3.3	1.5	0.5	0.3
.500 μ	21.3	4.2	2.2	1.2	0.3	
.450 μ	16.3	1.8	1.3	0.7		

this investigation, the trend of the isochroms would necessarily have been such as to bring all the curves together at a common point corresponding to the temperature of the acetylene flame. In other words, if the spectrum of the acetylene flame were identical throughout with that of the carbon rod at the same temperature, the isotherm of the spectrum of the rod at that temperature would be a horizontal line. It is obvious, however, that if the wave-lengths of the middle of the spectrum should continue to increase faster than the red and the violet, a condition would presently be attained in which the ordinate of the isotherm would be greater in the yellow or green than at either end of the spectrum. We see indications of the approach of this condition in the diagram of isochroms (Fig. 9) from which it is evident that the curves for .65 μ and .60 μ would cut each other and would cut the curve for .70 μ at some temperature not far above 1400°, whereas the isochroms for the shorter wave-lengths would not be likely to cut the curves for the red until some much higher temperature had been reached. The curves in Fig. 10 show the nature of this unexpected development of the spectrum in a somewhat different aspect. It will be seen from this figure that the growth in the extreme red so far lags behind that the regions of the full red and this in turn behind that of the orange and this in turn behind that of the wave-length .6 μ , that at 1400° the

isotherm instead of being concave as seen throughout, actually becomes convex. I have indicated by means of lighter lines *a*, *b* and *c* the form of curve which might have been expected had the type of isotherm which exists at lower temperatures been maintained.

Above 1400° it was found impossible to obtain consistent readings on account of the rapid disintegration of the carbon rods, but I was able to satisfy myself after repeated trials that at temperatures not far above 1500° this change in the character of the isotherms had progressed to the point at which the yellow regions of the spectrum possess an ordinate greater than that of the extreme red or violet. At a temperature of about 300° below that of the acetylene flame the spectrum of the carbon rod was relatively weaker in the red, stronger in the yellow and weaker again in the shorter wave-lengths than the spectrum of the acetylene flame. There is no reason to suppose that had it been possible to heat the rods to the temperature of the flame itself the law of increase of intensity for the various wave-lengths would have undergone such radical modification to bring the two spectra at that temperature into identity.

Spectro-Photometric Measurements upon Rods with Treated Surfaces.

In order to compare the radiation of rods of black surface with those the surface of which have acquired a gray coating by treatment in hydrocarbon vapor, rods were mounted in the usual manner and after the exhaustion of the air from the metal box, gasoline vapor was allowed to enter until the atmosphere surrounding the rod was saturated. The rod was then brought several times to a high state of incandescence for a few seconds at a time, by which means the entire surface became coated with a gray deposit of carbon similar to that obtained by the treatment of incandescent lamp filaments. The metal box was then again pumped out and spectro-photometric measurements similar to those already described were made upon the radiation from the treated surface. It was thought that as the result of this treatment the carbon rods would stand a more prolonged exposure at high temperatures and thus it might be possible to extend the measurements beyond the points reached with the rods of black surface. This was found to be the case. As has already been indicated in a previous paragraph, the indications of a thermo

junction at these high temperatures was subject to serious suspicion. I was obliged to content myself therefore with estimations of the temperature based upon the difference of potential between the terminals of the rod. Fortunately the relation between the electromotive force and the temperature up to 1400° was of such a character that but little error was to be feared in extrapolating. The relation between electromotive force in volts and temperature is shown in Fig. 11. From this curve temperatures above 1400° were determined.

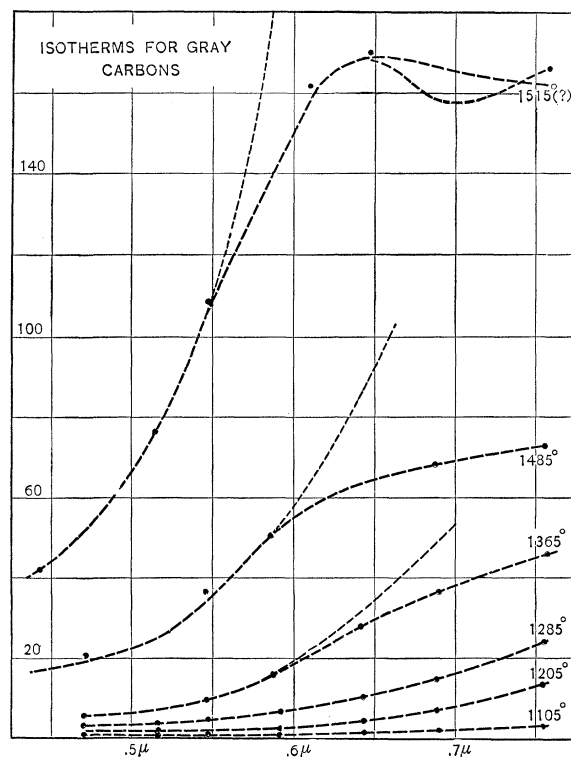


Fig. 11.

The work upon treated carbons was confined chiefly to high temperatures; a sufficient number of readings within the range already explored with the untreated carbons being taken to show that the distribution of intensities at the lower temperatures did not

differ materially from that in the spectrum of the former. The set of isotherms shown in Fig. 12, the data for which are given in Table III., will suffice to indicate the general character of the results. It

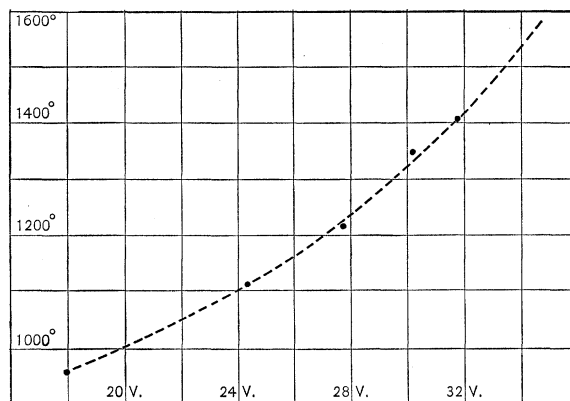


Fig. 12.

will be seen that in this case as in that of the untreated carbon the convexity of the curve between $.6\mu$ and the red end of the spectrum is well marked at 1365° ; and that at 1515° there was a well pronounced maximum at about 65μ . The greater stability of the

TABLE III.

Relative intensities of various regions in the spectrum of gray (treated) carbon, the brightness of the spectrum of the acetylene flame being taken as unity throughout and the intensity of the region $.6\mu$ in the spectrum of carbon being taken as equal in brightness to that of corresponding region in the flame spectrum when the temperature of the rod is 1000°C .

	Value of $\frac{\text{Intensity of Carbon}}{\text{Intensity of } \text{C}_2\text{H}_2}$ at Temperatures Given Below.					
λ	$1515^\circ(?)$	1485°	1365°	1285°	1205°	1105°
$.760\mu$	166.0	72.7	45.5	23.8	13.3	2.4
$.690\mu$	158.0	67.0	36.3	15.6	6.0	1.7
$.647\mu$	170.0	52.5	28.3	10.7	3.6	1.5
$.613\mu$	161.8					
$.589\mu$	140.0	36.6	17.2	6.9	2.8	1.3
$.548\mu$	108.8		10.2	5.4		0.7
$.518\mu$	76.6			4.6	2.3	0.5
$.470\mu$		20.5	5.6	3.5		0.3
$.440\mu$	41.3					0.2

treated carbon made it possible to obtain consistent measurements on a number of rods at temperatures above 1500° and to establish beyond doubt the form of the curves.

It is obvious that for the study of the spectrum of incandescent carbon at this and higher temperatures the conditions would be much more favorable in the case of the incandescent lamp than with rods mounted in a large vacuum chamber like that used in the present investigation. Lamp filaments in the process of manufacture are brought by thorough carbonization into a condition to withstand permanently much higher temperatures than the rods at my disposal were capable of doing. There is as yet it is true no direct means of determining the temperature of the lamp filament; but the curve for the relation of electromotive force of temperature (Fig. 11) is of such a character as to lead us to expect that comparisons of the spectra of incandescent lamps, in which electromotive forces were used as a criterion of the degree of incandescence would at least enable us to confirm the existence of the remarkable phenomenon brought out by the present experiments and to extend observations of it to still higher temperatures.

Mr. Ernest Blaker has since the completion of the measurements described in this paper made comparisons of the spectrum of incandescent lamps with treated filaments and of lamps the filaments of which before exhaustion had been coated with lamp black with the spectrum of the acetylene flame. The results of his measurements confirm very completely those which I have described in this paper and contribute important evidence in favor of the existence of this anomaly from the law of distribution of intensities in the spectrum of glowing carbon.

THEORETICAL ASPECTS OF THE FOREGOING DATA.

The efforts of students of radiation have of late years been directed particularly to the testing of the various formulæ by means of which the mathematical physicists have attempted to express the intensity of radiation as a function of wave-length and temperature. The equation reached from quite different points of view by Wien¹ and Planck,²

¹ Wien, Wiedemann's Annalen, 58, p. 662, 1896.

² Planck, Drude's Annalen, 1, p. 69, 1900.

$$I = c_1 \lambda^{-5} e^{-\frac{c_2}{\lambda T}},$$

in particular, has been the subject of exhaustive discussion and of experimental tests. To this end Paschen¹ determined with the bolometer the distribution of energy in the infra-red spectra of various bodies from 15° C. to 1300°. The materials thus subjected to measurement were oxide of copper, platinum, lamp black, and graphitic carbon. The range of wave-lengths explored extended from 9.2 μ to 0.7 μ . Lummer and Pringsheim² and still more recently Mendenhall and Saunders³ have made similar determinations with the ideal black body; and Lummer and Jahnke⁴ have compared the infra-red spectrum of such a body with that of platinum. Wanner⁵ working with Paschen made careful spectro-photo metric measurements of the visible radiation from the ideal black body. To test the applicability of the Wien-Planck formula to these measurements of the radiation the equation is given the form,

$$\log I = \gamma_1 - \gamma_2 \frac{1}{T},$$

in which

$$\gamma_1 = \log (c_1 \lambda^{-5}),$$

$$\gamma_2 = \frac{c_2}{\lambda} \log e.$$

The isochromatic curves are then plotted with the logarithm of the intensities as ordinates and the reciprocal of the absolute temperature as abscissæ. The agreement of the equation with the observations is found in the fact that isochroms thus plotted, at least as far as the work of Paschen and Wanner is concerned, always take the form of straight lines and that the quantity, c_2 , computed for various wave-lengths is found to be a constant. Lummer and Pringsheim on the contrary find in the discussion of their measurements that the

¹ Paschen, Wiedemann's Annalen, 58, p. 445, 1896; also, Wiedemann's Annalen, Vol. 60, p. 662, 1897.

² Lummer and Pringsheim, Deutschen Phys. Gesellschaft, I., p. 23; II., p. 163, 1900.

³ Mendenhall and Saunders, Astrophysical Journal, Vol. 13, p. 25, 1901.

⁴ Lummer and Jahnke, Drude's Annalen, Vol. 3, p. 283, 1900.

⁵ Wanner, Drude's Annalen, 2, p. 141, 1900.

constant c_2 increases steadily with a wave-length from 13500 at 1.2μ to 16500 at 5μ and 18500 at 8.3μ . The value of c_2 computed by measurements from Beckman at wave length 24 was found to be 24250. Lummer and Pringsheim find moreover that the logarithmic isochroms, especially when extended to higher temperatures, are not straight lines, but show a slight convexity towards the $\frac{1}{T}$ axis.

Exception has also been taken to the Wien-Planck formula on the ground that it gives for infinite temperatures a finite limit to the value of the intensity; a result which Rayleigh¹ in a recent paper has characterized as *physically improbable*.

Rayleigh proposes form

$$I = c_1 T \lambda^{-4} e^{-\frac{c_2}{\lambda T}}$$

but Lummer and Pringsheim find that this likewise fails to properly express their experimental results. Lummer and Jahnke propose in view of these discrepancies to give the equation the general form

$$I = c T^5 (\lambda T)^{-\mu} e^{-\frac{c}{(\lambda T)^2}}$$

an expression which coincides with Wien's formula for $\mu = 5$ and with Rayleigh's for $\mu = 4$. They find the measurements of Lummer and Pringsheim satisfied when μ lies between 4.5 and 5 and $\sqrt{}$ lies between .9 and 1.0. If we accept the value $\mu = 5$ and $\sqrt{} = 0.9$ this equation always leads to a finite value of intensity for infinite temperature. All other values of these quantities give infinity as the limit of intensity.

Whether logarithmic isochroms or the value of the quantity c_2 , computed from measurements upon carbon rods, would aid in deciding between the various equations under discussion is a question. The data given in this paper would not lead us to class the carbon rod studied as *black bodies*. The emissive power of various forms of carbon is well known to be smaller than that of the ideal black body and there is no reason to suppose that it is independent of the temperature. The relative lagging behind of the intensities in the

¹ Philosophical Mag., Vol. 49, p. 539, 1900.

red might perhaps be taken as an indication of a tendency to approach the finite maximum demanded by the Wien-Planck formula; but the isochrom for $.76$ shows that the effect if it exists must be looked for at some much higher temperature than that covered by these measurements. In spite of these doubts as to the applicability as to the measurements on carbon rods to the problem of the law of radiation of the ideal black body, I have plotted the various iso-

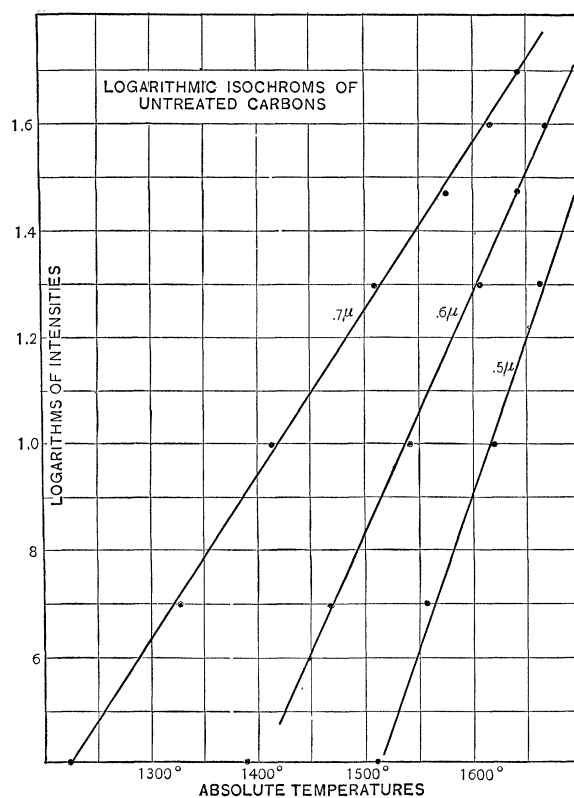


Fig. 13.

chroms obtained in the course of this investigation in logarithmic form; absolute temperatures being taken as abscissæ and the logarithm of the intensity as ordinates. As will be seen from Fig. 13, in which three curves from Fig. 9 are reproduced, these loga-

rithmic isochroms are straight lines. The range of temperatures is doubtless too small to bring out the curvature found by Lummer and Pringsheim ; but they show clearly the change of direction with the wave-length mentioned by them on page 222 of their paper before the German Physical Society.¹

In carrying on portions of the work described in these papers I have had valuable help from Drs. C. H. Sharp and Leopold Kann and from Mr. L. W. Hartman, to all of whom I desire to express my obligations and to extend my hearty thanks.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY, April 24, 1901.

¹Lummer and Pringsheim, Verhandl. d. Deutschen. physikal. Gesellsch., 1899, p. 222.