ON THE DISTRIBUTION OF ENERGY IN THE
VISIBLE SPECTRUM.

BY EDWARD L. NICHOLS.

THE direct determination of the distribution of energy in the visible spectrum of incandescent bodies is a somewhat difficult matter. Even with the most sensitive forms of linear bolometer or with the radiometer the deflections obtained by exploring the spectrum of artificial light sources are very small excepting in the red. The proper correction of this portion of the observed curve for slit width is likewise a matter of some uncertainty. The visible spectrum of sunlight, it is true, is of sufficient strength to admit of direct measurement and the spectrum of the electric arc affords easily measurable intensities; but the distribution of energy in the former is so seriously affected by varying atmospheric absorption as to render the sun worthless as a source of comparison in spectrophotometric work and the fluctuations in the brightness of the arc are also very great.

It is possible with an exceedingly sensitive radiometer to explore the visible spectrum of an artificial source of light such as the acetylene flame up to about $.45\mu$ and I have been in possession for some time of a collection of data for this source of light obtained from measurements by G. W. Stewart and by Mr. W. W. Coblentz. Given such a curve, one can compute the curves of distribution for all spectra which have been compared with the acetylene flame by means of the spectrophotometer; but I have hitherto postponed these computations through a feeling of distrust in the accuracy of the corrections for slit width.

Knut Ångström,¹ in a recent paper, has published a curve of the distribution of intensities in the visible spectrum of the Hefner lamp. Ångström's values were obtained by an indirect method based upon Wien's equation

¹ Ångström, *PHYSICAL REVIEW*, Vol. XVII., p. 302; also *Royal Society, Upsala 3d series*, Vol. XX., 1904.

$$I_{\lambda} = C_1 \lambda^{-5} e^{-\frac{C_2}{\lambda T}}$$

In his measurements he avoids the difficulty arising from the very feeble intensities of the visible spectrum of this source of light by measuring the quantity

$$L_{\lambda} = \int_0^{\lambda} I_{\lambda} d\lambda = C_1 \int_0^{\lambda} \lambda^{-5} e^{-\frac{C_2}{\lambda T}}$$

where L_{λ} is the entire radiation lying between 0 and λ . The constants C_1 and C_2/T were determined by a series of such measurements and the value of the intensity of each wave length of the spectrum was then computed.

If we know the relative intensities of the spectra of the Hefner lamp and of the acetylene flame, and these are readily obtained by means of the spectrophotometer, the curve for the distribution of intensities of the acetylene flame may be deduced from Ångström's values for the Hefner lamp. I have recently shown¹ that the curve thus obtained is essentially identical with that obtained by the direct exploration of the spectrum of the latter source, to which reference has already been made.

The agreement of these results greatly strengthens our confidence in the validity of both and renders it desirable to compute the corresponding curves for the numerous sources of light of which we already possess spectrophotometric comparisons either with the Hefner lamp or with the acetylene flame. Materials for such computations are sufficiently abundant. We have, for example, the series of spectrophotometric comparisons of the Hefner flame with petroleum flames, gas flames, the light of the Welsbach mantle, the zircon light, daylight and sunlight made by Koettgen² and numerous similar comparisons of light sources with the acetylene flame, made from time to time in the Physical Laboratory of Cornell University. It is with the results of computations made upon such data that the present paper deals.

Ångström, in the paper already cited, determined by means of his compensated pyrliometer the heat in calories per second

¹ Nichols' Standards of Light, Proc. of International Elec. Congress of St. Louis, 1904

² Koettgen, Wied. Ann., 53, p. 793.

received by a surface of 1 sq. cm. at meters distance from the Hefner flame. If the various curves for the distribution of energy in the visible spectrum of light sources are plotted to the same scale as

TABLE I.
Distribution of intensities in spectra of Hefner and C_2H_2 flames.

Wave-lengths.	Hefner.	Acetylene.	Wave-lengths.	Hefner.	Acetylene.
	Intensities from Ångström's Curve.	Intensity by Radiometer.		Intensities from Ångström's Curve.	Intensity by Radiometer.
.46	0.22	0.39	.62	5.40	4.86
.48	0.47	0.65	.64	7.00	5.88
.50	0.82	0.88	.66	8.60	6.61
.52	1.20	1.33	.68	10.55	8.10
.54	1.65	1.80	.70	12.60	9.65
.56	2.26	2.42	.72	15.10	11.40
.58	3.30	3.08	.74	17.80	12.90
.60	4.20	3.97			

Ångström's curve for the Hefner flame, with ordinates so chosen as to represent in each case a source of unit intensity, the areas of these curves would give the luminous energy received from each source in unit time per square centimeter of surface when the illumination is one lux. It was shown many years ago by Crova that the intensity of the yellow of the spectrum is proportional to the candle power of the source. This relation, which one would expect to find approximately true on account of the high luminosity of that portion of the spectrum, one can readily verify by means of the spectrophotometer. I have accordingly reduced the various curves to be considered to this unit intensity by making the ordinate for wave-length $.590 \mu$ equal in every case to that of Ång-

Fig. 1.

ström's curve for the Hefner flame. Ångström's curve and the corresponding curve for the acetylene flame, which are the reference curves for the reduction of the spectrometric data to be employed, are shown in Fig. 1 and the numerical data are given in Table I. Curve 2 in that figure is from direct determinations of the visible spectrum of the acetylene flame made with the radiometer, while the crosses ($\times$) show the values for four wave-lengths computed from a spectrophotometric comparison of the acetylene and Hefner flames reduced by means of Ångström's curve for the latter.

GAS AND PETROLEUM FLAMES.

In spite of the fact that the ordinary gas flame is somewhat indefinite, as regards the character of its spectrum, owing to the variations in the character of the fuel consumed and the temperature of combustion with different burners, it is of interest to determine the general character of such flames since these have frequently been employed as sources for spectrophotometric comparisons. Koettgen in the article already referred to has measured the spectrum of ten gas flames with reference to the Hefner lamp. The

Fig. 2.

distribution in the energy of three of these, described as the *Triplex lamp*, *Siemen's precision burner (No. 1)* and *Sugg's burner*, have been computed by means of Ångström's curve. The results are given

in Table II. together with the corresponding data for an ordinary "bats-wing" burner the relation of which to the acetylene spectrum was known. The results are plotted in Fig. 2 in which the corresponding curve for acetylene is shown in broken line for purposes of comparison. The ordinates of these curves are all the same for wave-length $.590\mu$ and are equal to that of Ångström's curve for the Hefner flame. The curve for the triplex burner (1) is almost identical throughout with the curve for the Hefner lamp. The others lie between it and the acetylene curve. These curves, and the same is true of the other curves in the present paper, give the actual distribution of intensities in the visible spectra of the sources to which they pertain and their areas are proportional to the light-giving energy. The question of the energy of visible radiation from the various sources of light to be considered is discussed in a subsequent paragraph.

TABLE II.

Distribution of Intensities in the Spectra of Ordinary Gas Flames.

Wave- Lengths.	From Comparisons with Hefner Flame (Koettgen's Data).			From Comparison with Acetylene Flame.	
	Triplex Burner.	Siemens No. 1.	Sugg's Burner.	Wave- lengths.	Bat's Wing Burner.
$.45\mu$	0.19	0.22	0.27	$.45\mu$	0.11
.49	0.63	0.70	0.81	.50	0.52
.51	.98	1.07	1.17	.55	1.76
.55	1.92	2.00	2.07	.60	4.40
.59	3.50	3.50	3.50	.65	7.70
.61	4.80	4.69	4.63	.70	12.70
.65	8.01	7.34	7.04		
.69	12.48	10.8	10.0		

Koettgen has also compared the flames of seven petroleum lamps with the Hefner flame. One of these, the flame of an ordinary lamp with a flat wick (curve 5, Fig. 2) is of greater importance than the others since it is of a type that has been used in a number of spectrophotometric comparisons. Its spectrum corresponds very closely with the Hefner and with the triplex gas burner. Six of the seven lamps investigated by Koettgen would have intensity curves lying between those of the triplex burner and of the Siemen's precision burner, curve 3, Fig. 2. Only one of the entire set of petroleum flames given in Koettgen's table lies outside these

limits and this one, the flame from the lamp known as the *Triumph patent* (curve 6, Fig. 2) differs but slightly from the Siemen's gas burner in its distribution of intensities. Curves 5 and 6 may be taken as representing the extremes of variation in ordinary petroleum flames, the range of which appears to be much smaller than that of gas flames.

TABLE III.

Distributions of intensities in the spectra of petroleum flames, from comparisons with the Hefner flame (Koettgen's data).

Wave-Lengths.	Flat Burner.	Triumph Burner.
.45	0.22	0.23
.49	0.81	
.51	0.99	1.11
.55	1.94	2.03
.59	3.50	
.61	4.76	4.73
.65	7.42	7.36
.69	11.50	11.40

INCANDESCENT CARBON.

The spectrophotometric data available for the computation of energy in the visible spectrum of incandescent carbon is contained chiefly in my articles on the visible radiation from carbon¹ and in Blaker's² spectrophotometric comparisons of the light from the filament of incandescent lamps. The former of these investigations consisted in spectrophotometric comparisons of the light from untreated carbon rods at temperatures between 1273° abs. and 1673° abs., with that of an acetylene flame. The relative measurements of different wave-lengths have been reduced to absolute intensities by the use of the curve for the acetylene flame in Fig. 1, and the results are given in Table IV. which shows the distribution of intensities for various parts of the spectrum in the case of a carbon rod heated successively to 1273°, 1373°, 1473°, 1573° and 1673° of the absolute scale.

These values for the three temperatures 1273°, 1573° and 1673° abs., reduced to a common ordinate in the yellow for comparison

¹ Nichols, PHYSICAL REVIEW, Vol. XIII., p. 65; Proc. of the American Academy of Arts and Sciences, Vol. XXXVII., p. 73.

² Blaker, PHYSICAL REVIEW, Vol. XIII., p. 345.

TABLE IV.

Intensity of the spectrum of an untreated carbon rod at various temperatures of the absolute scale.

Wave- Lengths.	Intensities (Absolute).				
	1273°	1373°	1473°	1573°	1673°
.45	0.054	0.121	0.320	0.62	4.32
.50	0.220	0.642	1.93	3.60	19.5
.55	0.815	2.99	7.94	16.51	63.7
.60	2.00	9.01	23.9	55.58	168.7
.65	6.93	28.0	63.0	141.1	315.0
.70	21.2	70.4	162.1	289.5	530.7
.75	52.1	174.0	352.0	578.1	883.6

with other sources, are given in Table V. They correspond, approximately at least, to those which would be found for carbon rods having the temperatures in question but of such a size as to possess in every case the same illuminating power as the Hefner lamp.

TABLE V.

Untreated Carbon.—Continued.

Wave-Lengths.	Intensities (Reduced).		
	1273°.	1573°.	1673°.
.45	—	0.08	0.16
.50	0.20	0.26	0.44
.55	1.20	1.40	1.58
.60	4.21	4.08	4.01
.65	13.9	10.30	7.56
.70	42.5	21.1	12.73
.75	104.0	42.2	21.20

The reduced intensities for these three temperatures are likewise shown graphically in Fig. 3. The unreduced intensities are so great, especially in the red, that they cannot be represented upon the same scale with the other curves in a diagram of reasonable dimensions. The general trend of the curves and their close similarity in character to those obtained with gas and oil flames will be evident from the figure.

Ångström, in the paper already cited, gives a curve for the distribution of intensities in the visible spectrum of an incandescent lamp the filament of which, measured by his method, had a temperature of 2000° abs. This curve reduced to correspond at wave-

length $.590\mu$ with the curve for the Hefner flame, is likewise given for the sake of comparison in Fig. 3.

In the course of my investigation of the visible radiation from carbon, just cited, observations were made on carbon rods previously treated by flashing in an atmosphere containing hydrocarbon vapors. The surface of the rods was thus coated with a deposit of the well

Fig. 3.

Fig. 4.

known silvery gray form of carbon characteristic of the treated filament of the incandescent lamp. Spectrophotometric measurements at temperatures from 1600° abs. upwards, showed the development of an interesting and unexpected deviation from the usual law

of radiation for carbon and this phenomenon was subsequently studied in much greater detail by Blaker.¹ As he likewise used the acetylene flame as a reference source in his measurements it is possible to reduce the spectrophotometric readings to absolute measure by means of the acetylene curve. The results, in form corresponding to that for untreated carbon in Fig. 3, are given graphically in Fig. 4. In these measurements, which were made upon the filament of an incandescent lamp, it was not possible to determine the temperatures directly by means of a thermo-junction as had been done in my investigation of untreated rods. The temperatures given are estimated by means of the relation between the resistance and temperature in such filaments as determined by Le Chatelier.² While it is not likely that the scale of temperatures in Blaker's work is directly comparable with those for the untreated

Fig. 5.

carbons, or with the temperature of the incandescent lamp measured by Ångström, it is at least instructive to compare the curves obtained. The curve for Blaker's lamp at 1671° abs. is accordingly plotted

¹ Blaker, *l. c.*

² Le Chatelier, *Journal de Physique*, (3), Vol. I., p. 203.

on the same scale as the curve for the untreated carbon rod at 1673° and the corresponding curve for Blaker's lamp at 2011° abs. with the incandescent lamp measured by Ångström (see Fig. 5). It will be seen that the curves are almost coincident as far as wave-length $.65\mu$ beyond which the intensities for treated carbon fall off and the marked selective radiation of the latter begins to manifest itself.

THE ELECTRIC ARC.

Although numerous spectrophotometric studies of the electric arc

Fig. 6.

have been made, but few of these cover a sufficient range of wave-length to be available for the determination of the distribution of intensities throughout the visible spectrum. The three curves in Fig. 6 are from data (Table VI.) computed from measurements by Crova,¹ by W. S. Franklin and the present writer,² and from a comparison of the electric arc with the acetylene flame.³

These curves show the type of radiation characteristic of incandescent carbon at very high temperatures, but the idiosyncracies

TABLE VI.

Distribution of intensities in the spectrum of the arc light.

Wave-lengths.	Intensities from Comparisons by		
	Crova.	N. & F.	N.
.45	0.90	0.67	0.65
.50	1.35	1.47	1.67
.55	2.38	2.55	2.59
.60	3.96	3.86	3.73
.65	5.66	5.30	4.87
.70	7.65	7.03	6.28
.75	9.60	8.68	7.55

¹ Crova, Comptes Rendus, 87, page 322.

² Nichols and Franklin, American Journal of Science, Vol. 38, p. 100.

³ Nichols, Journal of Franklin Institute, Nov., 1900.

peculiar to treated carbon do not appear. The curve of distribution for the arc lamp will necessarily vary with the diameter of the carbons, the length of the arc, the current density and the angle which the line of sight makes with the axis of the lamp. The curves here presented refer to measurements taken under conditions such that light from all portions of the incandescent carbon was received upon the slit of the spectroscope. If the light from the crater alone were isolated, and its spectrum explored, a curve of much higher temperature would be obtained and we should expect to find the maximum of intensities lying within the visible spectrum. I am unfortunately not in possession of data for the computation of such a curve.

INCANDESCENT OXIDES.

The sources of light of this class for which we have the necessary data, for the computation of the distribution of energy, are the

Fig. 7.

Welsbach mantel, the zircon light, the magnesium light and the lime light. The results are given in Table VII. and the corresponding curves in Fig. 7.

It was shown some years ago¹ that the light from the lime cylinder when first heated in the usual way by means of the oxyhydrogen flame differs greatly in character and intensity from that of the same cylinder after prolonged exposure to the action of the flame. These

¹ Nichols & Franklin, l. c.

TABLE VII.
Distribution of Intensities in the Spectra of Incandescent Oxides.

From Comparison with the Hefner Flame (Koettgen's Data).				From Measurements by Nichols and Franklin.			From Measure- ments by Rogers.	
Wave- Lengths.	Wels- bach (I.).	Welsbach (II.).	Zircon.	Wave- lengths.	New Lime.	Old Lime.	Wave- Lengths.	Magnes- ium Flame.
.47 μ	0.92	0.72	0.71	.45 μ	2.16	0.42	.45 μ	—
.51	1.91	1.61	1.53	.47	2.16	0.72	.48	2.86
.55	2.71	2.49	2.35	.49	2.25	0.97	.50	2.67
.59	3.50	3.50	3.50	.52	2.53	1.58	.54	2.49
.63	4.33	4.68	5.73	.56	2.73	2.60	.57	3.11
.65	—	—	6.88	.59	3.50	3.50	.61	3.74
.67	4.66	5.19	8.35	.61	4.09	4.09	.64	4.45
.69	4.75	5.04	9.47	.67	7.19	6.77	.67	4.98
.72	4.21	4.72	—	.75	*12.6	9.51		

spectrophotometric measurements form the basis of curves 2 and 3 in Fig 7. Curve 2 represents the distribution of intensities of the freshly ignited lime. It differs from the various curves of incandescent carbon in the great excess of energy of shorter wave-lengths. The ordinate at wave-length .45 μ for example is about nine times as great as that of the Hefner flame and about four times as great as that of the arc in the same region. In the course of ten minutes after ignition the brightness of these portions of the spectrum suffers decadence, rapidly at first and then more and more gradually, and the distribution of energy in the spectrum goes over into the form indicated in curve 3. During this interval of time, however, what may be termed the permanent incandescence of the lime increases by the gradual heating up of the cylinder and the curve approaches nearly in form that of incandescent carbon; as may be seen by comparing curve 3 with the curves of the arc lamp. A detailed study of these changes has long since been described.¹ The curve of the Zircon light (1), Fig. 7; deduced from measurements by Koettgen, is identical with that for the old lime through the shorter wave-lengths of the spectrum but shows greater intensities in the red than either of the curves for the lime light.

The curves for the Welsbach or Auer mantels are from spectrophotometric studies made by Koettgen.² These mantels had been

¹ Nichols & Crehore, PHYSICAL REVIEW, Vol. II., p. 161.

² Koettgen, l. c.

in uninterrupted incandescence for twenty-four hours, after which time, according to observations of that investigator, they showed no further material change in spectral distribution. While these two mantels differed materially as to the quality of the light emitted, one being relatively stronger throughout the shorter wavelengths and correspondingly the weaker in the red than the other, the type of the two curves is the same and they are altogether different from the other curves considered in this paper. The maximum intensity for the visible spectrum lies at wave-length $.67\mu$ but whether this is the maximum for the entire spectrum or a secondary maximum due to the selective radiation of the material can be determined only by the exploration of the infra-red.

The quantitative study of the spectrum of the magnesium light is difficult on account of the fluctuating character of the flame of magnesium even when burned in lamps with automatic feed. Spectrophotometric measurements of this spectrum have however been made by W. H. Pickering¹ and by F. J. Rogers.² From their results, which are in good agreement, curve 4 in Fig. 7 has been computed. Magnesium oxide is the only incandescent solid, for which we have any data, the energy in the spectrum of which is *greater in the violet than in the yellow and green*. It would appear from the form of the curve that there is a maximum in the ultra violet; a suspicion confirmed by the fact of the extraordinary actinic activity of this source of light. The type of the curve is similar to that for freshly ignited lime (curve 2), and it seems highly probable that if it were possible to make measurements upon lime at the instant of ignition, the curve would correspond still more closely to that of magnesia. It is possible to secure such measurements only in cases in which, as in the magnesium flame, the light is derived from the oxide at the instant of its formation by the combustion of the metal.

SUNLIGHT AND DAYLIGHT.

Numerous spectrophotometric measurements of direct sunlight of the light reflected from the sky and in various conditions of the atmosphere have been attempted. Of these the measurements of

¹ Pickering, Am. Jour. of Science, 37, p. 100.

² Rogers, Am. Jour. of Science, Vol. 43, p. 301.

direct sunlight by H. C. Vogel,¹ W. H. Pickering,² W. S. Franklin and the present writer,³ and by Koettgen⁴ are in excellent agreement considering the varying atmospheric conditions. The determinations of Koettgen, who compared sunlight with the Hefner

Fig. 8.

standard, have been adopted as the basis of computations for curve 2 in Fig. 8. His measurements extend through a greater range of wave-lengths and the comparisons are made with a source of light about which we have more definite information than is the case with the other available data. Measurements of daylight from cirrus clouds by the same writer have been selected for the same reason and the results of the computation are given in curve 3 of that figure. Curve 1 is from the direct spectrophotometric measurements of the sun's spectrum made by Langley.⁵

These curves are drawn with greatly increased ordinates.

Plotted to the same scale as in previous figures curves 2 and 3 would appear as shown by the dotted lines 4 and 5.

It is noteworthy that curves 1 and 2 not only have the same maximum but are closely coincident excepting in the red. The divergence in that region is due to the selection of Langley's smoothed curve which was drawn tangent to the crests of the maxima in that region and so does not show the effect of atmospheric absorption.

¹ Vogel, Berliner Monatsberichte, 1880, p. 801.

² W. H. Pickering, Proc. Am. Acad. of Arts and Sciences, Vol. 15, 1880.

³ Nichols and Franklin, American Journal of Science, Vol. 38, p. 100.

⁴ Koettgen, l. c.

⁵ Langley, Researches on Solar Heat, 1884, p. 139.

A COMPARISON OF THE ENERGIES OF VISIBLE RADIATION.

The areas of the various curves of distribution of intensity, already described, taken between the red and violet limits of the spectrum, afford a measure of the total energy of luminous radiation from the sources of light to whose spectrum the curve applies. Ångström's value for the light energy of the Hefner standard flame is

$$20.6 \times 10^{-8} \frac{\text{gm. cal}}{\text{sec. cm.}^2};$$

the square centimeter of surface being situated at a distance of one meter from the flame in a horizontal direction. Reducing this numerical quantity to ergs, a more convenient unit for this purpose, we find that a square centimeter of surface at a distance of one meter from the Hefner flame receives *8.3 ergs per second* of light-giving energy. Assuming that the various curves in this paper

TABLE VIII.

Temperatures and ergs per lux-centimeter-second.

Source.	Ergs.	Temperature. ¹	Source.	Ergs.	Temperature.	
Carbon rod (untreated).	29.0	1273° abs.	Hefner flame.	8.68	{ 1934° abs. P. 1830° “ A.	
	23.1	1373° “				
	17.8	1473° “	Petroleum flat flame.	8.69		
	14.2	1573° “				
	9.14	1673° “				
Lamp filament Ångström.	7.26	2000° “ A.	Gas {	Triplex.	9.13	1897° “ P.
				Batswing.	8.40	2053° “ <i>thj.</i>
		Siemens.		8.26		
		Sugg.		7.70		
Lamp filament (treated). Blaker.	18.5	1351° “	Acetylene.	7.12	2173° “ <i>thj.</i>	
	9.69	1528° “			2876° “ P.	
	7.38	1631° “	Zicron.	7.17		
	7.34	1769° “ <i>Ch.</i>				
	6.35	1921° “	Lime {	old.	5.89	
	6.42	2011° “		new.	7.21	
Arc {	Nichols.	5.92	Welsbach. (I.)	4.39	{ 2450° “ P. 2073° “ <i>thj.</i>	
	Crova.	5.85		(II.)		4.50
	{ N. & F.	5.79	3690° “ W. & B. ²	Magnesium flame.	5.53	2258° “ <i>thj.</i>
				Sunlight.	4.85	5068° “ P.
			Daylight.	5.53		

¹ Temperatures marked *thj.* have been determined by the thermojunction; *A.* by Ångström's method; *Ch.* by Le Chatelier's formula; *P.* by Paschen's equation.

² Waidner and Burgess, PHYSICAL REVIEW, Vol. XIX., p. 241.

represent sources all of which are of equal photometric intensity (namely, one Hefner) so that in every case the illumination is one lux, the ergs per second received upon a square centimeter of surface at meters distance from each of the various sources of light in question will be given by multiplying the ratio of the area of the corresponding curves to the area of the curve for the Hefner flame, by 8.63. It has been assumed, as already stated, that curves plotted with equal ordinates for wave-length $.59\mu$ correspond to equal photometric intensities of the sources. The areas of the curves thus plotted have been measured with the planimeter, and the results computed as just indicated are given in table VIII.

It will be seen from the table that the energy for unit illumination is by no means constant. In the case of sources of light whose radiation approximates to the law for a black body, that is to say for sources in which the incandescent substance is carbon, the energy per lux-centimeter diminishes with rising temperature; being 29 ergs per second for the carbon rod at 1273° abs., 7.12 ergs at the temperature of the acetylene flame, 5.92 to 5.79 ergs for the arc light and 4.85 ergs for sunlight.

Treated carbon, which has slightly selective radiation, shows decidedly smaller values than untreated carbon or than the carbon particles in flames. The metallic oxides, which are more strongly selective, furnish greater photometric intensity, per erg of luminous energy, than any of the sources in which carbon is the light-giving substance. Of these magnesium oxide, zirconium oxide and calcium oxide show very powerful selective radiation in the blue and violet, a region which is photometrically unimportant on account of the low luminosity of such waves. The selective radiation of the Welsbach mantel lies in a region near the maximum of luminosity and this source of light accordingly gives a larger photometric intensity per erg than any of the sources examined; namely, 4.39 ergs per lux-centimeter. The Welsbach mantel, however, owes its photometric superiority to a deficiency of red rays and to this deficiency the objectionable green color of this source of light is due.

It is noteworthy that of the incandescent bodies whose radiation approximates to the law for black bodies, the sun affords a maximum of photometric intensity per unit of luminous energy and that *the*

maximum of the energy curve of the sun's spectrum coincides with the maximum of luminosity for the normal human eye. Daylight

Fig. 9.

diffusely reflected from the sky, as in curve 3, Fig. 9, has a smaller photometric intensity per erg than direct sunlight.

RELATIONS BETWEEN TEMPERATURE AND LUMINOUS ENERGY PER LUX-CENTIMETER.

It is obvious that there should exist, at least for sources having a common law of radiation, as in the case of carbon, a definite relation between the luminous energy per lux-centimeter and the temperature of the source of light. Estimates of the temperature of many of the sources already considered have been made by a variety of methods, but unfortunately the results are by no means consistent. If we take those sources for which the maximum of the energy curve has been determined and compute the absolute temperature from

Paschen's equation $\lambda_{\max} T = 2,940$, we may plot a curve for which ordinates are ergs per lux-centimeter and abscissæ are temperatures (see curve 3, Fig. 9). Flame sources for which temperatures have been directly determined by means of the thermocouple or by Ångström's method will not fall upon this curve for the reason that absolute temperatures determined by means of Paschen's equation, using Lummer & Pringsheim's constant for a black body, are always much higher for such sources than those obtained by direct measure-

Fig. 10.

ment. The Welsbach mantel, on account of its peculiar selective radiation falls far below this curve, and the same is true of the flame of the magnesium ribbon as computed from the relative temperature found by Rogers.

In the case of the Hefner lamp, the acetylene flame and the arc, two positions are indicated upon the diagram. The round dots falling upon curve 3 are " λ_{max} " temperatures, the crosses connected with these by a dotted line are respectively the temperature of the Hefner flame as determined by Ångström, that of the acetylene flame from measurements with the thermojunction and the temperature of the arc according to Waidner and Burgess. It seems certain from this figure that if we had consistent measurements of temperature for a body such as carbon between 1200° abs. and the temperature of the arc, the curve would show a sharp inflection at about 1700° . There are definite indications of such a trend in curve 2 for treated carbons and although the measurements with the thermojunction for untreated carbon do not carry us past the point of inflection, the lamp filament measured by Ångström at 2000° abs. lies nearly upon a continuation of curve 1.

If instead of taking the ergs per lux-centimeter we plot the intensity of the spectrum of these sources of light at wave-length $.7 \mu$ as a function of the temperature, the ordinates being in each case those which correspond to an illumination of one lux at meters distance, we get the curve shown in Fig. 10, which has an inflection point at the same temperature. Magnesium oxide and the Welsbach mantel, indicated respectively by the crosses "Mg" and "W," lie far below the curve for the carbon sources and it is evident that in optical pyrometry, where the variation of intensity of red light is used in the determination of the temperature of such a source, the "black temperature" will be very much higher than the actual temperature of the glowing body.

PHYSICAL LABORATORY OF CORNELL UNIVERSITY,
December, 1904.