PUBLICATIONS

OF THE

Dominion Astrophysical Observatory

VICTORIA

Vol. II, No. 12

THE WEDGE METHOD AND ITS APPLICATION TO ASTRONOMICAL SPECTROPHOTOMETRY

BY H. H. PLASKETT

ABSTRACT

The Wedge Method.—The essential features in this photographic method of spectrophotometry, which was devised by Merton and Nicholson, are the use of a neutral tint wedge in front of the spectroscope slit and the use of a source, the intensity distribution in the spectrum of which is known, as a standard. The *theory* of the method is given, and it is shown that the relative intensity (I_λ) in the spectrum of the unknown source is, in terms of the intensity (J_λ) in the standard source, $I_\lambda = J_\lambda \, 10^{m\sigma_\lambda (h_\lambda - h'_\lambda)}$. In this formula m is the ratio of collimator to camera focal length, σ_λ is the wedge constant and h_λ, h'_λ are the heights respectively in the wedge spectra of the unknown and standard source measured up to some constant blackening. It is further shown that the wedge method meets all the theoretical requirements of an accurate method of spectrophotometry. The importance of securing *uniformity of illumination* on the wedge is emphasized and a method of eliminating any errors due to this cause by reversal of the wedge is indicated. A more accurate and rapid *method of measurement* of the wedge spectra is described, which involves the use of a simple microphotometer. The *calibration* of the wedge to determine the value of σ_λ is given in some detail. In this connection the use of a source which meets some of the requirements of a photometric standard is emphasized. It is believed that the resulting values of σ_λ are accurate to within two per cent.

Colour Temperatures of Laboratory Standards.—The wedge method is used to determine the relative intensity distribution in the spectra of a *filament lamp*, calibrated by the Nela Laboratory, an *acetylene flame*, using the Eastman Kodak burner, and the *positive crater of the carbon arc* (cored carbons, 5.6 amps.). The *colour temperature* of a source is that temperature at which a black body would have to be maintained in order to give the same relative intensity distribution in the visible spectrum as the source. It is found that the wedge method reproduces the colour temperatures of the filament lamp, as determined at the Nela Laboratory, to within ±1%; inversely it is shown that if this be true the wedge constant σ_λ must be accurate to within ±1.5%. The colour temperature of the acetylene flame, using the filament lamp as a standard, is found to be 2340° ±10°K, as compared with the temperature of 2360° ±10°K found by Hyde and Forsythe. The colour temperature of the carbon arc (cored carbons, 5.6 amps.) is found to be 3080° ±30°K, and this result is discussed in the light of other investigations.

Intensity Distribution in the Solar Spectrum.—A careful investigation is made by the wedge method of the relative intensity distribution in the continuous spectrum of the sun. From Rowland's chart and his wave length tables 16 regions were selected, ranging in width from 1.3A in the violet to 18A in the red, in which there were no solar absorption lines of intensity greater than zero on Rowland's scale. The wedge spectra were made with the large reflector and the universal spectroscope in the one prism form with a purity of 5000. The solar spectra were made at each of five zenith distances on July 21, 1921. The positive crater of the carbon arc (colour temperature 3080° K) was used as a standard; the optical paths of the two sources differed only by a condensing system in the case of the arc and the terrestrial atmosphere in the case of the sun. The transmission coefficients of the condensing system were determined by computation, and of the atmosphere by the use of the ordinary Lambert formula from the measured solar wedge spectra for each of the five zenith distances. It is shown that the final results for the relative intensity distribution in the solar spectrum outside the earth's atmosphere, fit a black body curve over the range 0.40μ–0.67μ. The difference to the violet of 0.47μ between these results and those of Abbot and Wilsing can be ascribed neither to errors in the various methods of spectrophotometry nor to a variation in solar radiation, but rather to a distortion of the results of Abbot and Wilsing by solar absorption lines. A brief discussion follows on the reconciliation of the solar temperatures found by application of the various laws of radiation.

Intensity Distribution in Stellar Spectra.—A preliminary investigation is made by the wedge method of the relative intensity distribution in the spectra of six typical stars. Some experimental difficulty was experienced in securing satisfactory spectra. Expressing the relative intensity distributions as colour temperatures, the following values result: γ Cassiopeiae (Boe) 15,000°K, ξ Persei (Bo) 15,000°K, α Cygni (cA2) 9,000°K, δ Cassiopeiae (A5) 9,000°K, α Aurigae (gGo+F5) 5,500°–6,000°K, β Geminorum (Ko) 5,000°–5,500°K. These results are in fair agreement with those found by Wilsing and Scheiner, by Coblentz and by Sampson. The conclusion is reached from the data given by the wedge method, that the somewhat discrepant results of Wilsing and Scheiner for class B are probably due to actual departure from strict black body intensity distributions. The conclusion is confirmed by the white colour of the O-type stars, which on Saha's ionization theory are the hottest of the stars. The importance of determining the relative intensity distribution in these "early type" spectra is emphasized.

Introduction

A problem of considerable importance from both the astronomical and the physical viewpoint is the measurement of intensity in spectra. Spectrophotometry applied to sources of continuous spectra, such as the sun and the stars, furnishes the probable temperatures by an application of the laws of radiation. Applied to line spectra measures of intensity give promise of yielding much information on atomic structure, and in astronomy have already given an empirical law for the determination of stellar absolute magnitude. The problem of measurement of intensities in spectra is, however, rendered difficult by the lack of a method which is accurate, simple and adaptable. Thus, while the spectro-bolometer meets the condition of accuracy, it will only do so in the hands of experienced observers. Again, while the various forms of visual polarizing spectrophotometers are both accurate and comparatively simple to operate, they do not permit the registration of the intensity in the whole spectrum at one time, nor can they readily be applied to the measurement of intensities in faint sources or in line spectra.

A promising method of spectrophotometry, the possibilities of which have yet to be fully explored, had its origin in some work on the colour sensitivity of photographic plates by Mees and Wratten[1]*. In front of their spectroscope slit was placed a small neutral tint wedge so that the resultant spectrum on the plate resembled "a range of mountains" in which the crests showed places of maximum sensitivity and valleys minimum sensitivity. From this apparatus was developed by Merton and Nicholson[2] a method of spectrophotometry of the greatest theoretical accuracy and simplicity. In addition to a wedge spectrum of the source under examination, in their case a line spectrum, Merton and Nicholson also obtained a wedge spectrum on the same photographic plate or on the same batch of plates of a source, the intensity distribution in the spectrum of which was known. By measuring the heights of the two spectra at various wave lengths they were then able to determine "relative absolute" intensities of the line spectra of hydrogen and helium.

*References to the Introduction and Part I will be found at the close of Part I.

A preliminary investigation on the star γ Cassiopeiae[3] had shown that the wedge method could be applied to astronomical spectrophotometry, but had given no indication of either the peculiarities of the method or the accuracy of its results. The object of the present paper was, therefore, two-fold: first to determine the performance of the wedge method under standard laboratory conditions, and then secondly to apply it to the determination of intensity distribution in the spectra of the sun and some typical stars. Part I of the paper, accordingly, contains the complete theory of the method and an account of its laboratory applications, and Part II describes the results of the application of the method to astronomical spectrophotometry. The more important results of the investigation have been some improvements in technique of the method, the reproduction of the colour temperatures of laboratory sources to within one or two per cent, and a new determination of the energy distribution in the continuous spectrum of the sun, the limiting errors of which have been fixed with some degree of certainty.

The work described in this paper has been in progress for some three years. The length of this period has been due in part to interruption by other work, and in part to difficulties which have arisen during the course of the investigation. In the progress of this work my father, Dr. J. S. Plaskett, has always shown the keenest interest. When difficulties have arisen he has always been ready, at considerable sacrifice of time, to discuss them, and when new apparatus has been necessary his help in matters of mechanical design has been invaluable. Acknowledgment is due to Prof. H. N. Russell for a helpful discussion of the method during a brief visit to the observatory in 1921, and also to Dr. Hyde and Dr. Forsythe of the Nela Laboratory for supplying and calibrating the filament lamp used in Sec. 3.

Dominion Astrophysical Observatory,
Victoria, B.C.
May 4, 1923.

PART I.—THE WEDGE METHOD AND ITS LABORATORY APPLICATION

In this part of the paper is given a description of the wedge method and its application to the determination of the intensity distribution in certain standard sources. The theory of the method, together with some improvements in technique which have resulted from considerable experience in its application, are given in the first section. The method of calibrating the wedge is described in some detail in the second section, since it is upon this calibration that the accuracy of intensity distributions given by the wedge method depends. Finally, in the third section the relative intensity distribution in the spectra of certain laboratory standards is studied, namely a tungsten filament lamp standardized by the Nela laboratory, the acetylene burner of the Eastman Kodak Research Laboratory and the positive crater of the carbon arc.

Section 1.—Description of the Method

In this section following a brief general description of the wedge method, there is given in turn the theory of the method, a note on the mode of securing uniformity of illumination on the wedge, and a description of the measurement of the spectra.

General Description. The essential features in the wedge method of spectrophotometry, as used by Merton and Nicholson[2], may be readily described. In front of the spectroscope slit is placed a neutral tint wedge of the form shown in A, fig. 1. At its apex a the wedge is ground "infinitely" thin; its approximate dimensions are: height 6 mm., width 4 mm. and thickness at the base b 2 mm. The wedge is cemented to a piece of optical glass of the same refractive index, the whole forming a plane parallel plate which does not disperse or deviate the light. The light from the source, the intensity distribution in the spectrum of which is to be determined, is arranged to fall

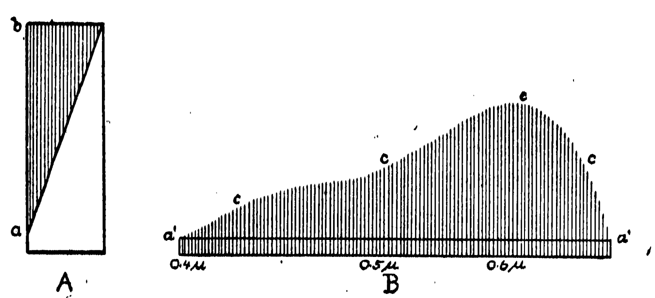

Fig. 1

on the wedge in a beam of *uniform* intensity along the wedge height ab. After transmission by the wedge and dispersion by the spectroscope, the light from the source forms a spectrum B, fig. 1 (see also Plate at end of number) on the photographic plate. The top bounding curve ccc of this spectrum varies in height, as measured from $a'a'$, depending upon the distribution of intensity with wave length in the source, the absorption in the wedge and the spectroscope, the lack of normality of dispersion in the latter and the colour sensitivity of the plate—all functions of wave length. Of these various quantities it is desired to determine only the intensity distribution in the spectrum of the source.

The absorption of the wedge is found from the calibration, and the effects of the other variables are eliminated by taking under the same conditions and on the same plate, a wedge spectrum of some standard source, such as the acetylene flame, the intensity distribution in the spectrum of which is known.

Theory of the Wedge Method. Let h_λ be the height of the spectrum measured at wave length λ from the line $a'a'$ (fig. 1B) up to a certain blackening or density D. On the wedge this corresponds to a height mh_λ measured from the apex a (fig. 1A), where m is a magnification factor given by the ratio of collimator to camera focus. Let I_λ be the intensity at wave length λ of the light falling uniformly on the wedge from the source the intensity of which is to be found and let K_λ be the intensity transmitted by the wedge at the height mh_λ. Then, where P_λ is the coefficient of extinction of the neutral tint glass, it follows from the ordinary laws of absorption that

$$K_\lambda / I_\lambda = 10^{-mh_\lambda \tan \alpha . P_\lambda}$$

where α is the angle of the neutral tint wedge at the apex a (fig. 1 A), and hence $mh_\lambda \tan \alpha$ is the thickness of the wedge of the height mh_λ. The quantity $P_\lambda \tan \alpha$ is a constant for the wedge, hereafter designated by σ_λ, and is actually the density of the wedge at unit height above the apex a (fig. 1 A). Hence there results

$$I_\lambda = K_\lambda\, 10^{m\sigma_\lambda h_\lambda} \quad \ldots\ldots (1)$$

in which on the right hand side σ_λ is determined by the wedge calibration, mh_λ by the measurement of the spectrum and only K_λ is unknown. By definition K_λ is an intensity which, after transmission by the spectroscope, produces a constant blackening D on the photographic plate over the whole range of spectrum. If now a second wedge spectrum be made on the same photographic plate with an equal exposure time of a source, the intensity J_λ of which is known, and the wedge spectrum height h'_λ measured to the same blackening D, it is clear that for this spectrum

$$J_\lambda = K_\lambda\, 10^{m\sigma_\lambda h'_\lambda} \quad \ldots\ldots (2)$$

where everything is known but K_λ. Dividing (1) by (2) gives

$$I_\lambda = J_\lambda\, 10^{m\sigma_\lambda (h_\lambda - h'_\lambda)} \quad \ldots (3)$$

where all the quantities on the right hand side are known, and hence the intensity distribution in the unknown source determined. It should be noted that the values given by (3) are not in absolute units (ergs $cm^{-2}\ sec^{-1}$), but are purely relative. In practice the value of I_λ/K_λ (a function of λ) is obtained from (1) using the measures of the spectrum of the unknown source and the value of K_λ (also a function of λ) from (2), using measures of the standard spectrum. The product of these quantities for each λ then gives I_λ, the "relative absolute" intensity distribution in the spectrum of the unknown source.

Equation (3), which is the fundamental equation of the method, involves one basic assumption, namely that the quantities K_λ appearing in (1) and (2) are identical. Recalling that K_λ is the intensity which after transmission by the spectroscope produces a constant blackening D on the plate over the whole range of spectrum this intensity will be changed to $b_\lambda K_\lambda$ before falling on the photographic plate, where b_λ is a factor depending upon the absorption of the spectroscope and its lack of normality of dispersion. Since the same spectroscope is used for both the unknown and the standard source, b_λ will be identical for each. The basic assumption that the two values of K_λ are identical is then equivalent to the assumption, that two monochromatic sources are of equal intensity when they produce the same blackening D on the same photographic plate after exposures of equal duration. Since clearly this latter assumption is not vitiated by the failure of the reciprocity law, the variation of contrast (photographic Purkinje effect) or inertia with wave length, and since further the absorption of the spectroscope is eliminated, it is evident that the wedge method meets all the requirements of an accurate method of spectrophotometry.

Under practical working conditions it is not always feasible to meet the requirements of the above simple theory. It thus becomes important to determine theoretically the effect (1) of a difference of exposure times between the unknown and the standard source and (2) of measuring the heights of the unknown and standard spectra up to different blackenings or densities. These may be considered in turn: (1) The work of Hurter and Driffield[4], Schwarzschild[5] and others has shown that over the straight line part of the characteristic curve of a photographic plate, the relation between intensity I_λ, exposure time t and density D is given by* $D = \gamma_\lambda (\log I_\lambda t^p - \log i_\lambda)$

or
$$I_\lambda = (i_\lambda / t^p)\, 10^{D/\gamma_\lambda}$$

where p is Schwarzschild's constant, i_λ is the inertia and γ_λ the contrast of the plate, the two latter being functions of wave length. Let t be the exposure time for the unknown source with a corresponding value of K_λ, and t_1 the exposure time for the standard with a corresponding value of K'_λ. Recalling that K_λ before falling on the photographic plate is changed to $b_\lambda K_\lambda$ by the absorption and dispersion of the spectroscope, there results—for the unknown source $b_\lambda K_\lambda = (i_\lambda/t^p)\, 10^{D/\gamma_\lambda}$; for standard $b_\lambda K'_\lambda = (i_\lambda/t_1^p)$ $10^{D/\gamma_\lambda}$ or $K_\lambda/K'_\lambda = (t_1/t)^p$. That is the fundamental equation (3) will take the form

$$I_\lambda = \left(\frac{t_1}{t}\right)^p J_\lambda\, 10^{m\sigma_\lambda (h_\lambda - h'_\lambda)}$$

Provided only that p, Schwarzschild's constant, is independent of wave length, this equation will give "relative absolute" intensity distributions equally well with (3). As far as the present writer is aware there is no trustworthy evidence of a variation of p with λ. The results of J. Stark[6] are sometimes quoted[7] as evidence of such a variation, but a reference to the original paper shows that Stark has found certain indices m and n to vary but these indices actually are $m = \gamma_\lambda$ and $n = p\gamma_\lambda$. Accordingly the variation found by Stark is almost certainly due to the well established variation of contrast (γ_λ) with wave length (the photographic Purkinje effect)[8]. On the other hand the conclusions reached by R. A. Mallet[7] in a recent investigation, that p is a constant for all variations of intensity and exposure within the normal range and that it is independent of those factors which "ultimately determine the sensitivity of the plate to light," make it highly probable that p does not vary with wave length. In the practical application of the

* Throughout this paper all logarithms are to base 10.

method it is therefore probably justifiable to use different exposure times for the unknown and standard source, provided they do not differ by more than ten to one; beyond this ratio small systematic variations of p would produce appreciable errors in the resultant values of I_λ. (2) Let the spectrum of the unknown source be measured to a density D with a corresponding value of K_λ, and of the standard source to a density D' with a resultant value of K'_λ. If now the exposure times of the two sources be the same, it follows immediately (see above) that $K_\lambda/K'_\lambda = 10^{(D-D')\gamma_\lambda}$ and (3) becomes $I_\lambda = 10^{(D-D')\gamma_\lambda} J_\lambda 10^{m\sigma_\lambda(h_\lambda - h'_\lambda)}$. Since γ_λ is a function of λ, it is evident that measures to different densities will introduce an error, the amount of which will depend upon $(D-D')$. In the practical application of the method, therefore, while variation of exposure within certain limits is probably safe, it will be advisable, and this procedure has been followed, always to measure the wedge spectra of the standard and the unknown sources up to the same density.

Uniformity of Illumination. It is of the utmost importance, as reference to the foregoing description and theory of the method will show, that the light from the source should fall in a uniform patch on the wedge along the height *ab*, fig. 1A. The effect of non-uniformity of illumination is in general equivalent to a change by an unknown amount of the wedge constant σ_λ, with the result that the relative intensity distribution given by (3) will be more or less seriously in error. Unfortunately this essential condition for the satisfactory performance of the method is not easy to meet. Considerable experience has shown that neither mere inspection of spectra taken without the wedge, nor even quite elaborate arrangements of apparatus afford any guarantee that the illumination will be uniform. Thus in a series of experiments with the acetylene flame and the carbon arc, though every precaution in the way of frequent tests and careful arrangement of the apparatus was taken, the resulting intensity distributions were found to be in error by some thirty per cent—an error which was eventually traced back to non-uniformity of illumination on the wedge. Eventually an accurate and simple method was found by which uniformity of illumination could be tested. If the illumination is uniform, reversal of the wedge will make no difference in the measured relative intensity distribution. With this check it is possible to arrange the apparatus so as to ensure approximate uniformity. Beyond this it is not necessary to go, for if the spectra be taken in pairs wedge erect and wedge reversed for each arrangement of the apparatus, in the mean of each pair the effect of non-uniformity will be eliminated.

Measurement of Spectra. In their original paper, Merton and Nicholson[2] measured their spectra by means of process screen enlargements. A negative enlargement of the wedge spectrum was made through a process screen; on this enlargement at each required wave length the last dot which could be seen, representing the threshold density, was marked and the height measured up to it. While this procedure eliminates personal error, it is probably somewhat inaccurate and is undoubtedly very wasteful of time. Unless precautions are taken in exposing and developing the contact positive and the negative enlargement, the threshold density will not be the same for standard and unknown sources; this, as shown in the above theory, will introduce an error due to the photographic Purkinje effect. Equally vital is the criticism that the method of measurement takes too long. Actual measurement cannot commence until the contact positive and satisfactory, "contrasty" process screen enlargement have been made. The time involved in the measurement, including these essential preliminaries, is thus prohibitive, and when, as has been the case in the present investigation, the number of spectra to be measured exceeds three hundred, the difficulty of measurement makes the method unpractical.

In the present paper a much simpler method of measurement has been used. Since it is required to measure at each wave length the height from the line $a'a'$, fig. 1 B, up to a point in the spectrum where the blackening is equal to D, all that is necessary is a simple form of microphotometer. As the observatory did not possess a microphotometer, a few modifications of the well known Hartmann spectrocomparator[9] have resulted in a very satisfactory piece of apparatus for this purpose. The light from a "daylight" tungsten lamp L passes through a ground glass screen A and a green filter (transmission $0{\cdot}49\mu-0{\cdot}60\mu$) on to two mirrors C_1 and C_2. From these it passes through the wedge spectrum at W and a density standard at S. The objectives O_1, O_2 form images of the wedge spectrum and the density standard at the interface F of the prisms P_3, P_4, where

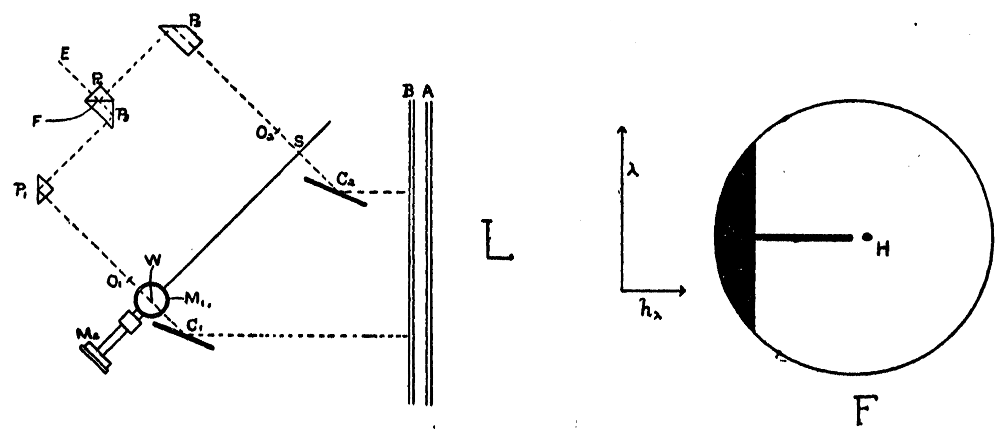

Fig. 2

the images are combined. The result is that on looking through the eyepiece the field F is seen. The wedge spectrum W can be seen through the small hole H and the horizontal line; surrounding the hole H can be seen the standard density patch at S. By turning the micrometer screw M_2 the wedge spectrum is moved in the direction of the λ arrow and any desired wave length may be set on. Then by turning the micrometer M_1 the wedge spectrum is moved in the direction of the h_λ arrow until a match of density in the wedge spectrum, as seen through the hole H, is obtained with the density standard patch surrounding H. A reading of the micrometer screw M_1 thus gives the required value of h_λ for any required wave length in the wedge spectrum.

It will be observed by those familiar with the Hartmann spectrocomparator, that only two additions have been required to convert it into a simple microphotometer for the measurement of wedge spectra. The one of these is the additional micrometer carriage M_2 for moving the spectrum in wave length. The final mechanical design of this micrometer is due to J. S. Plaskett and it was constructed by a machine shop in Victoria. It is held in place on the lower stage of the spectrocomparator by set screws so that it may be readily removed or replaced. The other necessary addition was the pattern on the interface F of the prisms P_3, P_4. One of the spare sets of prisms was separated, cleaned and a fresh coat of silver deposited on the appropriate face. By means of a soft iron gramophone needle, sharpened to a chisel-shape edge, the silver was removed from the hole H and the horizontal line. The actual diameter of the hole was 0·25 mm, and its projected image on the plate was elliptical with axes 0·07 mm. (in the h_λ co-ordinate) and 0·05 mm. (in the λ co-ordinate). This has been found a convenient size as it comprises a sufficient number of grains to make accurate density matching possible and yet is small compared with λ and h_λ.

Certain precautions in the use of the instrument are essential for accurate measurement. Three of these may be mentioned. (1) The density standard at S, which consists of a photographic plate with a number of patches the densities of which range from 0·3 to 1·0, should be the same emulsion as the wedge spectrum undergoing measurement. (2) By means of the usual adjustments on the spectrocomparator, the magnification of the two microscopes should be made identical. (3) When the wedge spectrum W and the standard S are removed, the hole H and the surrounding region should be of equal brightness. This condition is readily met by using two equal density patches at S and W and adjusting the mirrors until they appear of equal blackening. Of these precautions (1) and (2) are important because they make the matching of densities easier and (3) is essential in order that all spectra be measured to the same blackening *D*. Observing these precautions, very satisfactory measures can be made. The practice has been to measure each plate twice, making two density matches at each wave length at each measure. The resulting values of h_λ are therefore the means of four measures; as a rule the various measures for a given spectrum and wave length do not differ among themselves by more than $\pm 0{\cdot}04$ mm., which gives some idea of the accuracy of the method of measurement. A spectrum can be completely measured, i.e., the mean value of h_λ obtained for some twelve to fourteen wave lengths, in about an hour—a period which compares very favourably with that which experience has shown to be necessary for the process screen enlargement method.

The chief features in the wedge method, as described in this section, may now be summarized:—

(1) It has been shown, that the wedge method gives the intensity distribution I_λ in the source under investigation, in terms of J_λ, the intensity distribution in the standard, from the equation

$$I_\lambda = J_\lambda \, 10^{m\sigma_\lambda (h_\lambda - h'_\lambda)} \quad . \; . \; . \; . \; (3)$$

where m is a magnification constant, σ_λ the wedge constant and h_λ, h'_λ the measured heights in the two spectra up to a density *D*. The method eliminates errors due to absorption or lack of normality in dispersion in the spectroscope, and all errors due to peculiarities of the photographic plate. A slight extension of the theory shows that the exposure times of the unknown and the standard source may be varied within certain limits (10 : 1) without introducing appreciable error, but that the two spectra must always be measured to the same density.

(2) By taking spectra in pairs, wedge erect and wedge reversed, it has proved possible to detect and eliminate any errors due to non-uniformity of illumination on the wedge.

(3) A new and simpler method of measuring wedge spectra is described in which a Hartmann spectrocomparator is used as a microphotometer. This method of measurement gives probably more accurate results in a fraction of the time required for the process screen method.

Section 2.—Calibration of the Wedge

Entering as it does exponentially into the formula (3) for intensity distribution, the wedge constant σ_λ must be determined with the greatest accuracy. Two calibrations of the wedge, W.iv, used throughout this investigation, have been made. The first, owing probably to undetected non-uniformity of illumination, though other factors contributed, gave values for the wedge constant in error by some 25 per cent. Consequently, though the spectra were satisfactory and the measures accurate, the relative intensity distributions computed with this incorrect wedge constant were all in error. Results of a bizarre nature for the intensity distribution in the sun and stars were therefore obtained (see abstract to American Astronomical Society[10]), which led to considerable investigation to determine their cause. The final outcome was that the results of the first calibration were suspected and a new and considerably more accurate determination of the wedge constants was made. In this section it is proposed to consider this final calibration in some detail, treating in turn the theory, the experimental details and the final results.

Theory of the Calibration. The wedge is placed in front of the spectroscope slit and the light from the source is arranged to fall on the wedge in a uniform beam. Let I_λ be the intensity at wave length λ in the source and h'_λ, for a certain exposure, the corresponding height of the wedge spectrum measured up to a certain density. Then from equation (1)

$$I_\lambda / K_\lambda = 10^{m\sigma_\lambda h'_\lambda}$$

If now the intensity of the source is changed by the factor j, then for the same exposure time and for a measure of the spectrum to the same density the height will be h''_λ where

$$j\, I_\lambda / K_\lambda = 10^{m\sigma_\lambda h''_\lambda}$$

Dividing and taking logarithms gives $\log j = m\sigma_\lambda\, (h''_\lambda - h'_\lambda)$ or

$$\sigma_\lambda = \frac{\log j}{m(h''_\lambda - h'_\lambda)} \quad \cdot \cdot \cdot \cdot \cdot \ (4)$$

The dimensions of σ_λ are $[L]^{-1}$ and its physical meaning is, as pointed out in sec. 1, the density at unit height on the wedge. The exact value of σ_λ therefore depends upon the units in which the wedge spectra are measured: throughout this paper the units are revolutions on the one half mm. pitch micrometer screw (M_1 of fig. 2) of the Hartmann spectrocomparator. It will be noted from equation (4) that to determine the wedge constant σ_λ for a given wave length it is necessary to find only the value of m, the magnification constant, the difference in height of the two wedge spectra measured to the same density, and the value of j, the factor by which the intensity of the source is changed.

Experimental Details.—The apparatus consists of (1) the source, (2) a condensing lens, (3) an arrangement for changing the intensity by some factor j, and (4) the spectroscope with the wedge in front of the slit. The parts of the apparatus are best considered in turn.

(1) *Source of Light.* It is essential that the intensity of the source of light be constant during the exposure of a pair of spectra. Otherwise there is no guarantee that the intensity is changed in the exact ratio j by whatever means is adapted for that purpose. The sources hitherto used in wedge calibration have been as follows: Merton and Nicholson[2], a helium vacuum tube, Toy and Ghosh[11] in their calibration of the Goldberg wedge, a mercury arc and a metal filament lamp; and the writer a Pfund iron arc in his γ Cassiopeiae paper[3], and a mercury arc for his first erroneous calibration of the wedge W.IV. Clearly these sources do not meet the most elementary requirements of photometric standards, and are therefore likely to introduce more or less serious errors into the resulting wedge constants.

In the present calibration the acetylene flame of the Eastman Kodak Research Laboratory burner has been used. This burner gives a cylindrical flame some 5 cms. in height and about 3 mm. in diameter at its widest part. The flame is protected by a cylindrical metal chimney in which there is a re-entrant rectangular opening of 3 mm. aperture set at about 2 cms. above the burner tip. The light from the flame, defined by this small aperture, has been found by Sheppard and Mees[12], and more recently by L. A. Jones[13], to serve as a source of constant intensity. The burner which was supplied and calibrated by the Eastman Kodak Research Laboratory gives 1·2 candlepower at a pressure of 9 cms. of water; provided the gas pressure is controlled to within 0.2 cms. the intensity variations are negligible[13]. The pressure was maintained at the required 9.0 ± 0.1 cms. with the aid of a water manometer and a valve. The acetylene used was a commercial preparation, Prestolite, dissolved in acetone under pressure. In order to purify the gas it was passed in turn through an aqueous solution of chromic trioxide (chromic acid), a 35 per cent solution of sodium hydroxide and anhydrous calcium chloride. This method of purification was suggested by Prof. E. H. Archibald, of the Department of Chemistry, University of British Columbia. He points out that acetone impurities in the acetylene will be oxidized by the chromic acid to acetic acid and carbon dioxide and that the latter will be taken out by the sodium hydroxide solution; aldehydes and ammonia will be removed by the acid solution and sulphuretted hydrogen by the sodium hydroxide. It is probable therefore that the dried gas delivered to the burner is very closely pure acetylene. In short, since in this investigation the necessary conditions of gas pressure and purity have been observed, it may be taken that the acetylene flame given by the Eastman Kodak Research Laboratory burner is a secondary photometric standard and meets those requirements of constancy essential in a source for the wedge calibration

(2) *Lens.* The condensing lens was an old Petzval portrait lens made by Dallmeyer of 4 cms. aperture and 12 cms. focal length. On account of its wide angular aperture

it was possible to project a two-or three-fold magnified image of the 3 mm. aperture of the acetylene flame on to the slit, and yet at the same time fill the collimator. A recess between the two principal components allowed the insertion of diaphragms for changing the intensity of the transmitted light.

(3) *Methods of varying the intensity.* A problem of considerable difficulty in the wedge calibration is to find a suitable method of varying the intensity of the source by some definite and readily determined factor j. The method adapted has to be a compromise between the utmost accuracy and that essential condition of the wedge method, uniformity of illumination on the slit. In the present investigation two independent methods have been used, neither of which is entirely satisfactory but which in the mean may be expected to give accurate results. In the one case diaphragms pierced with holes have been inserted in the recess for that purpose in the Petzval lens, and in the other a slowly rotating sector has been interposed close to the spectroscope slit. Two diaphragms were used, each drilled with 61 symmetrically and identically placed holes; the apertures in the one diaphragm were all 2·0 mm. approximately and in the other 3·2 mm. The value of j is given by the square of the ratio of the mean diameters of the holes and is approximately $j = 2 \cdot 6$. The sector consisted of a circular brass disc some 15 cms. in diameter with a 120° aperture cut in it. The sector was balanced by soldering additional strips of brass at appropriate places, so that it was always in neutral equilibrium. The assumption involved in the use of the sector is that the intermittent light integrates itself by simple summation, an assumption which Sheppard and Mees[14] find to be justified for speeds not exceeding 100 r.p.m. Accordingly the sector was driven by a small electric motor at an average rate of 90 r.p.m. The value of j is of course approximately 3·0.

(4) *Wedge and Spectroscope.* The wedge (W.IV) to be calibrated was mounted in a small brass cell so that it could be reversed and so that the wedge itself was in contact with the slit. The wedge (approximate dimensions 6 x 4 x 2 mm. at base) was made by Hilger with astronomical spectrophotometry in view; its density at the apex was, of course, zero and at the base or thick end less than two. The spectroscope was the former Ottawa instrument designed by J. S. Plaskett and described elsewhere[15]. It was mounted on a firm wooden base and has proven very satisfactory for laboratory purposes. The spectroscope was used in the one-prism form with a short focus (29 cms.) Zeiss Tessar lens of 4·5 cms. aperture as camera objective. The definition was excellent, though the field was not perfectly flat over the whole range of spectrum; a compromise focus gave, however, satisfactory results. In order to determine the value of m, which it will be recalled from sec. 1 is the ratio of collimator to camera focus, a somewhat accurate method was chosen. In a small brass diaphragm which could be mounted, like the wedge cell, in front of the slit, was cut a slot some 10 mm. in length and about 0·25 mm. wide. This slot was crossed by two fine micrometer wires separated by some 6 mm. When the diaphragm was placed with the slot in line and in contact with the slit and an iron arc spectrum taken, the resulting spectrum was crossed by two narrow white lines, like dust marks on the slit. The ratio of the true separation of the wires, determined from a contact shadow photograph of the diaphragm, to the measured separation on the spectrum gave the value of m for each wave length. The advantage of this

method over that adopted by Merton and Nicholson[2] (also used in Part II of this paper) and over that adopted by Toy and Ghosh[11], is that there are no errors due to unequal spreading of the images.

This description of the experimental details of the calibration may well be concluded with an account of how the spectra were made. Four spectra on two plates were required to give one set of values for the wedge constant σ_λ. For the first plate the wedge was placed in the erect position, that is, with the apex a (fig. 1 A) at the bottom of the slit. Two spectra were then made, each with identical exposure times, one with the sector, say, interposed and the other with the sector removed. A small diaphragm was placed in front of the wedge after each exposure, a mirror introduced in the optical path and a comparison spectrum of the iron arc inserted at the base of each wedge spectrum. For the second plate precisely the same arrangement was followed, except that the wedge was reversed. Reversal of the wedge thus ensured that any error due to slight non-uniformity of illumination would be eliminated in the mean of the measures of $h''_\lambda - h'_\lambda$ for the two plates. In this way ten plates comprising twenty spectra were made with the sector and a similar number with the diaphragms. For the green to the red Ilford Panchromatic plates were used, and for the blue to the violet Seed 23 and Seed 30 plates.

Results of the Calibration. To determine the value of σ_λ it is necessary to know the value of j, the corresponding difference in height of the two spectra $h''_\lambda - h'_\lambda$, and the value of m, where

$$\sigma_\lambda = (\log j)/m\ (h''_\lambda - h'_\lambda) \quad . \ . \ . \ . \ (4)$$

The value of j is given in the case of the sector by the ratio 360°/angle of opening. The angle of the opening was measured at three points along the radius by means of an accurate protractor reading to minutes of arc. After each set of three determinations the protractor was rotated through 180° and re-centred; in all 36 readings of the angle were made, with a probable error of the mean of 1′·2. Precautions were taken to avoid errors due to parallax in setting on the edge of the sector opening. There was some evidence that the sides of the sector opening were not exactly radial though the amount of error did not exceed 10′. This was adopted as the error in the angle of the sector rather than the probable error of the mean of the 36 measures. The resultant values, with errors, of the angle and j were:—Angle of Sector (mean of 36 measures) = 119° 45′·3 ± 10′ j = 360°/ (119° 45′·3 ±10′) = 3·006 ± ·004: log j = 0·4780 ±0·0006. In the case of the diaphragms the value of j is given by the square of the ratio of the diameters of the holes drilled in the two diaphragms. Of the 61 holes drilled in each diaphragm, 17 were selected at random in each and their diameters determined on the measuring machine. The resultant mean values expressed in revolutions, where 1 revolution is 0·5 mm., are:

Mean diameter of 17 (3·2 mm.) holes, D_1 = 6·4791 ± 0·0021

Mean diameter of 17 (2·0 mm.) holes, D_2 = 4·0556 ± 0·0041

$$\therefore j = (D_1/D_2)^2 = 2{\cdot}5523 \pm 0{\cdot}0038 : \log j = 0{\cdot}4069 \pm 0{\cdot}0006$$

The errors of D_1 and D_2 are simply the probable errors of the means of the measures and they are carried through to give the resultant probable error for log j. Summarizing the values of log j are: Sector 0·4780 ± 0·0006 : Diaphragms 0·4069 ± 0·0006.

The value of m is given by the ratio—true separation of wires in gauge to separation as measured on the spectra. Five plates were obtained during the calibration on each of which was a contact shadow image of the diaphragm (giving the true separation) and an iron arc spectrum with shadow lines giving the separation as produced by the spectroscope. The values of m were determined at 11 wave lengths and the mean values plotted against wave length. The values ran from $m = 1 \cdot 727$ for $0 \cdot 39\mu$ up to $m = 1 \cdot 730$ for $0 \cdot 43\mu$ and back to $m = 1 \cdot 723$ for $0 \cdot 67\mu$. The variation is, of course, due to the fact that the field of the camera lens is not perfectly flat.

In order to determine σ_λ the only other quantity now required is $(h''_\lambda - h'_\lambda)$, which is the difference in height of two wedge spectra exposed equal times to the one source, the intensity in which is changed by the factor j. The spectra were measured on the Hartmann spectrocomparator, as described in sec. 1. A typical set of results for two pairs of spectra taken on October 10th, 1922 on Seed 23 plates with exposure times all equal to 5 minutes is given in Table 1. The intensity of the source was changed by means of the sector, that is $\log j = 0 \cdot 4780$. The first column gives the wave length in the spectrum at which the heights were measured, the second column the value of m as determined above, and the third column gives the difference in height of the two spectra made with the wedge erect with the corresponding value of σ_λ in the fourth column. The fifth and sixth columns give values of $h''_\lambda - h'_\lambda$ and σ_λ for the two spectra made with the wedge reversed. The final column contains the mean values of σ_λ for each wave length from

TABLE 1.—TYPICAL SET OF RESULTS FOR σ_λ

λ	m	Wedge Erect		Wedge Reversed		Mean Value
		$h''_\lambda - h'_\lambda$	σ_λ	$h''_\lambda - h'_\lambda$	σ_λ	σ_λ
Spectra measured up to a density 0·6						
0·3930μ	1·727	1·60	0·173	1·61	0·172	0·172
0·3969	1·727	1·68	0·165	1·82	0·152	0·158
0·4046	1·727	1·78	0·155	1·79	0·155	0·155
0·4119	1·728	1·90	0·146	1·88	0·147	0·146
0·4202	1·729	1·85	0·149	1·94	0·142	0·146
Spectra re-measured up to a density 0·9						
0·3969	1·727	1·64	0·169	1·68	0·165	0·167
0·4046	1·727	1·79	0·155	1·90	0·146	0·150
0·4119	1·728	1·86	0·149	1·95	0·142	0·145
0·4202	1·729	2·02	0·137	1·94	0·142	0·140
0·4308	1·730	2·02	0·137	2·06	0·134	0·135

the wedge erect and wedge reversed results. It will be observed that the spectra have been measured in duplicate, once to a density 0·6 and once to a density 0·9. At a given wave length the values of σ_λ wedge erect and wedge reversed, measured to density 0·6 and 0·9 should all be identical. Any difference may be safely ascribed to accidental error plus a certain amount of non-uniformity of illumination on the wedge. The mean value of σ_λ for a given wave length from Table 1 will eliminate any error due to non-uniformity of illumination, and the accidental error will be taken care of by other sets similar to those contained in the table.

From ten sets of results similar to that given in Table 1, it has been possible to form mean values of σ_λ for 18 wave lengths. The means have been obtained in the following manner. For a given wave length each value, wedge erect and reversed, has been given weight unity; when it is the mean of measures to two densities, each value, wedge erect and reversed, is given weight one and a half. This procedure has been adopted since two determinations of σ_λ from different plates are of greater weight than two determinations from the same plate. The resultant weighted means of σ_λ are given in Table 2. The first column contains the wave length, the second the weighted mean value of σ_λ from those spectra in which the intensity was changed by the sector, the third column the weighted mean values of σ_λ from those spectra in which the intensity was changed by the diaphragms and the fourth column contains the difference sector-diaphragm expressed as a percentage. These differences are obtained from values of σ_λ carried to the fourth place, and hence will not as a rule be identical with those obtained from the same values rounded off to the third place. In the fifth column are given the weighted mean values of σ_λ from both determinations, and the sixth and seventh columns contain respectively the probable error of this weighted mean and the number of observations on which it is based. In fig. 3 the weighted mean values of σ_λ given in the fifth column

TABLE 2.—MEAN VALUES OF WEDGE CONSTANT

λ	Sector	Diaphragms	% Diff. (S–D)	Weighted Mean σ_λ	p.e. Weighted Mean	Number of Observations
0·3930μ	0·172	0·170	+1·7%	0·171	± 0·001	4
0·3969	0·163	0·162	+0·2	0·162	·001	6
0·4046	0·150	0·151	−0·7	0·150	·001	8
0·4119	0·147	0·153	−4·3	0·149	·001	8
0·4202	0·140	0·145	−3·5	0·142	·001	9
0·4308	0·137	0·132	+3·2	0·136	·002	9
0·4415	0·134	0·133	+1·1	0·133	·002	11
0·4529	0·123	0·125	−1·9	0·124	·002	11
0·4603	0·114	0·118	−3·3	0·116	·002	11
0·4872	0·113	0·111	+2·2	0·112	·001	11
0·4957	0·114	0·106	+6·8	0·110	·001	10
0·5233	0·110	0·110	−0·2	0·110	·001	5
0·5371	0·113	0·111	+2·1	0·112	·001	5
0·5616	0·109	0·109	+0·5	0·109	·001	10
0·6137	0·106	0·106	+0·3	0·106	·002	8
0·6394	0·106	0·106	+0·4	0·106	·002	5
0·6496	0·105	0·104	+1·0	0·105	·003	5
0·6678	0·097	0·098	−1·4	0·098	·002	8

of Table 2 are plotted against wave lengths and a smooth curve drawn through them. From this curve can be read off the value of σ_λ for any desired wave length.

This discussion of the results of the calibration may be concluded by indicating the nature and the probable amount of the errors which enter into the final mean values of σ_λ. Accidental errors due to exposure times for a pair of spectra being not identical, or due to errors in measurement will in the mean eliminate themselves. Three sources of systematic error must, however, be considered: (1) in the value of $(\log j)/m$, (2) non-uniformity of illumination, and (3) errors due to sector and diaphragms. (1) The value

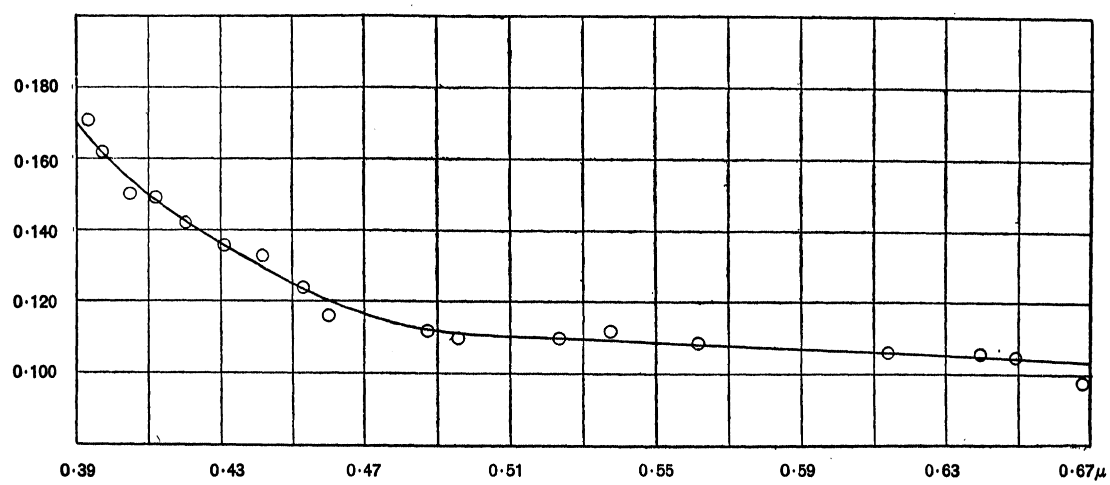

Fig. 3. Wedge Constant σ_λ

of log j for both the sector and the diaphragm and the value of m the magnification constant have been determined with an accuracy such that the systematic error due to this cause is less than 0·2 per cent. (2) The mean difference wedge erect and wedge reversed is +1·9 per cent, showing that on the average the image of the flame was weaker at the top of the slit. In the mean wedge erect and reversed, the error due to this slight non-uniformity should be eliminated. Similarly the slight differences between measures made with the two densities 0·6 and 0·9 amounting in the mean to +1 per cent, may be likewise ascribed to non-uniformity and in the mean of the two measures any error may be expected to disappear. (3) This only leaves for consideration the difference between the results for the sector and the diaphragm. The mean of the differences in the fourth column is +0·2 per cent and without reference to signs it is 1·9 per cent. The run of the signs does not appear systematic, and it may be concluded that the assumptions involved in the use of the sector and diaphragms to change the intensity are probably justified. Summarizing, it appears that the values of σ_λ as obtained from the curve in fig. 3 should be accurate to within two per cent.

Section 3.—Relative Intensity Distribution in Laboratory Standards

The purpose of the work described in this section was two-fold. In the first place it was desired to test the accuracy with which the wedge method would reproduce the relative intensity distribution of standard sources calibrated in other laboratories; and in the second place it was necessary to determine the relative intensity distribution of the radiation emitted by the positive crater of the carbon arc, since this was the source used as a standard in the astronomical work described in Part II. Accordingly, after some introductory remarks on standards of radiation the section is divided into two main parts—the one referring to results with two laboratory standards and the other to the relative intensity distribution in the carbon arc.

Radiation Standards. The primary standard of intensity distribution is the laboratory black body, the temperature of which above 1373°K is determined by an application of the laws of radiation (Stefan's, Wien's and Planck's). By its aid a well-established high temperature scale[16] has been fixed which includes melting points ranging from 1828°K for palladium to 3675°K for tungsten. Investigators[17], notably Coblentz, Hyde and Forsythe, and Priest, have further established that other sources of continuous spectra have the same relative intensity distribution in the region $0\cdot4\mu$ to $0\cdot7\mu$ as a black body maintained at certain definite temperatures. Thus purified acetylene gas[18] burned in the Eastman Kodak Research Laboratory burner at a pressure of 9 cms. of water has the same relative intensity distribution as a black body maintained at a temperature of 2360°K. Such temperatures are termed "colour temperatures," where the colour temperature of a source of continuous spectrum is that temperature at which a black body would have to be maintained, in order to give a relative intensity distribution identical with that of the continuous spectrum of the source. Colour temperatures may be determined radiometrically (that is the exact energy distribution measured by a bolometer or thermo-couple) as Coblentz has done, by optical pyrometry in two wave lengths, by colour matching according to the method of Hyde and Forsythe, or by Priest's method of colour matching with the aid of rotary dispersion. All methods, as repeated interlaboratory comparisons have shown [17, 18, 19,] are in close agreement. The result is that sources, such as the acetylene flame and seasoned filament lamps, the colour temperatures of which have been determined by any one of these methods, furnish accurate secondary standards of relative intensity distribution.

In the investigation described in this section three sources have been used, two of which are such secondary standards. These sources are the acetylene flame, a tungsten filament lamp and the carbon arc. Each one of these together with its necessary experimental accessories will be described here in order to avoid repetition throughout the remainder of the section. The Eastman Kodak Research Laboratory *acetylene burner*, together with the arrangements for purifying the Prestolite acetylene gas and maintaining the pressure at $9\cdot0 \pm 0\cdot1$ cms., have already been described in sec. 2. The relative intensity distribution in this source[18] has been determined radiometrically by Coblentz and by Hyde and Forsythe spectrophotometrically and by colour matching. These investigators are now agreed that the colour temperature of the flame, limited, of course, by the 3 mm. aperture (see sec. 2) is $2360° \pm 10°$K. The *ribbon tungsten lamp*, which was very generously supplied and calibrated by the Nela Research Laboratory of the General Electric Co., is a seasoned lamp with a tungsten filament some $3\cdot5$ cms. in length, $0\cdot15$ cm. in width and of a thickness to give one-half ohm resistance. Current for the lamp was furnished by a 16 volt storage battery connected up through a variable

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resistance and a Weston D.C. ammeter. With this arrangement it was found possible to maintain the current through the filament lamp at any desired value within ±0·2 amperes. The colour temperatures of the lamp for various currents were determined by Dr. W. E. Forsythe[20]. Typical of his results are the following:—12 amps., T=2010°K; 16 amps., T=2439°K; 20 amps., T=2830°K. It has been assumed, though this was not explicitly stated, that these colour temperatures refer to the central portion of the filament. The *positive crater of the carbon arc* used in the present investigation was given by cored carbons and a current of 5 to 6 amperes. The arc burned in a hand feed lamp with the positive carbon horizontal. Current was supplied by the 220 volt D.C. generator of the observatory with a suitable resistance in the circuit to reduce the current to the required amount. The carbons were 1·4 cms. in diameter with a paste core of 0·3 cms.; the great advantage of the core is that it tends to hold the crater central and steady, an important feature when it is the intensity distribution in the crater itself that is desired. The carbons used in the investigations described in this section and Part II were all carbons from one batch supplied to the observatory some years ago by Bausch and Lomb. The temperature of the positive crater of the carbon has been determined in a variety of ways[21] with temperatures ranging from 3400°K to 4200°K. The only colour temperatures are those of Priest[19] who finds 3780°K for solid carbons and 3420°K for cored carbons in a 10-ampere arc. From this range of temperatures it is evident, if the arc is to be used as a secondary standard of intensity distribution, that the colour temperature must be determined for the particular current and batch of carbons used.

Filament Lamp and Acetylene Flame. The primary purpose of the work, now to be described, was to find the accuracy with which the wedge method would reproduce the colour temperatures, that is the relative intensity distributions, of the filament lamp and the acetylene flame. A magnified image of the 3 mm. aperture of the acetylene flame, or the central 3 mm. of the ribbon filament as required, was formed at the spectroscope slit by the Petzval condensing lens; the spectroscope and condensing lens were the same as described in sec. 2. In front of the slit was placed the wedge, W.IV, the calibration of which has been given, in its small cell which could be reversed. The wedge spectra were taken on Ilford Panchromatic Plates out of one box, on the assumption that the photographic properties for equal development were identical for all the plates within the accidental error—an assumption the accuracy of which can be tested from internal evidence on the plates, and has always been found justified. The spectra were made in pairs, wedge erect and reversed, for each source and experimental arrangement. An iron arc comparison spectrum was made at the base of each spectrum for purposes of identifying wave lengths. Negative enlargements of some of the spectra will be found in the Plate (Nos. 1, 2, 3, 4) at the end of this number. The following spectra were made:

Lamp (12 amps)—3 pairs spectra. Exposures 10 to 25 secs.; mean = 16 secs.
Lamp (16 amps)—3 pairs spectra. Exposures 10 to 35 secs.; mean = 20 secs.
Lamp (20 amps)—3 pairs spectra. Exposures 12 to 35 secs.; mean = 22 secs.
Acetylene flame—5 pairs spectra. Exposures 15 to 60 secs.; mean = 35 secs.

The exposure times, it will be noted, lie well within the 10:1 limits specified in sec. 1, and were brought to this approximate equality by the use of sectors and diaphragms.

In order to determine the value of m, the magnification factor, use was made of the diaphragm for that purpose described in sec. 2.

Equation (1) of sec. 1 gives the relation $I_\lambda/K_\lambda = 10^{mh_\lambda\sigma_\lambda}$; from this equation the value of I_λ/K_λ can be found for any of the above sources. The heights h_λ of the wedge spectra at certain selected wave lengths were measured on the Hartmann spectrocomparator, as described in sec. 1, up to a constant density of 0·7. The value of m was determined from measures of plates made with the magnification diaphragm, and the necessary values of σ_λ were read off from the curve fig. 3. A typical example of the method of reduction is given in Table 3 for an acetylene flame spectrum, wedge erect, secured on January 4th, 1923. The first column contains the wave length at which measurement was made, the second the mean measured height h_λ, the third the value of m, and the fourth the value of σ_λ. The fifth column contains the product $m\sigma_\lambda h_\lambda = \log I_\lambda/K_\lambda$ and in the sixth column is given the anti-logarithm or I_λ/K_λ. The method of reduction, it will be noted, is simple and can be rapidly carried out on a slide rule. The 10 acetylene flame spectra and the 6 spectra from the lamp at each of three currents were measured and reduced in this way. In order to mean the values for a given source it was necessary to multiply each set of values, similar to those contained in Table 3, by a factor so that all would have a common value over a certain region of the spectrum.

TABLE 3.—EXAMPLE OF PRELIMINARY REDUCTION: ACETYLENE FLAME

λ	Mean h_λ	m	σ_λ	$m\sigma_\lambda h_\lambda$	I_λ/K_λ
0·4603μ	0·46	1·730	0·120	0·096	1·25
0·4872	0·49	1·729	0·112	0·095	1·24
0·4957	0·43	1·728	0·111	0·083	1·21
0·5233	1·34	1·727	0·110	0·255	1·80
0·5430	2·28	1·727	0·109	0·429	2·69
0·5616	2·92	1·726	0·108	0·544	3·50
0·5915	4·44	1·726	0·107	0·821	6·62
0·6137	5·18	1·726	0·106	0·947	8·85
0·6394	6·17	1·725	0·105	1·116	13·06
0·6496	6·44	1·725	0·104	1·153	14·22
0·6678	5·66	1·725	0·104	1·014	10·33

The procedure of course is legitimate, since the values of I_λ/K_λ are only relative, and all that is eventually required is a relative intensity distribution. Any errors due to non-uniformity of illumination on the wedge will be eliminated of course in these means, since they contain an equal number of wedge erect and reversed spectra. The mean values of I_λ/K_λ for each source are given in Table 4 which is self explanatory.

In order now to determine the relative intensity distribution in these sources it is necessary to know the value of K_λ. This, of course, may be obtained by regarding any

TABLE 4.—MEAN VALUES OF I_γ/K_γ FOR VARIOUS SOURCES

λ	Lamp 12 amps. 6 spectra	Lamp 16 amps. 6 spectra	Lamp 20 amps. 6 spectra	Acetylene Flame 10 spectra	λ	Lamp 12 amps. 6 spectra	Lamp 16 amps. 6 spectra	Lamp 20 amps. 6 spectra	Acetylene Flame 10 spectra
0·3930μ	....	....	0·18	....	0·5233	1·14	2·19	2·60	1·88
0·4072	....	....	0·64	....	0·5430	1·66	3·00	3·41	2·66
0·4202	....	0·60	0·98	....	0·5616	2·22	3·72	4·03	3·46
0·4326	....	0·92	1·53	0·72	0·5915	4·56	6·56	6·57	6·28
0·4529	0·50	1·43	2·01	1·15	0·6137	6·23	8·56	7·87	8·28
0·4603	0·60	1·68	2·23	1·29	0·6394	9·96	12·52	10·90	12·04
0·4872	0·60	1·49	1·84	1·24	0·6496	11·28	13·29	11·79	13·16
0·4957	0·63	1·45	1·76	1·22	0·6678	8·38	9·10	7·70	9·23

one of the four sources as standard, computing its relative intensity distribution from its colour temperature by the aid of Wien's law and hence deriving the value of K_λ. For simplicity the data in Table 4 are treated in the following manner. (1) The lamp at 20 amps. and Nela colour temperature 2830°K is taken as a standard and the value of K_λ computed; from this value of K_λ the relative intensity distributions in the lamp at 12 and 16 amps. are computed and compared with the Nela values. (2) The lamp at all currents is taken as a standard, the mean value of K_λ computed and the relative intensity distribution in the acetylene flame determined.

(1) According to the Nela calibration[20] the colour temperature of the lamp at 20 amps. is T=2830°K. The relative intensity distribution in this source may be computed from Wien's law $J_\lambda = c_1 \lambda^{-5} e^{-c_2/\lambda T}$ where c_1 may have any arbitrary value, since only relative intensities are needed, and where $c_2 = 14350$ micron degrees has been used throughout this paper in accordance with the Optical Pyrometry Report of 1919[16] and the Report for 1920[17]. The resultant values of J_λ, K_λ and I_λ for the lamp at 12 and 16 amps. are given in Table 5. The first column contains the wave length, the second the computed relative intensity distribution J_λ for a source with colour temperature 2830°K, the third column contains the values J_λ/K_λ for the lamp at 20 amps. (identical with the fourth column of Table 4), and the fourth column is the resultant value of K_λ, given by the ratio (column 2/column 3). The fifth and seventh columns contain I_λ/K_λ for the lamp at 12 and 16 amps. (taken from Table 4), and the sixth and eighth columns are the resultant values of I_λ, given by multiplication of K_λ (column 4) and I_λ/K_λ for the two currents. The relative intensity distributions I_λ in the sixth and eighth columns have been multiplied by arbitrary factors, 0·934 and 0·679 respectively, in order to bring them into agreement at the wave length 0·6137μ. These values of I_λ are plotted in fig. 4 against the wave length, the upper set of points being for 12 amps. and the lower

TABLE 5.—RELATIVE INTENSITY DISTRIBUTION IN THE LAMP AT 12 AND 16 AMPS.

λ	J_λ (comp.) T=2830° K	J_λ/K_λ (20 amps.)	K_λ	I_λ/K_λ 12 amps.	I_λ 12 amps. × 0·934	I_λ/K_λ 16 amps.	I_λ 16 amps. ×0·679
0·4202μ	2·00	0·98	2·04	....	....	0·60	0·83
0·4326	2·44	1·53	1·59	....	....	0·92	0·99
0·4529	3·29	2·01	1·64	0·50	0·77	1·43	1·53
0·4603	3·63	2·23	1·63	0·60	0·92	1·68	1·86
0·4872	5·02	1·84	2·73	0·60	1·53	1·49	2·76
0·4957	5·50	1·76	3·12	0·63	1·84	1·45	3·07
0·5233	7·19	2·60	2·76	1·14	2·94	2·19	4·11
0·5430	8·50	3·41	2·49	1·66	3·86	3·00	5·07
0·5616	9·78	4·03	2·43	2·22	5·04	3·72	6·14
0·5915	11·91	6·57	1·81	4·56	7·70	6·56	8·06
0·6137	13·51	7·87	1·72	6·23	10·00	8·56	10·00
0·6394	15·35	10·90	1·41	9·96	13·12	12·52	11·99
0·6496	16·06	11·79	1·36	11·28	14·33	13·29	12·27
0·6678	17·30	7·70	2·25	8·38	17·61	9·10	13·90

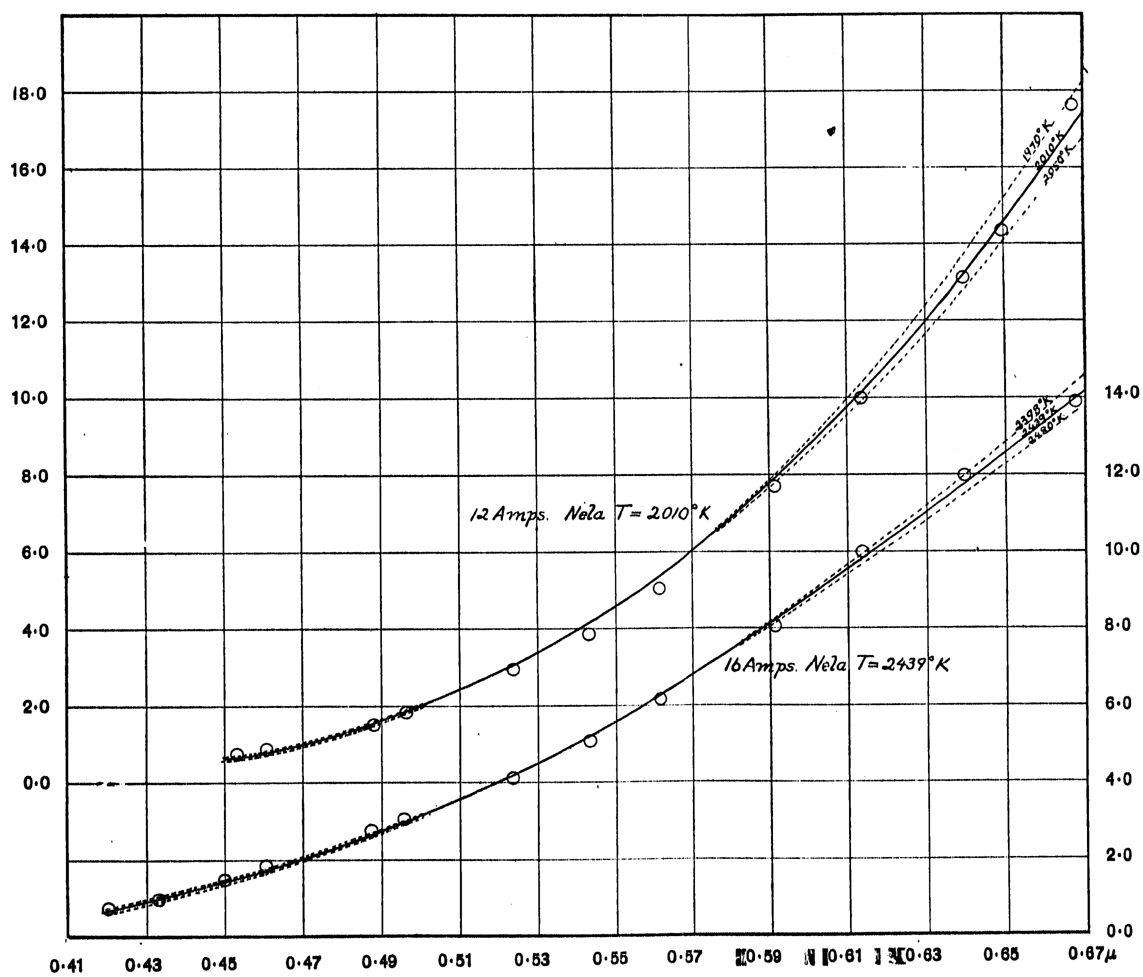


FIG. 4. Intensity Distribution in Lamp: 12 Amps. and 16 Amps.

for 16 amps. The full curves passing through the observed points are the relative intensity distributions computed from the Nela colour temperatures[20] by Wien's law. The dotted curves correspond to relative intensity distributions ±40° of the Nela colour temperatures. From the agreement of the observed points given by the wedge method and the relative intensity distributions given by the Nela laboratory, it will be seen that the wedge method has reproduced very closely the actual relative intensity distribution in the lamp; the uncertainty is not greater than ±20°, that is the 12 amp. observations might be fitted by curves lying between 1990°K or 2030°K and the 16 amp. observations by curves between 2419°K and 2459°K. From these facts it seems legitimate to conclude that the wedge method is of comparable accuracy with other and longer established methods of spectrophotometry.

More precisely the results in Table 5 may be used to give an upper limit to the error in the wedge constant σ_λ. While equation (3) of sec. 1, viz.:

$$I_\lambda = J_\lambda\, 10^{m\sigma_\lambda(h_\lambda - h'_\lambda)} \quad . . . (3)$$

is not actually used to compute the relative intensity distribution, it is, of course, applicable to the final mean values of the relative intensity distribution. In this equation assume that all errors in the observed I_λ are due entirely to errors in wedge constant σ_λ. Then if σ_λ is the wedge constant from the calibration which gives the observed I_λ, and σ'_λ is the *true* wedge constant which would give rise to the true I'_λ corresponding to the Nela colour temperature, then $I_\lambda = J_\lambda\, 10^{m\sigma'_\lambda(h_\lambda - h'_\lambda)}$: $I'_\lambda = J_\lambda\, 10^{m\sigma'_\lambda(h_\lambda - h'_\lambda)}$: $I'_\lambda / I_\lambda = 10^{m(h_\lambda - h'_\lambda)(\sigma'_\lambda - \sigma_\lambda)}$.

$$\text{or} \quad \delta\sigma_\lambda = \frac{1}{m(h_\lambda - h'_\lambda)} \log \frac{I'_\lambda}{I_\lambda} \quad . . . (5)$$

This equation is only applicable to cases where $m(h_\lambda - h'_\lambda)$ exceeds unity, otherwise minute accidental errors in measurement would lead to completely erroneous results. The equation has, therefore, been applied only to the observed values of I_λ for the lamp at 12 amps. where the values of $m(h - h'_\lambda)$, except for the wave lengths 0·5233, 0·5430, 0·5616 which have been omitted, exceed unity. The computation is summarized in Table 6, where the first column contains the wave length, the second the Nela relative

TABLE 6.—UPPER LIMIT TO ERROR IN WEDGE CONSTANT

λ	I'_λ (comp.) T=2010°K	I_λ (obs.) 12 amps.	I'_λ/I_λ	log I'_λ/I_λ	$m\ (h_\lambda - h'_\lambda)$	$\delta\sigma\lambda$	%
0·4529μ	0·74	0·77	0·962	−·0168	−2·31	+·007	+5·6
0·4603	0·88	0·92	0·957	−·0191	−2·09	+·009	+7·5
0·4872	1·55	1·53	1·013	+·0056	−1·55	−·004	−3·6
0·4957	1·83	1·84	0·995	−·0022	−1·20	+·002	+1·8
0·5915	7·80	7·70	1·013	+·0056	+1·43	+·004	+3·7
0·6137	10·04	10·00	1·004	+·0017	+2·00	+·001	+0·9
0·6394	13·16	13·12	1·003	+·0013	+2·61	+·000	+0·0
0·6496	14·48	14·33	1·011	+·0047	+2·82	+·002	+1·9
0·6678	16·89	17·61	0·959	−·0182	+3·37	−·005	−4·8

intensity distribution for the lamp at 12 amps. (computed from the colour temperature by Wien's law), the third the observed intensity distribution from Table 5, and the fourth and fifth columns contain the ratio I'_λ/I_λ and its logarithm respectively. The quantity $m(h_\lambda - h'_\lambda)$ appearing in the sixth column is the average difference in height (multiplied by m) of the spectrum of the unknown source (12 amps.) and the standard source (20 amps.). Since the spectra are on the average of equal height at some median wave length (about $0 \cdot 5430\mu$), the sign of this quantity will be negative in the blue, where $h'_\lambda > h_\lambda$, and positive in the red. By a simple transposition of (3) it will be seen that $m(h_\lambda - h'_\lambda) = (\log I_\lambda/J_\lambda)/\sigma_\lambda$; therefore to compute the values of $m(h_\lambda - h'_\lambda)$ appearing in the sixth column, it is only necessary to divide by σ_λ the logarithm of the ratio of I_λ (column 3, Table 6) to J_λ (values in column 2, Table 5, multiplied by $0 \cdot 454$, so that at $0 \cdot 5430\mu$ $I_\lambda = J_\lambda$). The resulting values of $\delta\sigma_\lambda$, expressed numerically and as a percentage of σ_λ, appear in the two last columns of Table 6. Individually the values cannot be regarded as of any significance, but in the mean they should give an upper limit to the error in the wedge constant. The average value of $\delta\sigma_\lambda$ in the last column is $+1 \cdot 4$ per cent, and its meaning is, that if the difference between the observed values of I_λ and the Nela values were entirely due to error in the wedge constant, that error in the mean would not exceed $+1 \cdot 4$ per cent. It may, therefore, safely be said that the wedge constants given in sec. 2 are certainly correct to $\pm 1 \cdot 5$ per cent, a limit closely similar to that assigned from internal evidence of the calibration itself.

(2) In this part of the section there is now left for consideration only the relative intensity distribution in the acetylene flame. In accordance with the plan previously proposed the lamp at the three currents has been used as a standard; the relative intensity distributions have been computed from the Nela colour temperatures by Wien's law and the values of K_λ determined for each current in precisely the same manner as shown in Table 5.

TABLE 7.—VALUES OF I_λ FOR ACETYLENE FLAME

λ	K_λ (12 amps.)	K_λ (16 amps.)	K_λ (20 amps.)	Mean K_λ	I_λ/K_λ Ac. Flame	I_λ
0·4326μ	....	1·17	1·12	1·14	0·72	0·82
0·4529	1·11	1·10	1·15	1·12	1·15	1·29
0·4603	1·09	1·06	1·15	1·10	1·29	1·42
0·4872	1·94	1·83	1·92	1·90	1·24	2·36
0·4957	2·18	2·12	2·20	2·17	1·22	2·65
0·5233	1·96	2·00	1·94	1·97	1·88	3·70
0·5430	1·84	1·82	1·75	1·80	2·66	4·79
0·5616	1·80	1·78	1·71	1·76	3·46	6·09
0·5915	1·28	1·32	1·28	1·29	6·28	8·10
0·6137	1·21	1·21	1·21	1·21	8·28	10·01
0·6394	0·983	0·989	0·991	0·988	12·04	11·89
0·6496	0·955	0·994	0·958	0·969	13·16	12·75
0·6678	1·51	1·62	1·58	1·57	9·23	14·49

The results are given in Table 7, where the first column is the wave length and the succeeding three columns give the values of K_λ for 12, 16, 20 amps. respectively. The value of K_λ for 20 amps. in the fourth column is the same as that in Table 5, except that it is multiplied by a factor 0·704 to bring K_λ for 0·6137μ equal to 1·21. The values of K_λ for all three currents should, of course, be identical and in the fifth column of Table 7 their mean is given. In the sixth column I_λ/K_λ for the acetylene flame taken from Table 4 is given, and in the final column the resultant value of I_λ is obtained from

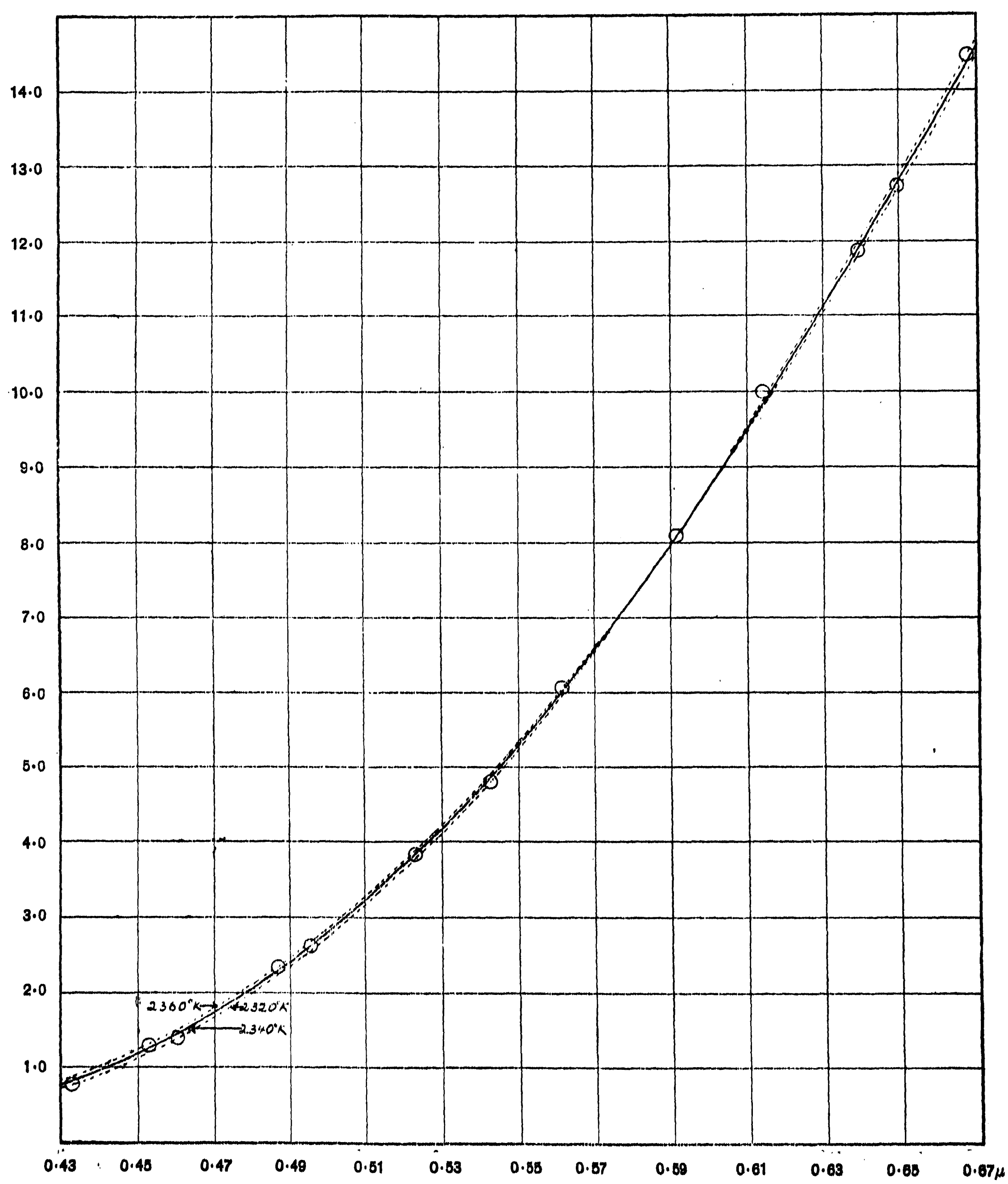


FIG. 5. Intensity Distribution in the Acetylene Flame

the product of the mean K_λ and I_λ/K_λ. The relative intensity distribution in the acetylene flame, observed values from the last column of Table 7, is plotted in fig. 5. The full curve through the observations is the computed relative intensity distribution from Wien's law for a temperature of 2340°K. The dotted curves on either side are for 2340° ±20°K. It will be seen that the observed values are best fitted by a colour temperature of 2340°K with an uncertainty of about 10°. This may be compared with the accepted value[18] of 2360° ±10°K. The two colour temperatures are thus in agreement within the limits of their probable errors, but the difference between them is probably real. The lower value obtained in the present investigation is to be attributed possibly to residual impurities in the acetylene gas, or differences in purity of the gas used here and at the Nela Laboratory. In any case it cannot be attributed to the possible ±1·5% errors in the wedge constant, since errors due to this cause would be negligible for the 16 amp. standard, where $m\ (h_\lambda - h'_\lambda)$ is small, and would be of opposite sign for 12 amp. and 20 amp. standards on account of the difference in sign of $m(h_\lambda - h'_\lambda)$. For the next part of this section, therefore, where the acetylene flame is used as a standard to determine the relative intensity distribution of the carbon arc, a colour temperature of 2350° ±10°K will be adopted.

Positive Crater of the Carbon Arc. The purpose of the work to be described briefly in this final part of sec. 3 was to determine the relative intensity distribution in the positive crater of the carbon arc (cored carbons, current 5·6 amps.). It was necessary to know this since the same arc was used as the standard for the astronomical spectrophotometry described in Part II. The colour temperature of the arc was determined using the lamp at 20 amps. and the acetylene flame as standards. The arrangement of apparatus for these two standards was the same as already described. For the carbon arc a slightly different method was followed. The Petzval condensing lens formed a magnified image, about 1·3 cms. in diameter, of the positive crater of the carbon arc on a ground glass screen with a circular diaphragm of 1·2 cms. The light of the crater, diffused and transmitted by this first ground glass, fell on a second ground glass some 15 cms. away and an equal distance in front of the slit. The result was that the light from the positive crater alone, but transmitted by the two ground glass screens, fell in a uniform diffuse beam on the wedge. It will be noted that the optical paths of the standards and the carbon arc differ in the presence of the ground glass screens. It must, therefore, be borne in mind, that the colour temperature of the positive crater as determined in this investigation, is not that of the bare crater, but of the crater as modified by transmission through two ground glass screens.

With these arrangements of apparatus spectra were taken in pairs, wedge erect and reversed, of each of the three sources. The spectra were taken on Ilford Panchromatic plates out of one box, the usual assumption being made that the photographic properties of the plates for equal development were identical within the accidental error. The following spectra with an iron arc comparison at the base of each were made:—

Carbon Arc: 6 pairs spectra, 2 pairs for each of three different + carbons. Mean exposure 2·4 minutes.

Acetylene Flame: 4 pairs spectra. Mean exposure 1·9 mins.

Lamp (20 amps.): 2 pairs spectra. Mean exposure 0·5 mins.

It will be noted that the exposure times lie well within the 10 : 1 ration specified in sec. 1. An example of the carbon arc spectrum will be found at the Plate at the end of the number, spectrum No. 5.

The spectra were measured on the spectrocomparator to a constant density of 0·7. The reductions were carried out in the same manner as described in the earlier part of this section; any errors due to possible non-uniformity of illumination will be eliminated in the means wedge erect and reversed. The necessary data for the relative intensity distribution in the positive crater of the carbon arc (cored carbon, current 5·6 amps.) are summarized in Table 8. The first column contains the wave length, the next three columns contain the mean value of I_λ/K_λ for each of three positive carbons designated

TABLE 8.—VALUES OF I_λ FOR CARBON ARC

λ	I_λ/K_λ for Carbon Arc				Ac. Flame Standard		Lamp (20 amp.) Standard	
	"A"	"B"	"C"	Mean	K_λ	I_λ	K_λ	$I_\lambda \times 0{\cdot}993$
0·4202μ	0·86	0·82	0·79	0·82	2·18	1·79	2·04	1·66
0·4326	1·15	1·12	1·14	1·13	1·89	2·14	1·77	1·99
0·4529	1·56	1·54	1·61	1·57	1·71	2·68	1·64	2·55
0·4603	1·70	1·68	1·76	1·72	1·60	2·75	1·64	2·80
0·4872	1·39	1·33	1·43	1·38	2·67	3·68	2·70	3·70
0·4957	1·30	1·25	1·30	1·28	3·08	3·94	3·12	3·96
0·5233	1·74	1·70	1·72	1·72	2·88	4·95	2·90	4·95
0·5430	2·25	2·18	2·18	2·20	2·57	5·66	2·63	5·75
0·5616	2·62	2·64	2·54	2·60	2·50	6·50	2·54	6·55
0·5915	4·05	4·14	4·03	4·07	1·86	7·57	1·87	7·55
0·6137	4·82	4·96	4·84	4·87	1·70	8·28	1·77	8·56
0·6394	6·50	6·75	6·38	6·53	1·41	9·21	1·42	9·20
0·6496	7·08	7·04	6·62	6·92	1·41	9·75	1·42	9·75
0·6678	4·41	4·64	4·12	4·39	2·34	10·28	2·34	10·20

for convenience "A," "B," "C," and the fifth column contains the mean value of I_λ/K_λ for all three carbons. In the sixth and seventh columns the acetylene flame (colour temperature adopted 2350° ±10°K) is used as a standard and K_λ and hence I_λ for the carbon arc determined. Similarly in the eighth and ninth columns the lamp (20 amps. colour temperature 2830°K) is used as a standard, and K_λ and I_λ for the carbon arc determined. The observed values of the relative intensity distribution, given in columns seven and nine, are plotted in fig. 6 against wave length. The curves drawn through these observed points are the computed intensity distributions from Wien's law corresponding to the colour temperatures noted on the curves. From Fig. 6 it will be observed that using the acetylene flame as a standard the colour temperature of the arc is 3100° ±40°K, the uncertainty being due to accidental error. Similarly when the lamp is used as a standard the corresponding colour temperature is 3060° ±10°K. From the law of propagation of error, as will be shown in Part II, sec. 4, it is possible to compute the limiting systematic error in the observed values of I_λ, due to the ±1·5 per cent possible

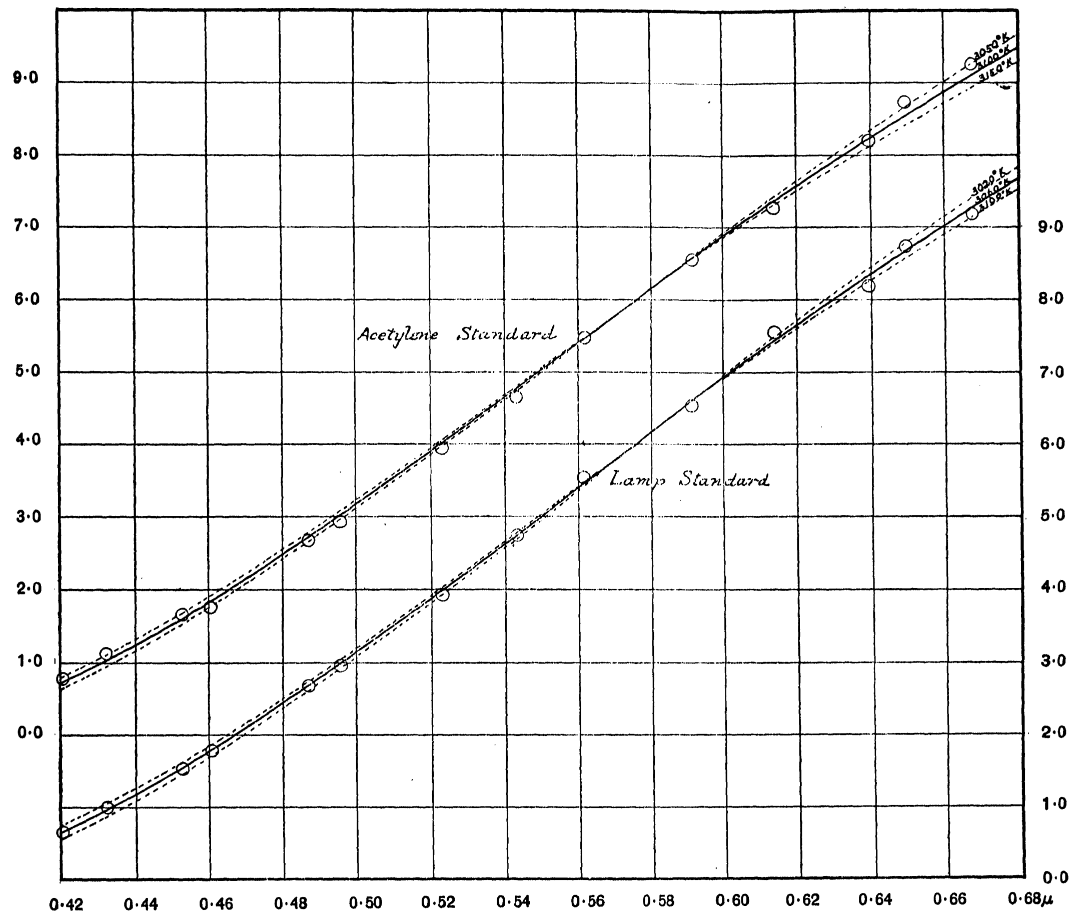


FIG. 6. Intensity Distribution in the Carbon Arc

error in the wedge constant, and due to the uncertainty of ±10° in the colour temperature of the acetylene flame and possibly also in the lamp. The necessary computations have been carried through, and the limiting systematic errors of the observed intensities, and hence of the resultant colour temperatures, have been found to be less than the accidental errors. It may, therefore, be safely concluded that these colour temperatures are not erroneous as a result of uncertainty in either the wedge constant or the colour temperatures of the standards.

The results in Table 8 may be treated in another way. It will be noted from the values of I_λ/K_λ in Table 8 that carbon "B" is systematically more and carbon "C" systematically less intense in the red. This intensity difference corresponds to a lower and higher colour temperature respectively. A mean value of K_λ for the flame and the lamp has been used, and the colour temperatures of carbons "B" and "C" determined in the usual graphical manner. The resulting colour temperatures, as may be readily verified, are for "B" 3050°K and for "C" 3125°K. It has, therefore, been decided to adopt as the relative intensity distribution of the positive crater of the carbon arc (cored carbons, current 5·6 amps.), a distribution corresponding to a colour temperature of

3080°K, with an uncertainty partly due to errors in determination and partly to variation from carbon to carbon of ±30°.

This temperature of 3080° ±30°K for the positive crater of the carbon arc is considerably lower than that resulting from any previous determination[21]*. The earlier temperatures, with the exception of Priest's[19], were determined from the total brightness, from the brightness at an effective mean wave length, or from the wave length of maximum energy. Unless the positive crater of the carbon arc radiates as a black body, these temperatures are not to be expected to agree with the temperature determined from the relative intensity distribution in the visible spectrum. The only comparable result is thus that of Priest[19], who obtains for the colour temperature (cored carbons, current 10 amps.) T = 3420° ±50°K. The method of colour matching followed by Priest will not distinguish between the true low intensity continuous blue and violet radiation, and the high intensity monochromatic radiation due to the cyanogen bands at $0 \cdot 42\mu$ and $0 \cdot 39\mu$ (see Plate No. 5). On this account, therefore, it is probable that his colour temperature will be higher than that obtained in the present investigation. Further the larger current used by him will probably account for 50° of the still outstanding difference. Since the existing evidence is not in direct contradiction to the low colour temperature reached in this investigation, and since systematic errors in the present determination have been shown to be negligible, it is probable that the adopted colour temperature of 3080° ±30°K for the positive crater of the carbon arc (cored carbons, current 5·6 amps.) is not seriously in error. It should, however, be emphasized that only a partial agreement can be expected between colour temperatures of arcs from different batches of carbons, and further that the present temperature of 3080°K refers only to the batch of cored carbons supplied to this institution by Bausch and Lomb some years ago.

Summary of Part 1. (1) On theoretical grounds it has been shown that the wedge method gives relative intensity distributions, which are free from any errors due to absorption or dispersion of the spectroscope and any errors due to peculiarities of the photographic plate. A method of testing for and eliminating errors due to non-uniformity of illumination on the wedge is given, and a simple method of measuring the wedge spectra is described.

(2) An accurate calibration of the wedge, W.IV, used throughout this investigation, is fully described. It is shown that the resulting values of σ_λ are certainly correct to ±1·5 per cent.

(3) It has been shown that the wedge method will accurately reproduce the relative intensity distributions in standards the colour temperatures of which have been determined elsewhere. Using a filament lamp calibrated by the Nela Laboratory and the acetylene flame as standards, a colour temperature of 3080° ±30°K has been found for the positive crater of the carbon arc (cored carbons, current 5·6 amp.)

* An earlier determination by the writer of the relative intensity distribution in the positive crater of the carbon arc (cored carbons, current 5·7 amps.) which is described in Nature (*107*, 648, 1921) gave a colour temperature of 3325°K. The reduction in this letter was made using the erroneous wedge constants from the first calibration. A re-calculation with the wedge constants of sec. 2 gives T = 2980°K. This re-calculated colour temperature is subject to an uncertain correction[18] due to the fact that an almost undiaphragmed flame burning unpurified acetylene was used. This evidence, such as it is, may be regarded as in a sense confirmatory of the low colour temperature derived from the more accurate determination of this section.

REFERENCES TO INTRODUCTION AND PART I.

[1] C. E. K. Mees and S. H. Wratten — British Journal of Photography, p. 384, 1907.

[2] T. R. Merton and J. W. Nicholson — Phil. Trans., Royal Society, A, *217*, 237, 1917.

[3] H. H. Plaskett — — Monthly Notices, R.A.S., *80*, 771, 1920.

[4] F. Hurter and V. C. Driffield — Journal Society Chemical Industry *9*, No. 5, 1890.
— Photographic Researches, Memorial Volume, p. 76, 1920.

[5] K. Schwarzchild — — Astrophysical Journal *11*, 89, 1900.

[6] J. Stark — — Annalen der Physik *35*, 461, 1911.

[7] R. A. Mallet — — Philosophical Magazine *44*, 904, 1922.

[8] F. E. Ross — — Astrophysical Journal *56*, 367, 1922.

[9] J. Hartmann — — Astrophysical Journal *24*, 285, 1906.

[10] H. H. Plaskett — — Popular Astronomy, *29*, 226, 1921.

[11] F. C. Toy and J. C. Ghosh — Philosophical Magazine *40*, 775, 1920.

[12] S. E. Sheppard and C. E. K. Mees — Theory of Photographic Process, p. 12, 1907.

[13] L. A. Jones — — Trans. Ill. Eng. Soc. No. 8, 1914.

[14] S. E. Sheppard and C. E. K. Mees — Theory of Photographic Process, p. 222, 1907.

[15] J. S. Plaskett — — Report of Chief Astronomer, Canada, p. 73, 1907.

[16] W. E. Forsythe — — Journal Optical Society America *4*, 305, 1920.

[17] E. P.Hyde, F. E. Cady, W. E. Forsythe — Physical Review *10*, 395, 1917.
W. E. Forsythe — — Journal Optical Society America *5*, 494, 1921; *6*, 476, 1922.

[18] E. P. Hyde, W. E. Forsythe, F. E. Cady — Physical Review *14*, 379, 1919.
W. W. Coblentz — — Scientific Papers. Bureau of Standards, No. 362, 1920.

[19] I. G. Priest — — Scientific Papers, Bureau of Standards, No. 443, 1922.

[20] W. E. Forsythe — — Letter to the Director, dated Sept. 23rd, 1921.

[21] E. Griffiths — — Methods of Measuring Temperature, p. 163, 1918.

PART II.—RELATIVE INTENSITY DISTRIBUTION IN THE SPECTRA OF THE SUN AND SOME TYPICAL STARS

The problems of astronomical spectrophotometry are of a dual nature. On the one hand are those difficulties common to all spectrophotometry—the elimination of errors due to absorption in the spectroscope and to the nature of the photometric receiver; and on the other hand are those problems peculiar to the study of astronomical spectra—the variable absorption of the terrestrial atmosphere, the distortion of the continuous spectrum by absorption lines and the faintness, with one exception, of the sources to be studied. The wedge method which appears, particularly in view of its proved laboratory value (sec. 3) well adapted to cope with these difficulties and problems, is applied in this part of the paper to astronomical spectrophotometry. The material to be described and discussed is divided into two sections. In the first of these is described in some detail a careful investigation of the relative intensity distribution in the visible solar spectrum, and in the second section appears a preliminary and tentative investigation of some stellar spectra.

SECTION 4.—INTENSITY DISTRIBUTION IN THE CONTINUOUS SPECTRUM OF THE SUN

The work described in this section was undertaken for the purpose of determining as accurately as possible the intensity distribution in the continuous spectrum (from $0 \cdot 4\mu$ to $0 \cdot 7\mu$) of the sun by the wedge method. After an introductory paragraph on previous work, the description is divided into five subsections; (1) selection of regions in the solar spectrum, (2) observing conditions and transmission coefficients of lenses (3) measurement and reduction of spectra, (4) atmospheric transmission coefficients, and (5) relative intensity distribution in the solar spectrum.

The two outstanding experimental investigations of the solar energy curve are those by Abbot[1*] and Wilsing[2]. Their results have the common characteristic that in the visible spectrum, the intensity distribution does not correspond to a black body curve but shows a marked drop to the violet of $0 \cdot 47\mu$. Abbot's results on the intensity distribution are a by-product of his determination of the solar constant. Since the atmospheric transmission coefficient for total radiation cannot be found directly, the following procedure is adopted. On the bolograph, registered by the spectro-bolometer at a given zenith distance, Abbot draws a smooth curve[3] to pass through a *mean position between crests and the troughs* due to solar absorption lines. The area under this curve, with small additive corrections for radiation in the extreme infra red and ultra violet, may be expressed in units corresponding to the total radiation as measured by the pyrheliometer at the same zenith distance. The energy curve outside the atmosphere is then determined from a number of such bolographs for various zenith distances in the usual manner, and the area under this extra-atmospheric curve expressed in the same total radiation units

*References to Part II will be found at the close of Part II.

will therefore give the total radiation outside the atmosphere. While this is the correct process to arrive at the true value of the solar content, the intensity distribution in the continuous solar spectrum, obtained as a by-product, will obviously be distorted by the absorption lines. Similarly Wilsing's results[2] will probably show a like distortion. Wilsing determines the intensity distribution in the visible spectrum photographically, using a Nicol to change intensities and a filament lamp, calibrated by a black body, to eliminate the colour curve of his plates. By widening the slit he blends the fine solar absorption lines into the continuous spectrum, and then measures the intensities at intervals of 50 A. commencing at $0 \cdot 39\mu$. By shifting his plate slightly on the microphotometer he avoided strong lines, but it is evident that the greater number of fine absorption lines will be included in his measures, and that an incorrect intensity distribution will result. Since the solar absorption lines are most closely crowded together in the blue and violet regions of the spectrum, it is probable that Abbot's and Wilsing's results will show a most marked distortion there. It was the primary purpose of the present investigation to determine the nature and the probable amount of this distortion.

(1) *Selection of Regions in the Solar Spectrum.* If the intensity in the *continuous* spectrum is to be measured, it is clearly most important to select regions where there are a minimum number of absorption lines. For this purpose Rowland's large scale map (1 A = 3 mm.) of the solar spectrum and his wave length tables were used. From the chart regions were selected which appeared free from absorption lines; of these regions all those which contained, from the wave length tables, lines of intensity 1 or stronger on Rowland's intensity scale (1 to 1,000), or which were bordered by lines stronger than intensity 4, were eliminated. The regions finally selected are given in Table 9. In the first column is the mean wave length of the region, and in the second is its width in A.U. In the third main column are given the number of lines in the region of Rowland intensity 0,00,000,0000 where 1 is a line "just clearly visible" and "below 1

TABLE 9.—REGIONS IN THE SOLAR SPECTRUM

Mean λ	Width A.U.	No. Lines Region of Intensity				Mean λ	Width A.U.	No. Lines Region of Intensity			
		0	00	000	0000			0	00	000	0000
$0 \cdot 4000\mu$	1·3	3	2	4	......	$0 \cdot 5062\mu$	4·5	1	3	4	5
0·4094	1·8	......	5	3	......	0·5222	7·3	6	5	4	9
0·4333	2·0	4	7	1	......	0·5358	8·2	1	4	7	10
0·4507	3·5	1	13	2	4	0·5609	12·3	1	5	14	17
0·4660	3·9	3	10	5	2	0·5824	15·2	2	8	15	11
0·4796	5·4	......	2	6	11	0·6035	15·0	5	1	2	26
0·4895	3·6	......	2	5	5	0·6209	8·8	......	3	2	5
0·4948	3·7	......	1	2	3	0·6687	18·0	......	......	5	5

the lines in order of faintness proceed from 0 to 0000, indicating lines more and more difficult to see." As a consultation of the table will show, the selected regions are satisfactorily free from absorption lines. In no region are there more than two lines of intensity 0 per A.U., and the average for all the regions is 0·5 lines of intensity 0 per A.U. Measures of the intensity of the continuous spectrum in these regions should therefore be relatively free from distortion due to absorption lines.

(2) *Observing Conditions and Transmission Coefficients of Lenses.* The observations to be discussed were made chiefly on July 21st, 1921, with the 72-inch (183 cms.) telescope and the universal spectroscope[4]. At the Cassegrain focus of the telescope was formed a solar image 30 cms. in diameter, the intensity of which was reduced by partially lowering the sectors over the principal mirror. The light from the central 6 cms. only of this solar image (0·2 of the apparent diameter) was transmitted by two ground glasses and fell in a uniform beam on the spectroscope slit. Over the slit in a small cell was mounted the wedge, W.IV, the calibration of which was given in sec. 2. The spectroscope was used in the one prism form with the medium focus camera. The resulting solar spectra were 5·4 cms. in length from $0\cdot4\mu$ to $0\cdot7\mu$, the dispersion varying from 23 A to the mm. at H δ to 123 A to the mm. at Hα. A slit width of 0·05 mm. gave a purity which by theory and test was of the order of 5000. This resolving power and linear dispersion are such as to ensure that each of the selected regions of Table 9 will be pure continuous spectrum, and that each will be wider than the projected diameter 0·05 mm. of the small hole H (fig. 2, sec. 1), through which the wedge spectrum is matched against some constant density. As a standard source was used the positive crater of the carbon arc (cored carbons, current 5·6 amp.), the colour temperature of which, after transmission by two ground glass screens, was found in sec. 3 to be 3080° ±30°K. In order to eliminate the variable reflection with wave length of the mirrors, the arc was mounted at the upper end of the telescope tube so that its light was reflected from both mirrors before reaching the wedge and the spectroscope. This was brought about in the following manner. A Zeiss-Tessar lens, aperture 3·5 cms., focus 22 cms., formed an image of the crater large enough to fill a pinhole opening at the focus of 7·6 cms. aperture Brashear lens. The light on emerging from the Brashear lens passed in a parallel pencil to the main 72-inch (183 cms.) mirror, was reflected from it to the Cassegrain mirror and then formed a greatly magnified image of the crater on the ground glass screen. To bring the exposure times of the standard source and the sun within the 10 : 1 ratio specified in sec. 1, a drop of oil was placed on each of the ground glass screens to make them more translucent and the spectroscope slit was widened to 0·07 mm. with a corresponding purity of 3300. Because of the flatness of the curves I_λ/K_λ, J_λ/K_λ, and since the square root of the (projected diameter)^2 of the measuring hole H (fig. 2) plus the (projected width)^2 of the slit are identical for the sun and arc to within 0·01 mm., it is evident that the small difference in slit width between sun and arc will not involve those errors discussed by Rayleigh[5] for the case of wide slits and functions the curvature of which is considerable.

The spectra were taken on Ilford Panchromatic plates of the one batch, the usual assumption being made that for equal development the photographic properties would be identical within the accidental error. A number of the spectra were taken in pairs, wedge erect and reversed, and it was found that the illumination on the wedge was uniform for both the sun and the arc. Any further necessary information on the observational data is summarized in Table 10. In the first column is the date G.M.T.

1921, on which the spectra were made; the solar spectra, it will be noted, were taken on the afternoon of July 21st, a day of exceptional transparency. Though the carbon arc spectra were not taken until a day after the solar spectra, it is improbable that there was any change in the reflection coefficients in this period. In the second column is given the source—the sun or the positive crater of the arc; in the third the mean zenith distance of the sun, in the fourth the number of spectra and in the fifth the average exposure time in minutes and fractions. It will be noted from the last column that in

TABLE 10.—OBSERVATIONAL DATA

Date G.M.T.	Source	Zenith Distance	No. Spectra	Mean Exposure	Date G.M.T.	Source	Zenith Distance	No. Spectra	Mean Exposure
				m					m
July 21·36	Sun	28° 29′	3	0·75	July 21·57	Sun	69° 09′	3	0·60
" 21·44	"	38° 48′	3	0·53	" 22·49	Arc	....	2	4·00
" 21·50	"	52° 11′	3	0·52	" 22·52	"	....	2	2·50
" 21·54	"	62° 31′	3	0·50	" 23·30	"	....	1	3·67

no case does the ratio of exposure times of the unknown and standard source exceed 1 to 8 and in the mean the ratio is 1 to 6, ratios which are well within the limits specified in sec. 1 to avoid error due to possible small variations of p, Schwarzschild's constant. Even if there were some variation of p with wave length, a thing for which there is at present no evidence (see sec. 1), a moment's thought will show, that since the colour temperature of the arc was determined with the exposure time of the standards *less* than the arc (sec. 3), and since the intensity distribution in the sun will be determined with its exposure time *less* than the arc, any error due to such a variation of p would be eliminated, or at most would only be a second order quantity.

The optical paths of the arc and the sun, before reaching the spectroscope, were not identical. Since in sec. 3 the colour temperature of the arc crater was determined only after the radiation had been transmitted by the same two ground glass screens which were used in front of the slit in the present investigation,* there is peculiar to the optical path of the arc only the two lenses and peculiar to the sun, exclusive of the earth's atmosphere, the two ground glass screens which were used to diffuse and reduce its light. An attempt was made to determine the transmission coefficients of these lenses and the ground glass screens experimentally; on account of the low intensity in the violet of the acetylene flame, which was used as a source. and on account of the small colour absorption in such thin blocks of glass, definitive results were not obtained. Accordingly the transmission coefficients were computed from the mean thickness of the glass and the coefficients given by Hovestadt[6]. The thickness of the various components of the lenses were measured by micrometer calipers on a circle of radius $R/\sqrt{2}$, which is

* It will be recalled that a drop of oil was placed on the ground glasses in the present investigation to reduce the exposure time of the arc. Assuming the total thickness of this oil to be 0·1 mm. (an over-estimate) and its transmission coefficients to be those of dense O·102 glass, its transmission will be unity over the whole spectrum within one-tenth of one per cent.

the circle inside and outside of which one-half the light passes. In the case of the cemented component of the Zeiss-Tessar the total thickness was measured at the appropriate radius, and the thickness of each of the components determined from diagrams published by Bausch and Lomb. The mean of eight measures for each component gave 1·74 cms. as the total mean thickness of the flint glass and 1·77 cms. as the total mean thickness of the crown glass in the two lenses. Similarly the thickness of the two ground glass screens was found to be 0·39 cms. The lenses were assumed to be O·340 (light flint) and O·203 (ordinary silicate crown); from the coefficients given by Hovestadt for these glasses at various wave lengths the appropriate transmissions for thicknesses of 1·74 cms. of flint and 1·77 of crown glass were determined. No account was taken of the loss by reflection which, from Fresnel's formula for perpendicular incidence, varies slightly with wave length; the error thus introduced is negligible being less than one-tenth of one per cent over the spectrum. The results were plotted against wave length, so that the transmission coefficients for the two lenses for any wave length could be read off. The coefficients for the two ground glass screens were similarly determined on the assumption that they were crown glass. The necessary values are given in Table 11, in which the first column contains the wave length (see Table 9), the second the transmission coefficients of the lenses and the third of the ground glass screens. The errors accompanying these values represent outer limits within which it is probable the true transmission lies. These outer limits were determined in the following manner. In the case of the lenses it was assumed, that they were (1) all flint (more absorbing) with a total thickness as measured *plus* 0·50 cms. and (2) all crown (less absorbing) with a total thickness as measured *minus* 0·50 cms. The transmission coefficients determined

TABLE 11.—TRANSMISSION COEFFICIENTS OF LENSES AND GROUND GLASS SCREENS

λ	a_λ (Lenses)	a_λ (Ground glass)	λ	a_λ (Lenses)	a_λ (Ground glass)
0·4000μ	0·89 ± ·05	0·98 ± ·01	0·5062μ	0·98 ± ·01	1·00 ± ·00
0·4094	0·91 ·03	0·99 ·01	0·5222	0·99 ·01	....
0·4333	0·94 ·02	0·99 ·01	0·5358	0·99 ·01	....
0·4507	0·96 ·01	0·99 ·01	0·5609	0·98 ·01	....
0·4660	0·97 ·01	1·00 ·00	0·5824	0·98 ·01	....
0·4796	0·98 ·01	....	0·6035	0·98 ·01	....
0·4895	0·98 ·01	....	0·6209	0·98 ·01	....
0·4948	0·98 ·01	1·00 ·00	0·6687	1·00 ·01	1·00 ·00

in the usual way for these two extreme cases gave the outer limiting errors of the coefficients of the lenses. As there was no uncertainty in the thickness of the ground glass, the limiting errors were obtained in this case on the assumption that they were (1) both flint and (2) both crown.

(3) *Measurement and Reduction of Spectra.* The wedge spectra, secured as detailed in Table 10, were measured on the spectrocomparator. In order to determine the micrometer settings for the regions given in Table 9, an iron arc spectrum was first measured, Hartmann constants computed and a curve of errors drawn. From these constants the micrometer setting corresponding to the required wave lengths were determined and

corrected from the curve of errors. The heights of the wedge spectra at these settings were then measured on the comparator in duplicate, once to a density of 0·7 and once to 1·1. On account of the strength of the carbon arc spectrum in the red it was possible to determine the values of h_λ with density 0·7 only as far as 0·5824μ, but with density 1·1 the heights along the whole length of the spectrum could be found. These measures gave the values of h_λ; the value of m, the magnification constant, was determined from the ratio—true height of wedge to height measured on the spectra—and the values of σ_λ, the wedge constant, were read from the curve fig. 3 for the appropriate wave lengths. Reductions were carried through separately for each of the two densities, and the values of I_λ/K_λ for the sun and J_λ/K_λ for the carbon arc determined from each spectrum precisely as shown in sec. 3. The relative intensity distribution in the arc crater was found from the colour temperature 3080°K (see sec. 3) by Wien's law, and this intensity distribution, corrected for transmission by the two lenses (see Table 11), gave the value of J_λ. From the carbon arc spectra then could be determined a value of K_λ for each density, and this applied to the solar spectra gave the necessary values of I_λ. A correction was applied to these values to eliminate the absorption of the ground glass screens (see Table 11), and the resulting 6 sets of values—3 spectra, two measures on each—were meaned for each zenith distance. The final results are given in Table 12, which contains the mean values of I_λ, the relative intensity distribution in the solar spectrum, for various air masses t (given by the secant of the zenith distance). In this table the first column contains the wave length of the regions (see Table 9) where the intensity was measured, and the succeeding columns contain five sets of values, one for each zenith distance at which the spectra were taken, of ${}_tI_\lambda$ with their limiting errors. The values are purely relative and have been adjusted to be in approximate agreement between the wave lengths 0·5062μ and 0·5609μ.

TABLE 12.—MEAN VALUES OF ${}_tI_\lambda$ FOR VARIOUS AIR MASSES t.

λ	t = 1·138		t = 1·283		t = 1·631		t = 2·167		t = 2·810	
0·4000μ	7·86	± ·53	7·71	± ·52	7·38	± ·48	6·41	± ·42	5·76	± ·37
0·4094	7·46	·36	7·15	·33	7·23	·35	6·51	·31	5·80	·27
0·4333	7·87	·26	7·85	·26	7·52	·26	7·28	·24	6·89	·22
0·4507	8·76	·23	8·87	·23	8·81	·23	8·18	·21	8·08	·20
0·4660	8·86	·18	9·04	·17	8·56	·17	8·26	·16	7·94	·15
0·4796	9·10	·15	9·06	·15	8·91	·14	8·94	·14	8·60	·14
0·4895	9·14	·13	9·09	·13	8·74	·13	9·00	·13	8·69	·13
0·4948	8·72	·12	8·86	·12	8·65	·12	8·58	·12	8·75	·12
0·5062	8·83	·10	8·94	·10	8·91	·10	8·84	·10	8·66	·10
0·5222	8·68	·09	8·72	·09	8·82	·09	8·82	·09	8·86	·09
0·5358	8·78	·09	8·73	·09	8·76	·09	8·78	·09	8·84	·09
0·5609	8·42	·09	8·32	·09	8·22	·09	8·26	·09	8·34	·09
0·5824	8·20	·11	8·12	·11	7·85	·11	8·10	·11	8·40	·11
0·6035	8·22	·12	7·40	·12	7·45	·12	7·66	·12	8·38	·12
0·6209	7·96	·13	7·20	·13	7·29	·13	7·52	·13	8·69	·14
0·6687	7·82	·17	6·02	·14	6·57	·16	7·04	·16	8·25	·18

The limiting probable errors which appear in Table 12 give the outer limits within which the correct value of ${}_tI_\lambda$ must lie. These limiting errors were determined from an application of the law of propagation of error. Referring back to sec. 1 it will be recalled that the relation between I_λ, the observed intensity distribution, J_λ the intensity distribution in the standard and the various measured quantities, was of the form

$$I_\lambda = J_\lambda\, 10^{m\sigma_\lambda(h_\lambda - h'_\lambda)} \quad . \; . \; . \; . \; (1)$$

If $\pm r_1$ is the limiting error of J_λ and $\pm r_2$ is the limiting error of the wedge constant σ_λ, it follows[7] that the resulting limiting error $\pm r$ of I_λ is given by

$$r^2 = (I_\lambda / J_\lambda)^2 r_1^2 + \left\{I_\lambda\, m(h_\lambda - h'_\lambda) \log_e 10\right\} r_2^2 \quad . \; . \; . \; (2)$$

The error $\pm r_1$ in J_λ arises from the uncertainty of $\pm 30°$ in the colour temperature of the arc as determined in sec. 3, and from the limiting errors for the transmission coefficients of the two lenses (see Table 11). The error $\pm r_2$ in the wedge constant has been taken as $\pm 1{\cdot}5$ per cent, an upper limit which was determined from the results with the Nela lamp (sec. 3). Since on the average the solar spectra and the carbon arc spectra were of equal height at some median wave length (say $0{\cdot}5222$), the sign of $m(h_\lambda - h'_\lambda)$, which is simply the average difference in height of the two spectra projected on the wedge and is determined from (1), will be positive in the blue and negative in the red. The quantities appearing in (2) are now all known and hence the value of $\pm r$ the resulting error may be determined. This gives ${}_tI'_\lambda \;\pm r'$; in order to determine ${}_tI_\lambda \;\pm r$ appearing in Table 12 it is now only necessary to correct for the absorption $a_\lambda \pm r''$ of the ground glass screens (see Table 11), where ${}_tI_\lambda \pm r = ({}_tI'_\lambda \;\pm r')/(a_\lambda \pm r'')$. With reference to this resulting error it is to be noted that whatever its sign may be, if it is plus in the blue it will negative in the red, and vice versa. This is a result of the fact that the spectra of the sun and the arc are on the average arranged to be of the same intensity, that is, of the same height, at some median wave length.

(4) *Atmospheric Transmission Coefficients.* From the values of ${}_tI_\lambda$ given in Table 12 may be determined relative values of the atmospheric transmission coefficients for each wave length. In the usual absorption formula ${}_tI_\lambda = {}_oI_\lambda\, a_\lambda^{\,t}$, ${}_tI_\lambda$ is the observed intensity at wave length λ and air mass t, ${}_tI_\lambda$, is the intensity outside the atmosphere, a_λ is the atmospheric transmission coefficient and t is the air mass given with sufficient accuracy by the secant of the zenith distance. Taking logarithms of both sides, namely $\log {}_tI_\lambda = \log {}_oI_\lambda + t \log a_\lambda$, there results a linear relation between $\log {}_tI_\lambda$ and the air mass t. Accordingly if $\log {}_tI_\lambda$ be plotted against t, the slope of the resulting straight line will give $\log a_\lambda$, and, it may be noted in parentheses, the intercept of the straight line on the axis $t = 0$ will give $\log {}_oI_\lambda$. This method which is that followed by Abbot[3], has been used to determine the relative atmospheric transmission coefficients. In fig. 7 some typical graphs are plotted for various wave lengths from Table 12; it will be noted that the observed points define, in most cases with some precision, a straight line, a fact which justifies the assumption of constancy of transmission implied in the method. The exceptional cases are for wave lengths to the red of $0{\cdot}5824\mu$, where there are only half the number of measures available. From graphs such as shown in fig. 7 the value of $\log a_\lambda$ for each of the 16

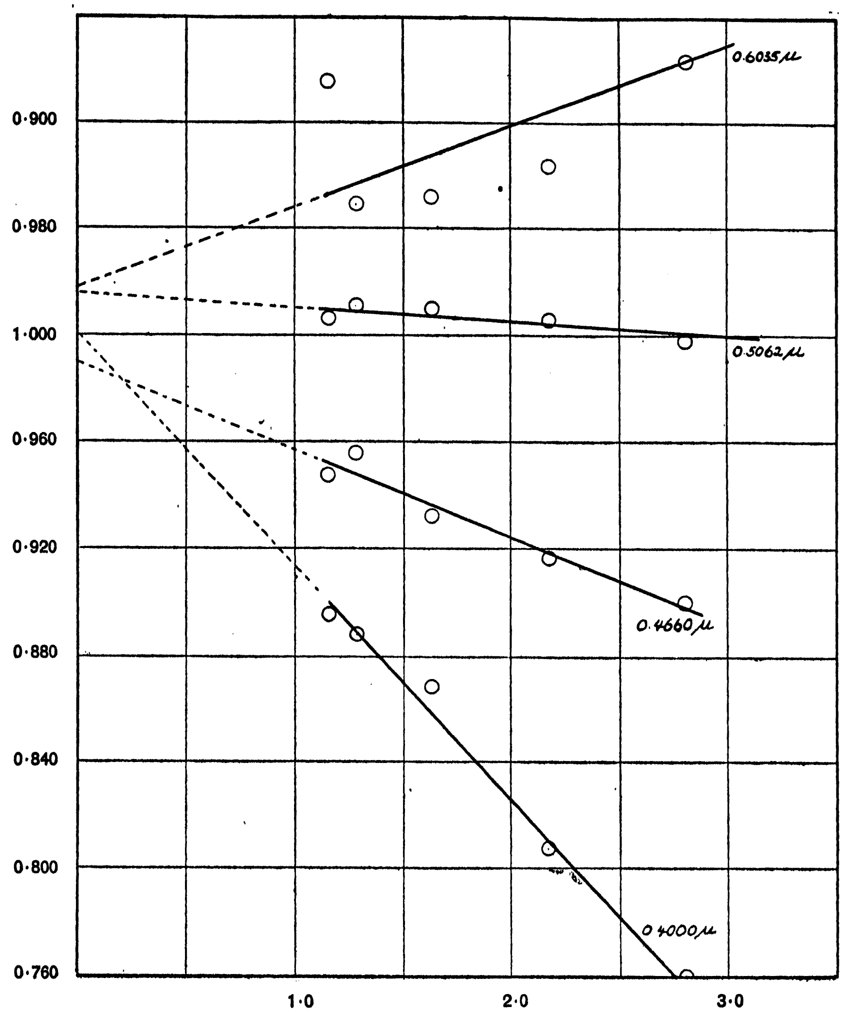


FIG. 7. Determination of Atmospheric Transmission

wave lengths is determined. Since the values of ${}_tI_\lambda$ in Table 12 are purely relative and have been arbitrarily brought into agreement in the region $0\cdot5062\mu$ to $0\cdot5609\mu$, it follows that the values of a_λ, determined according to this method, will be relative to the value a_λ arbitrarily taken as unity in the neighbourhood of $0\cdot5222\mu$. These relative quantities a_λ are plotted against wave length in fig. 8 and a smooth curve drawn through the observed points.

In order to act as a check on these experimentally determined transmission coefficients, values have also been computed according to the method of Fowle.[8] Taking the barometer reading at Victoria as 75 cms. and $1\cdot26$ cms. as the depth of the precipitable water in the atmosphere (corresponding to a vapour pressure of $0\cdot56$ cms. at a height of 223 m.) the value of a_λ for Victoria is given by $\log a_\lambda = 1\cdot21 \log a_{a\lambda} + 1\cdot26 \log a_{w\lambda}$, where $a_{a\lambda}$, $a_{w\lambda}$ are given by Fowle for a number of wave lengths. The results of this computation are in absolute values; multiplying by an arbitrary factor, they are brought into agreement with the experimentally determined relative values. These computed a_λ's are shown in fig. 8 by a dotted curve. It will be seen that the observed

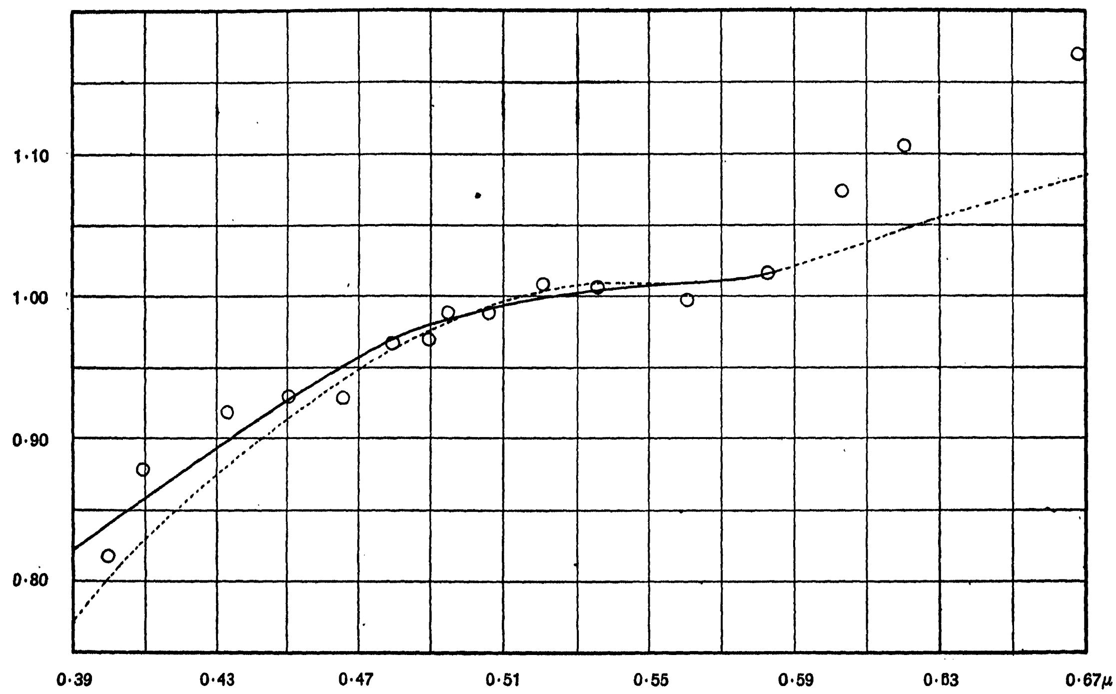


FIG. 8. Relative Atmospheric Transmission Coefficients

and the computed transmission coefficients are in fair agreement as far as 0·5824μ. To the red of that position, where the spectra could only be measured to one density, the observed and computed values are in marked disagreement. The relative values of a_λ

TABLE 13.—VALUES OF $a_\lambda{}^t$

λ	t = 1		t = 1·138		t = 1·283		t = 1·631		t = 2·167		t = 2·810	
0·4000μ	0·84	± ·03	0·82	± ·03	0·80	± ·04	0·74	± ·04	0·67	± ·05	0·60	± ·06
0·4094	0·86	·03	0·84	·03	0·82	·04	0·77	·04	0·71	·05	0·64	·06
0·4333	0·90	·02	0·89	·02	0·87	·02	0·83	·03	0·78	·04	0·73	·05
0·4507	0·93	·01	0·92	·01	0·91	·01	0·88	·02	0·84	·02	0·79	·02
0·4660	0·95	·01	0·94	·01	0·94	·01	0·91	·02	0·89	·02	0·85	·03
0·4796	0·97	·00	0·97	·00	0·96	·00	0·94	·00	0·93	·00	0·90	·00
0·4895	0·98	·00	0·98	·00	0·97	·00	0·96	·00	0·94	·00	0·92	·00
0·4948	0·98	·00	0·98	·00	0·97	·00	0·96	·00	0·95	·00	0·92	·00
0·5062	0·99	·00	0·99	·00	0·99	·00	0·97	·00	0·97	·00	0·95	·00
0·5222	1·00	·00	1·00	·00	1·00	·00	0·99	·00	0·99	·00	0·98	·00
0·5358	1·01	·01	1·01	·01	1·01	·01	1·01	·02	1·01	·02	1·01	·03
0·5609	1·01	·01	1·01	·01	1·01	·01	1·01	·02	1·01	·02	1·01	·03
0·5824	1·02	·00	1·02	·00	1·03	·00	1·03	·00	1·04	·00	1·04	·00
0·6035	1·03	·04	1·04	·05	1·04	·05	1·04	·07	1·06	·09	1·07	·12
0·6209	1·05	·06	1·06	·07	1·06	·08	1·07	·10	1·10	·14	1·13	·18
0·6687	1·09	·08	1·10	·09	1·11	·10	1·14	·14	1·19	·19	1·25	·26

finally adopted are given in Table 13. To the blue of 0·5824μ the observed values are used, but to the red the computed values have been taken as being almost certainly more accurate. The limiting error has been taken as plus or minus the difference between the two sets of values, an amount which is likely to contain the correct values within its limits. In Table 13 the first column contains the wave lengths and the second contains the value of a_λ for air mass unity with its limiting error, the necessary qualities being obtained from fig. 8. The remaining five columns give the values of $a_\lambda{}^t$ with their limiting errors for the noted air masses; these are computed from the values in the second column logarithmically.

(5) *Relative Intensity Distribution in the Solar Spectrum.*—From the quantities ${}_tI_\lambda$ in Table 12 for five values of t, the air mass, and from the quantities $a^t{}_\lambda$ in Table 13 for the same air masses, it is possible to determine from the absorption formula ${}_tI_\lambda = {}_oI_\lambda\, a^t{}_\lambda$ the relative intensity distribution in the solar spectrum outside the atmosphere. The results of this computation are given in Table 14 for each wave length and air mass with the limiting probable errors carried through. Since the results under each value of t give the intensity distribution outside the earth's atmosphere, they should be identical and their mean may therefore be taken. The weighted mean values for each wave length are given in the last column of the table, weights having been assigned inversely as the squares of the limiting errors. The probable limiting error of this weighted mean was determined as follows. Since the limiting errors for a given wave length are necessarily of one sign, they can only be combined by taking their weighted mean. Let this weighted mean error be r_2. There is also an error due to accidental variations of ${}_oI_\lambda$ which may be computed in the usual manner; call this accidental error r_1. Then the limiting error of the weighted mean is given by $r^2 = r_1{}^2 + r_2{}^2$, and it is the value computed in this way which appears in the last column of Table 14.

TABLE 14.—VALUES OF ${}_oI_\lambda$

λ	t = 1·138		t = 1·283		t = 1·631		t = 2·167		t = 2·810		Mean Value	
0·4000μ	9·59	± 0·74	9·64	± 0·81	9·98	± 0·85	9·57	± 0·95	9·60	± 1·15	9·68	± 0·86
0·4094	8·88	0·54	8·72	0·59	9·39	0·67	9·17	0·78	9·06	0·94	9·00	0·66
0·4333	8·84	0·36	9·02	0·36	9·06	0·45	9·33	0·57	9·44	0·71	9·04	0·43
0·4507	9·52	0·27	9·75	0·28	10·01	0·35	9·74	0·34	10·23	0·37	9·80	0·32
0·4660	9·43	0·21	9·62	0·21	9·41	0·28	9·28	0·28	9·34	0·37	9·45	0·25
0·4796	9·38	0·15	9·44	0·16	9·48	0·15	9·61	0·15	9·56	0·16	9·49	0·15
0·4895	9·33	0·13	9·37	0·13	9·11	0·14	9·58	0·14	9·45	0·14	9·37	0·15
0·4948	8·90	0·12	9·13	0·12	9·01	0·12	9·04	0·13	9·51	0·13	9·11	0·14
0·5062	8·92	0·10	9·03	0·10	9·19	0·10	9·12	0·10	9·12	0·11	9·07	0·10
0·5222	8·68	0·09	8·72	0·09	8·91	0·09	8·91	0·09	9·04	0·09	8·85	0·10
0·5358	8·69	0·13	8·65	0·13	8·68	0·19	8·69	0·19	8·75	0·27	8·68	0·16
0·5609	8·34	0·12	8·26	0·12	8·14	0·18	8·17	0·18	8·26	0·26	8·26	0·15
0·5824	8·04	0·11	7·88	0·11	7·62	0·11	7·79	0·11	8·08	0·11	7·88	0·13
0·6035	7·90	0·39	7·12	0·36	7·16	0·49	7·23	0·62	7·83	0·89	7·41	0·47
0·6209	7·51	0·51	6·79	0·52	6·81	0·65	6·84	0·88	7·69	1·23	7·08	0·63
0·6687	7·11	0·60	5·42	0·50	5·76	0·72	5·92	0·96	6·60	1·38	6·05	0·70

These final weighted mean values are plotted graphically in fig. 9 by filled black circles. The vertical lines which pass through each observed point are determined in length by the limiting probable error. As has already been pointed out, if this limiting error is positive in the blue, it will be negative in the red, and vice versa. In view of generous limits which have been allowed for possible error in the colour temperature of the carbon arc, for possible error in the wedge constant, and for possible errors in the transmission coefficients of lenses, ground glass and the terrestrial atmosphere, it is highly probable that the true value of the intensity, as measured, lies well within the limits of the vertical lines. Using Planck's law $E_\lambda = c_1\lambda^{-5}(e^{c_2/\lambda T}-1)^{-1}$ where c_1 may be given any arbitrary value in the present case and c_2 has again been taken as 14350, it is possible to compute the relative intensity distributions for various temperatures. The two full curves correspond to the distributions for temperatures of 6700°K and 7000°K. It will be seen that the observed points, even to the violet of $0\cdot47\mu$, correspond fairly closely to a black body intensity distribution somewhere within these temperatures. The two dotted curves for temperatures of 6300°K and 7500°K show limiting values of the temperatures if the observed points are in error by nearly the full limiting amount.

For purposes of comparison Abbot's[1] mean values (1903-18) and some of Wilsing's[2] results (one-fourth of his observed points, the mean of series II and III), are plotted on fig. 9 as open circles and crosses respectively. The values of these two investigators are arbitrarily brought into agreement with the wedge results in the region $0\cdot535\mu$ to $0\cdot665\mu$. [In reality a correction should be applied to both Abbot's and Wilsing's results, which refer to the whole disc, to make them strictly comparable with the wedge results for the centre of the sun. This correction, which from Abbot's work would consist in a shift of λ max. by some 2 per cent to the violet and in an increase of the intensities to the violet of $0\cdot47\mu$ by amounts not exceeding 3 or 4 per cent, is, however, negligible in comparison with the differences which actually exist.] It will be observed that all three values are in fair agreement as far as $0\cdot47\mu$, but that to the violet of that wave length the wedge values are higher, and correspond far more closely to black body conditions.

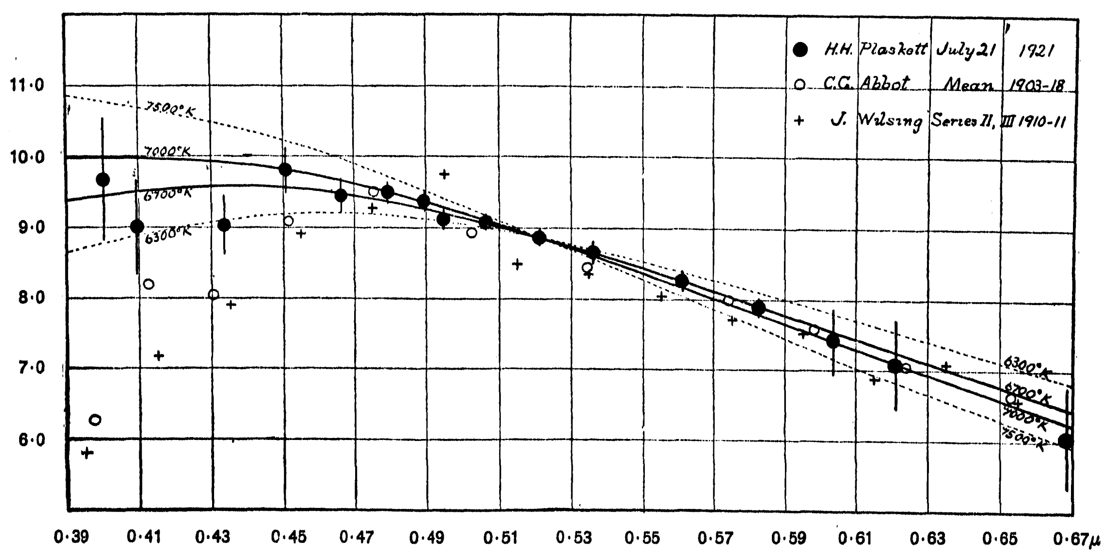


Fig. 9. Intensity Distribution in the Solar Spectrum

The difference between these results is not due entirely to errors in the present investigation, since the results of Abbot and Wilsing lie well below the generous limiting errors of the wedge method. Nor, on the other hand, can it be ascribed to errors in the methods of Abbot and Wilsing, since these investigators used entirely different methods which have given, as fig. 9 shows, accordant results. Nor can this difference be assigned with any degree of probability to a variation in the solar intensity distribution on July 21, 1921, since the recent highly accurate observations of Abbot[9] show only somewhat uncertain variations of the order of 4 per cent for days of high and low solar constant, whereas the differences in question run from 10 per cent to 50 per cent. Since this difference cannot be ascribed with any probability either to errors in the methods or to a variation of solar intensity distribution on July 21, 1921, the one remaining possibility is the effect of absorption lines. It will be recalled that whereas Abbot and Wilsing included in their measures the effect of the absorption lines, in the present investigation special precautions have been taken to measure intensities only in regions relatively free from absorption lines. It may, therefore be concluded with some probability that the values obtained in the present investigation are higher in the violet because they are freer from distortion by the closely crowded absorption lines in that region. No degree of finality can, however, be claimed for the actual values of the present investigation; all that can be said is that they represent a closer approximation to the relative intensity distribution in the *continuous* spectrum, and suggest that that intensity distribution corresponds to black body radiation.* The correct values will be found only when sufficiently high dispersion to open out well the narrow regions of pure continuous spectrum has been employed, together with any accurate method of spectrophotometry.

In conclusion, reference may be made to the bearing which these results have on the interesting problem of general solar radiation. One of the chief difficulties is to reconcile the observed intensity distribution (corresponding to a temperature of 6200°K to 7000°K) with the observed total radiation (corresponding to a temperature of 5740°K). If it be agreed, however, as the present investigation suggests, that the intensity distribution corresponds to that of a black body, Milne[10] has shown that part of this wide discrepancy in temperature will disappear. He has found that in radiative equilibrium the intensity distribution corresponds to that of a black body, only displaced to the violet. He concluded that for the *whole disc* the temperature deduced from the total radiation will be 3·1 per cent smaller, and for the *centre* of the disc, where the wedge observations were made, 4·3 per cent smaller than that deduced from the usual form of Wien's displacement law. Using the figures quoted by Milne from Abbot, the total radiation from the centre of the disc corresponds to a temperature of 6160°K, and on Milne's theory the intensity distribution should correspond to a temperature of 6400°K. This temperature of 6400°K, it will be noted, lies within the limiting temperatures given by the wedge method. It is accordingly not improbable that a new and definitive determination of the intensity distribution in the *continuous* spectrum of the sun, the need for which has been shown by the present investigation, will lead to a temperature in agreement with that deduced from total radiation.

* This result is in some measure confirmed by the work of Fabry and Buisson [Comptes Rendus, 175, p. 156, 1922] on the solar energy curve in the ultra-violet ($0 \cdot 29\mu$—$0 \cdot 39\mu$). Using a photographic method of spectrophotometry with the carbon arc as standard at an assumed colour temperature of 3750°K, Fabry and Buisson measured the intensities in the solar spectrum in regions comparatively free from absorption lines and found the energy distribution in the region $0 \cdot 29\mu$—$0 \cdot 39\mu$ to correspond to that of a *black body* maintained at a temperature of 6000°K.

Section 5.—Intensity Distribution in the Spectra of Six Typical Stars

In this section it is proposed to outline some preliminary and tentative applications of the wedge method to stellar spectra. After a discussion of the observational methods, in which there are still some unsolved difficulties, the results are briefly given and discussed in the light of work by other investigators.

Observational Data. The stellar wedge spectra were secured with the 72-inch (183 cms.) telescope and the universal spectrocsope. The short focus camera and a slit width of 0·074 mm. were used in order to reduce as much as possible the exposure times. Considerable difficulty was experienced in securing uniformity of illumination on the wedge. Owing probably to minute irregularities in the clock drive and rapid changes of atmospheric refraction, the method[11], previously successful, of trailing the star image backwards and forwards along the slit, gave wedge spectra crossed by numerous streaks. Since such wedge spectra were clearly useless for purposes of measurement, numerous attemps were made to obtain a method of taking the spectra free from this defect. Three different methods were tried. (1) As the trouble probably lay partly in the clock, means of changing its rate, other than by the differential slow motion[4] were tested. A lamp resistance in the circuit of the motor running the differential housings allowed the use of the quick slow motion for trailing the star. In this way a great many more trails were secured for an exposure of a given length, but the streaks persisted and were, if anything, more marked. Additional weights were then screwed on to the governor balls, and the clock rate thus changed by a method independent of the differential gears. The streaks still persisted. (2) Various cylindrical lenses were placed in a mounting over the slit and the stellar image elongated to the full length of the wedge. In order to eliminate any lack of uniformity in this collapsed extra focal image, due to the shadow of the Cassegrain mirror, a special diaphragm was used over the mirror surface. None of the spectra secured in this way were satisfactory; all showed a general non-uniformity of illumination with, in some cases, streaks. (3) The stellar image was brought to a focus below the slit so that the extra focal patch on the slit was some 2 to 3 mm. in diameter. A cylindrical lens (53 cms. focal length) was then introduced in the beam so that the extra focal patch was changed to a line image of 2 to 3 mm. in length elongated along the slit. This line image was trailed backwards and forwards along the slit, so that at the beginning and end of a trail it was completely off the wedge. The trailing was accomplished by weights screwed to the governor balls. This method has been found to give uniform spectra, provided the seeing is not better than 1 on a scale of 5. On nights, however, when the seeing is reasonably good and the greater part of the light from line image goes into the slit the streaks re-appear—a fact which strongly suggests that slight changes in declination, due to irregular refraction, are in a measure responsible for this phenomenon.

The stellar spectra discussed in the present investigation were all secured on two exceptionally transparent nights, Nov. 6 and Nov. 8, 1920. A summary of the necessary observational data is given in Table 15. The first column contains the source, star or carbon arc, the second the magnitude and the third the spectral type of the star. In the

TABLE 15.—OBSERVATIONAL DATA

Star	Mag.	Type	No. Spectra	Exp.	Plate	Star	Mag.	Type	No. Spectra	Exp.	Plate
γ Cassiopeiae.....	2·2	Boe	3	29	S. 30	C Arc..........	......	....	5	10	S. 30
ϵ Persei..........	3·0	Bo	4	44	S. 30	α Aurigae.......	0·2	gGo+F5	4	27	Il. Pan.
α Cygni..........	1·3	cA2	4	23	S. 30	β Geminorum...	1·2	Ko	2	54	Il. Pan.
δ Cassiopeiae......	2·8	A5	4	45	S. 30	C Arc..........	......	....	6	29	Il. Pan.

remaining columns are given the number of spectra secured, the average exposure time in minutes and the type of plate used. Attention may be drawn to one or two facts contained in the table. The stars were selected for their range in type, for their brightness and for their high declination (to avoid atmospheric dispersion). The positive crater of the carbon arc was used as a standard source in much the same manner as described in the previous section. It will be observed that the exposure times for the stars and the arc for each type of plate are well within the 10 : 1 limits specified in sec. 1. The "early type" stars were all taken on the fast blue sensitive Seed 30 plates; typical spectra are shown in the plate at the end of the number. The "late type" stars, which were more intense in the red, were taken on Ilford Panchromatic plates. No tests for uniformity of illumination by reversing the wedge were made, but it is probable that the method of trailing for the stars and the use of the ground glass for the arc will ensure the necessary uniformity. In short, the stellar wedge spectra are probably of sufficiently good quality to give preliminary values for stellar intensity distributions. They do not, however, by any means represent the ultimate possibilities of the method; the experience that has been gained since the spectra were taken, indicates numerous improvements which can be effected, provided a satisfactory method of obtaining uniform spectra, free from streaks, is found.

Reduction and Discussion of Results. The spectra secured as detailed in Table 15 were measured on the spectro-comparator to a constant density of 0·3 according to the method described in sec. 1. In the "early type" stars, where there are comparatively few absorption lines, measures were made at intervals of $0 \cdot 01\mu$. In the "late type" stars regions for measurement where there appeared to be comparatively few absorption lines were selected from the solar chart; it is not to be expected, however, that the resulting intensities will be entirely free from distortion by absorption lines, since the linear dispersion used was relatively small. The micrometer settings corresponding to the required wave lengths were found from the Hartmann constants and a curve of errors. In the reduction of the measures the usual assumption was made that the photographic properties of a batch of plates, for equal development, were identical within the accidental error. The value of I_λ/K_λ for the stars and K_λ for the arc (assumed temp. T = 3080°K, sec. 3) were determined in the usual manner. Corrections were made for the absorption of the condensing lenses, peculiar to the arc, and the cylindrical lens peculiar to the star according to the method used in sec. 4. The computations so far described resulted in the values ${}_tI_\lambda$ for each star at the zenith distance, or air mass t, at which the spectrum was taken. It was assumed that the atmospheric transmission coefficients for these two very transparent nights were identical with the coefficients previously determined for July 21, 1921 (sec. 4); and the mean values $_0I_\lambda$ for each star were then determined according to the method described there. Limiting errors due to uncertainty in wedge constant, temperature of the arc and so on were not carried through on account of the large accidental errors of the individual intensities. The final resulting values of $_0I_\lambda$ for the "early type" stars are given in Table 16, and for the "late type" stars in Table 17. The tables are self explanatory.

TABLE 16.—MEAN VALUES OF $_0I_\lambda$ FOR "EARLY TYPE" STARS

λ	γ Cass.	ε Pers.	α Cygni	δ Cass.	λ	γ Cass.	ε Pers.	α Cygni	δ Cass.
0·39μ	13·18	12·49	9·62	....	0·46μ	7·24	7·31	8·26	7·89
0·40	10·51	10·29	9·84	9·63	0·47	7·11	6·49	7·71	7·37
0·42	8·74	8·71	8·48	8·58	0·48	6·82	6·43	7·52	6·97
0·43	9·74	8·84	8·07	7·27	0·49	7·23	6·25	7·22	6·93
0·44	8·45	8·51	7·78	7·68	0·50	7·82	6·26	7·06	7·93
0·45	8·42	8·07	8·04	8·44	0·51	....	....	6·45	....

TABLE 17.—MEAN VALUES OF $_0I_\lambda$ FOR "LATE TYPE" STARS

λ	α Aur.	β Gem.	λ	α Aur.	β Gem.	λ	α Aur.	β Gem.
0·4000μ	2·77	....	0·4898μ	4·18	3·99	0·6071μ	3·83	4·14
0·4094	2·36	....	0·5047	4·08	3·89	0·6209	3·77	3·84
0·4215	2·57	2·57	0·5175	4·23	....	0·6389	3·83	3·91
0·4336	3·31	2·95	0·5278	4·07	4·03	0·6620	3·44	3·53
0·4478	3·59	3·39	0·5485	4·28	4·28	0·6762	3·46	....
0·4659	4·13	3·65	0·5631	4·22	4·23			
0·4795	4·29	4·04	0·5820	4·02	4·02			

The relative intensity distributions, given in Tables 16 and 17 for each of the six stars, are shown graphically in fig. 10. The smooth curves, running through the observed values, are relative intensity distributions corresponding to the noted temperatures and computed from Planck's law. The following comments may be made:

γ Cassiopeiae. The observed points do not fall very closely on the curve, but the general run of the values may be said to correspond to a temperature of 15,000°K. It will be noted that the present relative intensity distribution is markedly different from that previously obtained in the first application of the wedge method[11]. This difference is to be attributed to errors in the former determination, the chief of which were inaccurate calibration of the wedge W.I and an assumed temperature of 3750°K for the carbon arc instead of the correct value 3080°K.

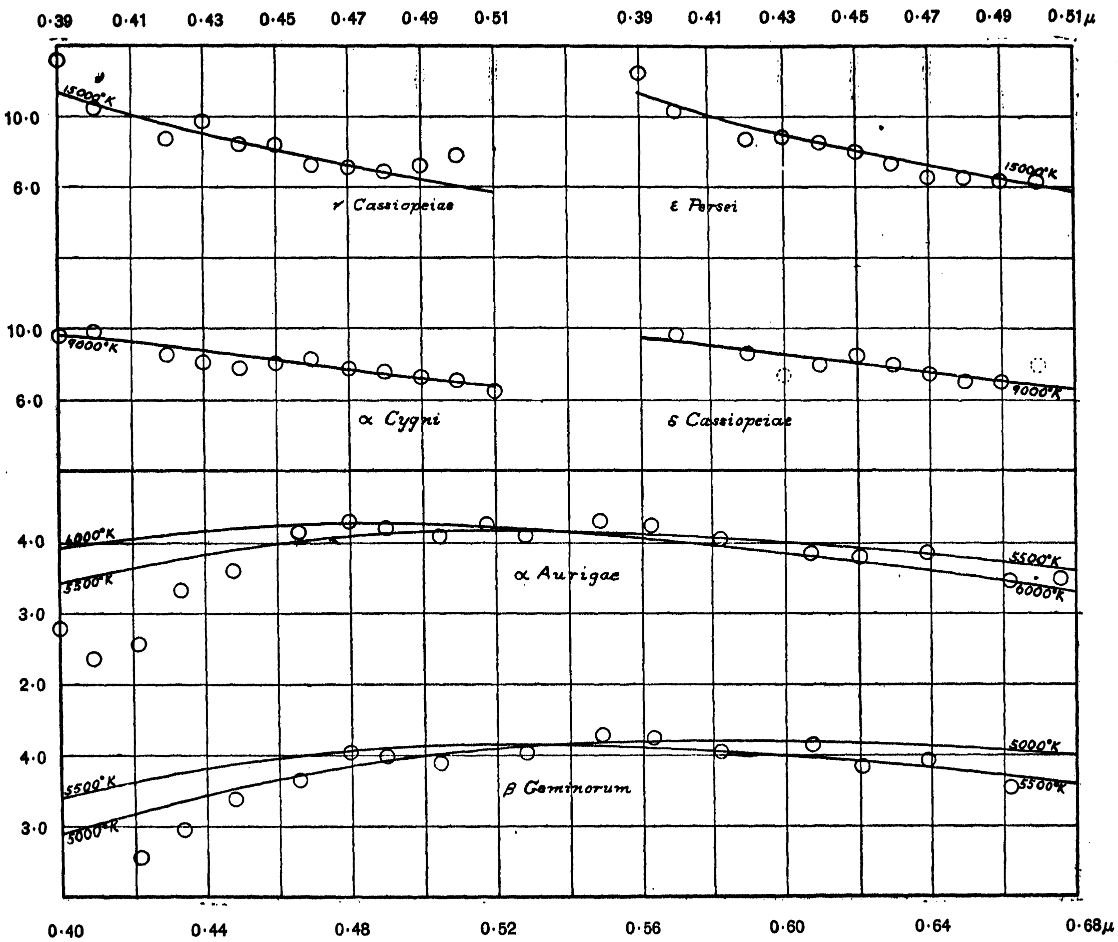


FIG. 10. Intensity Distribution in Typical Stellar Spectra

ε Persei. The observed points fit the 15,000°K curve much more closely than in γ Cassiopeiae. In particular, it is to be noted, there is no evidence of a secondary maximun near $0 \cdot 49\mu$.

α Cygni. Some difficulty was experienced in matching the observed points with a black body curve. The departures are probably to be attributed to accidental errors.

δ Cassiopeiae. In this star the values of ${}_oI_\lambda$ for $0 \cdot 43\mu$ and $0 \cdot 50\mu$ are of smaller weight than for the rest of the wave lengths. The intensity at $0 \cdot 43\mu$ is probably too low because of the presence of fuzzy absorption lines in that neighbourhood, and the intensity at $0 \cdot 50\mu$ is from one spectrum only, whereas the others are the mean intensities from four spectra. A distribution corresponding to a temperature of 9000°K fits the observed values satisfactorily.

α Aurigae. It will be seen that the observed intensity distribution, exclusive of values to the violet of $0 \cdot 46\mu$, corresponds to an intensity distribution between the temperatures of 5500°K and 6000°K. The drop in intensity of the observed values to the violet of $0 \cdot 46\mu$ is to be attributed, of course, to the effect of absorption lines, which could not be entirely eliminated with the small linear dispersion and wide slit width which were used.

β Geminorum. The observed values in this case depend only on two spectra, one of which was weak. An intensity distribution between the temperatures 5000°K and 5500°K fits the observed intensities, with the exception of those to the violet of $0 \cdot 46\mu$, satisfactorily. The depression in the violet is again the result of distortion by the absorption lines.

The final results, expressed as colour temperatures, are given in Table 18. In the first column appears the name of the star, in the second its type and in the third column the colour temperature as determined above by the wedge method. In the remaining three columns appear, where available, the temperatures determined radiometrically by Coblentz[12], with a visual spectrophotometer by Wilsing, Scheiner and Munch[13], and by Sampson's[14] recent ingenious photographic method. From this table it will be observed, that while for G and K-type stars all methods in the hands of different observers yield accordant results, for the early type stars there appear striking discrepancies, the cause of which has yet to be elucidated. These discrepancies show up most clearly in

TABLE 18.—STELLAR TEMPERATURES

Star	Type	Wedge	Coblentz	Wilsing, etc.	Sampson
γ Cassiopeiae	Boe	15,000°	....	6,800°	16,900°
ε Persei	Bo	15,000	....	7,400	....
α Cygni	cA2	9,000	9,000°	9,400	12,500
δ Cassiopeiae	A5	9,000	....	5,800	....
α Aurigae	gGo+F5	5,500–6,000	6,000	7,100	5,500
β Geminorum	Ko	5,000–5,500	5,500	4,900	....

the work of Wilsing[13] and his collaborators, where the temperatures of various stars of class B range from 6300°K (δ Persei, B5) to 22,500°K (κ Draconis, B5p). In view of the accordant temperatures obtained by these investigators for the "later types," it is difficult to believe that this range of 16,000° in temperature for the B-type stars is entirely due, though the suggestion has been made, to accidental error. It is more reasonable to suppose that abnormalities in the intensity distribution of the particular stars have introduced errors into the computed temperatures. A case in point is the star γ Cassiopeiae. While the observed intensities in this star fit a black body curve for 15,000°K fairly well (see fig. 10), there are certain anomalies in the intensity distribution the most remarkable of which is a secondary maximum in the neighbourhood of $0 \cdot 49\mu$. While it is quite possible that this secondary maximum is an accidental error—the spectra are neither numerous enough nor strongly enough exposed to make a decision possible—its existence, in conjunction with the temperature of 6800°K derived by Wilsing, Scheiner and Munch, makes it probable that there are departures from strict black body intensity distributions in γ Cassiopeiae. Again, while there are well established grounds for believing the O-type stars to have the highest known temperatures[15, 16], their relative intensity distributions, if colour is any indication, must assuredly be anomalous. As observed on the spectroscope slit at this institution by two independent observers, the O-type stars appear as a class to be white. One of the most striking examples is the double star[16] B.D. + 35°3930 (Σ2624), the north component of which has a type O5 (estimated temperature 22,000° K) and the south component is of type B0 (estimated temperature 13,000° K). The brighter O-type star appears to be almost as white as an A-type star in comparison with its fainter B-type companion. To conclude, three lines of evidence—the large range of temperatures for B-type stars, the observed intensity distribution in γ Cassiopeiae and the whiteness of the O-type stars—suggest the possibility of anomalies in the intensity distribution of these "early type" stars. Further investigation may, therefore, well be directed to the determination, not of colour temperatures, which may have little physical significance, but of the actual relative intensity distribution in stars of types B and O.

REFERENCES TO PART II

[1] C. G. Abbot — — Annals Astrophysical Observatory, Washington, *3*, 194, 1913; *4*, 199, 1922.

[2] J. Wilsing — — Publications Astrophysical Observatory, Potsdam, No. 66, 1913.

[3] C. G. Abbot — — Annals Astrophysical Observatory, Washington, *2*, 50-57, 1908.

[4] J. S. Plaskett — — Publications Dominion Astrophysical Observatory, Victoria, *1*, No. 1, 1920.

[5] Lord Rayleigh — — Scientific Papers *1*, 135 1871: Phil. Mag. *42*, 441, 1871.

[6] H. Hovestadt — — Jena Glass (English Ed.) p. 46, 1902.

[7] D. Brunt — — Combination of Observations p.48, 1917.

[8] F. E. Fowle — — Astrophysical Journal *38*, 392, 1913.
— Smithsonian Physical Tables p. 182, 1916.

[9] C. G. Abbot — — Annals Astrophysical Observatory Washintgon *4*, 207, 1922.

[10] E. A. Milne — — Monthly Notices R.A.S. *81*, 375, 1921.

[11] H. H. Plaskett — — Monthly Notices R.A.S. *80*, 771, 1920.

[12] W. W. Coblentz — — Bureau of Standards, Scientific Papers No. 438, 1922.

[13] J. Wilsing, J. S. Scheiner, W. Münch — Publications Astrophysical Observatory, Potsdam, No. 74, 1919

[14] R. A. Sampson — — Monthly Notices, R.A.S. *83*, 174, 1923.

[15] M. N. Saha — — Proc. Royal Society A, *99*, 135, 1921.

[16] H. H. Plaskett — — Publications Dominion Astrophysical Observatory, Victoria *1*, No. 30, 1922.

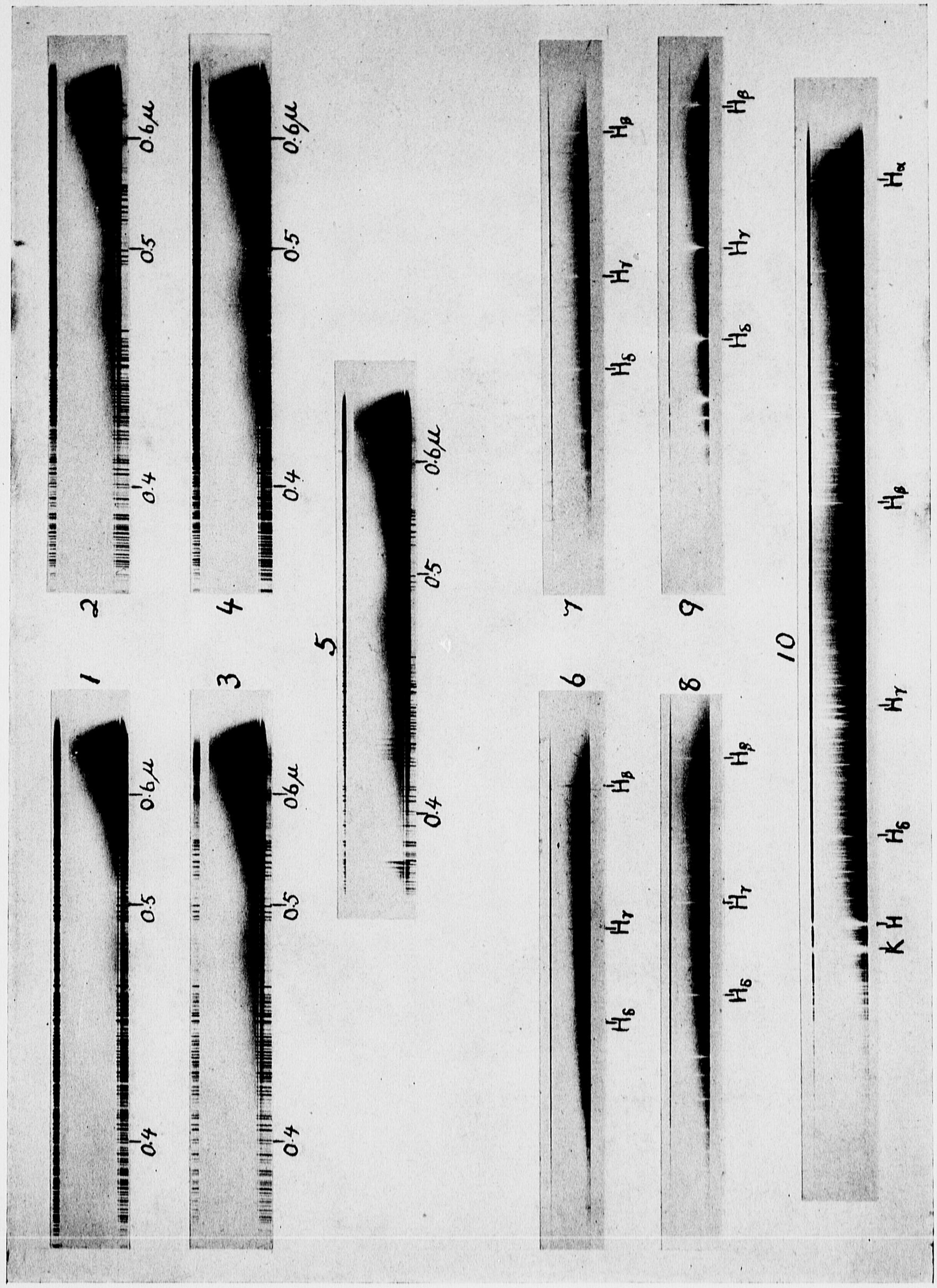
DESCRIPTION OF THE PLATE

Laboratory Wedge Spectra with Fe Arc Comparison (magnification ×2 approximately)

1.—Nela filament lamp, current 12 amps. Colour temperature 2010°K.
2.—Nela filament lamp, current 16 amps. Colour temperature 2439°K.
3.—Acetylene flame. Colour temperature 2360°K.
4.—Nela filament lamp, current 20 amps. Colour temperature 2830°K.
5.—Positive crater carbon arc. Colour temperature 3080°K.

Astrophysical Wedge Spectra (magnification ×2·5 approximately)

6.—γ Cassiopeiae. Colour temperature 15,000°K.
7.—ϵ Persei. Colour temperature 15,000°K.
8.—α Cygni. Colour temperature 9,000°K.
9.—δ Cassiopeiae. Colour temperature 9,000°K.
10.—Solar Spectrum. Colour temperature 6,700°K—7,000°K. (magnification ×2 approximately)



Typical Wedge Spectra