The errors in the estimation of temperatures which result from the uncertainty of the sensitive hue will thus exceed 100°. With observers having had more experience the difference will be somewhat reduced, but it will remain always quite large.

Crova's Pyrometer. — Crova endeavored to give to the method of estimation of temperatures based on the unequal variation of different radiations of the spectrum a scientific precision by measuring the absolute intensity of each of the two radiations utilized; but this method, from the practical point of view, does not seem to have given more exact results than the preceding ones.

The eye is much less sensitive to difference of intensity than to difference of hue, so that there is no advantage in making use of observations of intensity.

Crova compared two radiations,

$$\lambda = 676 \text{ (red)},$$
$$\lambda = 523 \text{ (green)},$$

coming from the object studied and from the oil lamp used as standard. For this purpose, by means of a variable diaphragm, he brings to equality one of the two radiations emanating from each of the sources, and measures afterwards the ratio of the intensities of the two other radiations.

The apparatus is a spectrophotometer. Placed before half the height of the flame is a total reflecting prism, which reflects the light from a ground glass, lighted by the radiations from an oil lamp, having first passed through two nicols and a diaphragm of variable aperture. On the other half of the slit is projected by means of a lens the image of the body to be studied.

Before using the apparatus it is necessary to adjust the extreme limits of the displacement of the spectrum so as to project successively on the slit, in the focus of the eyepiece, the two radiations selected ($\lambda = 676$ and $\lambda = 523$). For this purpose there is interposed between the two crossed nicols a 4-mm. quartz plate which reëstablishes the illuminations; for extinction again, the analyzer must be turned 115° 38′ for $\lambda = 523$, and

65° 52′ for $\lambda = 676$. The instrument is then so adjusted that the dark band produced by the quartz is situated in the middle of the ocular slit.

The apparatus thus adjusted, in order to make a measurement at low temperatures, inferior to those of carbon burning in the standard lamp, one brings to equality the red radiations with the diaphragm, then, without touching the diaphragm again, the green is brought to equality by turning the nicol.

The optical degree is given by the formula

$$V = 1000 \cos^2 \alpha,$$

denoting by α the angle between the two principal sections of the nicols.

For higher temperatures the operation is reversed; one brings first the green to equality by means of the diaphragm, then the red to equality by a rotation of the analyzer. The optical degree is then given by the formula $N = \frac{1000}{\cos^2 \alpha}$, and the rotation varying from 0° to 90°, the optical degrees vary from 1000° to infinity.

This method, which is theoretically excellent, possesses certain practical disadvantages:

1. Lack of precision of the measurements. In admitting an error of 10 per cent in each one of the observations relative to the red and green radiations, the total possible error is 20 per cent; now, between 700° and 1500° the ratio of intensities varies from 1 to 5: this leads to a difference of $\frac{1}{25}$ in 800°, or 32°.

2. Complication and slowness of observations. It is difficult to focus exactly on the body or the point on the body that one wishes to study. The set-up and the taking of observations sometimes require about half an hour.

3. Absence of comparison in terms of the gas scale.

The *a priori* reason that had led to the study of this method was the supposition that, in general, the emissive power of substances was the same for all radiations and that consequently its influence would disappear by taking the ratio of the intensities of the two radiations. The measurements of emissive power given previously prove that this hypothesis is the more often inexact.

Crova also suggested that the upper limit of the spectrum of an incandescent body might be used as a measure of its temperature, and Hempel has tried this method with a special form of spectroscope, using a luminescent screen for observing when the upper spectrum limit is beyond the visible radiations; but, as compared with the photometric and radiation pyrometers, only crude results can be obtained.

Use of the Flicker Photometer. — Lummer and Pringsheim have shown that the combination of a spectral apparatus with a flicker photometer permits of greatly increasing the accuracy of the method of comparison of the intensities of two colors, and also permits the use of Wien's law (page 251) in the calculation of temperatures.

Sighting on a black body at the absolute temperature T, and measuring the two intensities I_1 and I_2 corresponding to the wave lengths λ_1 and λ_2, we have from Wien's law:

$$\log\frac{I_1}{I_2} = 5\log\frac{\lambda_2}{\lambda_1} + \frac{c_2 \log \epsilon}{T}\left(\frac{1}{\lambda_2} - \frac{1}{\lambda_1}\right),$$

in which T is the only unknown. Thürmel has shown that the Purkinje effect does not vitiate the observations, and that results good to better than 2 per cent can be obtained, and that an observer will repeat his readings within this limit of error.

Here are some of Thürmel's observations on a black body:

TEMPERATURE WITH SPECTRAL FLICKER PHOTOMETER.

Ratio of wave lengths.	Temperature with— Optical apparatus.	Temperature with— Thermocouple.
660–480	1502°	1477°
660–500	1489	....
660–480	1742	1698
660–500	1703	....

Sighting on other objects than a black body will give incorrect temperatures, usually low, due to the difference in shape of the intensity curve from that of a black body, and on account of

the varying value of the absorption coefficient with wave length from one substance to another (see page 256).

Stellar Pyrometers. — Of recent years there has been an increasing interest among astronomers in the determination of the physical characteristics of the stellar bodies, resulting in the development and modification of physical instruments suited to their needs. Assuming that the ratio of intensities of two spectral colors, red and blue for example, varies according to Planck's law (page 251) for the terrestrial and celestial bodies sighted upon, M. Nordmann has recently constructed a heterochrome photometer and used it for the estimation of effective stellar temperatures.

With this apparatus, which is still in a somewhat crude state of development, measurements are made, in the various parts of the spectrum, of the brightness of the star under observation referred to that of an artificial star realized by means of a secondary electric standard, interchanging, in the path of rays common to the two stars, a series of monochromatic liquid screens.

Consider measurements with red and blue light.

If T, T', T'', . . . are known temperatures of definite light sources, given, for example, by electric furnaces and the carbon arc, and if R, R', R'', . . . and B, B', B'', . . . are the corresponding intensities of the images as measured through red- and blue-light filters respectively by means of the stellar photometer, then, according to Planck's law, the relation $\log\frac{R}{B}$ *vs.* $\frac{1}{T}$ is a straight line. With the apparatus once standardized at known temperatures therefore, it is only necessary to measure the red and blue intensities for any light source as a star, in order to find its apparent or black-body temperature. The temperature found will approach the true temperature the more nearly the spectral-energy curve of the star approaches that of the black body. In the form of apparatus used by Nordmann, it is also necessary to correct for the shift of equivalent wave length with temperature of the monochromatic screens used. This could be avoided by transforming the apparatus into a spectrophotometer in much the same manner as Henning's spectral pyrometer eliminates the colored glasses of the Holborn-Kurlbaum instrument.

Some of the results found by M. Nordmann for effective stellar temperatures absolute are as follows:

ρ Persei	2870°	Polaris	8,200°
ζ Cephii	4260	α Lyræ	12,200
Sun	5320	δ Persei	18,500
γ Cygni	5620	λ Tauri	40,000

M. Féry has realized a form of stellar pyrometer which eliminates the use of colored screens. The principle of this apparatus, which is based on Wien's displacement law (page 249), consists in modifying the color of a comparison lamp by changing the

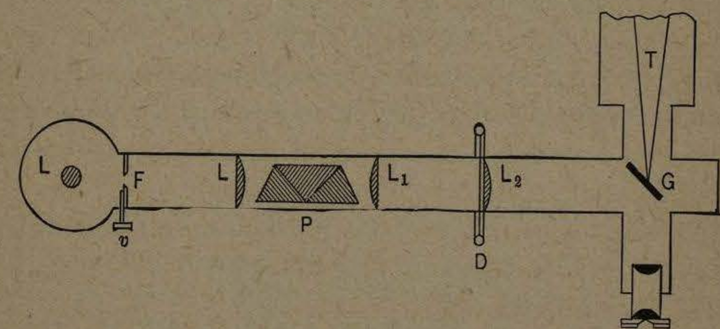

Fig. 125. Féry Spectral Pyrometer.

ratio of the monochromatic intensities which it emits, so as to match this color with that of the star whose temperature is to be measured.

In order to realize this principle, the light from the lamp L (Fig. 125), after passing through the slit F, is dispersed by the direct-vision prism P, and, by means of the lenses L and L_1, forms a spectrum in the plane of a diaphragm D, to which we shall return. A third lens L_2 forms, on the half-silvered mirror G, a white or undispersed image of the face of the prism P.

The light from the star is concentrated by a telescope objective, whose tube is shown at T, and an image of the star is formed on the nonsilvered part of the mirror G, and may be examined by

an ocular simultaneously with the adjacent luminous area due to light from the comparison lamp.

Fig. 126 gives the details of the diaphragm D of Fig. 125. The spectrum is formed between the two screens V and V'; this last is semicircular and may be turned about A as an axis. This rotation of V' causes the ratio of the intensities of the extreme red and blue rays to vary and gives to the field as projected by the lens L_2 (Fig. 125) the desired color.

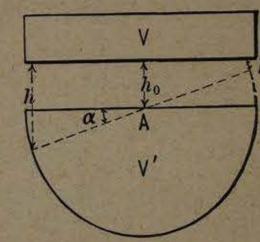

Fig. 126. Detail of Diaphragm.

Both of the above types of apparatus may be calibrated for the lower temperatures by means of an electric furnace, and for the higher stellar temperatures by taking the arc and sun temperatures as fixed points.

Spectrophotometric measurements of the apparent temperatures of the sun and 109 stars have been made by Wilsing and Scheiner, using as comparison source an incandescent lamp calibrated against a black body. Light of five wave lengths was used, and the observations were reduced in terms of Planck's law, using an equation similar to that of p. 255. Here are some of their results, assuming $c_2 = 14{,}600$.

WILSING AND SCHEINER'S STELLAR TEMPERATURES (ABS.).

Sun	5130 to 5600°	α Leoni	8700°
ζ Pegasi	7900	α Lyræ	8100
α Pegasi	8700	γ Geminorum	6900

We shall return to the question of the sun's apparent temperature in Chapter XI.

Action of Light on Selenium. — It has been known for a long time that light incident upon selenium changes the electric resistance of the latter, and pyrometers based on this principle have been devised. Light from an incandescent source whose temperature is sought falls upon a selenium cell forming part of an electric circuit in which are a battery and ammeter. As the light varies in intensity due to changes in temperature, the resistance of the selenium varies, and the indications of the ammeter may be empirically calibrated in terms of temperature. As selenium is quite insensible to the invisible heat waves, the lower limit of this method is above incandescence. Selenium also requires some time to recover its original resistance after being acted upon by light, and this lag might prove troublesome. As a dial instrument is used, the method could readily be made recording.

CHAPTER IX.

VARIOUS PYROMETRIC METHODS.

While some of the several types of pyrometer which we have described in the preceding chapters have, by a process of elimination, become generally recognized as meeting most requirements for high-temperature measurements, scientific and industrial, there nevertheless remain several methods, some of which are useful in special fields of investigation or practice, and others mark some important development in the history of pyrometry. We shall mention briefly a few of these methods.

Wedgwood's contraction pyroscope, the oldest among such instruments, presents to-day hardly more than an historic interest, for its use has been almost entirely abandoned. It utilizes the permanent contraction assumed by clayey matters under the influence of high temperature. This contraction is variable with the chemical nature of the paste, the size of the grains, the compactness of the wet paste, the time of heating, etc. In order to have comparable results, it would be necessary to prepare *simultaneously, under the same conditions*, a great quantity of cylinders, whose calibration would be made in terms of the gas thermometer. Wedgwood employed cylinders of fire clay, baked until dehydrated, or to 600°; this preliminary baking is indispensable, if one wishes to avoid their flying to pieces when suddenly submitted to the action of fire. These cylinders have a plane face on which they rest in the measuring apparatus, so as always to face the same way (see the frontispiece). The contraction is measured by means of a gauge formed by two inclined edges; two similar gauges of 6 inches in length, one an extension of the other, are placed side by side; at one end they have a maximum separation of 0.5 inch, and at the other a minimum separation of 0.3 inch. Longitudinally the divisions are of 0.05 inch; each