indicating changes of temperature. The other is connected to a battery B and rheostat R in series with a milliammeter or potentiometer for measuring the current required to reduce the deflection of the galvanometer to zero. If A is the area of the aperture

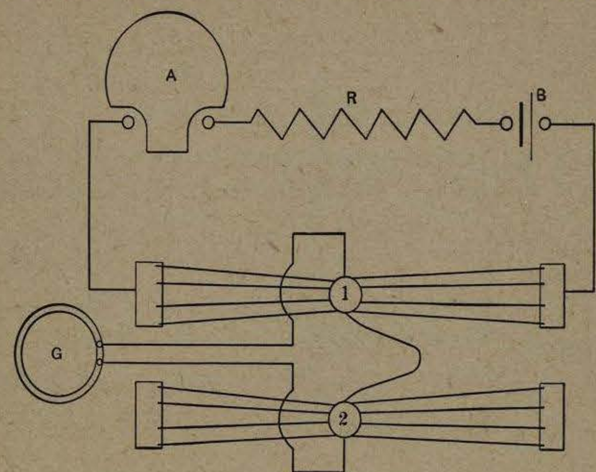

Fig. 95. Callendar's Radio-balance.

in $\overline{cm.}^2$, H the intensity of radiation received in watts per $\overline{cm.}^2$, a the absorption coefficient of the surface of the disk, P the Peltier effect in volts ($P = T\frac{dE}{dT}$ when T = absolute temperature and $\frac{dE}{dT}$ the thermoelectric power), C the balancing current in amperes, and R the effective resistance of the couple, the equation giving the value of the radiation in absolute measure is

$$aAH = PC - C^2R.$$

The value of R in the small correction term for the joule effect is readily determined by observing the neutral current $C_0 = \frac{P}{R}$, for which the joule effect balances the Peltier effect. In practice, two similar disks with similar connections are mounted side by side in a thick copper box, and are balanced against each other in order to avoid changes of zero due to exposure to stray radiation, sunshine, or to rapid variations of temperature. For the

measurement of temperature with such an instrument, H may be expressed in terms of the emissivity, distance, and temperature of the source, or the instrument may be calibrated empirically by means of a black body.

The Radiomicrometer. — We may illustrate the use of this instrument for temperature measurements by describing the experiments of Wilson and Gray. These physicists measured

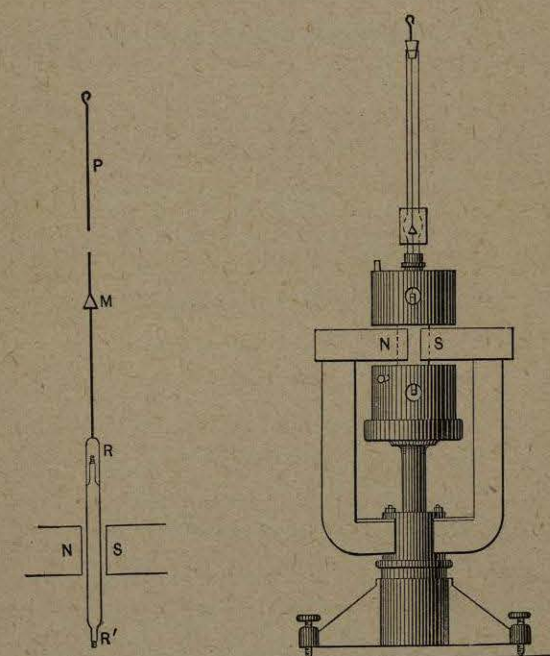

Fig. 96. The Radiomicrometer.

the intensity of radiation by means of a thermoelectric couple, a method first conceived by Deprez and d'Arsonval. A movable coil made of two different metals (silver and palladium) is suspended by a silk cocoon fiber between the poles of a magnet. The solar radiation is allowed to fall upon one of the junctions, while upon the other junction is directed a source of heat which exactly balances the first. As the temperature of this auxiliary source is necessarily the lesser, it is necessary that the apparent angle which it subtends at the galvanometer be the greater.

Wilson and Gray used an apparatus similar to the radiomicrometer of Boys. The suspending fiber is of quartz; the metals employed are bismuth and antimony. The electromotive force so produced is twenty times greater than that obtained with the palladium-silver couple. The metallic strips R and R' (Fig. 96) are very thin (0.1 mm.), which renders the construction of the apparatus quite delicate. In order to protect the movable coil against air currents, it is inclosed in a metallic case; an open tube lets pass in the radiation; diaphragms set inside this tube prevent air disturbances.

Instead of measuring, as may be done, the deflection of the mobile parts, these observers preferred to employ a null method making use of another radiation, that from a modification of the *meldometer* of Joly, an apparatus used also for the calibration of the radiomicrometer. The meldometer (Fig. 128) consists of a strip of platinum heated by an electric current; the dimensions are as follows: 102 mm. in length, 12 mm. in breadth, and 0.01 mm. thick. This strip they placed in the midst of an inclosure surrounded by water. Fastened at one end, it is held in place at the other end by a spring and carries on this end a lever to which is fixed a mirror arrangement serving to optically amplify the variations in the length of the strip resulting from its heating by the passage of the more or less intense current.

The relation between the change of length and the temperature is determined by means of the fusion of very small fragments ($\frac{1}{10}$ milligram) of bodies whose fusing points are known. Wilson and Gray used the following, which for the gold and palladium are certainly too low:

Silver chloride	452°
Gold	1045
Palladium	1500

With this apparatus they apparently verified, up to the fusion of platinum, the law of radiation given by Stefan:

$$E = \sigma (T^4 - T_0^4).$$

For the purpose of graduation, the meldometer was removed to a distance, so that its action on the radiomicrometer was

always the same, and it was assumed that the intensity varies as the inverse square of the distance. It is besides necessary to know the emissive power of platinum; Wilson and Gray took as starting points the results given by previous experiments:

$t°$	Emissive power.
300°	$\frac{1}{5.4}$
600	$\frac{1}{4.2}$
800	$\frac{1}{3.9}$

And by extrapolation they found $\frac{1}{2.9}$ at the temperature of 1250°, the temperature which balanced the solar radiation with the somewhat large apparent angle subtended by the meldometer. In admitting, then, with Rosetti and Young, a zenith absorption of 30 per cent, the temperature of the sun, supposed to be a black body, was found equal to about 5900° C.

This figure, although reasonable numerically in the light of later work, must be considerably uncertain, on account of the errors involved in the fusing points employed for graduation, and because of the fact that the radiation from platinum does not obey Stefan's law. Furthermore, the constants for platinum were found in terms of those of copper oxide, a substance they found, incorrectly, to depart more from a black body than polished platinum.

Wilson has also given 5500° C. as the best result from his own experiments, using a black body as comparison source. Wilson and Gray also found the temperature of the carbon arc to be 3330° C., a result now known to be considerably low (see Chap. XI).

The Bolometer. — Although the principle of measuring the intensity of radiation by the change in resistance of a metallic strip had been used by several observers before Langley, he nevertheless deserves the credit for first constructing a practical instrument and developing it to a very high state of sensibility. There have been several types of bolometer used, although in all of them the Wheatstone bridge method of measuring resistance is employed. For spectrophotometric work, usually two narrow strips of extremely thin platinum serve as adjacent arms of the bridge; in the Smithsonian instrument used by Langley and Abbot, the strips are 12 mm. long, 0.06 mm. wide, and so thin that the resistance is about 4 ohms; the measuring current is 0.03 milliamperes. The measurements are the same as those with the resistance thermometer used with a bridge, and, in special work, an extremely sensitive galvanometer, usually a Kelvin multiple-coil instrument of low resistance, short period, and the highest possible current sensibility, 10^{-10} to 5.10^{-11} amperes per mm. at 1 m. A spectrometer of proper design is of course also essential in spectral radiation work.

For measurement of the total energy, the grid form, or surface bolometer, such as used by Lummer and Kurlbaum in their verification of the radiation laws, is preferable. In their instrument, they had four similar bridge arms of platinum foil composed of 12 connected strips 32 by 1 mm. and 0.001 mm. thick; two diagonal arms being placed one behind the other and exposed to the radiation. The highest temperature sensitiveness attained with the bolometer is 10^{-7} deg. C. per 1 mm. deflection. The portion of the instrument receiving radiation is inclosed within a well-screened and jacketed case, which may be evacuated if desired, and a lens or mirror used for concentrating the radiation.

In Callendar's form of absolute bolometer, which is of the grid or surface type, the intensity of radiation in absolute measure is determined by observing the value of the electric current required to produce the same rise of temperature in the grid as the radiation to be measured. Callendar has also introduced several instrumental improvements, such as automatic experimental compensation of that part of the grid not receiving radiation directly thus eliminating the creep in attaining a maximum. This instrument is also made self-recording. Callendar has also developed several modifications in bolometer design that may prove serviceable in temperature measurements, particularly when a relatively large area is available.

Although the bolometer does not appear to have been used as

a pyrometer, it can readily be adapted for that purpose; and instruments of sufficient sensitiveness and robustness could readily be devised. They can of course be made self-registering.

The Radiometer. — This appears to be the least adapted for temperature measurements of the radiometric instruments we have mentioned. The apparatus consists of two blackened vanes

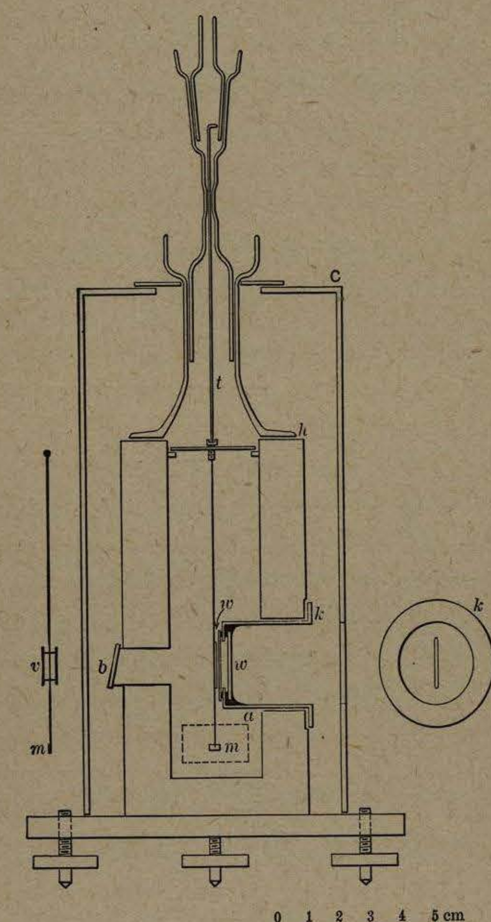

Fig. 97. Radiometer.

hung in vacuo on a fine quartz fiber (Fig. 97). Radiation falling on a vane deflects the suspended system, whose angle is read, as in the case of a galvanometer, with mirror, scale, and telescope. The readings are influenced by many factors, notably by the residual gas pressure, the location of the vanes, and the nature of the window. The instrument is not transportable and cannot be calibrated in absolute measure. Its sensitiveness is, however, very great.

Standard Pyrheliometers. — The International Union for Coöperation in Solar Research in 1905 adopted temporarily Ångström's compensation pyrheliometer as standard. In this instrument, radiation is received on a metallic strip, beside which, but shielded from the radiation, is a similar strip through which is sent a measured electric current of such strength that the temperatures of the two strips are the same, as measured by attached thermo-couples. The assumption is then made that the strip carrying the current may be substituted for that receiving the radiation.

Calling Q the heat produced in gram calories per minute by the current, proportional therefore to the radiation intensity, r the resistance of the strip, and i the current, we have, following Ångström:

$$Q = \frac{60}{4.19} \cdot \frac{ri}{ba} = \text{const.} \cdot i^2,$$

where a = absorbing power of blackened strip surfaces and b = width of strips. The early instruments were made with platinum strips, but Callendar having shown that the temperature coefficient of this metal is a serious source of error, strips of manganin are now used. Ångström has used his pyrheliometer in a considerable number of laboratory investigations, including a study of the radiation from incandescent lamps and from the Hefner standard. The latter he determined to radiate $\frac{0.0147 \text{ gr. cal.}}{\text{mm. cm.}^2}$.

As used by Callendar, Abbot, and others, the Ångström instrument, compared with absolute radiometric apparatus, gives slightly too small values of radiation intensity.

At the Astrophysical Laboratory of the Smithsonian Institution, Abbot and Fowle have recently devised an absolute radiometric instrument composed of a black-body receiver combined with a flow calorimeter. V. A. Michelson in 1894 had also used a black-body receiver combined with a Bunsen calorimeter. A

form of the Smithsonian standard pyrheliometer is illustrated in part in Fig. 98, in which a is the diaphragmed chamber with conical base for receiving the radiation which first passes through the blackened tube b, also supplied with diaphragms c, c, and an electromagnetically operated shutter gh. The water enters at e_1 and, after circulating over the walls d and l of the double water jacket, passes out at e_2 into an automatic weighing apparatus. At f_1, f_2, f_3, f_4 are the coils of platinum-resistance thermometers giving the temperature of the water before and after absorbing the radiation. The constants of the instrument are determined by placing a heating coil at m and measuring the input of energy electrically. It was found that the calorimeter recorded practically 100 per cent of the energy supplied by the heating coil.

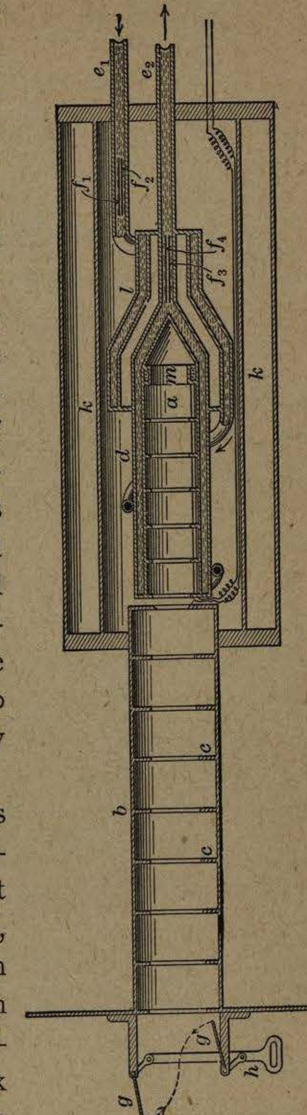
Fig. 98. Smithsonian Standard Pyrheliometer.

Either of these pyrheliometers could be used to measure temperatures, and it is not impossible that an instrument of the latter type, or of Michelson's, may be of use in absolute pyrometric apparatus in those researches where it is essential that the receiver be a black body and where it may be desired to measure the radiation in absolute units. Secondary pyrheliometers have also been designed recently by Abbot, Marvin, and others.

Thermoelectric Telescopes. — *The Féry pyrometer* was the first convenient form of instrument making use of total radiation and based on Stefan's law (page 245) to come into practical use for temperature measurements. As in the case of the photometric pyrometers, the limitations as to the realization of a black body apply here also with even greater emphasis, as an instrument using the whole spectrum, visible and invisible, is most sensitive to selective radiation effects.

Use is made of the Stefan-Boltzmann law,

$$E = \sigma (T^4 - T_0^4),$$

in the following way: Radiation from an incandescent body is focused upon a very sensitive thermocouple and raises its temperature. The electromotive force thus generated at the junction actuates a sensitive potential galvanometer in series with the couple in exactly the same way as in the Le Chatelier thermoelectric pyrometer; so that we have here a radiation pyrometer which is direct-reading by means of a pointer on a scale, and may therefore readily be made a recording instrument.

The difficulty in construction of such an instrument is realizing a material for lens which is transparent for all radiations visible and invisible, so that the pyrometer may be calibrated directly in terms of Stefan's law, and so that its indications will be reliable at temperatures however high. This is effected in the laboratory type of instrument by use of a fluorite lens which for temperatures above 900° C. satisfies the conditions of not altering appreciably the radiations transmitted through it; that is to say, the ratio of the radiations absorbed to the radiation transmitted is constant.

At low temperatures a large proportion of the energy exists in the form of long wave lengths, and as fluorite has an absorption band in the infra-red (near 6 μ), it will absorb a considerable proportion of the radiation, and therefore Stefan's law can no longer be assumed.

Fig. 99 illustrates the construction of the original laboratory form of the instrument, where F is the fluorite lens, P a rack and pinion for focusing the radiations upon the thermojunction of iron-constantan, and protected from extraneous rays by the

screens C, D, shown also in section at AB. The thermojunction is of exceedingly small dimensions, only a few thousandths of a millimeter wide, and is soldered to a silver disk. The leads are brought out to the insulated binding posts b, b', so placed as to reduce the chances of extraneous thermal currents to a minimum. The circuit is completed through a sensitive galvanometer provided with a scale. A diaphragm fixed in size and position, EE, gives an opening of constant angle independent of the focusing, whereby the cone of rays striking the junction is not changed in size by focusing.

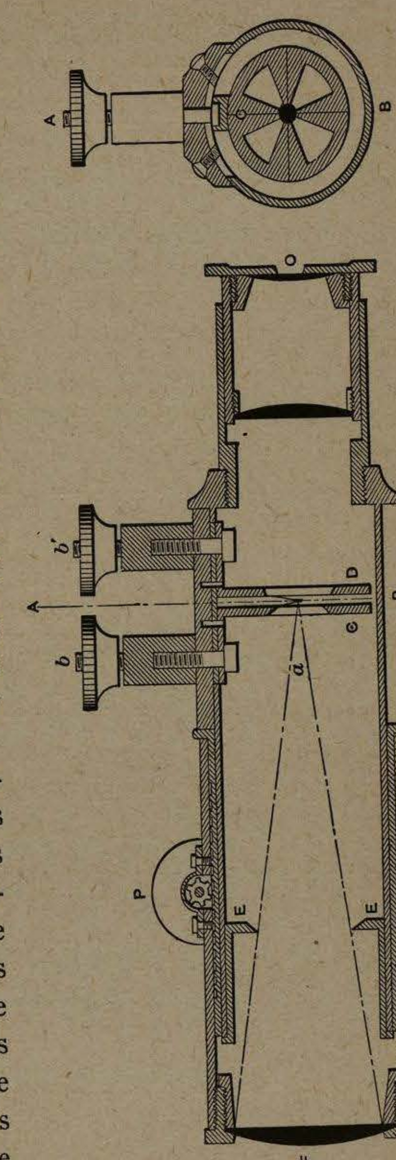

Fig. 99. Féry Telescope Pyrometer.

In making a temperature measurement, it is necessary to sharply focus the image of the incandescent object upon the thermojunction by means of the eyepiece O, and care must be taken that this image is of greater size than the junction. This adjustment once made, the pyrometer operates indefinitely while sighted upon the same object, and readings of the galvanometer scale give temperatures directly from the calibration.