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The instruments we are about to describe are the result of investigations begun under a grant from the Hodgkins Fund in 1913. They are derived in principle from the highly successful pyrheliometer of K. Ångström.[1] In that instrument there are two strips of blackened manganin, one of which is shaded from the solar radiation, the other exposed. The shaded strip is heated by an electric current whose strength can be graduated until the temperatures at the back of the two strips are equal, as shown by means of thermo-elements attached to the rear of the two strips. When the equality of temperature is brought about, as shown by zero deflection of the galvanometer, it is assumed that the energy of radiation absorbed in the exposed strip is equal to the energy of the electric current dissipated in the shaded one. To eliminate errors the uses of the strips are reversed, so that the formerly shaded strip is exposed to radiation, and the formerly exposed strip is shaded and heated by the electric current.

In another instrument of K. Ångström, called by his son the pyrgeometer,[2] a pair of blackened manganin strips alternate with a pair of polished gold-plated ones, and the whole grid of four strips, arranged centrally nearly in the plane of the surface of a nickel-plated box, is exposed to the night sky. The bright strips lose very little heat by radiation, while the black ones lose comparatively a good deal, and so the effect is to cool the blackened strips with respect to the bright ones, and this state of affairs is indicated by means of thermo-elements attached to the series of strips. It is provided that the electric heating current can be used to warm the blackened strips until their temperature is restored to that of the bright strips as indicated by the zero of the galvanometer. This instrument was not regarded by its inventor as a primary instrument, and following his

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[1] Astrophysical Journal, Vol. 9, page 332.

[2] Smithsonian Misc. Coll., Vol. 65, No. 3, page 28.

procedure the constant of such instruments is determined by exposing them within inclosures of constant-lower-temperatured walls.

It might appear that the pyrgeometer could also be employed in daytime to determine the radiation scattered from sunlight by the sky, if at such times the sensitive strips were covered by a hemisphere of glass to cut off exchange of rays of long wave lengths. In such a case the heating current would require to be applied to the bright strips rather than the black ones. This use of the instrument is, however, defeated by the fact that the absorption coefficient of the bright strips for sky-light is not even approximately zero, and varies greatly with the wave length, especially in the blue and violet and ultra-violet parts of the spectrum.

It was our purpose to devise a standard instrument for measuring the solar radiation scattered inward by the sky in daytime, and it was our hope that the instrument suitable for this purpose should also be applicable to the measurement of nocturnal radiation as well. We began experiments for this purpose in 1912; and now, after having devised and constructed six different forms of instrument, we have satisfied ourselves that the last two types are very satisfactory for the purpose.

The name Pyranometer,[1] selected for the instrument we have devised, is taken from Greek words (πῦρ, fire; ἀνά, up; μέτρον, a measure) signifying that which measures heat above. The name was chosen with reference to the fact that the instrument is designed to measure the energy of radiation to or from a complete hemisphere lying above the measuring surface.

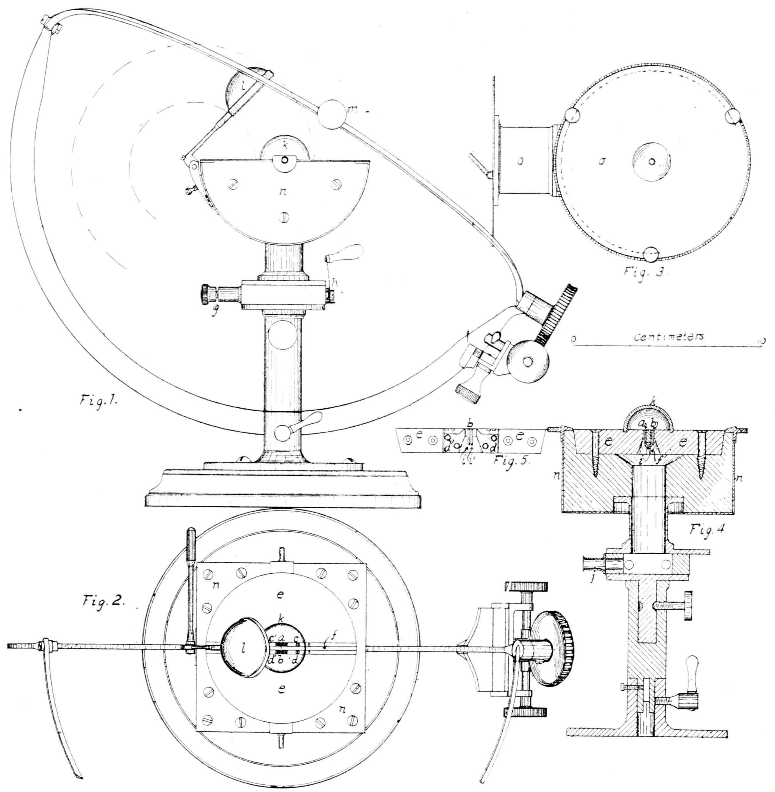
PYRANOMETER A. P. O. 6

Referring to the accompanying illustration, figure 1 is a side view; figure 2, looking down from above; figure 3, an attachment not used in measuring total sky radiation, but employed when it is desired to restrict the measurements to the sun alone; figure 4, a cross section taken at right angles to the view presented in figure 1 and omitting the wooden base and apparatus for shading the sun. In figure 5 are details showing the arrangement of the sensitive strips and thermo-couples. The instrument shown is the sixth form we have devised. In the fifth form there is but one sensitive strip instead of two as shown here. The fifth form of instrument is more sensitive than the sixth form, but has a certain source of error which was to a

[1] We make our acknowledgments to Miss M. Moore and to Dr. Casanowicz for advice in selecting this name.

considerable extent avoided in the sixth form, of which more will be said hereafter.

A and *B* are strips of manganin, each exposing surfaces 6 mm. long and 2 mm. wide. The strips are bent through 45° at the ends of the exposed portion and soldered with great care on to the lower parts of the split copper blocks *C*, C^1, *D*, D^1, in such manner that the solder goes exactly to the bend where the manganin strip becomes



exposed. The strips *A*, *B*, are situated in the center of the polished nickel-plated copper block *E* and are separated the one from the other by the copper strip *F*. Electrical insulation between the strips *A*, *B* (with their attached copper blocks *C*, C^1, *D*, D^1), and the plate *E* and strip *F* are provided by means of thin vertical separating strips of mica, coming exactly to the common surface of the plate *E* and manganin strips *A*, *B*. Conductors (not shown) run from the blocks *C*, C^1, *D*, D^1, to the switch *H*, and thence to the pair of binding posts *G*, of which only one of the two appears in figure 1. Between the switch *H* and the blocks *C*, C^1, *D*, D^1, the electrical current for heating the strips *A*, *B*, divides into two. Appropriate resistances are placed in the two circuits, so that although the strip *B* is ten times as thick as the strip *A*, and has a correspondingly smaller electrical resistance, compensation is provided by means of the said electrical resistances so that the current divides in the proper proportion to heat the strip *A* at exactly the same rate as strip *B*.

The two **U**-shaped thermo-elements, *I*, I^1, are arranged in series, with their warm and cold junctions respectively attached by thin waxed paper to the back of the strips *A* and *B*, so that the difference of temperature (if any) between the strips *A* and *B* is indicated by means of a galvanometer connected into circuit with them by means of a flexible conductor (not shown in the figure) which enters the instrument by means of the tube *J* shown in figure 4. We employ tellurium-platinum for the thermo-elements on account of the great thermo-electric power of this combination, the non-corrosion of platinum by melting tellurium, and the small thermal conductivity of tellurium. The difficulty of forming tellurium into the **U**-shaped elements shown was at first considerable, but was overcome after some practice.

The principle of operation of the instrument may now be understood. Radiation falling simultaneously upon the strips *A* and *B* communicates to each the same quantity of heat; but the rise of temperature after a steady state is produced thereby is different in the two because the strip *B* is ten times as thick as the strip *A*, and so its thermal conductivity to the ends is greater. Hence a deflection of the galvanometer occurs. This deflection is balanced, after again shading the strips, by means of an electric current divided between the strips *A* and *B* so as to produce equal heating effects in each. By suitable adjustment the deflection of the galvanometer which was produced by the absorption of radiation is reproduced by the heating of the electric current. In these circumstances the energy of the electric current transformed into heat in either strip is equal to the energy of the radiation absorbed by either strip. The instrument is primarily designed to measure radiation on a horizontal surface, but it can be used in any position.

The remaining details of the instrument will be easily understood. *K* is an optically figured hollow hemispherical screen of ultra-violet crown glass 25 mm. in diameter and 2 mm. thick, whose purpose is to admit direct or scattered solar radiation, but to prevent the exchange of long wave-length radiation between the manganin strips and the sky. A nickel-plated shutter, *L*, is provided for shading the instrument from the sun or sky. A small metal screen, *M*, subtending 0.0011 hemispheres, is mounted on an equatorial axis operated by a worm-wheel arrangement. This screen is used to shade the sun from the strips, in case it is desired to measure the sky alone, and not the sun and sky in combination. A nickel-plated box, *N*, enclosing a wood block in which lies the plate *E*, is provided to keep the copper plate *E* from external disturbances of temperature by wind currents. Around this box *N* fits a nickel-plated cover, *O*, shown in figure 3, for use in observing the sun alone, in making comparisons with the pyrheliometer. When the cover shown in figure 3 is employed, the equatorial mounting of the sun-screen *M* is removed, and the worm attachment is used for rotating the solar cover box *O*, just described.

The following data were used to determine the constant of Pyranometer A. P. O. 6:

	Cm.
Length of strips between soldered portions	0.623
Width of thin strip (mean of 5 places)	0.198
Width of thick strip (mean of 5 places)	0.201
	Ohms
Electrical resistance of thin strip	0.2740
Electrical resistance of thick strip	0.0369
Electrical resistance in series with thin strip	0.819
Electrical resistance in series with thick strip	0.364
Assumed absorption of the lamp black	0.98
Assumed transmission of the glass hemisphere (allowing for 2 reflections with index of refraction, 1.5)	0.92

(Thickness of strips determined by weighings approximately 0.00034 and 0.0030 centimeters).

(Resistance of the two thermo-couples in series 30 ohms).

From these data the current in the thin strip is $\frac{.401}{1.494}$ times the current in the outside electrical heating circuit. Hence the current squares are as 0.0719 to unity. Hence the constant of the instrument (when glass covered) is

$$K = \frac{.0719 \times .2740 \times 60}{4.185 \times 0.623 \times 0.198 \times 0.98 \times 0.92} = 2.54,$$

so that the energy of radiation corresponding to a given heating current C measured in amperes is 2.54 C^2 calories (15° C.) per cm.^{2} per minute. If used at night without glass for measurement of long-wave rays, the constant should probably be taken at

$$2.54 \times \frac{92}{100} \times \frac{98}{95} = 2.41.$$

The reader will perceive that the instrument may be used for the sun alone, the sun and sky in combination, the sky alone by day; or by removing the glass screen *K* it may be used for nocturnal radiation. We have not as yet employed the instrument much for the measurement of nocturnal radiation nor have we as yet compared its readings under that arrangement with the radiation of enclosures at different temperatures. We hope to make such experiments in future. We have made numerous comparisons between the instrument as arranged for day observations and the pyrheliometer. A series of observations of this kind, interspersed by readings on the whole sky, is shown in table I. A close agreement with the results of Pyrheliometer A. P.

TABLE I.—*Summary of Results of March 31, 1916*
North Tower, Smithsonian Institution

Sec. Z	Pyranometer A. P. O. No. 6				Pyrheli-ometer A. P. O. No. 9 (Calories)	Pyrheli-ometer A. P. O. No. 9. / Pyranometer A. P. O. No. 6.
	Sky alone Glass on (Calories)	Sun and sky Glass on (Calories)	Sun alone Glass on (Calories) (x Sec. Z)	Sun alone* No glass on (Calories) (x Sec. z)		
1.340 (A. M.)	.....	.....	.....	1.232	1.218	.988
1.330 (A. M.)	.....	.....	.....	1.084†	1.193	1.10†
1.235 (P. M.)	.1783	1.150	(1.200)	.....	(1.190)	(.991)
1.383	.....	.....	1.013	.....	.998	.984
1.400	.....	.....	.995	.....	.990	.995
1.420	.....	.....	.949	.....	.983	1.035
1.435	.....	.....	.975	.....	.987	1.011
1.485	.....	.....	.....	1.000	.993	.993
1.502	.....	.....	.....	1.019	1.020	1.001
1.545	.....	.....	.....	.947	.964	1.018
1.564	.....	.....	.....	.956	.967	1.011
1.665	.1978	.....	.....	.....	.....	.....
1.689	.1703	.....	.....	.....	.....	.....
1.730	.1757	.....	.....	.....	.....	.....
1.768	.....	.635	(.830)	.	.....	.....
1.802	.....	.640	(.875)	.....	.....	.....
1.874	.1463	.....	.....	.....	.....	.....
1.897	.1500	.....	.....	.....	.....	.....
2.050	.....	.....	.780	.....	.775	.994
2.097	.....	.....	.798	.....	.770	.966
2.280	.1359	.....	.....	.....	.....	.....
2.338	.1359	.....	.....	.....	.....	.....
2.415	.....	.404	(.660)	.....	.....	.....
2.480	.....	.388	(.648)	.....	.....	.....
2.567	.1220	.....	.....	.....	.....	.....
2.943	.....	.....	.668	.....	.6825	1.021
3.055	.....	.....	.702	.....	.680	.969
3.280	.....	.....	.608	.....	.6325	1.040
3.420	.....	.....	.633	.....	.6493	1.024
3.760	.0851	.....	.....	.....	.....	.....
3.90	.....	.2471	(.613)	.....	.5706	(.930)
4.05	.0945	.....	.....	.....	.....	.....
4.45	.....	.....	.....	.504	.5220	1.034

General mean 1.006
Omitting observations Nos. 2 and 18........................ 1.005

* Constant of instrument different from preceding column, allowance being made for the removal of the glass.
† Ammeter probably stuck.
() Result on sun obtained by subtracting sky from sun and sky combined.

O. 9 is found for all altitudes of the sun when the pyranometer readings are reduced to vertical incidence. This confirms the accuracy of the instrument for observations of the entire sky.

PYRANOMETER A. P. O. 5

As stated above, we employed but one sensitive strip in Pyranometer A. P. O. 5, embedding the cool junctions of the thermo-elements in the copper plate *E*. This form is several times as sensitive as Pyranometer A. P. O. 6, so much so that we employed with it a potentiometer current to bring the very large galvanometer deflections to zero, and then balanced the potentiometer current by heating the strip. Unfortunately, a defect of this pyranometer is a secondary deflection, caused by the warming of the portion of the plate *E* under glass as soon as the shutter is opened. This secondary deflection was found very large, sometimes even as great as a quarter of the primary one. Its direction was sometimes in one sense, sometimes in the other, for reasons that we have not fully understood. There is, however, a method of reading whereby this source of error is very nearly eliminated. It was noticed that when heating the strip with the electric current no secondary deflection occurred, and the primary deflection was complete in 20 seconds. When heating by radiation a nearly complete temporary halt of the deflection occurred at about 20 seconds after exposure, before the secondary deflection appreciably manifested itself. Hence we balanced the radiation deflection exactly on the 20th second by the potentiometer current, closed the shutter, waited two full minutes for restored zero conditions, and then balanced the potentiometer deflection by the heating current.[1] Under these conditions the error is practically negligible, and on account of its great sensitiveness Pyranometer A. P. O. 5 is regarded as a valuable instrument.

Its constant is determined as follows: Length of strip, 0.628 cm.; width, 0.294 cm.; electrical resistance, 0.300 ohms. Radiation = KC^2 where $K = \frac{0.300 \times 60}{4.185 \times 0.628 \times 0.294 \times 0.98 \times 0.92} = 25.9.$

We have employed this Pyranometer A. P. O. 5 in numerous measurements of radiation from the sun, sun and sky, sky alone, and

[1] The secondary plate heating effect is not wholly absent from the two strip form of Pyranometer No. 6, but it is very greatly reduced in its percentage importance. To entirely eliminate it, however, we have found it necessary to close the shutter 30 seconds after opening, and then to wait at least one minute before balancing with the electric current.

new fallen snow. In comparisons with the pyrheliometer it gave very nearly equal results when corrected to vertical incidence. The reflecting power of snow for combined sun and sky rays was found to be 70 per cent.

Some of the results found from the measurements with Pyranometer A. P. O. 5 are given in table II. We draw attention to the results on cloudy and partly cloudy days, which indicate that the sky light as a whole, on days when it is cloudy but not thick enough to rain, is of the order of two or three times the intensity of the sky light excluding the direct sun on clear days.

The pyranometer is a very handsome instrument as constructed by Mr. Kramer. It may be used readily by anyone equipped with the

TABLE II.—*Summary of Readings of February, 1916. North Tower, Smithsonian Institution, Pyranometer A. P. O. 5*

Date	Sec. Z	Sky alone. (Calories)	Sky and sun. (Calories)	Sun alone. Calories (x Sec. Z)*	A. P. O. 9 Calories†	A. P. O. 9 Pyranometer No. 5	Kind of sky
1916 Feb. 17.	2.33	.224	....	....	....	....	Sky 4/5 cloudy.
	2.495	.274	....	....	....	....	3/4 cloudy.
	2.84	....	.313	....	....	....	(Sun mostly hidden.)
	3.00	.165	....	....	....	....	1/2 cloudy.
	3.10	....	.296	....	....	....	(Cirro-cumulus.)
Feb. 18.	2.045 A. M.	.157	....	....	....	....	Lower 30° all cloudy. Upper 60° 1/2 cloudy.
	2.015	.210	....	....	....	....	Lower 30° all cloudy. Upper 60° 1/3 cloudy. Sun shining through thin haze.
	1.905	.306	....	....	....	....	Lower 30° all cloudy. Upper 60° 2/3 cloudy. Sun shining.
	1.710 P. M.	.192	....	....	....	....	Lower 30° 9/10 cloudy. Upper 60° 1/5 cloudy. Sun clear but hazy.
	1.720	....	.728	....	....	....	Upper clouds increasing. Sun still clear.
	1.750	.263	....	....	....	....	Upper 60° 3/4 cloudy. Sun covered by clouds.
Feb. 21.	1.750 A. M.	.1060	....	....	....	....	Light cirri in southern half of sky, partly covering sun. Otherwise very clear.
	1.700	....	.800	(1.16)	....	....	Sky same, sun clear.
	1.683	.1266	....	....	....	....	Same.
	1.667	....	.952	(1.40)	....	....	Same. Cirri decreasing.
	1.570 P. M.	.1127	....	....	....	....	Few cirri low in south. Very clear.
	1.580	....	.992	(1.39)	(1.38)	.993	
	1.589	.1163	....	....	....	....	
	1.593	....	.962	(1.35)	(1.36)	1.008	
	3.60	.0780	....	....	....	....	Cloudless. Some smoke in west from fire at 2 hr. 45 min. at Bureau of Engraving.
	3.75	.0780	....	....	....	....	
	3.95	....	.313	(932)	(.912)	.979	
	4.13	....	.291	(890)	(.883)	.992	
	4.28	.0746			Mean..	...992	

* Values in this column obtained by interpolating for "sky alone," subtracting interpolated values from "sky and sun" and multiplying by secant Z.

† Values in this column obtained by plotting logarithmically seven readings of pyrheliometer A. P. O. 9 made at various times during the afternoon and interpolating from this plot values to correspond with values of secant Z.

auxiliary apparatus used with the Ångström pyrheliometer. Its readings on the sky and sun by day appear to be truly expressed in calories per square centimeter per minute, for in solar comparisons values found agree within experimental error for all zenith distances with those of our standardized pyrheliometers. We are undertaking further experiments to test its accuracy for long wave-rays such as compose nocturnal radiation. While we have hitherto employed only ultra-violet crown glass screens, it is obvious that such screens might be covered with stained gelatine, or other screens of special glass employed to restrict the measurements to special regions of spectrum, as might be desirable in botanical investigations. While the two strip form is preferable from its greater freedom from temperature disturbances, the single strip form is so much more sensitive that for observations in deep shade, as in a forest, it would be more suitable.

As in the case of the silver disk pyrheliometer, we are authorized to state that the Smithsonian Institution will undertake to furnish pyranometers at cost to those who are engaged in investigations which will be greatly promoted by the use of this instrument. The cost cannot yet be exactly estimated, but it will not exceed $150 for the pyranometer itself. This does not, of course, include a galvanometer, ammeter, or batteries. Suitable slide wire resistances will be included. If desired, an equatorial mounting additionally will be be furnished at cost, so that the instrument can be used as a pyrheliometer at right angles to the solar beam.

SUMMARY

The authors have designed and tested with satisfactory results an instrument for measuring solar and sky radiation by day and terrestrial radiation by night. Two forms of the instrument are described. Either form will be furnished at cost by the Smithsonian Institution to institutions or individuals doing important investigation which will be promoted by using the instrument.