SMITHSONIAN MISCELLANEOUS COLLECTIONS

VOLUME 56, NUMBER 19

THE SILVER DISK PYRHELIOMETER

(WITH ONE PLATE)

BY

C. G. ABBOT

Director, Astrophysical Observatory of the Smithsonian Institution

(PUBLICATION 2008)

CITY OF WASHINGTON

PUBLISHED BY THE SMITHSONIAN INSTITUTION

March 31, 1911

WASHINGTON, D. C.
PRESS OF JUDD & DETWEILER, INC.
1911

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In 1902 the writer designed a mercury pyrheliometer based on the fundamental device of Pouillet, as modified by Tyndall. This instrument was described in the Annals of the Astrophysical Observatory of the Smithsonian Institution, volume 2. As the measurements have gone on at Washington, Mount Wilson, and Mount Whitney for the determination of values of the solar constant of radiation, various alterations have seemed desirable, which led in 1909 to the form of instrument here described.

The silver disk, *a*, shown in cross-section, is bored radially with a hole to admit the cylindrical bulb of a thermometer, *b*. The hole in the disk has a thin lining of steel, so that a small quantity of mercury may be introduced without alloying the silver, in order to make a good heat conduction between the silver disk and the thermometer bulb. A soft cord soaked in shellac is forced down at the mouth of the hole to prevent the escape of mercury, and a ring of Chatterton wax is sealed over the outside of the cord to make the closure more perfect.

The thermometer, *b*, is bent at a right angle, as shown, in order to make the instrument more compact and less fragile. A nickeled brass tube (shown partly cut away in the figure) supports and protects the thermometer. A slot is cut in the right-hand side of the support tube throughout almost its whole length to permit the reading of the thermometer. At the top of the support tube a short piece is removable, in order that heat may be applied to the overflow bulb of the thermometer, to dislodge mercury which sometimes collects there during transportation. The thermometer is graduated to tenths of degrees centigrade from — 15° C. to + 50° C. Two points, 0° and + 50°, are first marked on the stem by the makers, and then the thermometer is graduated by equal linear intervals without regard to the variations of cross-section of bore of the stem. Before insertion in the instrument, a careful calibration of the thermometer stem is made.

The silver disk, *a*, is enclosed by a copper cylindrical box, *c*, halved together for convenience in construction. Three small steel wires, not shown in the figure, support the silver disk. These wires lie in the plane of the center of the disk at 120° intervals apart. Midway between them are three brass screws, not shown, which may be screwed through the walls of the box, *c*, up to their heads. These screws in that position clamp the silver disk tightly. Their purpose is to prevent the breakage of the thermometer if jarred during transportation. These screws must be loosened during observations.

The copper box, *c*, is enclosed by a wooden box, *d*, to protect the instrument from temperature changes. This box is also halved together and fastened by long wood-screws, one of which is seen near the letter, *d*, in the figure.

Sunlight may be admitted through the tube, *e*. This tube is provided with a number of diaphragms, f_1 f_2 f_3, having circular apertures. The aperture, f_3, nearest the silver disk is slightly smaller than the others, and slightly smaller than the disk itself. Thus it limits the cross-section of the sunbeam whose intensity is to be measured. The entire interior of the tube, *e*, the box, *c*, and the silver disk, *a*, are painted dead black with lamp-black mixed in alcohol, with a little shellac added to cause the lamp-black to stick. To secure a fine, even coat, the mixture is filtered through cheesecloth before applying, and on the disk it is warmed with an alcohol lamp until the brush marks disappear.

A rotatable shutter, *g*, with three nickeled parallel metal plates, *h h h*, is provided for cutting off the sunlight as desired. The top of the tube, *e*, carries a screen, *k*, large enough to shade the wooden box, *d*. This screen also supports the thermometer tube, and the axis of the exposing shutter just mentioned. A small hole in the part which supports the thermometer admits a little guiding beam of sunlight, *i*, whose use is to assure the observer that the instrument points towards the sun.

The pyrheliometer is carried upon an equatorial stand, as shown in the figure. A worm and wheel mechanism is provided for following the sun. No clockwork is needed, as it is sufficient for the observer to move the worm slightly two or three times a minute.

The purpose of the silver disk pyrheliometer is merely to furnish readings proportional to the intensity of radiation of the sun, and comparable one with another at all times and places, but not to furnish independent means of reducing these readings to true heat units. Pouillet, it is true, determined the dimensions of his pyrheliometer, and from them reduced his results approximately to calories per square centimeter per minute. But owing to several uncertainties not necessary to mention here, it is not practicable to achieve sufficient accuracy in such standardizations of pyrheliometers of this type. They must therefore be regarded as secondary instruments, useful only for relative readings, unless standardized by comparison with true standard pyrheliometers. Such standardizations have been made at the Astrophysical Observatory.[1]

Regarding the silver disk pyrheliometers as secondary instruments, an abridged method of reading is possible, which materially reduces the labor of observation and reduction. In ordinary calorimetry the thermometer is read as frequently as possible, often at 10 or 20 second intervals, in order that a graphical representation of the whole march of temperatures may be made. In this way the most exact determination is possible of the rate of rise of temperature due to the source of heat itself, irrespective of cooling or warming due to the surroundings. In the use of the pyrheliometer as a secondary instrument the true value of the rate of rise of temperature due to solar heating is not material. If a simplified method of observation can furnish results which are under all circumstances greater or smaller by a constant fraction than the true rate of rise, such results are equally as valuable as the true ones would be. For the standardization constant of the instrument corrects such errors. By numerous experiments it has been shown that the short method of reading the instrument to be described below satisfies the condition just explained, well within the error of the observations, hence it has been adopted.

In order to promote pyrheliometric measurements of the solar radiation in other parts of the world, with instruments whose indications are quite comparable, Secretary Walcott loaned, in 1910, three silver disk instruments which were constructed at the cost of the Hodgkins fund and carefully standardized. These instruments were sent to Messrs. M. A. Rykatchew of St. Petersburg, J. Violle of Paris, and C. Chistoni of Italy. Unfortunately the first two mentioned were broken in transportation, but they have since been replaced. In the latest sendings the pyrheliometer proper is wrapped at its heavy end in cotton, and tied into its box in such a way that the projecting thermometer is wholly free, and could not possibly come in contact with any parts of the box. This box is enclosed in

[1] See Abbot and Aldrich: Astrophysical Journal, March, 1911.

a soldered tin case. This, in turn, is surrounded by a larger wooden box, having ten spiral chair-seat springs fastened within, so as to give elastic support to the inner case. To prevent too much movement of the inner case, wads of excelsior are put between the boxes at the eight corners. To prevent severe jarring of the outside box, wads of excelsior in canvas are also tacked outside the outer box at its eight corners.

Besides the three pyrheliometers mentioned, two have been sold by the Institution to the United States Weather Bureau and to the Physical Laboratory of the Agricultural Department of the United States. Three others are being prepared by request for use in South America—one at Arequipa, Peru, two in Argentina.

With each instrument is sent out a calibration sheet, and also the following:

Directions for Using the Abbot Silver Disk Pyrheliometer

Setting Up

The pyrheliometer is in the long box; the mounting in the cubical box.

1. If the mercury column of the thermometer is broken, remove the little screw at the side near the upper end of the nickel-plated tube, and take off the upper portion of the tube. Then heat the exposed stem cavity of the thermometer gently in a smoky flame (a match flame is good) until the mercury is expelled from the cavity. Then, holding the thermometer vertical, shake the instrument repeatedly with a downward jerk until the mercury columns join.

2. Remove the two little ivory plugs (using pliers if necessary) and unscrew the two brass screws under them, and also unscrew the third similar screw seen through the trunnion on the other side of the case. About three complete turns of each screw is proper. Insert the two ivory plugs. *When packing the instrument again for a journey, screw in the three screws as far as they will go.* Their purpose is to clamp the silver disk to protect the thermometer during transportation.

3. Unscrew the two pivots from the sides of the ring of the mounting, insert the pyrheliometer so that the thermometer is *not* next to the worm wheel, and screw in the pivots.

4. Unclamp the half ring and set the polar axis approximately for the latitude of the place. The thermometer should be next to the *upper* end of the axis.

Adjustments

5. For quick adjustment in right ascension guide the pyrheliometer with one hand and loosen the lower right-hand milled screw (as seen from the upper end of the polar axis). The worm may then be lowered out of engagement with the wheel and the change made.

6. To follow the sun, adjust in right ascension and declination until the sun shining through the little hole in the upper plate forms its image on the scratched spot on the nickeled piece below. When exposing to solar radiation rotate the worm screw a little (about once every half minute) to follow the sun.

7. When about to observe, push aside the cover, leaving only the shutter to shade the silver disk. When through with each series of readings, close the cover to keep out dust.

Observations

8. When reading the thermometer the observer should hold his head so that the reflection of each dark line of the scale near the degree to be observed, as seen in the mercury thread, is coincident with the corresponding dark line. This prevents parallactic errors of reading.

9. Having adjusted the instrument to point at the sun and opened the cover, read the thermometer exactly at 20 seconds after the beginning of the first minute. Read again after 100 seconds, or at the beginning of the third minute, and immediately after reading open the shutter to expose to the sun. Note that the instrument is then correctly pointed. After 20 seconds read again. After 100 seconds more (during which the pointing is corrected frequently), or at the beginning of the fifth minute read again, and immediately close the shutter. After 20 seconds read again. After 100 seconds read again, or at the beginning of the seventh minute, and immediately open the shutter. Continue the readings in the above order, as long as desired. Readings should be made within 1/5 second of the prescribed time. Hold the watch directly opposite the degree to be observed, and close to the thermometer. Read the hundredths of degrees first, the degree itself afterward.

10. For example:

Reading	1	2	3	4	5	6
Time	$11^h55^m20^s$	57^m00^s	57^m20^s	59^m00^s	59^m20^s	$0^h01^m00^s$
Reading	15°.12	14°.25	14°.80	17°.58	17°.36	16°.09
Condition	Shaded		Exposed		Shaded	

Reading	7	8	9	10
Time	01^m20^s	03^m00^s	03^m20^s	05^m00^s
Reading	16°.58	18°.99	18°.75	17°.29
Condition	Exposed		Shaded	

Air temperature 15°. Pyrheliometer "S. I. Q."

Reductions

11. Subtract readings (2) from (1); (3) from (4); (6) from (5); (7) from (8); (10) from (9).

12. Take the algebraic means

$$\frac{(1)-(2)+(5)-(6)}{2};\quad \frac{(5)-(6)+(9)-(10)}{2};$$

and to them add [(4)—(3)] and [(8)—(7)] respectively.

13. Call the results above R_1 and R_2. Find roughly the mean temperatures T_1 and T_2 during the intervals of exposure (3) to (4) and (7) to (8).

14. Add to R_1 and R_2 the percentage corrections for graduation furnished with the instrument, then, after correcting, add to R_1, $K[(T_1-30°)R_1]$ and to R_2 add $K[T_2-30°)R_2]$. K is a constant furnished with the instrument. If the prevailing temperature of the air differs much from 20°, add 0.0014R for each 10° the air temperature falls below 20°. The results (which we will call R'_1 and R'_2) are the final rates of rise per 100 seconds during the exposures (3) to (4) and (7) to (8) as reduced to the standard bulb temperature of 30°, and standard stem temperature of 20°.

15. (Note.) The approximate method of procedure stated in (12) and (14) is much easier than the exact method, and having been found by experiments to yield closely comparable results under all circumstances of use, within the error of measurement, it has been adopted, and the standardization of the instrument is made by this method.

16. To reduce the results R^1_1 and R^1_2 to standard calories per square centimeter per minute, or to the scale provisionally used up to 1910 by the Smithsonian Institution, multiply by the factors furnished from the Smithsonian Institution with each instrument.

17. Under favorable circumstances an experienced observer can read to a probable error of $\frac{3}{10}$ per cent for a single reading. The sample readings here given differ more than this, for they were made at sealevel with variable sky.

18. Example of reduction:

Number	1	2	3	4	5	6	7	8	9	10
Reading	15°.12	14°.25	14°.80	17°.58	17°.36	16°.09	16°.58	18°.99	18°.75	17°.29
Differences	0°.87		2°.780		1°.27		2°.410		1°.46	
Cooling correction			1°.070				1°.365			
R_1 and R_2			3°.850				3°.775			
T_1 and T_2			16°.2				17°.8			
Scale correction	$-0.0020R_1=$		−0°.008		$-0.0022R_2=$		−0°.008			
KR (T−30°)	$-(0.0011)(13.8)R_1=$		−0°.058		$-(0.0011)(12.2)R_2=$		−0°.051			
Air correction	$+0.0007R_1=$		+0°.003				+0°.003			
R^1_1 and R^1_2			3°.787				3°.719			

Several questions have arisen regarding the accuracy of the silver disk pyrheliometer:

1. As to the effect of variations of the light of the sky, it might seem that since the pyrheliometer is exposed to about 80° of solid angle, of which the sun occupies only about 0.°2, the sky light might be quite considerable. To test this question a screen which limited the solid angle to 5° was fixed to one instrument, and another instrument with the usual arrangements was compared with it at Washington. No alteration of the relative readings due to the use of the screen could be found on a very clear day. On another day, less clear, a change of relative readings of about 0.5 per cent was found. On a very poor day the effect may reach 1 or even 2 per cent. On Mount Wilson the sky is so clear that its effect would be negligible.

2. As regards the inclination of the instrument, experiments were made by affixing a mirror to one pyrheliometer, so that the sun at about 45° from the zenith could be observed in two positions, vertical and horizontal, of the instrument, without shifting the mirror with respect to the pyrheliometer. Thus equipped, the pyrheliometer was compared with a second, read in the usual manner. No alteration of the relative readings could be found depending on the inclination.

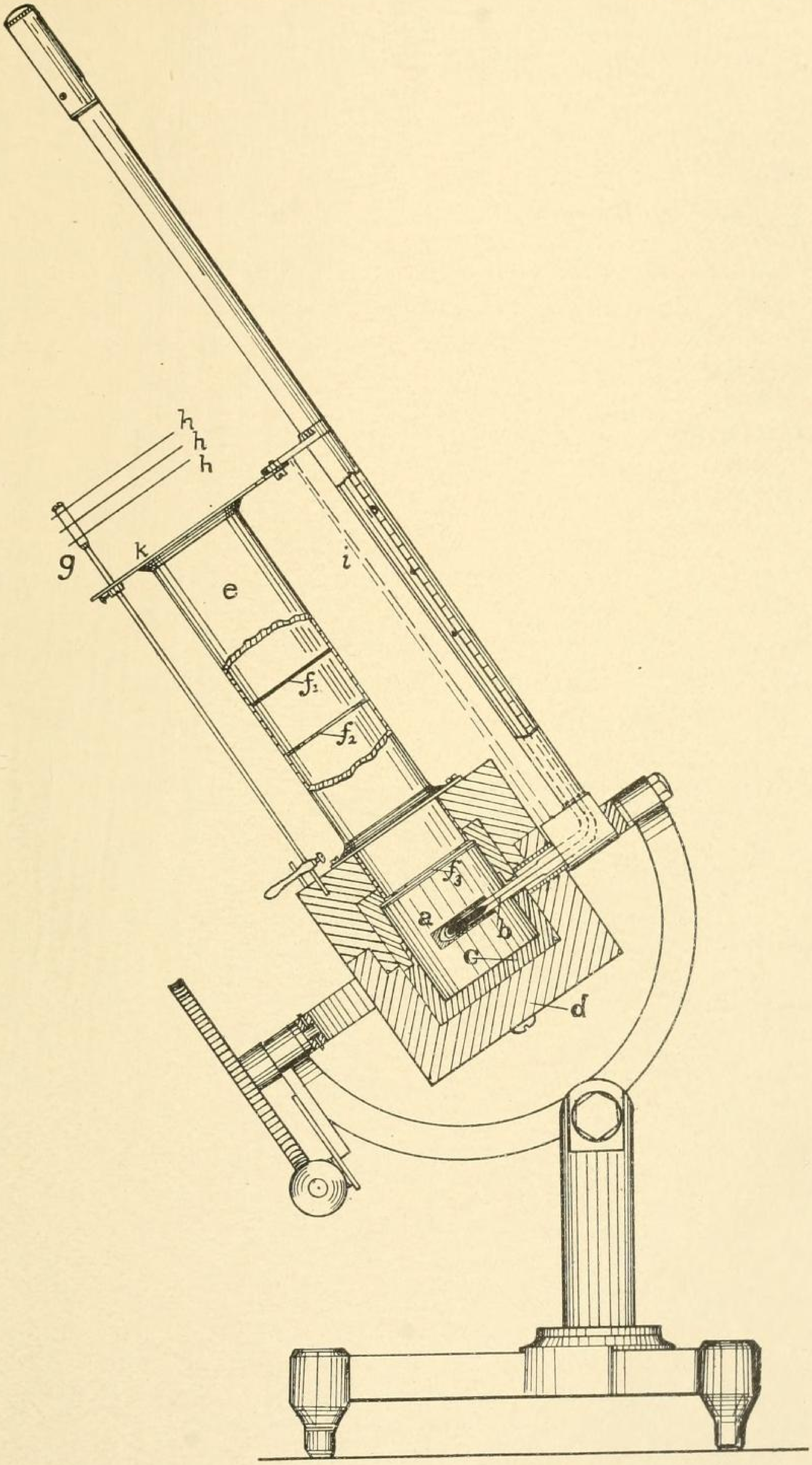
3. As regards atmospheric pressure, a metal box was fitted to one pyrheliometer and a glass plate fixed over the tube for admitting sun rays, so that the air could be exhausted from the interior of the pyrheliometer. Comparisons were made at atmospheric pressure, and at about 1/760 of atmospheric pressure, with another instrument read as usual. No changes of the relative readings depending on air pressure could be discerned.

4. As regards age of the blackened surface of the *silver disk*, we have not very long-continued records. But a *copper disk* instrument has been employed on Mount Wilson since the spring of 1906, and has been many times compared with other copper disk instruments there. It has been several times cleaned and re-blackened. There is no evidence that changes as great as 1 per cent have ever occurred due to defects in the blackening. The instrument appears now to have the same relative readings compared with another instrument at Washington which has been unchanged and seldom used since 1906, that subsisted between them five years ago. Another copper disk instrument was loaned in 1907 to the Weather Bureau. Its blackening has been unchanged, and it now (1911)

gives the same relative readings compared with the one at the Astrophysical Observatory that it did in 1907.

5. As regards accidental error of observation, persons with good eyesight and experience in observing appear to read with a probable error, for a single determination, at high sun, not exceeding 3/10 per cent. As a single determination depends on six readings, and the rise of temperature determined is only about 3°, this requires a probable error of single readings of temperature not exceeding 0.°005, or 1/20 division of the scale. It seems almost incredible that this degree of accuracy should usually be attained, but comparisons of instruments by two observers simultaneously, if made under excellent sky conditions, so indicate.

A silver disk pyrheliometer ready for shipment, including standardization and boxing, costs the Smithsonian Institution about $100. While it is not desired to manufacture them extensively, the Institution has in several instances consented to prepare and sell them. In cases where this evidently will tend to promote valuable and regular series of solar observations, the Institution is prepared to furnish silver disk pyrheliometers at the price above stated.



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