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SMITHSONIAN PYRHELIOMETRY REVISED

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In a paper entitled "The Silver Disk Pyrheliometer"[1] it was stated that in order to promote pyrheliometric measurements of the solar radiation in other parts of the world with instruments whose indications are quite comparable, several copies of the Silver Disk Pyrheliometer have been sent out by the Smithsonian Institution. The number of these instruments which have now been sent out has reached about twenty. The present paper gives a revision of the constants of these instruments and a statement of their dependence on experiments to determine the standard scale of radiation.

Three copies of the Standard Water-flow Pyrheliometer[2] have been prepared at the shop of the Astrophysical Observatory. The principle of these instruments consists in receiving the solar radiation in a blackened chamber composing a perfect absorber or "absolutely black body" and in carrying away the heat developed as fast as formed by a current of water circulating around in the walls of the receiving chamber. The rate of flow of the water, the rise of temperature due to the solar heating and the aperture through which the solar rays enter being known, the heating due to the solar rays is determined in calories per square centimeter per minute. In test experiments heat may be introduced electrically within coils in the absorption chamber, and this may be measured as if it were solar heat. The complete recovery of such test quantities of heat serves to prove the accuracy of the instrument.

Quite recently a new standard pyrheliometer which we have called "Standard Water-stir Pyrheliometer No. 4" has been devised and tested by us. This instrument employs the ordinary method of calorimetry. A blackened tubular chamber for the absorption of the solar heat is provided as for the water-flow pyrheliometer. In the new instrument the absorption chamber is enclosed by a known quantity of water in a copper vessel, so that the whole apparatus comprises what is in effect a calorimeter for the method of mixtures.

[1] Smithsonian Miscellaneous Collections, Vol. 56, No. 19.

[2] See Annals, Astrophysical Observatory, Vol. 2, pp. 39 to 47, 1908. Also The Astrophysical Journal, Vol. 33, pp. 125 to 129, 1911.

The water in the instrument is vigorously stirred[1] by means of a stirring device run by an electric motor. A platinum resistance thermometer, fully bathed by the water of the pyrheliometer serves to determine its rate of rise of temperature due to the absorption of solar rays, and also its rates of change of temperature before and after exposure to these rays, due to the influence of the surroundings. In this manner we may determine the intensity of the radiation of the sun in terms of the rise of temperature per minute of a calorimeter of known water equivalent, and we may be assured that the solar rays are completely absorbed to produce heat, because they are absorbed by a blackened surface forming the inside of a deep chamber closely approximating to the "absolutely black body." In this new instrument, as in the water-flow pyrheliometers, means are provided for the introduction electrically of known quantities of heat to test the accuracy of the apparatus. A full description of the new water-stir pyrheliometer and of the water-flow pyrheliometers, Nos. 2 and 3, will appear in Vol. 3 of the Annals of the Astrophysical Observatory, now in preparation.

The following table is a summary of the experiments made with test quantities of electrical heating with standard pyrheliometers Nos. 2, 3 and 4:

Pyrheliometer.	Dates.	Number tests.	Heat recovered.	Average deviation.
			Per cent.	*Per cent.*
Water-flow 2 ..	1910—May 12, 16, 25, 26, 31; June 7.........	21	99.1	1.8
Water-flow 3 ..	1910—April 18, 22, 23........................	16	99.85	0.63
Water-flow 3 ..	1911—Oct. 10, 11	12	100.66	1.4
Water-stir 4...	1912—Oct. 24, 25.............................	6	100.05	0.53

From these experiments it appears that the test quantities of electrical heating were recovered by each instrument to within one per cent of the quantity introduced.

The results of comparisons of the standard pyrheliometers with secondary pyrheliometers are summarized in the following table:

Dates.	Number comparisons.	Standard used.	Secondary used.	Standard / secondary.	Probable error.
1910—May 10, 17, 28; June 4	16	2	A.P.O. 8	0.3772	0.0022
1910—Apr. 22......................	6	3	A.P.O. 8	0.3765	0.0009
1910—Oct. 31; Nov. 1..............	8	3	A.P.O. IV	0.5149	0.0013
1911—June 27......................	3	3	A.P.O. 8bis	0.3792	0.0018
			A.P.O IV	0.5094	0.0011
1911—Oct. 14, 15, 16, 22, 25, 31; Nov. 2, 6, 7..............	21	3	A.P.O. 8bis	0.3770	0.0007
1912—Nov. 16, 19, 21..............	18	4	A.P.O. 9	0.3618	0.0012

[1] Successful use requires rapid stirring.

Intercomparisons between the secondary pyrheliometers named in the preceding table are as follows:

Dates.	Number comparisons.	Secondaries used. A.	Secondaries used. B.	Ratio $\frac{A}{B}$	Probable error.
1910—June 21	17	S.I. 5	A.P.O. 8	1.0242	0.0019
1911—Apr. 25	7	S.I. 5	A.P.O. 8bis	1.0389	0.0019
1912—Dec. 20	18	S.I. 5	A.P.O. 8bis	1.0281	0.0013
1909—Oct. 23, 31	9	A.P.O. 8	A.P.O. IV	1.3611	0.0021
1911—June 22, 28; Sept. 14	19	A.P.O. 8bis	A.P.O. IV	1.3518	0.0017
1910—July 28	6	A.P.O. 9	A.P.O. IV	1.3820	0.0008
1911—June 28	8	A.P.O. 9	A.P.O. IV	1.4102	0.0046
1911—June 28	8	A.P.O. 9	A.P.O. 8bis	1.0469	0.0010
1912—Feb. 6, 10	12	A.P.O. 9	A.P.O. 8bis	1.0328	0.0011
1912—Nov. 8	10	A.P.O. 9	A.P.O. 8bis	1.0470	0.0013
1912—Nov. 11	19	A.P.O. 9	A.P.O. 8bis	1.0445	0.0014

Combining the results of the two preceding tables we obtain the following constants which we now adopt for the secondary pyrheliometers named above. These constants and others which are derived from them in the remainder of this paper we designate as Smithsonian Revised Pyrheliometry of 1913:

From $\frac{\text{S.I. 5}}{\text{A.P.O. 8}}$ and $\frac{\text{S.I. 5}}{\text{A.P.O. 8bis}}$ we find $\frac{\text{A.P.O. 8}}{\text{A.P.O. 8bis}} = \frac{1.0311}{1.0242} = 1.0068$

From $\frac{\text{A.P.O. 8}}{\text{A.P.O. IV}}$ and $\frac{\text{A.P.O. 8bis}}{\text{A.P.O. IV}}$ we find $\frac{\text{A.P.O. 8}}{\text{A.P.O. 8bis}} = \frac{1.3611}{1.3518} = 1.0068$

From $\frac{\text{A.P.O. 9}}{\text{A.P.O. 8bis}}$ (49 values) we find $\frac{\text{A.P.O. 9}}{\text{A.P.O. 8bis}} = \ldots\ldots$ 1.0426

From $\frac{\text{A.P.O. 9}}{\text{A.P.O. IV}}$ and $\frac{\text{A.P.O. 8bis}}{\text{A.P.O. IV}}$ we find $\frac{\text{A.P.O. 9}}{\text{A.P.O. 8bis}} = \frac{1.3981}{1.3518} = 1.0343$

From $\frac{\text{A.P.O. 8bis}}{\text{A.P.O. IV}}$ (19 values) we find $\frac{\text{A.P.O. IV}}{\text{A.P.O. 8bis}} = \ldots\ldots$ 0.7398

These results leave no choice as to the values to be adopted for $\frac{\text{A.P.O. 8}}{\text{A.P.O. 8}_{\text{bis}}}$ and $\frac{\text{A.P.O. IV}}{\text{A.P.O. 8}_{\text{bis}}}$, but are less satisfactory as regards $\frac{\text{A.P.O. 9}}{\text{A.P.O. 8}_{\text{bis}}}$. However it will be seen that the discordance in this ratio almost wholly depends on the six comparisons $\frac{\text{A.P.O. 9}}{\text{A.P.O. IV}}$ of

July 28, 1910. It is possible that A.P.O. 9 was inadvertently not fully exposed at this time. We shall adopt:

$$\frac{\text{A.P.O. 8}}{\text{A.P.O. }8_{\text{bis}}} = 1.0068. \quad \frac{\text{A.P.O. 9}}{\text{A.P.O. }8_{\text{bis}}} = 1.0426. \quad \frac{\text{A.P.O. IV}}{\text{A.P.O. }8_{\text{bis}}} = 0.7398.$$

From $\frac{\text{Standard 2}}{\text{A.P.O. 8}}$ and $\frac{\text{A.P.O. 8}}{\text{A.P.O. }8_{\text{bis}}}$ we find $\frac{\text{Standard 2}}{\text{A.P.O. }8_{\text{bis}}} = 0.3772 \times 1.0068 = 0.3798.$

From $\frac{\text{Standard 3}}{\text{A.P.O. 8}}$ and $\frac{\text{A.P.O. 8}}{\text{A.P.O. }8_{\text{bis}}}$ we find $\frac{\text{Standard 3}}{\text{A.P.O. }8_{\text{bis}}} = 0.3765 \times 1.0068 = 0.3791.$

From $\frac{\text{Standard 3}}{\text{A.P.O. IV}}$ and $\frac{\text{A.P.O. IV}}{\text{A.P.O. }8_{\text{bis}}}$ we find $\frac{\text{Standard 3}}{\text{A.P.O. }8_{\text{bis}}} = 0.5149 \times 0.7398 = 0.3809.$

also $0.5094 \times 0.7398 = 0.3768.$

From $\frac{\text{Standard 4}}{\text{A.P.O. 9}}$ and $\frac{\text{A.P.O. 9}}{\text{A.P.O. }8_{\text{bis}}}$ we find $\frac{\text{Standard 4}}{\text{A.P.O. }8_{\text{bis}}} = 0.3618 \times 1.0426 = 0.3772.$

Besides these values we have given two direct comparisons of $\frac{\text{Standard 3}}{\text{A.P.O. }8_{\text{bis}}}$.

In combining the results to obtain the best value of the constant of Secondary Pyrheliometer A. P. O. 8_{bis}, we have been guided by the view that a completely independent set-up of apparatus is a more weighty condition than is a small probable error. This amounts to saying that we have considered constant errors of more importance than accidental ones. But admitting this, we have also taken some notice of the number of observations made on different occasions, and of their accordance. These considerations have led us to the following values for Constant of Secondary Pyrheliometer A. P. O. 8_{bis}:

Value	0.3798	0.3791	0.3809	0.3768	0.3792	0.3770	0.3772	Mean 0.3786
Weight	3	3	3	1	1	4	3	±0.0003
Standard at.	No. 2 Wash^n.	No. 3 Wash^n.	No. 3 Mt. Wilson	No. 3 Mt. Wilson	No. 3 Mt. Wilson	No. 3 Mt. Wilson	No. 4 Wash^n.	

The constants of the silver disk pyrheliometers sent out by the Smithsonian Institution to various observers are derived by comparisons of those silver disk pyrheliometers with one or the other of the pyrheliometers named above. The following table gives the results of these comparisons for determining the constants of the various Smithsonian pyrheliometers[1]:

Date.	Number comparisons.	Secondaries used. A.	Secondaries used. B.	Ratio A/B	Probable error.
1910—Apr 8	11	S.I. 1	A.P.O. 8	1.0182	0.0025
1911—Jan. 25	9	S.I. 1	A.P.O. 8bis	1.0357	0.0024
1911—Jan. 25	10	S.I. 1	A.P.O. VIII	1.3943	0.0031
1911—Dec. 6	7	S.I. 1	A.P.O. 8bis	1.0246	0.0060
1912—Feb. 10	8	S.I. 1	A.P.O. 8bis	1.0268	0.0028
1911—Jan. 20, 23, 24, 25	24	S.I. 2	A.P.O. 8bis	1.0162	0.0016
1912—Nov. 8	9	S.I. 2	A.P.O. 8bis	1.0144	0.0017
1912—Nov. 8	9	S.I. 2	A.P.O. 9	0.9698	0.0013
1911—Jan. 19	6	S.I. 3	A.P.O. 8bis	1.0477	0.0024
1911—Jan. 20	6	S.I. 3	S.I. 2	1.0271	0.0024
1910—Apr. 8	10	S.I. 4	A.P.O. 8	1.0117	0.0023
1911—Dec. 3	4	S.I. 4	A.P.O. 9	0.9803	0.0016
Data for S.I. 5 given in preceding table.					
1911—Mar. 10	8	S.I. 6	A.P.O. 8bis	1.0327	.0017
1911—Mar. 21	9	S.I. 7	A.P.O. 8bis	1.0408	.0022
1912—May 18, 20	22	S.I. 8	A.P.O. 8bis	1.0032	.0018
1911—Apr. 25	10	S.I. 9	A.P.O. 8bis	1.0130	.0021
1911—May 4	6	S.I. 10	A.P.O. 8bis	1.0013	.0012
1911—Dec. 18	6	S.I. 10	A.P.O. 9	0.9703	.0027
1911—Feb. 6	11	S.I. 11	A.P.O. 8bis	1.0044	.0024
1912—Sept. 28	9	S.I. 12	A.P.O. 8bis	1.0427	.0020
1912—Feb. 10	9	S.I. 13	A.P.O. 8bis	1.0466	.0017
1912—Feb. 10	15	S.I. 14	A.P.O. 9	0.9777	.0014
1912—Mar. 7	9	S.I. 15	A.P.O. 8bis	1.0491	.0014
1912—Mar. 11, 16	13	S.I. 16	A.P.O. 8bis	1.0352	.0018
1912—Mar. 16	15	S.I. 17	A.P.O. 9	0.9990	.0011
VARIOUS A.P.O. PYRHELIOMETERS.					
1906—Apr. 2	6	A.P.O. V	A.P.O. IV	1.0615	.0050
1908—Apr. 16, 29	9	A.P.O. V	A.P.O. VII	1.0786	.0035
1908—May 28	13	A.P.O. V	A.P.O. VIII	1.0815	.0016
1910—Dec. 8	5	A.P.O. V	A.P.O. 8	0.7864	.0012
1910—Dec. 13, 15	11	A.P.O. V	A.P.O. 8bis	0.7969	.0024
1911—Jan. 19, 20, 23, 24	34	A.P.O. V	A.P.O. 8bis	0.7927	.0013
1908—May 22–June 3	75	A.P.O. IV	A.P.O. VII	0.9905	.0010
1909—June 1–Sept. 1	160	A.P.O. IV	A.P.O. VII	0.9955	.0007
1910—May 17–Oct. 25	700	A.P.O. IV	A.P.O. VII	0.9892	.0005
1912—May 4–Aug. 12	60	A.P.O. IV	A.P.O. VII	0.9892	.0012

In accordance with the above table, the following values are now adopted as the constants of Smithsonian Silver Disk Pyrheliometers Nos. 1 to 17, which have been furnished to the parties mentioned in the table. The column headed " old value " gives the constant which was furnished at the time of sending out the instrument or subsequently when further data indicated some desirable change. These old values are to be displaced by the new ones which we now give. We believe that the new constants should enable observers to reduce their results to a consistent scale differing probably by less than 0.5 per cent from the true scale of calories per square centimeter per minute.

[1] Instruments which were broken in transportation are omitted from this list.

SMITHSONIAN REVISED PYRHELIOMETRY OF 1913.

Instrument.	New Constant 1913.*	Old values.	Where sent.
S.I. 1	0.3683	0.3709	U. S. Weather Bureau.
S.I. 2	0.3734	†0.3835	(1) Rykačev, Russia; (2) Obsy. Rio Janeiro, Brazil.
S.I. 3	0.3625	†0.3725	Violle, Paris, France.
S.I. 4	0.3713	0.3745	Chistoni, Naples, Italy.
S.I. 5	0.3672	0.3676 0.3662	U. S. Dept. Agriculture, Physical Laboratory.
S.I. 6	0.3666	†0.3771 0.3687	Officina Meteor. Buenos Aires, Argentina.
S.I. 7	0.3638	†0.3747 0.3662	Do.
S.I. 8	0.3774	0.3792	Central Observatory, Madrid, Spain.
S.I. 9	0.3737	†0.3843 0.3756	Imp. Coll. Science and Technology, London, England.
S.I. 10	0.3762	†0.3887 0.3798	K. Preuss. Meteor. Institut, Berlin, Germany.
S.I. 11	0.3769	0.3788	Meteor. Obs., Teneriffe.
S.I. 12	0.3631	0.3649	K. Preuss. Meteor. Institut, Berlin, Germany.
S.I. 13	0.3617	0.3636	Meteor. Centralanstatt, Zurich, Switzerland.
S.I. 14	0.3714	0.3767	University, Toronto, Canada.
S.I. 15	0.3609	0.3627	U. S. National Bureau Standards.
S.I. 16	0.3657	0.3672	University of Arizona, Tucson.
S.I. 17	0.3635	0.3687	Harvard Coll. Obs., Arequipa, Peru.
VARIOUS A.P.O. INSTRUMENTS.			
A.P.O. IV	0.5118	‡0.902 ‡0.858	Mount Wilson, Cal.
A.P.O. V	0.4776	‡0.848	Washington, D. C.
A.P.O. VII	0.5072	.....	Mount Wilson, Cal.
A.P.O. VIII	0.5150	.....	(1) U. S. Weather Bureau; (2) Mt. Wilson.
A.P.O. 8	0.3760	.....	Washington and Mt. Wilson.
A.P.O. 8bis	0.3786	0.3805	Do.
A.P.O. 9	0.3631	0.3683	Washington, Mt. Wilson, Mt. Whitney and Algeria.

* These values are the factors by which the corrected temperature rise in 100 seconds is to be multiplied to reduce the readings to calories (15°C.) per square centimeter per minute.

† These oldest values were obtained from a round-about series of comparisons of several years standing, which now proves to have been erroneous.

‡ For 60-second exposures. From Annals Vol. II and later publications.

Note: On the relation between the Ångström scale and that of the Smithsonian Institution.—Observations made at the United States Weather Bureau, at Potsdam, and at Pawlowsk have been kindly communicated to the Smithsonian Institution, and we select from them the results of direct comparisons between the best instruments. From these we find the following ratios between readings on the Smithsonian (1913) and Ångström scales of pyrheliometry:

Observers.	Instruments.		Station.	Ratio.
	S.I.	Ångström.		S. I. / Ångström.
Kimball	S.I. 1	104	Washington	1.047
Marten	S.I. 10	74	Potsdam	1.034
Savinoff	S.I. 2	79	Pawlowsk	1.037
			Mean	1.039

Summary.—A new form of standard pyrheliometer has been devised and tested. In this new instrument, as in the water-flow pyrheliometers, the solar rays are absorbed in a deep chamber approximating to the perfect absorber or "black body." Means are provided for introducing electrically test quantities of heat.

It is shown that with Standard Water-flow Pyrheliometers Nos. 2 and 3, and the new Water-stir Pyrheliometer No. 4, test quantities of heat may be measured to within 1 per cent.

A summary is given of all definitive comparisons of the three standards just named with Secondary Silver-disk Pyrheliometers, and also the net of inter-comparisons connecting all Smithsonian secondary pyrheliometers now in use. From these data are derived the best values of the constants of all these secondary pyrheliometers. This system of pyrheliometry we call "Smithsonian Revised Pyrheliometry of 1913."

It rests on 72 comparisons on 20 different days of 3 different years with 3 standard pyrheliometers of different dimensions and 2 widely different principles of measurement, all capable of recovering and measuring within 1 per cent test quantities of heat, and all closely approximating to the "absolutely black body." The 72 comparisons, 40 at Washington, 32 at Mount Wilson, were made in 6 groups. The maximum divergence of the mean results of these groups is 1 per cent. Hence it is believed that the mean result of all the comparisons made under such diverse circumstances must be within 0.5 per cent of the truth. The probable error is 0.1 per cent. It is believed that this standard scale is reproducible by the secondary pyrheliometers with the adopted constants given to within 0.5 per cent. The divergence of this scale from that of Ångström appears to be 3.9 per cent.