On the Ångström Absolute Pyrheliometric Scale

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Abstract

A critical examination of the original Ångström pyrheliometric scale has been made from the result of recent calibration of the new modified Ångström pyrheliometer using the sun as radiation source.

The mean marginal error of the old standard pyrheliometer is found to be +2.4 per cent. The influence of the small difference in aperture of the two models is esteemed to increase the correction insignificantly.

This result is equivalent in meaning that the original scale-values added with 2.4 per cent are given in the true energy scale.

The corrected values are nearly one per cent higher than in the pyrheliometric scale recommended by the Radiation Conference at Davos 1956.

A practical pyrheliometric standard scale is a question of specification of the aperture conditions or of the amount of circumsolar sky radiation to be allowed in the standard pyrheliometer. A proposal of such a specification is given and recommended by the Conference at Davos.

1. Introduction

At the International Meteorological Conference at Innsbruck 1905 the K. Ångström electrical compensation pyrheliometer was adopted as the standard instrument for absolute measurements of solar energy.

Since that time the pyrheliometer No 70 at the Physical Institute of the University of Uppsala has served as the Standard instrument to which all outgoing compensation-pyrheliometers have been referred and the instrument constants of all outgoing pyrheliometers have thus been evaluated to this standard.

The constant determinations were made at the Physical Institute by Professor K. ÅNGSTRÖM himself and after his decease 1910 under the supervision of his successors of the leadership of the Institute.

The constant was determined by considering:

1) the relation

$$baq = ri^2 \text{ or}$$

$$q = \frac{r}{ba} i^2 \text{ watt cm}^{-2}$$

$$q = \frac{60}{4{,}187} \frac{r}{ba} i^2 \text{ gr cal min}^{-1} \text{ cm}^{-2}$$

i is the mean intensity of the compensation-current in ampère.
r is the mean resistance of the two strips of manganin in ohm pro cm.
b is the mean width of the strips in cm.
a is the coef. of absorption.

According to the special proceeding of blackening used, the K. ÅNGSTRÖM value $a = 0.98$ has been accepted.

The calculated k_{calc}[1] $= \frac{60}{4.19} \cdot \frac{r}{b \cdot a}$ has been determined for every pyrheliometer.

2) The constant has also been obtained by comparison with the standard No 70 or one of the substandards. The radiation (q) is given

$$q = k_{\text{obs}} \times i^2 = k_N \times i_N^2$$

$$k_{\text{obs}} = k_N \left(\frac{i_N}{i}\right)^2$$

[1]) For the comparison of results with the new instruments the old value of K. Ångström 4,19 is maintained instead of the correct 0,07 % lower value 4,187.

The average value, k_{obs} of a series of comparisons on clear days is given in a constant certificate of the instrument.

The value of $k_N = 17.48$ was given by K. ÅNGSTRÖM and the ÅNGSTRÖM pyrheliometric scale refers to this value of the standard pyrheliometer No 70.

The constant-determinations at Uppsala, were treated by G. GRANQVIST (1912), by E. BÄCKLIN (1924, 1925) and E. BÄCKLIN and G. KELLSTRÖM (1930). Newly the whole Uppsala material 1910—1935 has been critically examined by COURVOISIER (1957). Particular stress was thereby laid upon verification of the constancy of the standard pyrheliometer No 70. From the 185 determination during the period 1910—1935, COURVOISIER found for the quotient $Q = \frac{k_{obs}}{k_{calc}}$ an average value of 1.0039 or a deviation from unity of 0.4 per cent.

The small defect in the blackening of the one of the strips of No 70, in 1928 first observed by BÄCKLIN (1930), could be eliminated by renewed blackening.

2. *The marginal effect of the standard pyrheliometer.* — If the strip exposed to the sun radiation is shaded at the border by the inner diaphragm in the proportion 4 mm² of the whole strip area 2 × 20 mm² i.e. of 10% and the adjoining screened strip is heated to its whole length of 20 mm by a compensation current it is evident that this current takes a little too low value with a correction factor of the instrument-constant corresponding to the unexposed part of the strip. This is the case concerning the standard pyrheliometer No 70 (length of the strips 20 mm, interior diaphragm 17.8 mm) and the pyrheliometers made on the model of this standard.

This marginal error was first mentioned and examinated by A. ÅNGSTRÖM (1914). By teoretical considerations and from experiments on No 158 ÅNGSTRÖM gave the probable value 1.3 per cent for the marginal error of this pyrheliometer.

In the mean time C. G. ABBOT at the Smithsonian Institution Washington (see Annals Astrophys. Obs., volumes 3 to 6) has developped his silver-disk pyrheliometer, which scale-factor had been determined by comparison with the absolute water-flow and water-stir pyrheliometers. MARTEN (1913) made a great number of comparisons between the compensation pyrheliometer and the silver-disk pyrheliometer and found a discrepance between the Ångström and Smithsonian scales of 3.4 % with lower radiation values for the Ångström instrument, though with a little greater angular aperture (greater circumsolar radiation) for the Ångström instrument.

MARTEN (1922) referred this discrepance owing to the marginal error after carefully investigations by series of measurements of solar intensity with alternations of the diaphragm. The experiments gave a mean value of 2.8 per cent for the correction-factor for the Potsdam pyrheliometer Å No 140 III. The Smithsonian scale of 1913 i.e. Ångström original scale + 3.5 per cent has been fairly generally accepted in U.S.A. and Central Europe. The constants of Ångström pyrheliometers were given in the Ångström original scale during 1910—1935 at Uppsala and afterwards during 1935—1956 in both Ångström and Smithsonian scales. From 1957 the constants are given in the Ångström original scale added with 1.5 % (cf. p. 253).

3. *Standardization of Ångström pyrheliometers carried out at the Swedish Meteorological and Hydrological Institute.* — Since 1940 the scale-factors of the outgoing Ångström pyrheliometers (from Albert Lindblad, Stockholm) have been evaluated at the Swedish Meteorological and Hydrological Institute. The constant values are given graphically on fig. 1—3 as continuation of the corresponding curves of the period 1910—1935.

The average mean of the pyrheliometric constants to a number of 70, obtained by comparison, to a greater part with Å 158, during 1940—1956 was $k_{obs} = 14.27 \pm 0.204$.

As seen from fig. 1 the earlier determinations 1940—48, the minor part, have given a little lower values. Some of the earlier pyrheliometers has been arranged with the one strip shielded by a fix screen. These pyrheliometers have a mean calibration-factor of 13.13.

In the year 1951 the standard pyrheliometer No 70 has been given over as loan to the Swedish Meterorological and Hydrological Institute in Stockholm by the Physical Institute at Uppsala by courtesy of Prof. A. LINDH, the Director of the Institute at that time.

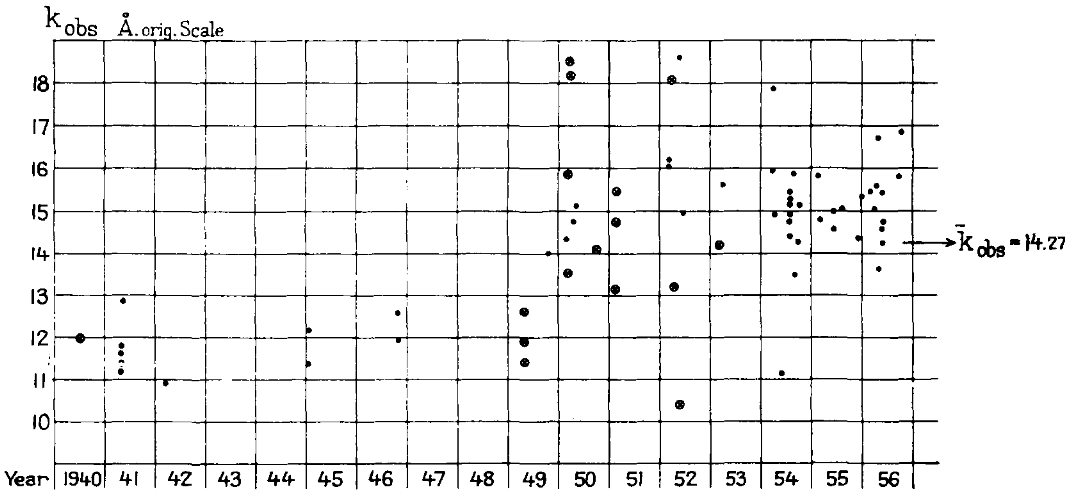

Fig. 1 ● *Right strip illuminated*

Fig. 1. The calibration factor, k_{obs}, of the individual pyrheliometers, tested 1940–1956, from the comparison with the standard Å pyrheliometer.

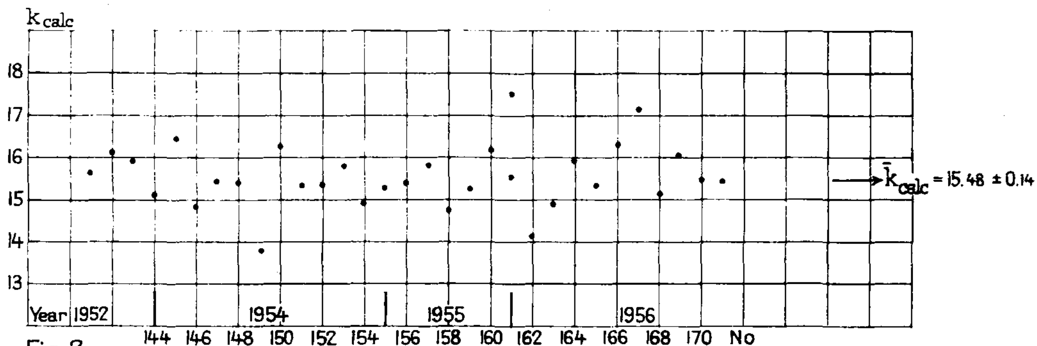

Fig. 2

Fig. 2. The individual calibration factors calculated, k_{calc}, of the new pattern of Å pyrheliometer.

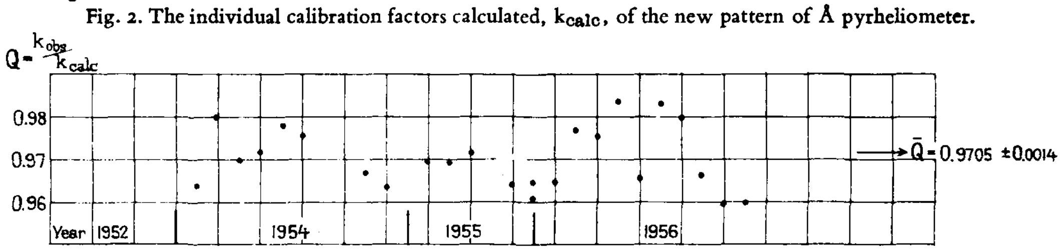

Fig. 3 a

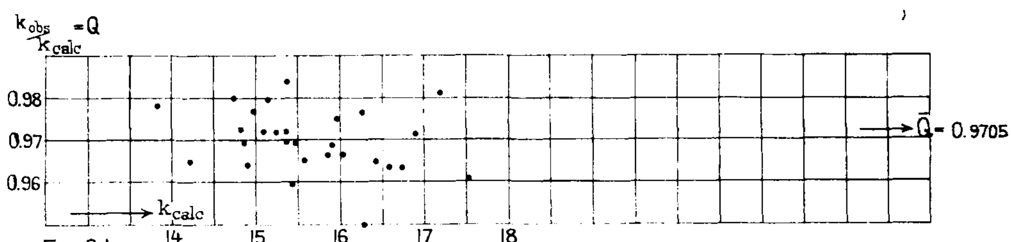

Fig. 3 b

Fig. 3a, 3b. Q-values of individual pyrheliometers of the new pattern.

After repair by means of renewed blackening the standard pyrheliometer No 70 was compared with the two substandards No 158 and No 153 used at the Swedish Meteorological and Hydrological Institute for the constant determinations of outgoing pyrheliometers. The result from the measurements in July and August 1951 has given the following values for

	No 158	No 153
k_{obs}	13,765 ±0.022	14,784 ±0.031
k_{obs}/k_{calc}	1.0012	1,005

The calibration factor of the standard Å 70 differs with 0.0031 or 0.31 per cent as a mean for both these sets. Courvoisier has found this difference to 0.4 %, as a mean considering the calibrations factors of all the other Ångström pyrheliometers.

In 1952 a new pyrheliometer has been constructed at the Institute as an exact copy of the original standard pyrheliometer No 70. Particular importance was attached to confirmity concerning tube, diaphragme, length of the strips, thus concerning aperture and mariginal effect. To this pyrheliometer were made three different receivers I, II and III.

From this time the constant determinations are made by the earlier methods discribed by Bäcklin (1930), i.e. 1) by calculation from the electrical resistance and the with of the strips and 2) by comparison, generally with the substandard pyrheliometer No 158.

In tab. 1 are given the constant factors of two groups of pyrheliometers with the same marginal effect as Nos 70 and 158.

Table 1

	No	k_{calc}	k_{obs}/k_{calc}
Group 1			
	I	15,00	0,990
	II	16,12	1,005
	III	15,96	1,006
		Mean	1,0003
Group 2	No	k_{calc}	k_{obs}/k_{calc}
	151	15,29	0,994
	152	15,40	0,994
	155	15,26	0,995
	159	15,18	0,991
		Mean	0,9935

4. *The new pattern of the Ångström pyrheliometer.* — In the last years an alteration reffering to the internal diaphragm is made for eliminating the shielding—error in the former instruments in that sense, that the diaphragm, close in front of the strips, is opened to the whole length of the strips. An automatic coupling system of the compensation current is introduced in that manner, that the circuit is currentless with the screen being in zero-position i.e. both strips exposed to the sun radiation. The current-connection through the shaded strip is made by turning the screen. The advantage in this arrangement is that more momentary observations can be made.

In Fig. 2 are given the calculated constants for the new pyrheliometers since 1952, to a number of 32. The average value of the calculated constants is $k_{calc} = 15.48$. This value differs slightly from the Uppsala mean 1910—1935 $k_{calc} = 15.14$ ($Q = 1.0039$).

For the new pyrheliometers compared with the substandard No 158 the average quotient Q (Fig. 3) is found

$$Q = \frac{k_{obs}}{k_{calc}} = 0.9705 \pm 0.0014$$

The average deviation of individual values is 0.006 or 0.6 per cent. Referred to the original standard No 70 according to the result above

$$Q_{corr} = 0.9717.$$

In the value of k_{obs} the influence of the small aperture-difference between the older and the new pattern of pyrheliometer has not been taken into account. As the aperture of the new pattern is somewhat smaller the correction to equal aperture can bee esteemed to give only any pro mille greater value of k_{obs} and Q.

This insignificance of aperture influence is also confirmed by the Q-material from Uppsala. The mean of Q for two separate groups of instruments, the one with short, the other with long tube is found to not differ more than 0.13 per cent, the group with long tube showing the greater value. This is, contrary to the statement by Dr. Courvoisier, in agreement with what is to be expected, since the long tube with smaller aperture and thus lower value of circumsolar radiation gives the higher value of k_{obs} by the comparison with a given standard pyrheliometer than an instrument with greater aperture (Cfr Courvoisier (1957), p. 10).

This value of Q_{corr} differs from unity with 2.8 per cent as the marginal error for the original standard No 70. If we take in account that the constant-value of the standard No 70 is 0.4 % too high in reference to the mean of the calibration-factors of all the Ångström pyrheliometers 1910—1935, we have the correction for the Ångström original scale to the true energy scale 2.4 ±0.14 per cent.

For the measurements with the earlier Ångström pyrheliometers the correction would be +2.4 per cent for the radiation values given in the Ångström original scale or —1.1 per cent for values given in the Smithsonian revised pyrheliometer scale of 1913.

From the result of a large number of comparisons 1932, 1937 and 1947 between an improved water-flow absolute pyrheliometer and the standard silverdisk-pyrheliometer ABBOT and ALDRICH (1948) concluded that the scale of Smithsonian revised pyrheliometry of 1913 is very nearly 2.4 per cent too high. The silverdisk instrument have remained unchanged. The correction to this new Smithsonian scale 1948 of the Ångström pyrheliometer readings in its original scale is thus +1.1 per cent.

In the newly adopted International Pyrheliometer Scale 1956, recommended by the International Radiation Conference Davos september 1956, the measurements may be given in the uncorrected Ångström scale increased by 1.5 per cent. This scale gives thus 0.9 per cent lower values than the above mentioned absolute scale based on calculated constants of the Ångström pyrheliometers without any marginal error and 0.4 per cent higher values than the Smithsonian scale of 1948.

5. *Accuracy of the calculated constants.* — The systematic error in the calculated constants can be evaluated from the error in the determinations of the electrical resistance and of the width of the strips.

An essential condition for the compensation principle, already pointed out by K. ÅNGSTRÖM (1893), is the similarity of the strips as receivers of the incoming sun radiation and for the watt-energy of the compensation current and great care is therefore taken by selection of the strips.

Cutting of the strips into sufficiently exactly equal width presents no great difficulty. The foregoing tests bears essentially on the equality in the electrical resistance pro unity of length; the resistance, not allowed to differ as more

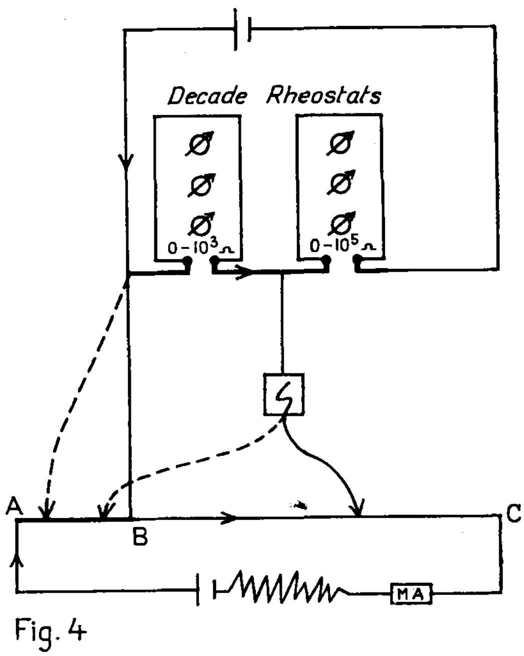

Fig. 4. The potentiometric arrangement for determination of the electrical resistance of the strips.

than one or two per cent (in most cases not exceeding one per cent). The value of r and of b refers to the mean width of the two strips.

Special care is taken to give the sensitive surfaces a well defined blackening, electrolytic deposit of Pt-black covered with a layer of fine grained stearin—soot, the absorption of which K. ÅNGSTRÖM (1898) had determined the value of 0.98.

The width of the strip was measured with microscope and Leitz ocular-micrometer, which permit an accuracy of 0.1 per cent. The determination of the electrical resistance pro cm (r) was made with a potentiometer arrangement with a sensitive galvanometer in zero-coupling (Fig. 4). The strip AB is inserted in an electrical currentcircuit in series connection with a calibrated measuring-wire BC of manganin of 1 mm diameter. The potential difference between two fixed points on the strip is egalized with the potential difference between two points on the measuring wire. The resistance of the strip between the two points has thus the same value as the known resistance on the measuring-wire. The arrangement of egalization by the potentiometer and a sensitive galvanometer is shown on Fig. 4.

The distance between the two fixed points was determined with comparator to 0.976 ± 0.001 cm. The calibration of the manganin measuring-wire gave as result the resistance $\alpha = 0.0005557$ ohm per mm.

From the equation

$$k = \frac{60}{4{,}187} \frac{r}{b \cdot a}$$

we have the procentual error of k

$$\frac{dk}{k} = \frac{dr}{r} + \frac{db}{b} + \frac{da}{a}$$

In the experiments the resistance of a given length (l) of the strip is compared and measured by the resistance in mm (L) of the measuring-wire.

We have $r = \frac{\alpha L}{l}$ where α is the resistance per mm of the manganin wire and

$$\frac{dr}{r} = \frac{d\alpha}{\alpha} + \frac{dL}{L} + \frac{dl}{l}$$

For the width (b) we have $b = \beta \times$ B where β is the magnification and B is the reading on the micrometer scale.

The values of $\frac{d\alpha}{\alpha}, \frac{d\beta}{\beta}, \frac{dl}{l}$ are of order of magnitude ±0.01 % and can be neglected in proportion to $\frac{dL}{L}$ and $\frac{dB}{B}$ which are estimated to each 0.1 per cent.

Thus $\frac{dk}{K} = \pm 0.2$ %, if $\frac{da}{a}$ is neglected.

Concerning the value of a, we have accepted the value of 0.98 found by K. ÅNGSTRÖM for the blackening mentioned. This is generally supposed to be the greatest possible value. It is to be remarked that, if a lower value of a is taken, the calculated pyrheliometer constants k_{calc} would be greater and the discrepance found above would be larger.

From experience with different pyrheliometers with only deposite of platinum-black and afterwards with this platinum-black covered with a layer of the fine grained stearin-soot, I have found an average difference of the constants in this both cases to be 1.4 per cent. The Ångström value 98.0—1.4 = 96.6 % is near the value determined by RUBENS and HOFFMANN (1922) for the absorption coeff. of electrolytic deposit of platinum-black.

6. *Error from difference in aperture.* — Considering that the new pattern of the Å pyrheliometer has been given a somewhat smaller aperture than the older model, this would cause an error in the k_{obs}-values, by the comparisons, in account of the difference in amount of circumsolar sky radiation entering in the respective instruments.

The aperture conditions of the two models in the parameters of PASTIEL (1948), the opening angel Z_0, the slope angel Z_p, and the limit angel Z_l are specified in tab. 2 for the two principal sections of the rectangular aperture. R is the limiting aperture, r half of the length resp. width of the strips, l the distance between the limiting diaphragma and the receiver.

Table 2

	No 158	No 168	No 158	No 168
	Section along	the strips	Section cross	the strips
	mm	mm	mm	mm
R	10,0	10,0	2,0	2,5
r	8,8	9,5	1,0	1,0
l	43,0	80,0	43,0	80,0
Z_0	12,6°	7,1°	2,6°	1,8°
Z_p	1,6°	0,4°	1,3°	1,1°
Z_l	23,1°	13,7	3,9°	2,5°

The smaller aperture angles shown in the table for the new pattern No 168 would result in a correspondent too high k_{obs} value. But in account of the steep slope of the circumsolar sky radiation the correction to equal aperture would be of the same order of magnitude as the mean error of measurements and thus insignificant in this regard.

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REFERENCES

ABBOT, C. G., 1913: Annals of the Astrophys. Observ. of the Smithson. *Institution*, Vol. **3**. p. 52—72.

ABBOT, C. G., 1922: Annals of the Astrophys. Observ. of the Smithson. *Institution*, Vol. **4**. p. 42—97.

ALDRICH, L. B., and ABBOT, C. G., 1948: Smithsonian pyrheliometry and the standard scale of solar radiation. *Smiths. Misc. Coll.* Vol. **110**, No. 5.

ÅNGSTRÖM, A., 1914: Das Ångströmsche Kompensationspyrheliometer und die pyrheliometrische Skala. *Met. ZS.* **31**, p. 369.

ÅNGSTRÖM, K., 1899: Über absolute Bestimmungen der Wärmestrahlung mit dem elektr. Kompensationspyrheliometer nebst einigen Beispielen der Anwendung dieses Instrumentes. *Annalen der Physik und Chemie.* Neue Folge, Bd. **67**, p. 633.

BOSSY, L., et PASTIEL R., 1948: Etude des proprietés fondamentales des actinomètres. *I.R.M. Belg. Mémoire XXIX.* Bruxelles.

BÄCKLIN, E., 1924: Bestimmung von Pyrheliometerkonstanten am Physikalischen Institut der Universität Uppsala. *Arkiv f. Mat. Ast. och Fysik*, 19 A No. **10**.

BÄCKLIN, E., 1925: Über die Konstanz der Ångströmschen Pyrheliometerskala. *Arkiv f. Mat. Astr.* och Fysik, Bd. 19A No. **18**.

BÄCKLIN, E., und KELLSTRÖM, G., 1930: Die Ångströmsche Pyrheliometerskala, *Met. ZS.* **47**, p. 52.

COURVOISIER, P., 1957: Contributions to Standard Pyrheliometry (introduction by A. Ångström and W. Mörikofer) *SMHI.* Communication., Ser. B. No. **13**.

GRANQUIST, G., 1912: Bericht über aktinometrische Arbeiten an Observatorium der Physikalischen Institution Uppsala, Tagungsber. *Int. Strahl. Komm.* Rapperswyl, p. 19. Anhang 4.

MARTEN, W., 1922: Zur Frage der absoluten pyrheliometrischen Skala. *Met. SZ.* **39**, p. 342.

NICOLET M., 1948: La mesure du rayonnement solaire. *I.R.M. Belg. Misc.* Fasc. XXI.

RUBENS H., und HOFFMAN, K., 1922: Über die Strahlung geschwärzter Flächen. *Berl. Sitzuugsber.* p. 424.

BER. INT. MET. DIREKTOREN-KONFERENS, Innsbruck 1905 p. 18.

TRANS. INT. UNION COOP. SOLAR RES., 1906. Manchester. Bd. 1. p. 239.

OMM., CIMO., 1953: Enquete sur l'activité en actinométrie dans le Monde.