SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 65, NUMBER 4

Hodgkins Fund

NEW EVIDENCE ON THE INTENSITY OF SOLAR RADIATION OUTSIDE THE ATMOSPHERE

BY
C. G. ABBOT, F. E. FOWLE, AND L. B. ALDRICH

(Publication 2361)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
JUNE 19, 1915

The Lord Baltimore Press
BALTIMORE, MD., U. S. A.

Hodgkins Fund

NEW EVIDENCE ON THE INTENSITY OF SOLAR RADIATION OUTSIDE THE ATMOSPHERE

By C. G. ABBOT, F. E. FOWLE, and L. B. ALDRICH

The following investigations were suggested by several criticisms of the work of the Astrophysical Observatory on the "Solar Constant of Radiation." We shall show: (1) That on fine days at Mt. Wilson there is no observable systematic change of atmospheric transparency from the moment of sunrise to about 10 o'clock, and (2) That the intensity of solar radiation even at 24 kilometers (15 miles) altitude, at less than one twenty-fifth atmospheric pressure, falls below 1.9 calories per square centimeter per minute.

It will be useful to preface the paper by a brief account of our earlier work. We shall draw attention also to various facts tending to support the result heretofore obtained, namely: The mean value of the "solar constant" is 1.93 calories per square centimeter per minute.

SUMMARY OF EARLIER WORK

In Vol. III of the Annals of the Astrophysical Observatory of the Smithsonian Institution, we published the methods employed, the apparatus used, and results obtained in determinations of the mean intensity of solar radiation outside the atmosphere during the years 1902 to 1912. The method employed was that of Langley.[1] It requires measuring the intensity of the total radiation of the sun with the pyrheliometer and also the measurement of the intensity of the rays of the different wave lengths with the spectro-bolometer. Measurements of both kinds are made repeatedly during a clear forenoon or afternoon from the time when the sun is low until it becomes high or vice versa. In this way we determine how rapidly

---

[1] "Report on the Mount Whitney Expedition," Professional Papers, Signal Service, No. 15, pp. 135 to 142, and table 120, values 1 to 5.

the rays of the sun as a whole and of individual wave lengths in particular increase in intensity as their path in air diminishes. From this we estimate the total intensity of the solar radiation outside the atmosphere altogether.

There are certain parts of the spectrum where by reason of powerful selective absorption of rays by water vapor and other terrestrial atmospheric vapors and gases, sufficiently accurate atmospheric transmission coefficients cannot be determined in this manner.[1] This offers no great difficulty, for, with Langley, we assume that these absorption bands would be absent outside the atmosphere. Hence the intensity of these parts of the spectrum outside the atmosphere can be determined by interpolation from the intensities found on either side of them.

Whatever the value of the atmospheric extinction of solar rays, all good solar constant work depends on accurate pyrheliometry expressed in standard calories.

During the investigation we devised two forms of standard pyrheliometer on quite different principles. These instruments agree with each other to within 0.5 per cent, and they yield values of the solar radiation ranging from 3 to 4 per cent above those found with different copies of the Ångström pyrheliometer. This latter instrument was adopted as the international standard for the measurement of radiation by the meeting of the International Meteorological Committee held at Southport in the year 1903 and by the International Union for Solar Research at its meeting at Oxford in the year 1905. Mr. A. K. Ångström has, however, lately pointed out that the Ångström instrument is subject to slight errors which cause it to read about 2 per cent too low, according to his opinion. If so, this brings the scale of the Ångström within less than 2 per cent of the scale of the Smithsonian Institution. The latter scale is fortified by the fact that in our several standard pyrheliometers it is possible to introduce and determine test quantities of heat. This has been repeatedly done in each of these instruments, and the test quantities of heat have been recovered to within 0.5 per cent.

---

[1] Investigations of Fowle showed, however, that transmission coefficients can be obtained even in the great infra-red bands of water vapor, whose employment would practically obliterate the bands outside the atmosphere. Hence we may conclude that if there are diffuse atmospheric bands not easily recognizable, they will be almost exactly allowed for by ordinary transmission coefficients. See Smithsonian Misc. Coll., Vol. 47.

The following table gives the results of nearly 700 measurements of the solar constant of radiation as published in Vol. III of the Annals above cited:[1]

TABLE 1—*Mean Solar Radiation Outside the Atmosphere*

Expressed in standard 15° calories per square centimeter per minute at mean solar distance

Station	Washington	Bassour	Mt. Wilson	Mt. Whitney	Total
Years	1902–1907	1911–1912	1905–1912	1909–1910	......
Altitudes (meters)	10	1,160	1,730	4,420	......
Observations	37	82	573	4	696
Mean result	1.968	1.928	1.933	1.923	1.933

The Washington results fall a little higher than the others. This may be due, in part at least, to the fact that most of them were made while sunspots were numerous, for our investigations at Mt. Wilson indicate that high values prevail when sunspots are at a maximum.

---

[1] We note here the following errors which have been found in Vol. III of the Annals, partly by ourselves, and partly by others who have kindly communicated them:

Page 119, figure 11, Nov. 8 misplotted. Should be 2.004, see p. 105.
Page 129, table 42, Nov., 1908, for 1.947 read 1.961.
Under "Mean," for 1.936 read 1.945.
Page 130, figure 16, Nov., 1908, for 1.947 plot 1.961.
Page 132, table 43, 14th column, for 592 read 607; for 1,338 read 1,363.
16th column, for —4.4 read —6.6; for —2.1 read —3.9.
Page 134, table 44, In 1908, for 1.936 read 1.945.
In "Total," for 1.9315 read 1.9333.
Under "General mean," for 1.932 read 1.933.
Page 138, table 47, Wave lengths, for .5995, .7200, .8085, .9215, 1.0640, 1.1474, 1.2230, 1.3800, read .5980, .7222, .8120, .9220, 1.0620, 1.1460, 1.2255, 1.3770.
Page 162, table 58, We withdraw the conclusion based on this table as to the direction of the change of distribution of solar radiation with change of "solar constant." A great body of as yet unpublished experiments leads to modifications.
Page 201, table. Under "Intensity," for 1,338 read 4,160.

In regard to the matter mentioned by Kron (Vierteljahr. Astron. Gesell. 49 Jahr., p. 68, 1914), we included in our statement, page 127, two days of 1911 in which the Bassour work was very satisfactory, but the Mt. Wilson work was not. We regret the errors in our figure 15 mentioned by Kron. The principal one is the omission of August 31. Two others are misplotting the Mt. Wilson values for September 4 and September 9. All the corrections improve the appearance of figure 15. See page 122 for the true values.

Our determinations rest on the assumption that for all excellent days the atmosphere may be regarded without sensible error as made up of layers, concentric with the earth, which may differ in transparency from layer to layer in any gradual manner, but which, within the time and space covered by a solar beam during a single morning of observation, are for each layer by itself sensibly of uniform transparency. As the relative transparency of the several layers is not assumed to be known, it is convenient to limit the duration of a single series of observations to the time interval during which the solar zenith distance is less than 75°. During this interval the rate of decrease of path of the solar beam in the atmosphere, with decreasing solar zenith distance, is sensibly the same in all the supposed atmospheric layers, and is proportional to the change of the secant of the zenith distance. For greater zenith distances than these this proportionality does not hold, because of the influences of curvature of the earth and of atmospheric refraction.

Figures 1 and 2, and table 2, show something of the variety of conditions of observation encountered; first, as regarding the intensity of sunlight at the observing station: second, as to the effect of atmospheric humidity on the infra-red spectrum; third, as the effect of dust upon the visible spectrum. We draw attention to the close agreement of the solar constant values obtained in these contrasting circumstances of observation.

TABLE 2—*Variety of Conditions of Observation*

Place	Barometer	Date	Temperature	Atmospheric water vapor pressure at station	Precipitable water[2]	Radiation observed Zenith distance 60°	Transmission coefficient Wave length $\lambda = .5\mu$	Corrected solar constant
	cms.			*mms.*	*mms.*	*calories*		
Washington	76.5	Feb. 15, 1907	3.0	1.45	4.8	1.352	.837	1.872
		May 14, 1907	29.0	14.60	22.6	0.939	.626	2.034
Bassour....	66.3	June 9, 1912	14.0	6.94	12.6	1.302	.855	1.903
		July 26, 1912	26.0	5.36	11.9	0.960	.684	1.915
Mt. Wilson.	62.5	Aug. 21, 1910	23.0	7.39	22.5	1.198	.852	1.933
		Aug. 21, 1911	23.0	2.50	11.2	1.370	.843	1.944
Mt. Whitney	44.7	Sept. 3, 1909	1.0	1.97	(0.90)	1.560	.905	1.951
		Aug. 14, 1910	2.0	2.05	0.60	1.607[1]	.923	1.923[1]

[1] This value is corrected as suggested in note 2, Annals III, page 113.

[2] Determined by Fowle's spectroscopic method, and gives the depth of liquid water which would result if all the atmospheric water vapor above the station should be precipitated. Experiments of 1913 show close agreement of this method in its results with those obtained for the same days by integration of humidity observed at all altitudes by sounding balloons.

From the foregoing the reader may see that the soundness of the theory of the atmospheric extinction of radiation employed by us is supported by the fact that its application to observations made under widely diverse conditions yields nearly identical values of the intensity of solar radiation outside the atmosphere. Nevertheless, it is maintained by some critics that our estimate of the atmospheric extinction is less than half large enough. It seems very singular that a grossly erroneous theory, according to which, however, the transmission coefficients of the atmosphere for green light are found to vary in different circumstances from 0.63 to 0.92, should nevertheless correlate its errors in such a way that all these diverse values of transmission coefficients should lead to equal values of the intensity of solar radiation outside the atmosphere.

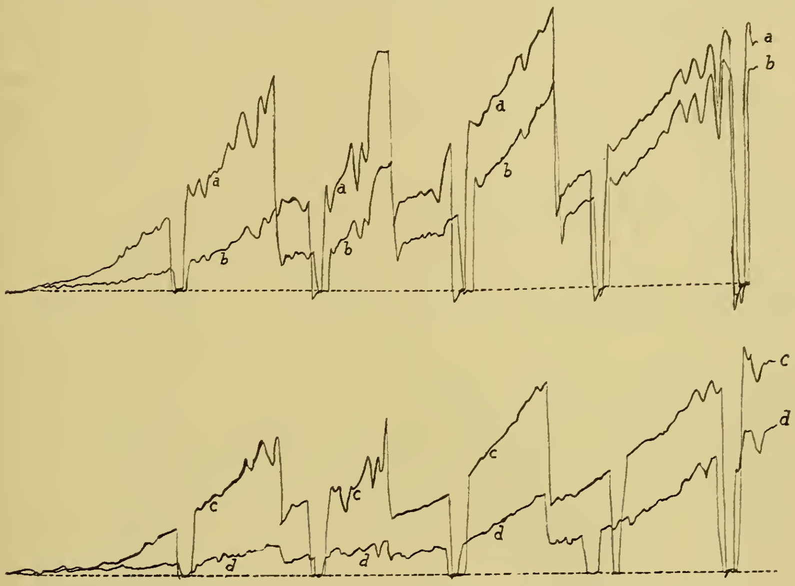


FIG. 1.—Illustrating Atmospheric Extinction on a Clear Day and on a Hazy Day.

Curve *a*, Bassour, June 9, 1912. Air-Mass, 1.5.
Curve *b*, Bassour, June 9, 1912. Air-Mass, 3.5.
Curve *c*, Bassour, July 26, 1912. Air-Mass, 1.6.
Curve *d*, Bassour, July 26, 1912. Air-Mass, 3.5.

In further support of our values of atmospheric transmission, we call attention to their connection with Lord Rayleigh's theory of the scattering of light by molecules and particles small as compared with the wave length of light. According to this the exponent of scattering varies inversely as the fourth power of the wave length, and thus

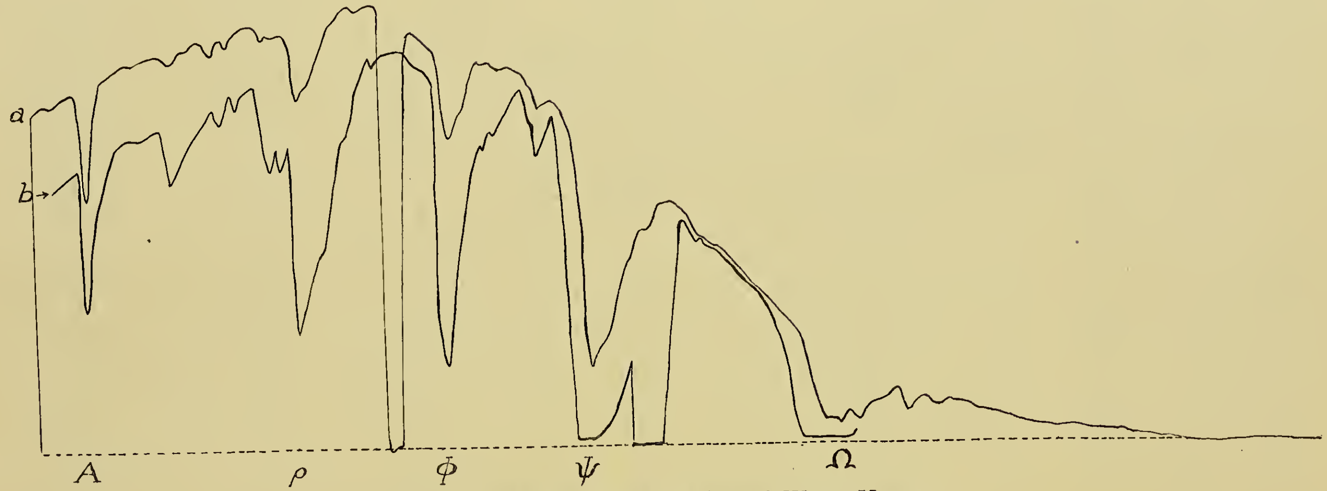


Fig. 2.—Illustrating Absorption of Water Vapor.
Curve *a*, Mt. Whitney, Aug. 15, 1910. Secant $Z = 1.08$.
Curve *b*, Washington, May 14, 1907. Secant $Z = 1.29$.

the product of fourth power of wave length by logarithm of transmission coefficient should be constant. As shown by one of us,[1] the coefficients of atmospheric transmission obtained on Mt. Wilson depend slightly on the total atmospheric humidity included between Mt. Wilson and the sun. The transmission coefficients may be reduced to dry air conditions by applying a very small correction to them. These corrected coefficients, a_0, are found to be in close harmony with Lord Rayleigh's theory, as is shown by the following table. The observed values of a are means for September 20 and September 21, 1914:

Wave length λ in μ	0.3504	0.3709	0.3974	0.4307	0.4753	0.5348	0.5742	0.6858	0.7644
Observed transmission a	.610	.671	.744	.786	.851	.892	.893	.950	.969
Corrected transmission a_0.....	.632	.686	.752	.808	.863	.898	.905	.959	.979
$\lambda^4 \log a_0$.........	—30.0	—31.1	—30.9	—31.8	—32.7	—38.2	—46.7	—40.3	—31.4

The deviation from a constant ratio in the yellow and red spectrum is doubtless due to the very large number of atmospheric absorption lines in this part of the spectrum.

By the aid of Lord Rayleigh's theory of the scattering of light, Mr. Fowle has determined from the Mt. Wilson experiments the number of molecules per cubic centimeter of dry air at standard temperature and pressure. He finds the value $(2.70 \pm 0.02) \times 10^{19}$, while Millikan obtained, by wholly dissimilar methods, $(2.705 \pm 0.005) \times 10^{19}$.

In the course of our experiments at Mt. Wilson, we found the solar radiation outside the atmosphere variable in short irregular periods of from five to ten days, and to have a variable range of from 2 to 10 per cent. That this variability is really solar was confirmed by independent simultaneous observing at Bassour in Algeria and still more recently by as yet unpublished experiments on the distribution of brightness over the sun's disk. This latter method is quite independent of atmospheric disturbances. It seems to us that if our solar constant results were erroneous to the extent that the solar constant is really 3.5 calories instead of 1.93, as some of our critics would persuade us, the probability of finding these real solar variations of from 2 to 10 per cent by simultaneous observing at stations separated by one-third of the circumference of the earth would be very small. We should suppose that if there are atmospheric con-

---

[1] F. E. Fowle, Astrophysical Journal, 38, 392, 1913; 40, 435, 1914.

ditions which lead to our underestimating by nearly 50 per cent the intensity of solar radiation outside the atmosphere, these would probably be variable from day to day; so that such minute real changes of the total intensity of the sun's radiation as we have found would have been swallowed up in the irregular local fluctuations of the transparency of the atmosphere.

CRITICISMS OF THE WORK

We turn from this summary of the work and the circumstances which heretofore indicated its validity, to a discussion of the criticisms which have been made of it by several authors, and the new experiments we have made to refute them. We take the following summaries of objections from several recent articles:[1]

1. Mr. F. W. Very remarks that there are several reliable actinometers, capable, when properly handled, of giving results correct to 1 or 2 per cent, but that unfortunately some of them may give results 20 per cent in error when inefficiently used or imperfectly corrected. Although Mr. Very says in another place that our determinations rest upon perfected instruments and admirable care, yet he has seemed to indicate by his praise of values of the solar radiation obtained from observations on the summit of Mt. Whitney, which reached 2.0 calories per sq. cm. per minute, that he perhaps considers our results to be 15 per cent too low, because in three different years we have never observed on Mt. Whitney values exceeding 1.7 calories per sq. cm. per minute.

2. It is pointed out that we employ the equation[2]

$$\log R = m \log a + \log A$$

as the equation of a straight line. In this equation R is the intensity of one wave length of radiation at the station; A, the corresponding

---

[1] F. W. Very, Astrophysical Journal, 34, 371, 1911; 37, 25 and 31, 1913; American Journal of Science, 4th Series, 36, 609, 1913; 39, 201, 1915; Bulletin Astronomique, xxx, 5, 1913.

F. H. Bigelow. Boletin de la Oficina Meteorológica Argentina, 3, 69-87, 1912; American Journal of Science, 4th Series, 38, 277, 1914.

E. Kron, Vierteljahrsschrift der Astronomischen Gesellschaft, 49, 53, 1914.

[2] As pointed out by Radau, Langley, and others, this equation is applicable only to homogeneous radiation, that is, radiation of approximately a single wave length. *It is always with this limitation that we employ it in our definitive solar constant determinations.* We have, however, pointed out that for a limited range of two or three air masses good observations of *total* solar radiation, when plotted thus logarithmically, deviate so slightly from the straight line that the smallness of the deviations is a useful guide to the

intensity outside the atmosphere; *m*, the air-mass, and *a* the coefficient of atmospheric transmission, assumed as constant. If log *a* only apparently, not really, is constant, our results are wrong. Both Mr. Very and Mr. Kron indicate pointedly that they believe log *a* is not constant, but that in fact the transparency of the atmosphere continually diminishes during the forenoon periods we have chosen for our observations, so that our transmission coefficients are too high, and our value of the solar constant too low on account of this source of error. Mr. Kron indicates possible errors of the solar constant values of not more than 5 per cent as due to this cause.

It appears, however, that Mr. Very attaches great weight to this second objection, for he says of the work of Abbot, Fowle, and Aldrich:

> The neglect of diurnal variation of atmospheric quality, and the erroneous supposition that the same coefficients of transmission can be used at all hours of the day, completely vitiate these reductions.

Again he says:

> The Smithsonian observations, for example, usually stop when the air-mass becomes as large as 3 or 4 atmospheres. Some do not even extend to 2 atmospheres. Reduced by Bouguer's formula these mid-day readings agree among themselves, but solely because they have stopped before reaching the point where disagreement begins. This is equivalent to shirking the difficulties, and the seeming extraordinary agreement of the measures is misleading. If the missing readings had been supplied the discrepancies would have been obvious. Such incomplete observations are incapable of elucidating the laws of atmospheric absorption except through the aid of more perfect measures. By supplying deficiencies under guidance of a criterion we may in some cases rescue observations which are, otherwise, useless.

Again he says:

> The portion of the diurnal curve between the limits of 4 and 10 atmospheres conforms tolerably well to the conditions needed for a determination of its slope and general form, and, as a rule, it would seem to be the best part of the curve to select for computation.

3. Mr. Very states that we adopt too high a value of the absorption of terrestrial radiation by water vapor and too low a value of its absorption of solar radiation.

---

excellence of the observing conditions. In such applications to pyrheliometry we recognize, however, that *A* would not be the solar constant. In this connection see figure 3, in which, although for a range of 20 air-masses there is a steady and well-marked curvature in the plot of pyrheliometry, any range of only two air-masses shows this but little. We, therefore, fail to see how Mr. Very's emphatic criticism of our procedure in this respect, which he gives in the French article above cited, is justified.

4. We suppose the layers of air to differ gradually from one to another in transparency. This, according to Mr. Very, may be true for some atmospheric elements, but there are others which are sharply restricted to definite layers or other definitely formed volumes, so that the ordinary air-mass formula fails for this cause.

5. A considerable amount of solar radiation is said by Mr. Very to be definitely lost to measurement in the atmosphere. The Smithsonian observations, he says, give merely the quantity $A—B$, where B represents the absorption occurring in fine lines of atmospheric origin, or radiation cut off by particles too gross to diffract the rays, or that which is arrested by bands of absorption not composed of fine lines, but large and diffused, and incapable of being distinguished certainly amidst the crowd of lines and bands which occur in the spectrum.

6. The authors underestimate, according to Very, the solar intensity in the infra-red part of the spectrum where terrestrial rays are sent out. For they suppose the energy there is comparable to that of a "black body" at 6,000°, whereas the sun's radiation is much richer in long waves than that of a body at 6,000°. The solar radiation does not correspond to that of a body of uniform temperature, but its infra-red part corresponds to a body at a higher temperature than does its visible part.

7. Mr. Kron is of the opinion that the authors underestimate the solar radiation in the ultra-violet spectrum, owing to the powerful atmospheric absorption there.

8. Mr. Bigelow finds from thermodynamic considerations that our solar constant values represent the intensity at about 40 kilometers altitude, where the atmospheric pressure is less than $\frac{1}{1000}$ of that at the sea level, but that between this and the limit of the atmosphere the radiation increases from 1.93 to 4.0 calories!

REPLY TO THESE CRITICISMS

First objection.—In regard to (1) we may remark, in addition to what we have said above, that nearly all the pyrheliometry now being done in the world is done with Ångström, Marvin, Michelson, or Smithsonian pyrheliometers. These represent five independent attempts to fix the standard scale of radiation. They have been many times compared with each other, and are found in accord to within less than 4 per cent, and now, in view of A. K. Ångström's researches, perhaps to less than 2 per cent. Of these scales of pyrheliometry, ours gives the highest readings. We have devoted much experimenting during many years to the establishment of the standard scale of pyrheliometry. Many observers reduce readings obtained with other pyrheliometers to the Smithsonian scale. Dr. Hellmann has indeed gone so far as to say publicly[1] that there is but one standard pyrheliometer, and that is at the Astrophysical Observatory of the Smithsonian Institution.

TABLE 3—*Ratios of Transmission Coefficients. Small and Large Air-Masses*

Date	Wave length in microns	.384	.431	.503	.598	.764	1.07	1.45	Mean	Air-mass range	
										small *m*	large *m*
Oct. 2, 1910	Ratio $\frac{\text{small } m}{\text{large } m}$	1.080	1.005	0.993	0.968	1.016	0.975	—	**1.006**	1.5-2.5	2.5-3.7
	Ratio $\frac{\text{published } m}{\text{large } m}$	1.031	1.014	.995	.983	1.007	.991	—	**1.003**		
Oct. 6, "	"	.851	.973	1.007	—	1.023	1.021	—	**0.975**	1.4-2.4	2.4-3.6
		.943	.992	1.005	—	1.016	1.019	—	**0.995**		
Oct. 24, "	"	—	1.057	.989	.964	.991	—	—	**1.000**	1.6-2.6	2.6-3.9
		—	1.036	.998	.988	.995	—	—	**1.004**		
Nov. 6, "	"	.995	.975	1.023	1.007	1.000	—	0.995	**0.999**	1.7-2.8	2.8-4.0
		.960	.979	1.012	1.000	.997	—	1.002	**0.992**		
Nov. 7,† "	"	1.094	1.030	1.038	1.016	—	—	—	**1.044**	1.7-2.7	2.7-4.2
		1.019	1.040	1.007	1.026	—	—	—	**1.023**		
Nov. 8, "	"	1.016	1.023	1.012	1.028	.984	—	—	**1.013**	1.7-2.8	2.8-4.1
		1.000	1.016	1.000	1.010	.993	—	—	**1.004**		
Nov. 17, 1911	"	1.109	1.035	1.112	1.026	1.019	1.012	0.964	**1.039**	1.7-2.5	2.5-4.3
		1.034	1.014	1.021	1.014	1.007	1.004	.991	**1.012**		
Nov. 19, "	"	—	1.002	.982	1.030	1.009	1.014	.984	**1.003**	1.7-2.6	2.6-4.4
		—	1.007	1.005	1.002	1.007	1.002	1.007	**1.005**		
Oct. 23, 1913	"	1.119	.957	1.000	.982	.995	1.014	1.033	**1.014**	1.5-3.0	3.0-4.5
		1.063	.999	1.007	.986	.993	1.007	1.024	**1.011**		
Oct. 25, "	"	—	1.007	1.035	.998	1.005	1.005	1.040	**1.015**	1.5-2.4	2.4-4.6
		—	1.030	1.019	1.007	1.002	1.012	1.038	**1.015**		
Oct. 26, "	"	0.991	1.042	1.042	.989	.995	1.007	—	**1.011**	1.6-2.4	2.4-4.5
		1.020	1.019	1.012	.989	.998	1.007	—	**1.007**		
Oct. 28, "	"	1.067	1.016	1.062	1.067	1.038	.984	1.007	**1.034**	1.6-2.5	2.5-5.0
		1.035	.992	1.002	1.007	1.005	.995	1.007	**1.006**		
Nov. 4, "	"	.863	1.007	.966	1.002	.982	.980	—	**0.967**	1.6-2.4	2.4-4.7
		.988	1.012	.998	1.008	.997	.998	—	**1.000**		
Nov. 5, "	"	1.054	.977	.968	1.014	1.002	.991	—	**1.001**	1.6-2.4	2.4-4.8
		.975	.994	.986	1.007	1.003	.997	—	**0.994**		
Nov. 7, "	"	1.014	1.014	.957	1.002	.993	.984	—	**0.994**	1.7-2.5	2.5-5.0
		1.037	1.014	.980	1.004	.998	.995	.998	**1.004**		
Nov. 8, "	"	.865	1.067	.982	1.028	1.038	1.012	1.005	**1.000**	1.7-2.5	2.5-5.2
		.938	1.017	.991	1.009	1.002	1.000	.995	**0.993**		
Means	"	**1.009**	**1.012**	**1.010**	**1.008**	**1.006**	**1.000**	**1.004**	**1.007**		
		1.003	**1.011**	**1.002**	**1.003**	**1.001**	**1.002**	**1.008**	**1.004**		

---

[1] Bericht über die Erste Tagung der Strahlungskommission des Internationalen Meteorologischen Komites in Rapperswyl bei Zurich, 2 September, 1912.

Second objection.—In view of the great importance attached by Mr. Very and others to the observation of solar radiation at great air-masses, we reexamined some of our observations of former years which were made at larger than the usual air-masses. For each of the days we give in the preceding table ratios of atmospheric transmission coefficients found for different air-mass ranges at many points in the spectrum, first, as obtained by comparing results found at small air-masses with those found at large ones, and, second, by comparing those heretofore published with those now obtained at large air-masses. For the determination of transmission at large air-masses, the observations were replotted, using Bemporad's air-mass tables instead of the secant of the zenith distance. The new plots did not include the observations at small air-masses, thus avoiding any prejudice of the observer which might have been caused by seeing them. The results of the comparison appear in the preceding table. It cannot be said that this indicates any considerable fall of transparency as the air-mass decreases. Had this been the case the ratios given would in general have been greater than unity. The slight tendency in that direction is hardly beyond the error of determination, and, besides, is to be attributed to the departure of Bemporad's air-masses from secant *Z* values used in our publications heretofore.

OBSERVATIONS OF SEPTEMBER 20 AND SEPTEMBER 21, 1914

For a more thorough test we selected two of the driest and clearest days on which we have ever observed on Mt. Wilson, namely, September 20 and September 21, 1914, for combined spectro-bolometric and pyrheliometric measurements, extending from the moment the sun rose above the horizon[1] until the close of our usual observing period at about 10 o'clock in the forenoon. During this interval we obtained on the first day 11 and on the second day 12 bolographs of the spectrum, extending from wave length $0.34\,\mu$ to wave length $2.44\,\mu$, and we made 33 pyrheliometric determinations of the solar radiation on the first day, and 34 such determinations on the second day. We observed the barometric pressure by means of a recording Richard barograph, and we observed the humidity of the air by means of a ventilated Assmann psychrometer.

The following tables include the barometric, hygrometric, and pyrheliometric data:

---

[1] We computed the apparent zenith distance of the lower limb of the sun at the instant of the start of the first bolograph on September 20 to be 88° 20′. The apparent zenith distance of the mountain horizon at that point is 88° 28′.

Table 4—*Pyrheliometry and Meteorological Observations*

Mt. Wilson, Cal., September 20, 1914

Hour angle		Barometer	Temperature		Pressure water vapor	Air-mass	Pyrheliometer readings		Precipitable water vapor
			Dry	Wet		(Bemporad)	IV	VII	(Fowle)
h.	*E* m.	*cm.*	°	°	*mm.*		*calories*[1]	*calories*[1]	*mm.*
6	06	....	16.5	9.7	6.11	....	....	....	....
5	54.8	61.9	....	....	....	19.31	0.530	....	....
	53.8	....	....	....	....	18.32	....	0.558	....
	50.8	....	....	....	....	15.82	.620	....	3.3
	49.8	....	....	....	....	15.10	....	.636	....
	46.8	....	....	....	....	13.89	.676	....	....
	45.8	....	....	....	....	13.33	....	.708	....
	42.8	....	....	....	....	11.44	.768	....	....
	41.8	....	....	....	....	11.03	....	.776	4.0
	38.8	....	....	....	....	9.97	.814	....	....
	37.8	....	....	....	....	....	....	....	....
	34.8	....	....	....	....	8.82	.883	....	....
	33.8	....	....	....	....	8.57	....	.900	....
	30.8	....	....	....	....	7.91	.922	....	....
	29.8	....	....	....	....	7.71	....	.951	....
	26.8	....	....	....	....	7.16	.976	....	4.1
	25.8	....	....	....	....	7.00	....	.979	....
	14.8	....	....	....	....	5.52	1.082	....	4.6
	13.8	....	....	....	....	5.42	....	1.093	....
	8	....	16.7	9.4	5.71	5.05	....	....	....
	4.8	....	....	....	....	4.67	1.146	....	....
	3.8	....	....	....	....	4.59	....	1.143	4.9
4	48.8	....	....	....	....	3.74	1.232	....	....
	47.8	....	....	....	....	3.69	....	1.229	....
	44.8	....	....	....	....	3.56	1.242	....	5.2
	43.8	....	....	....	....	3.52	....	1.262	....
	39	....	17.4	8.6	4.62	3.35	....	....	....
	32.8	....	....	....	....	3.11	1.292	....	....
	31.8	....	....	....	....	3.08	....	1.291	5.9
	9.8	....	....	....	....	2.53	1.371	....	....
	8.8	62.0	....	....	....	2.51	....	1.407	5.0
3	44	....	18.2	12.2	8.06	2.108	....	....	....
	38.8	....	....	....	....	2.044	1.435	....	....
	37.8	....	....	....	....	2.032	....	1.439	5.8
2	50.8	....	....	....	....	1.615	1.496	....	....
	49.8	....	....	....	....	1.609	....	1.497	6.6
	44	....	20.2	14.1	9.41	1.573	....	....	....
	2.8	....	....	....	....	1.383	1.516	....	....
	1.8	....	....	....	....	1.380	....	1.516	8.6
1	56	62.0	21.4	15.0	9.99	1.360	....	....	....

---

[1] See Note 1, Table 9.

Table 5—*Pyrheliometry and Meteorological Observations*

Mt. Wilson, Cal., September 21, 1914

Hour Angle	Barometer	Temperature		Pressure water vapor	Air-mass (Bemporad)	Pyrheliometer readings		Precipitable water vapor (Fowle)
		Dry	Wet			IV	VII	
E h. m.	*cm.*	°	°	*mm.*		*calories* [1]	*calories* [1]	*mm.*
6 00	....	15.4	5.1	2.21	....	....	....	....
5 54.8	62.1	....	....	....	20.36	0.489	....	....
53.8	....	....	....	....	19.34	....	0.523	....
50.8	....	....	....	....	16.62	.578	....	3.8
49.8	....	....	....	....	15.85	....	.616	....
46.8	....	....	....	....	13.89	.655	....	....
45.8	....	....	....	....	13.33	....	.689	....
42.8	....	....	....	....	11.86	.719	....	....
41.8	....	....	....	....	11.42	....	.755	4.9
38.8	....	....	....	....	10.31	.788	....	....
37.8	....	....	....	....	9.98	....	.798	....
34.8	....	....	....	....	9.10	.844	....	....
33.8	....	....	....	....	8.84	....	.857	....
30.8	....	....	....	....	8.12	.880	....	6.1
29.8	....	....	....	....	7.91	....	.903	....
26.8	....	....	....	....	7.33	.914	....	....
25.8	....	....	....	....	7.16	....	.944	....
20	....	17.2	8.0	4.12	....	....	....	6.5
15.8	....	....	....	....	5.76	1.027	....	....
14.8	....	....	....	....	5.66	....	1.049	....
11.8	....	....	....	....	5.34	1.061	....	....
10.8	....	....	....	....	5.25	....	1.086	7.1
4 58.8	....	....	....	....	4.32	1.148	....	....
57.8	....	....	....	....	4.25	....	1.163	....
52	....	17.1	6.2	2.48	4.00	....	....	7.2
41.8	....	....	....	....	3.46	1.248	....	....
40.8	....	....	....	....	3.42	....	1.250	7.4
26.8	....	....	....	....	2.97	1.297	....	....
25.8	....	....	....	....	2.94	....	1.312	7.5
15	....	17.7	7.1	3.06	2.67	....	....	....
5.8	....	....	....	....	2.47	1.366	....	....
4.8	62.15	....	....	....	2.45	....	1.370	8.0
3 42	....	18.4	10.3	5.92	2.097	....	....	....
35.8	....	....	....	....	2.022	1.419	....	....
34.8	....	....	....	....	2.010	....	1.438	8.2
2 51	....	20.3	10.9	5.74	1.625	....	....	....
47.8	....	....	....	....	1.606	1.492	....	....
46.8	....	....	....	....	1.600	....	1.498	8.7
2 00	6.22	22.2	13.2	7.49	1.381	....	....	....
1 49.8	....	....	....	....	1.348	1.529	....	....
48.8	....	....	....	....	1.345	....	1.533	8.3

---

[1] See Note 1, Table 9.

The two days, September 20 and September 21, are in almost complete agreement in every feature observed, except that the atmospheric humidity of September 21 slightly exceeded that of September 20, and this of course led to a slight difference in pyrheliometry. We give below our reduction of the spectro-bolometric work of September 20, and the circumstances of the observations will be found so completely set forth that if any readers should desire, they can re-reduce the day's work for themselves.

It is the principal aim of the investigation to determine if there was on these two days a systematic change of atmospheric transparency sufficient to vitiate solar constant values obtained by our usual method. Referring to our Annals, Vol. II, page 14, it may be shown that for solar zenith distances less than 70° the intensities of homogeneous rays observed at different zenith distances should be expressible by the relation:

$$\log e = \text{secant } z \log a + \log e_0$$

where e is the observed intensity of a homogeneous ray; e_0 its intensity outside the atmosphere; z the zenith distance of the sun; a a constant representing the fraction $\frac{e_1}{e_0}$ in which e_1 is the intensity which would correspond to $z=0$. The above equation being the equation of a straight line, the test of the uniformity of transparency depends on the closeness with which the logarithmic plots for individual wave lengths approximate straight lines.

For zenith distances much greater than 70° the function secant z must be replaced by another, $F(z)$, representing the ratio of the effective length of path of the beam in the atmosphere to that which corresponds to $z=0$. This quantity, $F(z)$, has been determined by Bemporad,[1] taking into account the curvature of the earth, the

---

[1] Mitteilungen der Grossh. Sternwarte zu Heidelberg IV, 1904. The following illustrates a computation of air-mass $F(z)$.

Example of Air-Mass Computation

For mean 120° meridian time:

1914, Sept. 20, $5^h\ 51^m\ 0^s$ (*i. e.*, $1^m\ 50^s$ after start of first bolograph).

Barometer 24.4 inches = 620 mm.		Temperature = 60° F. = 16° C.	
Longitude	118° 3′ 34″ W.	Equation of time	$+\ 6^m\ 22^s$
Latitude, ϕ,	34° 12′ 55″ N.	Correction for longitude	$+\ 7^m\ 46^s$
			$+14^m\ 8^s$
⊙ Declination, δ,	1° 17′ 28″ N.	Apparent time	$6^h\ 5^m\ 8^s$
Hour angle, t,	88° 43′ 0″ E.	Hour angle	$5^h\ 54^m\ 52^s$

Sun's true altitude h:

Sin $h = \sin\phi \sin\delta + \cos\phi \cos\delta \cos t$ $\quad h = 1°\ 47'\ 14''$

Sun's true zenith distance 88° 12′ 46″

atmospheric refraction, and the fall of temperature and barometer with elevation. His assumption regarding the rate of fall of temperature is not quite in accord with recent balloon work, and this leads him to values of $F(z)$ slightly too high, but this error would not exceed 0.5 per cent. As is well known, the atmospheric refraction is uncertain very near the horizon, so that it cannot be expected that the air-masses obtained with apparent zenith distances of 88°, computed from hour angles of observation, should be perfectly accurate.

Strictly, we should determine the value, $F(z)$, to correspond to the apparent center of intensity of the sun's light emission at the proper instant for every wave length, for on account of atmospheric extinction and refraction this is not coincident with the center of form of the sun. But we have found the correction to be always less than 0.5 per cent, and have neglected it.

A far more important consideration relates to the distribution in the atmosphere of the materials which diminish the intensity of sunlight, as the zenith distance increases. Bemporad's discussion assumes that the atmosphere is of uniform optical quality from top to bottom, so that equal masses of it transmit equal fractions of incident light. The researches of Schuster, Natanson, King, Fowle, and Kron show that on clear days at Mt. Wilson the atmospheric extinction, for a large part of the spectrum, seems to be in almost complete accord with the requirements of Rayleigh's theory of scattering. Where this holds, Bemporad's assumption also holds good. But it appears distinctly from Fowle's researches that in certain parts of the spectrum, notably in the yellow, red, and infrared, the atmospheric extinction is partly or mainly attributable to water vapor, or substances which accompany it. These atmospheric constituents, being mainly at low altitudes, require special consideration. We give in the following paragraphs our solution of this difficulty.

By Crawford's tables (Lick Observatory *Publications*, Vol. VII):

If apparent zenith distance is 87° 50′,	Refr. = 13′ 46″
If apparent zenith distance is 87° 58′,	Refr. = 14′ 14″
Hence assume	Refr. = 14′ 16″
Whence sun's apparent zenith distance is	87° 58′ 30″

By Bemporad's air-mass tables:

If apparent zenith distance is 87° 58′ 30″,	$F(z) =$ 19.650
But if $B = 620$, $T = 16°$	$F^1(z) - F(z) = -0.433$
Hence air-mass, $F^1(z)$,	= 19.216

Fowle has determined transmission coefficients similar in their application to the values a given above, but dependent on the total quantity of precipitable water in the atmosphere as determined spectroscopically. He gives the following values of the transmission coefficients for dry air ($a_{a\lambda}$) and for the equal of 1 cm. of liquid as water vapor ($a_{w\lambda}$) above Mt. Wilson. We employ values obtained from observations of 1910 and 1911, in preference to later ones, because obtained prior to the volcanic eruption of 1912.

TABLE 6—*Coefficients of Transmission for the Dry Atmosphere and for Atmospheric Water Vapor* (*Fowle*)

Wave length λ	.350	.360	.371	.384	.397	.413	.431	.452	.475	.503	.535	.574	.598	.624
$a_{a\lambda}$....	.632	.655	.686	.713	.752	.783	.808	.840	.863	.885	.898	.905	.913	.929
$a_{w\lambda}$....	.917	.940	.959	.959	.962	.965	.968	.967	.973	.976	.980	.974	.978	.977

Wave l'gth λ.	.653	.686	.722	.764	.812	.864	.987	1.146	1.302	1.452	1.603
$a_{a\lambda}$..........	.938	.959	.970	.979	.980	.982	.987	.987	.986	.989	.983
$a_{w\lambda}$..........	.987	.985	.989	.985	.990	.989	.991	.988	.990	.988	.986

These water vapor coefficients apply to smoothed energy curves, and are a measure of the general extinction associated with water vapor apart from its selective absorption.

By Rayleigh's theory the dry air coefficients may be calculated from the known number of molecules of air per cm.^{3} at standard temperature and pressure. This computation is in close accord with the values above given. We hold therefore that Rayleigh's theory of scattering would yield proper values of general atmospheric extinction, for clear days on Mt. Wilson, if water vapor were absent. As our observed general transmission coefficients in the infra-red spectrum are somewhat less accurate than elsewhere, owing to the necessity of interpolating the curves over the water vapor bands, and from other causes, we have thought it right to compute by Rayleigh's theory the true transmission coefficients in this region as they would be if molecular scattering alone were the active agent.

TABLE 7—*Computed Atmospheric Transmission and Extinction Coefficients*

Wave length...	.764	.812	.864	.922	.987	1.062	1.146	1.226	1.302	1.377
Computed $a_{a\lambda}$..	.979	.9838	.9873	.9903	.9925	.9954	.9959	.9969	.9975	.9980
$1-a_{a\lambda}$........	.021	.0162	.0127	.0097	0075	.0046	.0041	.0031	.0025	.0020
$1-a_{\frac{w}{2}\lambda}$........	.007	.005	.005	.005	.005	.005	.005	.005	.005	.010

As appears above, the computed transmission for wave lengths exceeding 1.37 μ is approximately unity, and the computed atmospheric extinction coefficient, as given in line 3, sensibly zero. Line 4 gives the general extinction for 0.5 centimeter of precipitable water vapor, corresponding to the humidity of September 20, 1914.

We are now in position to determine a correction to $F(z)$ as given by Bemporad. If the extinction were all molecular scattering, his values would be the true ones. If it were all due to water vapor, we ought to employ approximately secant z, because of the low level of water vapor. We have therefore determined for each wave length the weighted mean between Bemporad's $F(z)$ and secant z, giving weights in proportion to the numbers $(1 - a_{a\lambda})$ and $(1 - a_{\frac{w}{2}\lambda})$ for wave lengths less than 0.764 μ, and in proportion to the numbers $(1 - a_{c\lambda})$ and $(1 - a_{\frac{w}{2}\lambda})$ for wave lengths exceeding 0.764 μ. In one case we have made an exception, namely, for wave length 2.348 μ, which is within the band of carbon dioxide absorption. As this gas forms a nearly constant percentage of the atmosphere up to a level of more than 10,000 meters, we have used Bemporad's $F(z)$ at this wave length. In figures 3 and 4 the reader will see plotted the air-masses as used, and also the lesser air-masses corresponding to Bemporad's $F(z)$.

The following are the circumstances of the spectro-bolometric observations of September 20, 1914:

Extent of spectrum observed (in arc) 270′. Bolometer subtends 17″. Slit subtends 50″.

Extent of spectrum observed in wave lengths: $\lambda = 0.342\ \mu$ to $\lambda = 2.348\ \mu$.

Time elapsing after start $0^m\ 30^s$ to $7^m\ 15^s$.

Bolograph No.	1	2	3	4	5	6	7	8	10[1]	11
Time of start; 120th meridian mean time	*h. m. s.* 5 49 10	*h. m.* 5 59	*h. m.* 6 12	*h. m.* 6 25	*h. m.* 6 40	*h. m.* 6 55	*h. m.* 7 11	*h. m.* 7 33	*h. m.* 8 52	*h. m.* 9 40

Latitude, 34° 12′ 55″ N. Longitude, 118° 3′ 34″ W. Altitude, 1,727 meters.

[1] Bolograph 9 omitted because of interference of a guy wire.

In accordance with our usual course, described in Vol. III of our Annals, we measured the ordinates of smoothed curves on all the bolographs at 38 wave lengths. These were equally spaced in prismatic deviation, excepting that in a portion of the infra-red spectrum we observed at points twice as close together as in the other parts of the spectrum. Table 8 includes the measured ordinates of the smoothed curves (unit 0.1 mm.) and corresponding air-masses, according to Bemporad, for September 20. Our corrected air-masses appear only on figures 3 and 4. The third column of the table gives the factor to reduce to uniform scale throughout the spectrum.

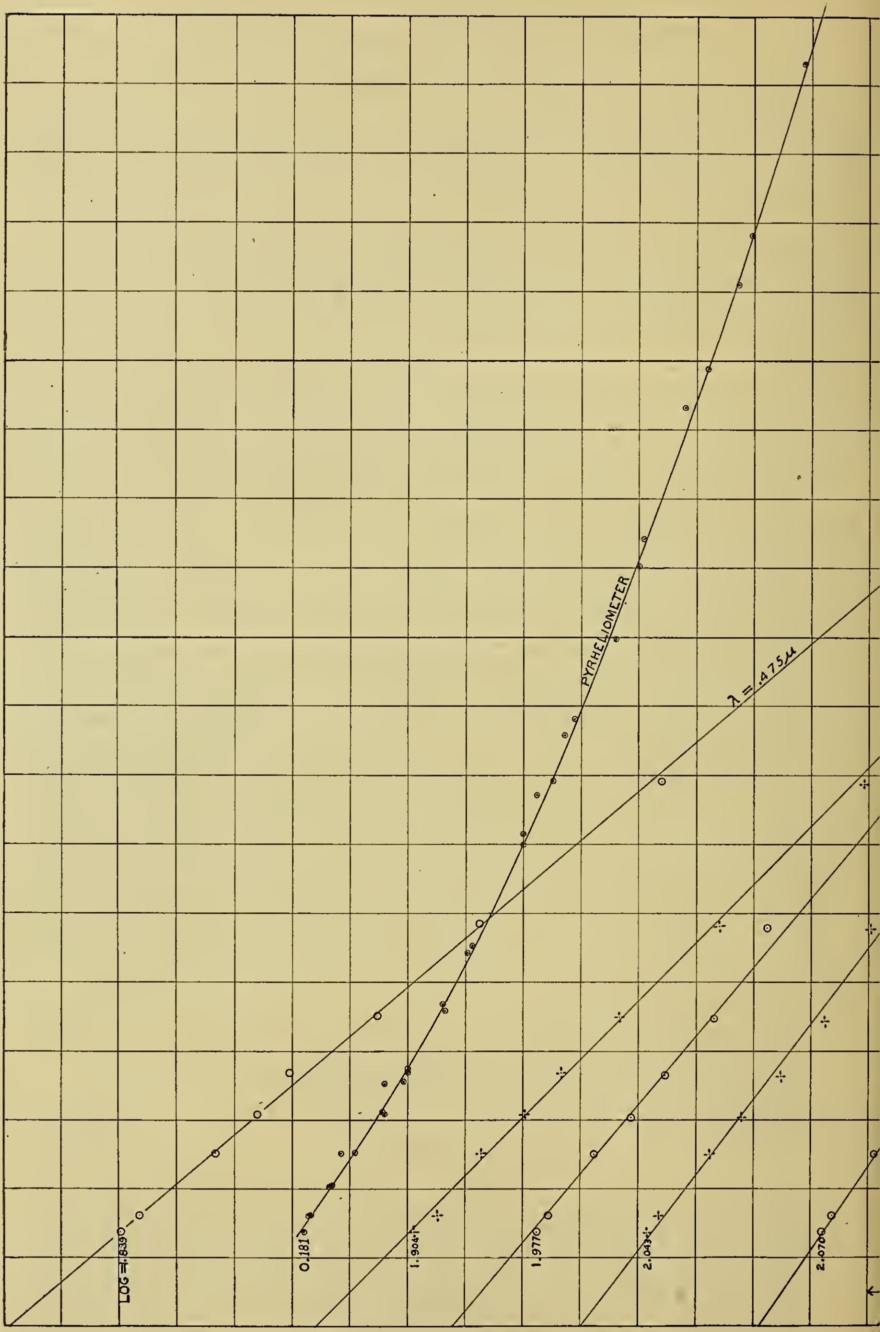
TABLE 8—*Air-masses and Smoothed Curve Ordinates*

Bolographs of September 20, 1914

Prismatic deviation from ω_1	Wave length	Correcting factor[1] for transmission through optical apparatus	Bolograph I		Bolograph II		Bolograph III[3]		Bolograph IV		Bolograph V		Bolograph VI		Bolograph VII		Bolograph VIII		Bolograph X[4]		Bolograph XI	
			Galvanometer deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass (Bemporad)	Deflection[2]	Air-mass	Deflection[2]	Air-mass	Deflection[2]	Air-mass
′	μ																					
240	0.342	.352	[5]	....	[5]	....	[5]	....	[5]	....	28	4.68	50	3.80	50	3.15	100	2.57	150	1.63	165	1.39
230	.350	.215	....	....	....	....	17	8.31	?30	6.14	72	4.67	108	3.79	148	3.14	212	2.56	340	1.63	365	1.39
220	.360	.139	....	....	....	....	41	8.26	?77	6.10	158	4.65	228	3.78	315	3.14	440	2.56	660	1.63	690	1.39
210	.371	.317	....	....	....	....	30	8.21	?70	6.07	90	4.63	132	3.77	196	3.13	240	2.55	345	1.63	370	1.39
200	.384	.270	....	....	....	....	46	8.16	111	6.02	152	4.61	217	3.75	290	3.12	356	2.55	530	1.62	553	1.39
190	.397	.264	....	....	30	12.3	131	8.12	244	5.99	350	4.59	453	3.74	500	3.11	630	2.55	840	1.62	860	1.39
180	.413	.630	....	....	40	12.2	92	8.07	160	5.96	210	4.58	280	3.73	338	3.10	390	2.54	510	1.62	520	1.38
170	.431	.584	?15	18.8	59	12.1	143	8.01	240	5.93	323	4.55	393	3.72	456	3.10	545	2.54	642	1.62	663	1.38
160	.452	.544	?36	18.5	126	12.0	94	7.95	440	5.89	562	4.53	650	3.70	740	3.09	845	2.53	1012	1.62	1033	1.38
150	.475	1.53	?33	18.3	79	11.9	153	7.91	220	5.86	268	4.52	320	3.69	345	3.08	380	2.53	443	1.62	447	1.38
140	.503	1.43	68	18.1	140	11.8	228	7.87	305	5.82	369	4.50	417	3.68	452	3.07	499	2.52	548	1.61	558	1.38
130	.535	1.33	100	17.9	223	11.6	340	7.80	430	5.80	497	4.48	550	3.67	595	3.06	648	2.52	716	1.61	709	1.38
120	.574	1.24	151	17.6	304	11.5	427	7.75	568	5.77	618	4.46	680	3.66	740	3.06	798	2.51	890	1.61	884	1.38
115	.598	1.20	220	17.5	377	11.5	528	7.73	650	5.75	708	4.45	780	3.65	838	3.05	897	2.51	983	1.61	973	1.38
110	.624	1.16	293	17.4	460	11.4	637	7.71	738	5.74	804	4.44	870	3.65	930	3.05	992	2.51	1062	1.61	1063	1.38
105	.653	1.12	425	17.3	608	11.4	780	7.69	896	5.73	950	4.44	990	3.64	1055	3.05	1110	2.51	1178	1.61	1164	1.38
100	.686	1.09	580	17.2	773	11.3	942	7.64	1045	5.71	1096	4.42	1143	3.64	1187	3.04	1238	2.50	1293	1.61	1266	1.38
95	.722	1.07	687	17.1	872	11.3	1033	7.63	....	5.69	1176	4.42	1210	3.63	1245	3.04	1296	2.50	1336	1.61	1312	1.38
90	.764	1.06	783	17.0	950	11.2	1093	7.61	....	5.69	1208	4.41	1244	3.62	1265	3.03	1310	2.50	1345	1.60	1317	1.38
85	.812	1.10	826	16.9	969	11.2	1102	7.59	....	5.68	1192	4.40	1225	3.62	1250	3.03	1294	2.49	1308	1.60	1277	1.38
80	.864	1.17	850	16.8	966	11.1	1086	7.56	....	5.66	1158	4.39	1183	3.61	1200	3.03	1243	2.49	1250	1.60	1220	1.38
75	.922	1.24	834	16.7	948	11.1	1046	7.54	....	5.65	1108	4.38	1120	3.60	1138	3.02	1170	2.49	1180	1.60	1144	1.38
70	.987	1.29	807	16.6	912	11.0	987	7.52	1010	5.63	1030	4.37	1040	3.60	1057	3.02	1098	2.49	1092	1.60	1063	1.38
65	1.062	1.28	719	16.5	830	11.0	878	7.50	913	5.62	920	4.37	920	3.60	943	3.02	960	2.48	978	1.60	947	1.38
60	1.146	1.26	626	16.4	732	10.9	770	7.47	813	5.60	819	4.36	820	3.59	840	3.01	852	2.48	860	1.60	846	1.38
55	1.226	1.23	543	16.3	652	10.9	688	7.45	714	5.59	722	4.35	727	3.58	742	3.01	758	2.48	759	1.60	752	1.37
50	1.302	1.20	489	16.2	580	10.8	613	7.43	626	5.58	650	4.34	640	3.58	662	3.00	673	2.48	690	1.60	660	1.37
45	1.377	1.17	452	16.1	519	10.8	546	7.41	560	5.57	580	4.34	577	3.58	589	3.00	600	2.47	623	1.60	580	1.37
40	1.452	1.14	420	16.0	478	10.7	498	7.37	503	5.55	520	4.32	516	3.57	528	3.00	535	2.47	560	1.60	510	1.37
35	1.528	1.12	392	15.9	436	10.7	448	7.35	455	5.53	465	4.31	463	3.56	470	2.99	475	2.47	488	1.60	466	1.37
30	1.603	.363	1100	15.8	1190	10.7	1240	7.33	1237	5.52	1268	4.31	1270	3.56	1280	2.99	1286	2.47	1311	1.60	1240	1.37
25	1.670	.356	982	15.7	1065	10.6	1111	7.31	1103	5.52	1130	4.30	1132	3.56	1144	2.99	1150	2.46	1178	1.60	1110	1.37
20	1.738	.353	862	15.6	935	10.6	977	7.28	980	5.50	992	4.29	998	3.55	1008	2.98	1011	2.46	1038	1.59	978	1.37
10	1.870	.370	620	15.5	682	10.5	708	7.25	718	5.47	720	4.28	722	3.54	730	2.97	733	2.45	758	1.59	720	1.37
0	2.000	.422	375	15.2	432	10.4	440	7.19	452	5.44	442	4.26	447	3.53	453	2.97	460	2.45	474	1.59	453	1.37
—10	2.123	.176	580	15.1	660	10.3	670	7.16	695	5.42	670	4.24	700	3.52	700	2.96	710	2.45	730	1.59	700	1.37
—20	2.242	.239	272	15.0	318	10.2	335	7.12	350	5.40	350	4.23	355	3.51	360	2.96	365	2.45	390	1.59	375	1.37
—30	2.348	.307	120	14.8	155	10.1	180	7.07	210	5.38	210	4.21	220	3.50	220	2.95	240	2.44	260	1.59	245	1.37

[1] This factor includes consideration of rotating sectors used, reflecting power of coelostat, and transmission in spectroscope.
[2] Galvanometer deflections are here expressed in tenths of millimeters.
[3] Bolograph III is a little low in a few points by interference of leaves of a tree.
[4] Bolograph IX is omitted because a guy wire interfered.
[5] Extremely doubtful points, and those for which deflections are less than 1 millimeter, are omitted.

After reducing the measured ordinates (by means of factors given) for transmission in the apparatus, in accordance with the practice of Langley and ourselves, we corrected these new ordinates of the bolographs for the slight changes of sensitiveness of the bolometric apparatus. We determined these changes of sensitiveness by comparing the areas included under the bolographic curves with the


LOG = 1.839
0.181
1.904
1.977
2.043
2.070
PYRHELIOMETER
λ = .475μ

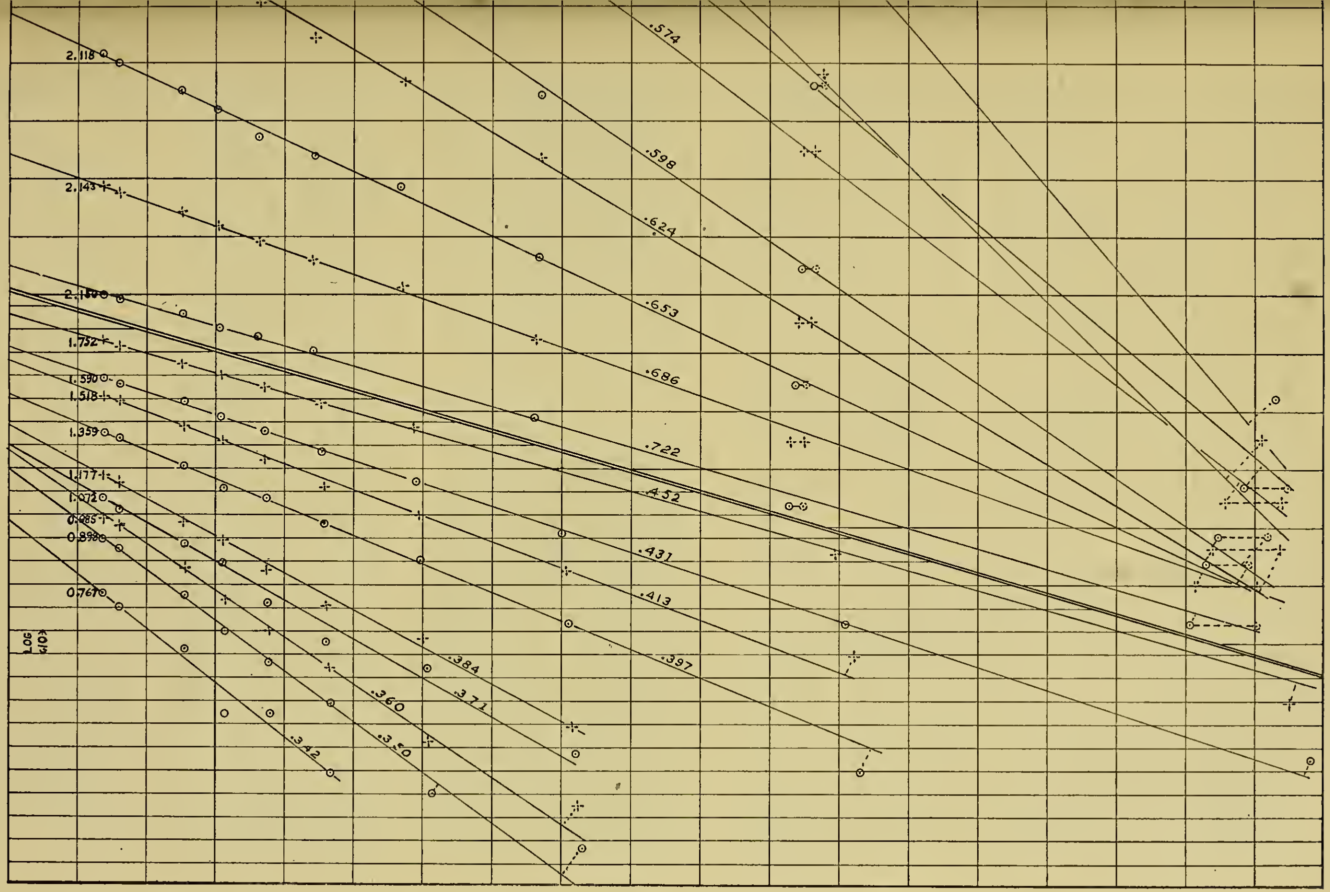


FIG. 3.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914. NOTE THE TWO SCALES OF ORDINATES.

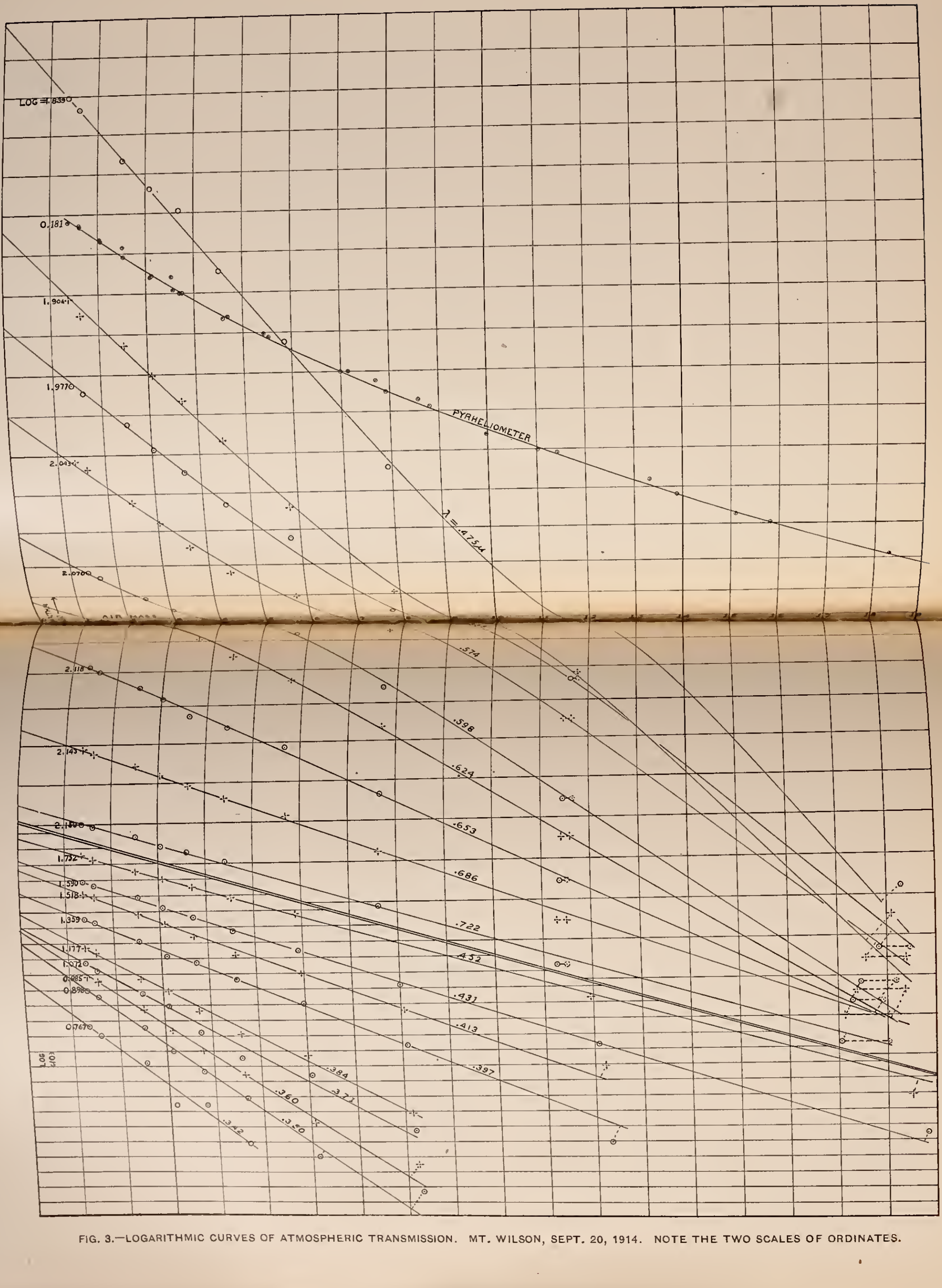


FIG. 3.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914. NOTE THE TWO SCALES OF ORDINATES.

readings of the pyrheliometer simultaneously obtained. The determination of these secondary correcting factors and of the mean bolometer constant for September 20 follows:

TABLE 9—*Sensitiveness of Bolographic Apparatus*

Bolograph	Hour Angle	Air-mass	Smooth-curve area of bolograph	Correction for ultra-violet	Correetion for infra-red	Correction for water vapor and oxygen bands	Corrected area	Corresponding pyrheliometry, calories	Factor to reduce corrected areas to calories	Correcting factor in percentage	Correcting logarithm.
	h *m*										
I	5 53.5	17.15	7475	—	+109	—2135	5449	0.583	1.070	+7.3	.031[1]
II	42.7	11.39	9630	—	127	2094	7663	.764	0.997	±0.0	.000
III	29.8	7.71	11129	—	132	2000	9261	.943	—	—	—[2]
IV	16.9	5.75	12436	—	138	1961	10613	1.066	1.004	+0.7	.003
V	2.0	4.46	13232	+1	136	1887	11482	1.159	1.009	+1.2	.005
VI	4 47.3	3.67	13930	25	140	1819	12276	1.233	1.003	+0.6	.003
VII	31.3	3.06	14622	41	140	1807	12996	1.294	0.996	—0.1	.000
VIII	10.0	2.53	15474	79	144	1692	14005	1.377	0.983	—1.4	.994
X	2 51.0	1.62	16576	163	150	1624	15265	1.495	0.979	—1.8	.992[3]
XI	03.0	1.38	16317	179	144	1609	15031	1.515	1.008	+1.1	.005
								Mean	0.997		

[1] The correcting factor for bolograph I is much above the usual magnitude. It was not used for the following reasons: Firstly, the pyrheliometer exposes $\frac{1}{200}$ hemisphere, which is a sky area much larger than the sun. At ordinary air-masses the light of this area of sky is negligible compared with sunlight. But at sunrise almost ⅔ of the solar beam is lost by scattering in the sky, hence the light of the sky close to the sun is a very perceptible fraction, perhaps 5 per cent, of that of the sun itself. Secondly the radiation of the pyrheliometer to cold air and to space, which at high sun may reach nearly 0.005 calorie, is at the horizon counterbalanced by the radiation of the immense thickness of the lower and warmer parts of the atmosphere, so that in comparison with high sun observations the pyrheliometer reading at sunrise is probably about 1 per cent too high for this second cause. Exact determinations of these corrections to pyrheliometry are proposed, but not yet executed. Accordingly bolograph I was omitted in the mean of column 10.

[2] Correction could not be determined because leaves of a tree intercepted the solar beam during a part of bolograph III.

[3] Bolograph IX omitted, because shadow of a guy wire fell on the slit during a considerable part of the time.

In figures 3 and 4 we give plots to represent the results of the spectro-bolometric observations of September 20 at different wave lengths. The plots given in figures 3 and 4 are logarithmic. The ordinates correspond to logarithms of the corrected heights of the bolographs at the 38 selected points, and the abscissae of the diagrams represent the corresponding air-masses according to the tables of Bemporad, corrected as heretofore explained.

The original plots have been made on two different scales. In the first, only those observations which we would ordinarily have used for determining the solar constant of radiation were included. They were plotted on the scales of ordinates and abscissae which we customarily employ, in which, in general, 1 cm.=0.01 in logarithm, and 1 cm.=0.1 air-mass. In the other plot we have included all the observations, using for this purpose a reduced scale of abscissae, in which 1 cm. = 0.5 air-mass.

We have read off from the plots so obtained the inclination of the best straight lines, giving logarithms of transmission coefficients; and also the intercepts on the axis of ordinates, giving logarithms of intensities outside the atmosphere. The plots were read up independently for three different ranges of air-masses. The first range is that which we customarily employ, from about 1.3 to about 4.5 air-masses. The second reading includes all points from 1.3 to 20 air-masses or thereabouts. The third reading was made with the portion of the curve which Mr. Very states to be the best, namely, from air-mass 4 to air-mass 10 or thereabouts. The results of all three readings are given in table 11. For September 20 this table gives also the percentage deviations, in ordinates, of the observed points from the natural numbers corresponding to the straight lines of the logarithmic plots which were chosen in the second reading to represent them. In order to show that the somewhat large percentage errors at some places are not inconsistent with experimental error of very moderate amount, we give for two bolographs the deviations expressed in millimeters on the original bolographs. The reader should bear in mind that the bolographic trace itself is nearly 1 millimeter wide, and subject to tremor. Also the line of zero radiation is interpolated between zero marks 1 minute of time, or 8 centimeters of plate, apart.

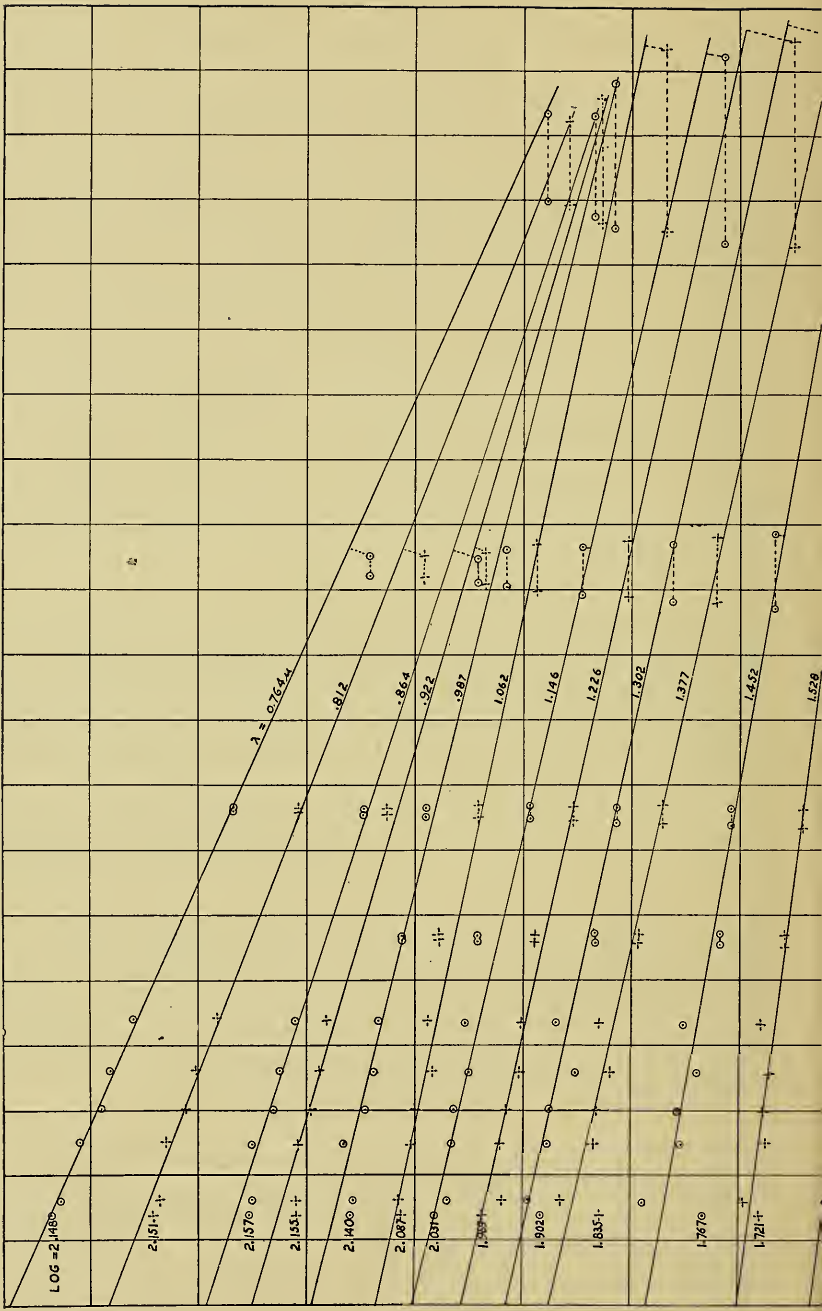
We then determined the area which the bolographic curve would include if it were taken outside the atmosphere, and we multiplied this area by the appropriate constant (see table 9) to give the result in calories per sq. cm. per minute. To this we added the small corrections to reduce the result to mean solar distance, and to zero atmospheric humidity, as explained in Annals, Vol. III, p. 43. All the details of the foregoing processes have been described and investigated in Vols. II and III of the Annals of the Astrophysical Observatory, and to these the reader is referred.

The following are the solar constant values obtained:

TABLE 10—*Solar Constant Values*

In standard calories (15°) per sq. cm. per minute at mean solar distance

Air-masses	1.3 to 4	1.3 to 20	4 to 12
Sept. 20	1.936	1.899	1.909
Sept. 21	1.960	1.955	1.929


LOG = 2.148
2.151
2.157
2.155
2.140
2.087
2.031
1.902
1.835
1.767
1.721
λ = 0.764 μ
.812
.864
.922
.987
1.062
1.146
1.226
1.302
1.377
1.452
1.528

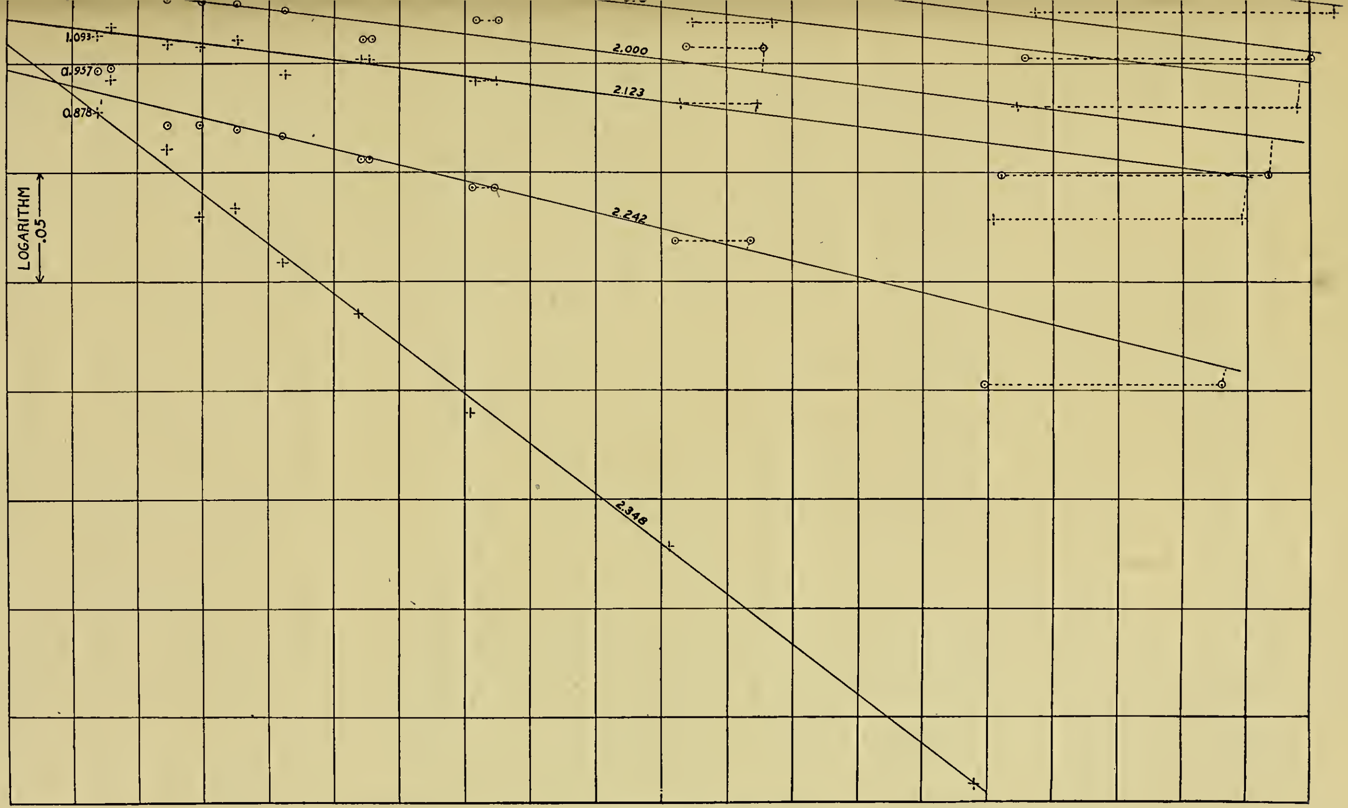


FIG. 4.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914.

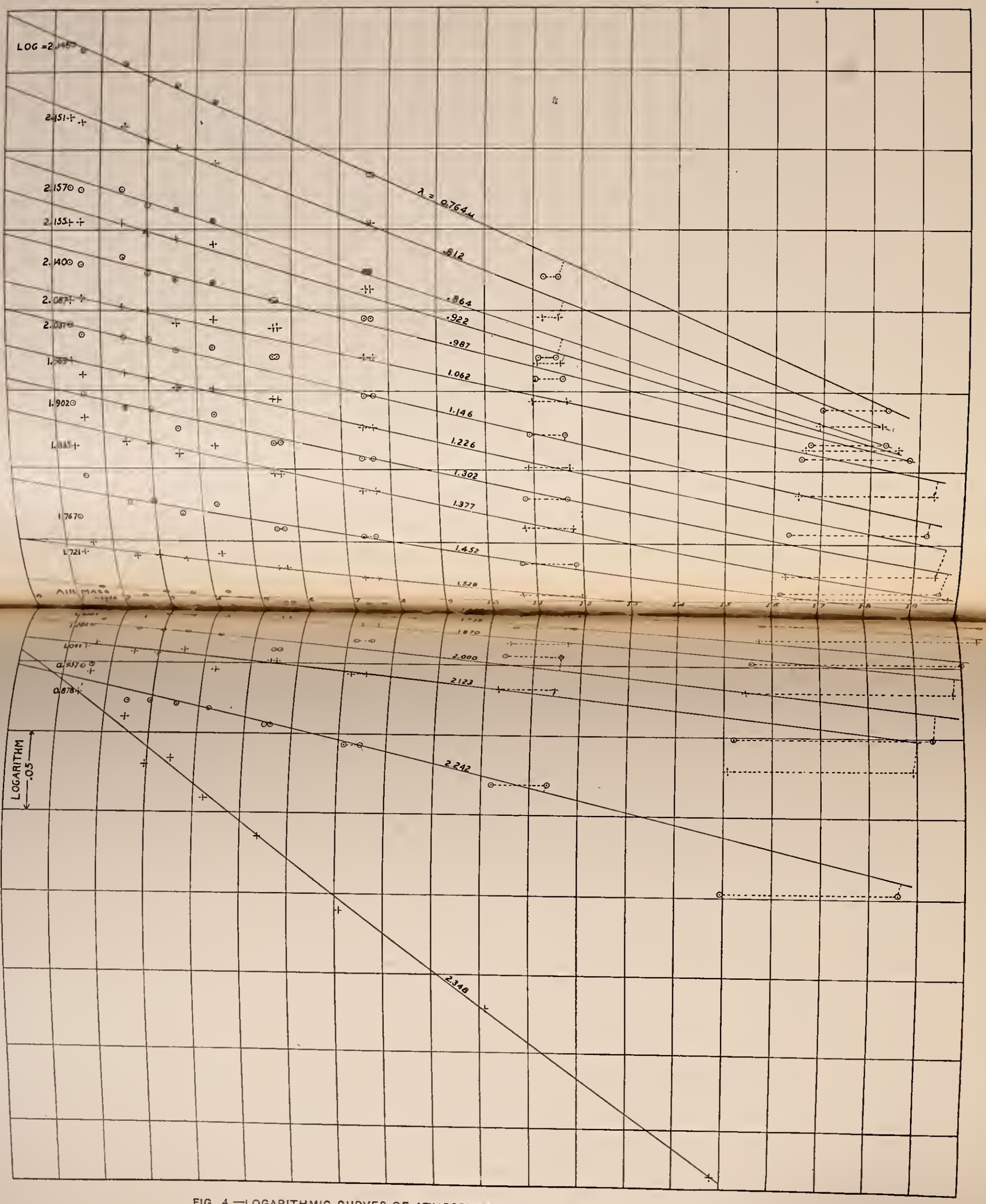


FIG. 4.—LOGARITHMIC CURVES OF ATMOSPHERIC TRANSMISSION. MT. WILSON, SEPT. 20, 1914.

TABLE 11—*Atmospheric Transmission Coefficients, and Accidental Errors*

Wave length	Atmospheric transmission coefficients						Percentage deviations, Sept. 20 Computed minus observed For observed intensities found on Bolographs Nos.										Linear deviations on original bolographs in millimeters	
	Sept. 21, '14 Air-masses			Sept. 20, '14 Air-masses														
	1.3 to 4	1.3 to 20	4 to 12	1.3 to 4	1.3 to 20	4 to 12	I	II	III	IV	V	VI	VII	VIII	X	XI	I	VII
μ																		
0.342	.621	.600	.637	.615	.585	—	—	—	—	—	0.0	+10.4	−27.9	+10.4	0.0	0.0	....	1.1
0.350	.621	.575	.575	.600	.600	.637	—	—	+51.4	−14.8	+ 2.3	− 2.3	− 3.5	+ 2.3	+ 1.6	− 0.5	....	0.5
.360	.643	.625	.658	.618	.667	.652	—	—	+34.9	− 7.2	0.0	− 3.5	− 2.8	+ 2.3	+ 1.6	− 1.2	....	0.8
.371	.661	.678	.682	.681	.679	.718	—	—	+11.7	+13.5	−20.2	−12.2	+ 2.3	0.0	− 2.3	0.0	....	0.5
.384	.681	.692	.697	.681	.692	.702	—	—	+ 1.2	+10.2	+10.2	− 7.2	0.0	− 2.3	+ 2.3	+ 1.2	....	0.0
.397	.745	.731	.728	.743	.753	.753	—	−28.8	0.0	+ 3.5	0.0	+ 1.2	− 6.7	0.0	+ 1.2	0.0	....	3.3
.413	.769	.766	.766	.764	.773	.783	—	+23.0	− 1.2	− 1.2	− 8.4	− 2.3	0.0	0.0	+ 1.2	0.0	....	0.0
.431	.778	.794	.802	.794	.798	.796	−18.9	0.0	− 3.5	0.0	− 1.2	0.0	0.0	+ 4.7	0.0	0.0	0.2	0.0
.452	.841	.824	.824	.820	.820	.832	−25.9	− 4.7	− 2.3	+ 2.3	0.0	− 0.7	0.0	0.0	0.0	+ 2.3	0.7	0.0
.475	.843	.836	.836	.859	.851	.830	+12.7	− 5.0	2.6	+ 0.2	− 0.9	+ 3.3	0.0	− 0.7	0.0	0.0	0.5	0.0
.503	.879	.867	.867	.881	.873	.875	+ 5.2	+ 1.4	− 2.6	− 1.6	+ 0.5	+ 0.9	+ 0.2	+ 1.4	− 1.9	− 0.7	0.3	0.1
.535	.891	.891	.891	.893	.892	.895	− 0.5	0.0	− 1.4	+ 4.0	− 0.7	− 0.5	− 0.5	+ 0.7	− 0.5	− 0.9	0.0	0.3
.574	.897	.900	.900	.889	.903	.904	0.0	0.0	− 6.2	+ 2.3	− 2.1	− 1.2	0.0	+ 0.9	+ 1.9	+ 1.6	0.0	0.0
.598	.900	.906	.908	.904	.911	.908	+ 8.1	0.0	− 2.3	+ 0.7	− 2.3	− 0.9	0.0	+ 0.7	+ 0.9	+ 0.7	1.7	0.0
.624	.900	.918	.925	.916	.921	.920	+11.2	0.0	+ 0.7	− 0.2	− 2.1	− 1.4	0.0	+ 0.9	− 0.5	+ 0.7	3.7	0.0
.653	.931	.942	.942	.933	.936	.938	+ 1.2	− 0.5	0.0	+ 1.2	− 0.5	− 1.9	− 0.2	0.0	0.0	+ 0.5	0.5	0.2
.686	.948	.954	.953	.953	.953	.954	+ 1.2	− 1.9	0.0	+ 0.9	0.0	0.0	+ 0.2	+ 0.2	0.0	0.0	0.7	0.2
.722	.959	.961	.960	.966	.961	.960	+ 1.2	− 1.9	0.0	+ 0.7	+ 0.2	0.0	+ 0.5	− 0.2	− 0.2	− 0.2	0.8	0.6
.764	.966	.970	.971	.973	.970	.968	− 0.2	− 2.6	− 0.2	—	+ 0.5	+ 0.5	− 0.2	+ 0.5	− 0.5	− 0.2	0.2	0.3
.812	.968	.977	.979	.980	.974	.972	0.0	− 2.6	+ 0.5	—	+ 0.5	+ 0.5	0.0	+ 0.7	− 0.9	− 0.9	0.0	0.0
.864	.968	.982	.984	.982	.978	.973	0.0	− 2.8	+ 0.7	—	+ 0.7	+ 0.5	0.0	+ 0.9	− 0.9	− 0.9	0.0	0.0
.922	.975	.985	.987	.982	.980	.978	+ 0.5	− 1.2	+ 1.2	—	+ 0.9	+ 0.2	− 0.2	0.0	+ 1.4	− 1.9	0.4	0.2
.987	.984	.990	.992	.986	.983	.982	0.0	− 0.7	+ 0.9	0.0	+ 0.5	− 0.5	− 0.5	+ 0.9	− 1.4	− 1.6	0.0	0.5
1.062	.984	.990	.992	.984	.985	.984	− 2.3	0.0	+ 0.5	+ 1.9	+ 0.9	− 0.7	+ 0.5	0.0	0.0	− 0.5	1.6	0.5
1.146	.989	.990	.993	.986	.984	.983	− 2.1	+ 0.9	0.0	+ 2.3	+ 1.4	0.0	+ 0.5	0.0	− 0.9	0.0	1.3	0.4
1.226	.984	.988	.990	.989	.985	.983	− 5.7	+ 0.5	0.0	+ 1.2	+ 0.5	− 0.5	0.0	0.0	− 1.6	0.0	3.1	0.0
1.302	.980	.987	.988	.984	.985	.984	− 4.7	0.0	0.0	− 0.7	+ 1.4	− 1.6	0.0	− 0.5	+ 0.2	− 1.4	2.3	0.0
1.377	.986	.990	.990	.980	.985	.983	0.0	+ 0.7	0.0	− 0.5	+ 1.6	− 0.7	− 0.2	− 0.7	+ 1.4	− 3.0	0.0	0.1
1.452	.986	.991	.991	.977	.988	.988	− 1.4	+ 0.9	+ 0.5	− 0.7	+ 1.4	− 0.7	+ 0.5	− 0.5	+ 2.3	− 4.2	0.6	0.2
1.528	.989	.993	.992	.991	.991	.990	− 2.1	+ 0.5	0.0	+ 0.2	+ 1.6	0.0	0.0	− 0.5	+ 0.9	− 0.9	0.8	0.0
1.603	.986	.994	.994	.995	.992	.991	0.0	+ 0.2	+ 1.2	− 0.5	+ 1.4	+ 0.5	0.0	− 1.4	0.0	− 3.5	0.0	0.0
1.670	.986	.994	.994	.998	.992	.992	− 0.7	0.0	+ 1.4	− 0.7	+ 0.9	+ 0.2	+ 0.2	− 0.9	0.0	− 2.8	0.7	0.2
1.738	.989	.991	.994	.995	.992	.991	− 0.7	0.0	+ 1.4	+ 0.2	+ 0.7	0.0	0.0	− 1.2	0.0	− 3.3	0.6	0.0
1.870	.984	.991	.995	.991	.992	.990	− 2.8	− 0.2	+ 0.7	+ 0.9	+ 0.5	0.0	− 0.2	− 1.6	+ 0.5	− 1.9	1.7	0.2
2.000	.973	.992	.995	.991	.991	.994	− 3.8	+ 2.6	+ 2.6	− 1.9	+ 0.2	+ 0.2	0.0	− 0.2	+ 1.6	− 0.5	1.6	0.0
2.123	.991	.991	.992	.989	.991	.992	− 4.7	+ 1.2	0.0	+ 0.5	− 2.1	+ 0.9	− 0.2	− 0.5	+ 0.5	− 0.5	2.7	0.1
2.242	.980	.979	.986	.966	.983	.983	− 1.9	+ 1.2	0.0	− 0.2	0.0	− 0.2	− 0.9	− 1.6	+ 2.8	+ 2.3	0.5	0.3
2.348	.863	.942	.940	.925	.951	.951	0.0	0.0	− 2.1	0.0	− 0.9	+ 0.9	− 3.3	+ 1.9	+ 5.0	0.0	0.0	0.7
Means:......................							− 1.2	− 0.6	+ 2.3	+ 0.5	− 0.3	− 0.5	− 1.1	+ 0.5	+ 0.4	− 0.6	0.9	0.3

We call attention to the decided difference between the behavior of nearly homogeneous rays, as observed by the bolometer, and of the total radiation, as observed by the pyrheliometer. The logarithms of the pyrheliometer readings of September 20 are plotted against Bemporad air-masses in the upper curve of figure 3, and the reader will readily perceive the pronounced and steady change of curvature of the resulting plots. This is in sharp distinction to the close approximation to straight lines shown in the logarithmic plots of the bolometric observations at single wave lengths. Forbes, Radau, Langley, and many others have discussed this relation between total radiation and air-masses, and have shown why such a curvature must occur in logarithmic plots of total radiation. It will be seen that our observations fully confirm their view, which depends upon the fact that the total radiation is composed of parts for which the atmosphere has very different transmission coefficients.

Referring to tables 2 and 11, and to Annals, Vol. III, table 47, the reader will see that the atmospheric transmission on September 20 and 21, 1914, was distinctly above the average, and indeed was as high as we have ever found on Mt. Wilson. Secondly, the quantity of water vapor between the station and the zenith, as found by Mr. Fowle's spectroscopic method, was unusually small and satisfactorily constant. Hence, we may conclude that the two days in question were, as they appeared to the eye, days of the highest excellence at Mt. Wilson. When we compare the results obtained from them on the solar constant of radiation, as given in table 10, with those obtained in other years, as shown in table 1 and in Annals, Vol. III, table 44, we see that the values were very close to the mean results of all our observations. We see further, from table 10, that the results obtained were very nearly the same, whether we used only the later observations, taken between air-mass 1.3 and air-mass 4, as in our usual investigations; whether we employ only the observations between air-mass 4 and air-mass 12, as recommended by Mr. Very; or, finally, whether we take all the observations from air-mass 1.3 to air-mass 20. In every case the result is the same almost within the error of computing.

From this we feel ourselves fully justified in drawing the conclusion that our former work has not been vitiated by the employment of too small air-masses, and that, in fact, hardly different results would have been obtained had we observed from sunrise of every day in which we have worked. On account of the uncertainty which attends the theory of the determination of air-masses, when zenith distances exceeding 75° are in question, we conceive that it will be better to confine our observations hereafter, as we have generally done in the past, to the range of air-masses less than 4, where the secant formula applies in all atmospheric layers, irrespective of optical density, refraction, or the earth's curvature.

Third objection.—We attach very little weight to any determinations of the solar constant of radiation which we have made hitherto, except those made by the spectro-bolometric method developed by Langley, as just employed for September 20, 1914, and which is the definitive method employed by the Astrophysical Observatory of the

Smithsonian Institution.[1] However, in Vol. II of our Annals we showed in the second part of the work that the results obtained by this method were harmonious with rougher ones obtained by considering terrestrial meteorological conditions. In the course of that discussion we used the data which were at that time available for determining the transmission through the moist atmosphere of the long-wave radiations such as the earth sends out. Mr. Very

---

[1] Messrs. Very and Bigelow describe as "the spectro-bolometric method" of determining the solar constant of radiation something quite different, viz.: They take our determination of the form of the solar energy curve outside the atmosphere. From this they determine the wave length of maximum energy, and from it they infer the temperature of the sun, supposing it to be a perfect radiator or "black body." They then determine the intensity of energy which a perfect radiator of the sun's size, and of the temperature which they thus decide upon, would give at the earth's mean distance. This value they regard as the solar constant.

In this determination they assume: Firstly, that our atmospheric transmission coefficients, which at other times they describe as altogether erroneous, do not distort the true form of the sun's energy curve outside the atmosphere; Secondly, that our determinations of the transmission of the optical apparatus (and these we ourselves admit to be determinations of great difficulty, and only moderate accuracy) also do not distort the form of the energy curve; Thirdly, that the position of the maximum of energy determines the proper temperature of the sun; Fourthly, that the total emission of energy of the sun is the same function of its temperature that the total emission of a "black body" is.

We are far from wishing to discredit the substantial accuracy of our determination of the form of the sun's energy curve outside the atmosphere, but we totally dissent from these authors' application of it. In the first place, the form of the energy curve as determined by us does not agree with the form of the energy curve of a "black body" at any single temperature whatever. In the second place, if the temperature of the sun could be properly inferred from the consideration of the position of maximum energy in its spectrum, even then there would be no reason to suppose that the radiation of the sun bears the same relation to its temperature as the radiation of a "black body" bears to its temperature. Since the sun is not a "black body" of uniform temperature, it may depart widely from the conditions of such a "black body."

The same method could just as reasonably be applied to the radiation of a mercury vapor lamp. The maximum of energy with such a lamp would be found in the green, as it is in the solar spectrum, and thereby, following Very and Bigelow, one could infer that the temperature of the lamp is of the order of six to seven thousand degrees absolute. Then, following still further our authors, we should assume that the mercury vapor lamp, the sun, and the "black body" at, say, 6,800° would give equal intensities of energy, provided these three sources were of equal angular size. Thus the radiation of all three would be about 3.5 calories per cm.^{2} per min. The absurdity of this conclusion is apparent.

has confused that discussion with our definitive determination of the solar constant of radiation, of which it forms no part at all. We do not care to discuss, at the present time, the coefficients for terrestrial radiation, as we are engaged in investigations of this matter which are not as yet completed. It has no bearing upon the definitive values of the solar constant obtained by us.

As for the dependence of the transmission of solar rays upon atmospheric water vapor, we have employed the hypothesis of Langley, namely, that there will be no water vapor outside the atmosphere. This gives us the highest results which can properly be reached. As we shall see in the conclusion of this article, our results obtained in this manner are supported by another line of investigation.

Fourth objection.—We perhaps do not understand just what Mr. Very has in mind in regard to this. Certainly there is no sheet of ice or anything of a continuous surface to be found in the air, so far as we know, which would answer to the description of the conditions referred to in the fourth objection. Some approach to it may be found in the case of a cloud. But we have repeatedly ascended from Pasadena to Mt. Wilson through clouds, and even in this case we always perceived that the upper edge of the cloud had a gradual thinning out for at least many meters. We do not conceive that there is any other layer in the atmosphere for which this is not true. A transition extending through at least many meters is all that we require when we speak of a " gradual " change of transparency from one atmospheric layer to another.

As Mr. Very hints, there are irregularities in the distribution of the various bodies of air. For instance, in the neighborhood of a mountain there are currents of air of different temperatures rising and falling along the slopes. These, to be sure, do not fall into the horizontal layers postulated in our hypothesis of the atmospheric transmission, but they disturb the regular distribution in altitude so little relatively to the whole thickness of the atmosphere, and furthermore, the differences of atmospheric transmission of these different bodies of air from their immediate surroundings are so slight, that their influence on the transmission coefficients which we obtain may be neglected.

Fifth objection.—We understand that it is here claimed that the general, apparently non-selective, losses to which the solar beam is subject in passing through the atmosphere are due not only to the scattering of radiation by particles small as compared with the wave length of light as indicated by Lord Rayleigh's theory, but also to a true absorption occurring in spectrum lines which are so fine as to have escaped discovery hitherto, although so numerous as to produce a profound effect upon the transmission of the atmosphere. Indeed, Mr. Very says in another place that one may prove that atmospheric losses in the atmosphere are at least three times as great as are indicated by Rayleigh's theory of scattering, or by the secant formula of extinction. We have found by balloon experiments, as we shall show, that the radiation at a level of about 25 kilometers, where more than twenty-four twenty-fifths of the atmosphere lies below, is still not greater than 1.9 calories per sq. cm. per minute. Hence the condition of affairs referred to by Mr. Very, if it exists, applies only to the very highest layers of the atmosphere, exerting less than one twenty-fifth part of its pressure. Apparently, however, his strongest evidence of this supposed condition of affairs is his fixed impression that the solar constant must be greater than we have found it.

As to the effect on solar radiation of particles too gross to diffract the rays, this must refer to dust particles, or agglomerations of dust and other materials about nuclei of one kind or another, perhaps about the hydrols which are thought by some to exist in the atmosphere. In regard to this we have only to refer to that line of table 2 which shows the transmission of the atmosphere for July 26, 1912, when it was filled with volcanic dust. The atmospheric transmission was then greatly reduced, but in a manner to make the sky white, not blue. Hence we may say that the particles composing the dust were large as compared with the wave length of light. But our values of the solar constant obtained both at Bassour, Algeria, and at Mt. Wilson, California, did not differ appreciably from those we had obtained in the clearest of skies.

It is urged that there are diffuse bands of atmospheric absorption which have escaped detection, but which, if taken account of, would increase the value of the solar constant of radiation. We call attention here to the results published by Mr. Fowle,[1] in which he determined in the ordinary manner, from Washington observations, transmission coefficients in the great infra-red water vapor bands. These transmission coefficients, as he showed, sufficed almost, or quite, to obliterate these bands from the energy curve of the sun outside of the earth's atmosphere, just as they ought to do, if effective, seeing that no water vapor exists in the sun. If, now, there are other bands which are so inconspicuous that they cannot be found

---

[1] Smithsonian Misc. Coll., Vol. 47.

without the most careful consideration of the atmospheric transmission coefficients, as indeed Mr. Fowle's researches on the relations of the transmission coefficients to Lord Rayleigh's theory of the sky light have shown, still their effects will be eliminated in the same manner as the infra-red bands were in the investigation just cited, because the transmission coefficients in such spectrum regions will be smaller than they would have been had the bands not been present there. We feel satisfied that the existence of such bands, even if there are any others than those which we know of, would hardly in the slightest degree influence the value of the solar constant of radiation.

Sixth objection.—In regard to this matter, we think Mr. Very has misinterpreted our procedure. We did not determine the quantity of energy contained in the extreme infra-red part of the emission of a "black body," of the size and distance of the sun, at 6,000° absolute temperature, and add that to what we have found from our spectro-bolometric observations. On the contrary, our procedure has been to piece out the spectro-bolometric curve as we have found it to be outside the atmosphere, by joining onto it, where our determination ends, a curve after the form of the distribution of energy computed by the Wien-Planck formula for the "black body" at 6,000°. If, now, the condition of the sun is such that its distribution of radiation in the infra-red corresponds to a "black body" at 7,000°, or some still higher temperature, then the real rate of the falling off of the curve in the infra-red, beyond the region that we observe, would be *more rapid* than that which we have assumed it to be. Accordingly the area included under such a curve would be *less* than we have assumed it to be, and thus our value of the solar constant of radiation will be *too large* on account of the error of our method of extrapolating in the extreme infra-red, rather than too small, as Mr. Very maintains. At all events, surely the difference so far down in the spectrum as this is altogether trifling in amount.

Seventh objection.—We agree with Mr. Kron that the ultra-violet spectrum may be a little more intense than we have supposed it to be. However, when we consider the rapid falling off of solar energy in the violet, and the reasonableness of it in view of the immense number of solar absorption lines and other solar circumstances, we see no probability at all that the part neglected would exceed 1 or 2 per cent, at most, of the value of the solar constant of radiation. In confirmation of this view, we point to the results of the balloon flights, which we shall shortly describe.

Eighth objection.—As Mr. Very, in a recent article, has shown that Mr. Bigelow's thermodynamic considerations are erroneous, it is not necessary to discuss them further.

SOUNDING BALLOON OBSERVATIONS

Now we come to the final piece of experimental evidence which we have secured, which seems to us to show that our solar constant results are undoubtedly very close to the true ones, and that if there be any circumstances which have led to the underestimation of the losses which the solar beam suffers in the atmosphere, they at any rate relate to the part of the atmosphere which lies beyond the altitude of 24 kilometers, and where the total pressure of it is less than one twenty-fifth of that which prevails at sea level.

In January, 1913, it was determined on the part of the Smithsonian Institution to support an expedition to California, in charge of Mr. A. K. Ångström, for the purpose of observing the nocturnal radiation at various altitudes. In connection with this work, the Institution invited the cooperation of the United States Weather Bureau for the purpose of sending up sounding balloons and captive balloons, in order to determine the humidity and temperature at various heights in the atmosphere, at the time of Mr. Ångström's experiments. While discussing the proposed expedition with Mr. Ångström, he inquired of us whether it might not be possible that an instrument could be devised for measuring the intensity of the radiation of the sun at the highest altitudes to be reached by sounding balloons. After due consideration of the matter, it was deemed by us feasible to do this.

Accordingly in the months of April, May, and June, 1913, there were constructed at the instrument shop of the Astrophysical Observatory, five copies of a special recording pyrheliometer, modified in form from the silver disk pyrheliometer which we ordinarily employ in solar-constant work.

The five instruments were sent up, in cooperation with the U. S. Weather Bureau, by Mr. Aldrich, at Avalon, Santa Catalina Island, California, in July and August, 1913. All were recovered, and all had readable records of more or less value. In these experiments, the balloon in one instance reached the height of 33,000 meters, but unfortunately, owing to the freezing of the mercury contained in the thermometers, the pyrheliometric records did not extend above an altitude of 14,000 meters in any case. There were, besides, certain sources of error which had not been anticipated at that time, so that the results of the expedition could only be regarded as of a preliminary character. The results, such as they are, indicate radiation values not exceeding 1.8 calories per cm.^{2} per min.

Early in the year 1914, we began to rebuild the instruments, which had been injured in their flights. On February 18, the preparations having been considerably advanced, Mr. Abbot wrote the following letter to Mr. Very, which is self-explanatory:

February 18, 1914.

Dear Mr. Very:

As you know, we are interested in the value of the solar constant of radiation. We know that you are also. In our view this quantity lies between 1.9 and 2.0 calories per sq. cm. per min. In yours it lies between 3.0 and 4.0 calories or possibly higher. All measurements made by us rest on the "Smithsonian Revised Pyrheliometry of 1913." They are 3.5 per cent higher than they would be on Ångström's scale, as shown by numerous comparisons made in America and Europe. In the interests of ascertaining the truth, which I know to be your sole object, as it is ours, will you be so good as to answer these questions:

1. Do you consider the "Smithsonian Revised Pyrheliometry of 1913" as satisfactorily furnishing the standard scale of radiation?
2. If not, why not?
3. If in error, is it too high or too low, and how much?

I assume that you are not likely to think its results as much as 5 per cent too *low,* and that the discrepancy between your ideas of the solar constant and ours lies mainly outside of our conclusions as to the realization of the standard scale of radiation. In this posture of affairs, I propose to try the following experiments, which I hope will be crucial:

By cooperation with the United States Weather Bureau we propose to send up with balloons five automatic-registering pyrheliometers in June or July next. In preliminary experiments last summer the balloons generally reached 20 to 30 kilometers altitude, and in one case 33 kilometers. Mr. Blair expects personally to attend to the balloons this year, and hopes to get them all above 30 kilometers, and some even to 40 kilometers. [This hope was disappointed, probably because the balloons used in 1914 were a year old.] These elevations are of course *derived* from barograph records, and it is not the *elevation* we care about, but the *pressure of atmosphere above.* This is given directly by the barographs, which will be calibrated, at the temperatures expected, by Mr. Blair. [Calibrations were finally made at the Smithsonian Institution.] We may expect the pressure reached will be less than 1 per cent of that at sea level. It is designed to make the pressure record on the same drum as the pyrheliometer record, so that there can be no error by differences of running of independent clocks.

I now come to a second group of questions.

4. Do you think that the intensity of the solar radiation in free space at the earth's solar distance is materially higher than that at a station within the atmosphere of the earth, where the barometric pressure is less than 1 per cent of that which prevails at sea level?
5. If so, how much and why?

I assume that you do not think the radiation in free space would be as much as 5 per cent the higher of the two. If so, the proposed balloon experiments may be expected to be conclusive to you as well as to me, if you are satisfied as to their accuracy.

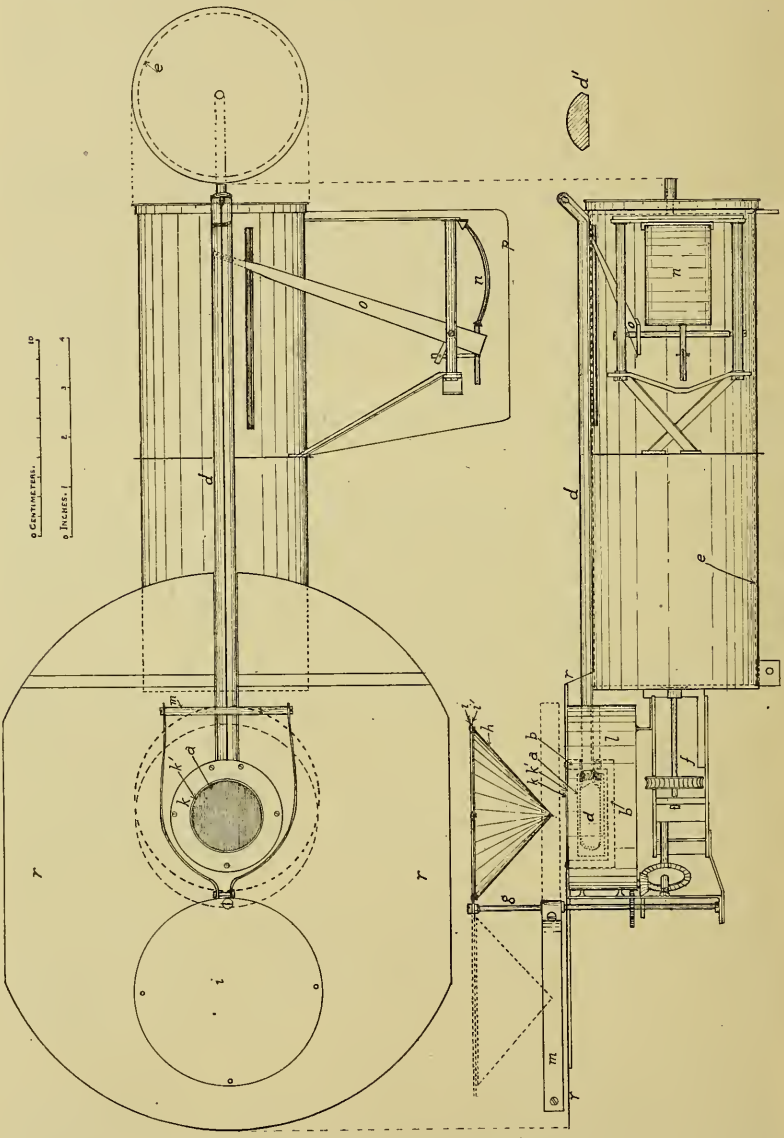


FIG. 5.—Balloon Pyrheliometer.

The apparatus is now in so forward a state of preparation that if you should be in Washington I hope you will do me the kindness to come and see it and discuss it. As that may be impracticable, I give the following details which may enable you to suggest sources of error which may be removed before the flights take place, or at least satisfactorily determined in advance by experiments.

This instrument is a modified form of our disk pyrheliometer. A blackened aluminum disk, *a* (fig. 5), encloses a thermometer, *d*, whose stem is shown in enlarged cross section at d^1. The cavity for the bulb of the thermometer within the disk, *a*, is filled up with mercury, and sealed at the mouth with thread and wax as in our pyrheliometers. The disk is enclosed in an interiorly blackened aluminum box, *b*. Two polished copper rings, *k* k^1, limit the solar beam to a cross section less than that of *a*. As the temperature of the disk *a* changes, the mercury in the stem fluctuates, thus allowing the sun to print on more or less of the length of the photographic drum, *e*, according to the temperature. Thus when the paper (solio paper) is removed, there is a record like this (see fig. 9):

A clock work *f* rotates the drum, and at the same time causes the shutter, *g h i* i^1, to be for four minutes in the position above the disk *a* as shown, then four minutes opened (as partially shown dotted at the left), then again closed as shown, and so on, rotating, at the end of each four minutes, 180° on *g* as an axis. The shutter comprises three parts. Of these *i* and i^1 are polished aluminum disks, and *h* a polished silver cone. The angle of the cone, *h*, is such that all rays from *a* must go either directly or by reflection to the sky, none to the earth. Hence when the shutter is closed the disk *a* observes the sky directly, or by reflection, though not the zenith sky. When the shutter is open the disk observes the sun plus the sky, at this time the zenith sky. Hence the difference between the radiation exchange when the shutter is open, or closed, is not entirely due to the sun, but in part to the difference between zenith and horizon sky, and to the imperfect reflection of silver. These differences are, however, not large, and they may be approximately determined. At high levels the skylight will diminish, and the difference of radiation exchange to surroundings (other than the sun) between shutter open and shutter closed may become very small indeed, compared to solar radiation. The shutter is made, when closed, to hide the sky to 30° zenith distance from all parts of the disk *a*, when the apparatus hangs as if suspended from the balloons. The apparatus is hung by a steel wire of nearly 25 meters length below the balloons.

In order to prevent the mercury in the thermometer from freezing, the cup *b* is wound outside and underneath with resistance wire, and batteries are taken along to heat the wire. Their action is automatically controlled by a curved strip of brass and invar *c* lying in a groove in the cup *b* and arranged to open against platinum points and complete circuit when the temperature of the curved strip goes below 0° C. [This arrangement was not used in the most successful flight, and is not shown in fig. 5.] The whole apparatus is covered with a blanket of black silk and down, excepting the top of the disk *a*, the shutter *h*, and the thermometer stem *d*.

Each instrument is to be repeatedly calibrated against silver disk pyrheliometers before sending it up, and the flights are to be made on cloudless days, and pyrheliometer readings taken on the ground during flight. A correction to the aperture for zenith distance of the sun will be made.

As stated above, similar experiments have already been made with considerable success in 1913. Records to 13,000 meters were obtained, but for lack of the heating apparatus above mentioned the mercury froze, and prevented higher records. Since then the apparatus has been wholly rebuilt, with Richard clocks, and the best possible driving mechanism, so that backlash of the drum is nearly eliminated.

Neither you nor I have read, or ever can read, the pyrheliometer outside the atmosphere. It is now proposed to cause automatic pyrheliometers to observe as high up as possible. In the interest of learning the truth I beg that you will be so good as to suggest to me wherein the proposed experiments are likely to fail, so that all possible precautions may be taken against failure. Undoubtedly it will be impossible to get results to 1 per cent, but—

6. Do you see any reason why the experiments should not be decisive as between a solar constant of 1.9—2.0 calories and one of 3.0—4.0 calories?

I await with much interest your replies to my six (6) questions, and any suggestions you may have the goodness to offer.

In response to this communication, Mr. Very was kind enough to send two letters which contain very valuable suggestions. We quote a portion of the letters as received.

(a) Without actually experimenting myself with such actinometric apparatus as you use, I should not care to express an opinion as to its efficiency.

(b) I regard the upper isothermal layer of the atmosphere as due mainly to local heating through absorption of solar radiation. Until we get above that layer, I should expect to find increment of solar radiation with each increase of altitude. It seems to me improbable that this limit will be reached at 40 kilometers.

(c) Any plan for a high level measurement of solar radiation which has even a small prospect of success may be worth trying. It is to be regretted that yours involves the local application of electric heating, which seems to me very risky and liable to produce all sorts of complications and unforeseen results. . . . I would suggest that ascension should be made at night with a little electric lamp to give the record, to see what sort of a record you would get when the sun is away. The combination of night and day records might enable you to eliminate some errors inevitable in the method. . . . If your disk and its attachments are too massive four minutes exposure may not be long enough. You cannot use a very long exposure because the balloon ascension ends too soon. It behooves you therefore to have your thermometer and disk made on the smallest possible scale. Another thing which may be unavoidable in your construction is the very circumscribed protecting case. The same instrument may read differently in a wide, roomy case. . . . The knowledge of how such an apparatus as you are proposing will behave in the absence of the sun seems to me almost indispensable. Thus I should be apprehensive that the interpositions of the metal cone above the heat-measuring disk will act as a wind shield to some extent. There will, therefore, be less cooling from contact with the air during shade that there would be if the wind effect were constant, and the fall of temperature in shade will be too small in the day observation. At night there might even be a rise of temperature when the cone is interposed, and it is desirable to learn whether this is so, and the amount of the change. . . . During the most rapid part of the ascent, the instrument is exposed to a strong resultant air current, which may exceed 7 meters per second. This powerful wind blowing directly upon the face of the instrument must tend to keep it at air temperature, and will diminish the effect of the sun's rays. During calibration, steady, artificial, vertical air currents, of 1 to 10 meters per second, should be made to impinge upon the face of the instrument, and the results tabulated in comparison with the record of a standard instrument, not thus affected. It is partly on account of this strong downward air current that I do not approve of your shallow cup, because this construction allows nearly free access of air currents to the heated surface, which is liable to work great harm to the observations unless corrections are determined from elaborate researches. . . . I like the principle of the Violle actinometer, namely, that of a wide, encompassing jacket at constant temperature; and although some sort of a compromise must be made in your case, it might be better to use a broader disk (even though this diminishes the sensitiveness of the arrangement) and to place this disk at the center of a double-walled alcohol jacket several inches in diameter. This will surely diminish the wind effect, although I should still want to calibrate the thing with the same strong downward currents as noted above. . . . By rights the temperature of the alcohol jacket should be recorded, as in Violle's instrument. This would require another thermometer, and a duplicate registering apparatus. With an alcohol jacket the mercury thermometer would work down to nearly —40° centigrade, and, with the greater protection of a circumscribed aperture and partial shielding from the wind, I should suppose that the apparatus might continue to register when the outside air is quite a little colder than this. But here I am only guessing, and there is the same objection to doing that in the present case as there is to answering your "six questions." I prefer to leave the guessing to you, and only say: Try it! And I wish you success.

In view of Mr. Very's excellent suggestions, four of the instruments were arranged to be used by day, and one, with a row of electric lights above the thermometer for recording purposes, was arranged to be sent up at night. In two of the day instruments the proposed electric heating was dispensed with. In place of it, there was substituted a chamber of water (*l,* fig. 5), completely enclosing the sides and bottom of the aluminum cup, within which is placed the aluminum disk. A large number of copper strips for conducting heat were disposed in all directions through the water chamber, and soldered to the inside wall of it, so as to bring the water in intimate thermal conductivity with the immediate surroundings of the aluminum disk. Thus it was hoped to make use of the latent heat of freezing of the water, so that, in fact, the water jacket would act as a constant temperature case, to prevent the cooling of the thermometer below the freezing point of water. This worked excellently.

A change was made from the practice of 1913 in attaching the barometric element as a part of the pyrheliometer, instead of sending up a separate meteorograph. Barometric elements, loaned by the Weather Bureau, were mounted as shown at *n,* figure 5. The light aluminum arm, *o,* passing through a slot in the side of the cover cylinder, rests upon the photographic paper on the drum, *e,* between the thermometer, *d,* and the drum. A little longitudinal slot is cut in the aluminum arm, *o,* at the point where it passes under the thermometer, so that, as the drum revolves, the sun prints through the thermometer stem and the slot, and makes a trace of the position of the arm, *o,* appearing as a dark narrow streak between two light streaks.

No temperature record was obtained in the pyrheliometer flights of 1914. Certain corrections to the barometric readings depending on the temperature were worked up by a consideration of the temperatures found in other flights, as will appear in its place. It would have been better if the mounting of the barometric element had been wholly of invar, so as to reduce these corrections, but no essential harm seems to have resulted.

The size of the apparatus was made as small as seemed practicable, and its entire weight, including about one-half pound of water but exclusive of silk, feathers, and cotton used for wrapping, was only three pounds for the water jacketed instruments. The electrically heated instruments, with their battery[1] and devices for operating it, weighed about four pounds.

METHOD OF READING PYRHELIOMETER RECORDS

The records indicate the rate of rise of temperature of the aluminum disk during exposure of it to the sun, and the rate of fall of temperature of it during shading. One desires to know the rate of rise during exposure as it would be if there were no cooling due to the surroundings. In reading a record, it was fastened upon a large sheet of cross-section paper, with the degree marks of the balloon pyrheliometer record lying parallel to the section lines, in abscissae. A fine wire was then stretched parallel to a branch of the zigzag trace, and the tangent of its inclination to the degree marks was read upon the cross-section paper. Each such tangent was determined by several readings. The tangent representing each solar heating was then corrected by adding to it the mean value derived from the coolings preceding and following it. Thus we obtained, in arbitrary units, values proportional to the solar heatings. The same method of reading was applied to the records obtained while calibrating the balloon pyrheliometer, at Omaha, and at Washington, before and

---

[1] A special form of Roberts cell was developed, comprising tin, nitric acid, and carbon. Each cell was of 20 grams weight, 1.3 volts potential, and furnished an average of 0.4 ampere for 2 hours.

after the flight, against standardized pyrheliometers, and so the results were reduced to calories per sq. cm. per minute.

SOURCES OF ERROR

I. EFFECT OF AIR CURRENTS

In relation to the important point raised by Mr. Very regarding the effect of a downward current of air, a balloon pyrheliometer was calibrated in a current of air. The method of doing this is shown in figure 6, in which *a b* represents a 20-inch pipe connected to the blower *c*, and causing the current of air of known velocity to pass over the balloon pryheliometer *d*. In this situation the balloon pyrheliometer was compared, with and without flow of air, with the standardized silver-disk pyrheliometer. The rate of flow of the air was taken at 5 meters per second, which would be the maximum rate of ascent of the balloon during its flight.

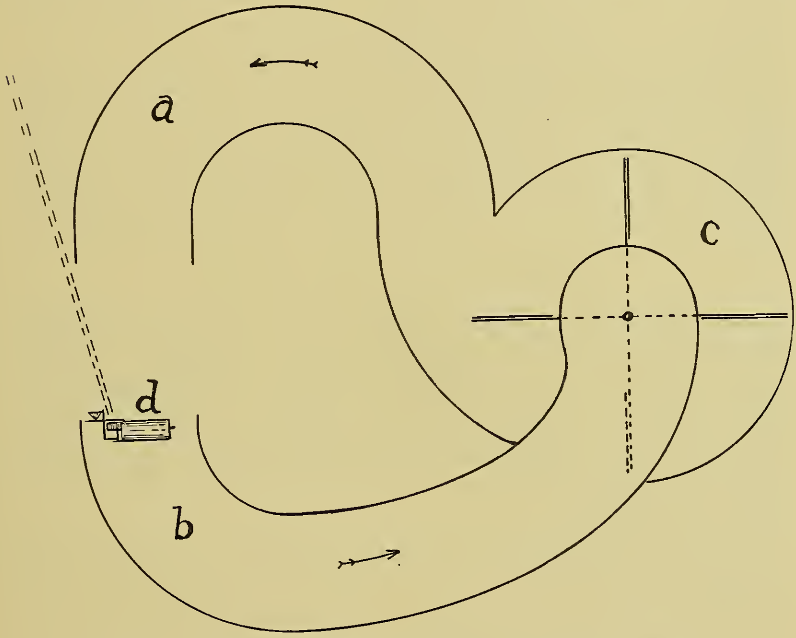


FIG. 6.—Testing the Balloon Pyrheliometer in Air Currents.

The results of these experiments were surprising to us, for we had assumed, with Mr. Very, that the effect of the downward current of air would be to increase the rate of cooling of the aluminum disk when the shutter was *open*. The contrary appears to be the case, for the corrected readings of the balloon pyrheliometer were, at the first, about 16 per cent higher when the current of air was in operation than when read in still air.

We reduced this source of error very greatly, by attaching to the instrument a flat plate of blackened tin (*r*, fig. 5), level with the copper ring diaphragms which admit the light to the aluminum disk, and extending out from the copper disk to about 25 centimeters in diameter. This tin plate deflected the current of air in such a manner that the magnitude of the error we had found became reduced to 4 per cent. It seemed to us that the error must be proportional to the number of molecules carried down by the current of air, and that it would therefore decrease directly in proportion to the pressure of air in which the instrument found itself. Accordingly we believe that at the altitude reached by the instrument, namely, 24 kilometers, where the pressure of the air is only one twenty-fifth of that which prevails at sea level, the effect of this source of error will be to increase the reading of the pyrheliometer by only about 0.2 per cent.

2. VARIATIONS IN SKY EXPOSURE

As indicated in Mr. Abbot's letter, there was expected a difference in the radiation exchanged by the instrument with the sky, depending upon whether the shutter is opened or closed. This difference grows less and less as the instrument goes to higher and higher altitudes, but there could readily be a source of error here if the instrument were compared on the ground with another instrument exposing the disk very differently.

To avoid this source of error, one of our older pyrheliometers, No. V, was reconstructed, so that it might be exposed to the sun and sky in exactly the same manner as the balloon pyrheliometer. In fact, one of the balloon pyrheliometers was taken to pieces, and the copper diaphragms and the shutter were transferred to pyrheliometer No. V, so that, in respect to its exposure, pyrheliometer No. V became identically similar to the balloon pyrheliometer No. 3. The two instruments were then compared, and the result of the 16 determinations gave us the ratio of their readings: $\frac{\text{No. 3}}{\text{No. V}} = 1.882 \pm 0.024$. We then returned pyrheliometer No. V to its original condition, except that we retained the same copper diaphragms, so as to prevent any error from the measurement of the size of the aperture; and we compared it with silver disk pyrheliometer No. 9. By 14 comparisons we determined the constant of pyrheliometer No. V in these circumstances to be 0.849 ± 0.003, to reduce its readings to calories per cm.^{2} per minute. From this we find the constant of balloon pyrheliometer No. 3 to be 0.451 ± 0.006.

In this way, it appears to us, the source of error above mentioned was avoided. A few comparisons were also made at Omaha directly between balloon pyrheliometer No. 3 and silver-disk pyrheliometer No. 9. These show the magnitude of this error, for assuming that no such error as above considered exists, the results of these comparisons yield for the pyrheliometer No. 3 the constant 0.414, which differs by 8 per cent from the value obtained by the preferred process.

3. ROTATION OF THE INSTRUMENT

Another source of error which was not inconsiderable depended upon the rotation of the balloon during its flight, for the instrument not only rotated, but swung around a small cone, so that the average angle made by the sun rays with the surface of the aluminum disk was not given immediately by a knowledge of the latitude of Omaha and the declination and hour angle of the sun at the time of exposure. Fortunately the record of the flight gave means of determining this small correction. The record of the degrees marked upon the thermometer stem, instead of being a series of parallel fine lines as they are shown in figure 9, became broadened out as the instrument rotated. By measuring the distance apart of the edges of the broadened lines, as compared with results found in check experiments made by moving the instrument through known angles, the half angle of the cone during the highest part of the flight was determined and found to be about 9 degrees. It was then computed that a correction of about 1.2 per cent should be added to the readings over and above that of about 8 per cent which was due to the zenith distance of the sun.

4. RATE OF THE CLOCKWORK

At Omaha, on July 2, 1914, during calibrations, the mean period occupied by a complete rotation of the shutter was found 8^m 17^s; at Washington, on December 26, 1914, during calibration, 8^m 18^s. Other records give similar indications of substantial constancy of rate of the clockwork. However, on February 4, 1915, at +19° C., the mean rate of the drum was .02154 mm. per sec., while at −46° C., the mean rate found was .0217 mm. per sec. This indicates a change of 1 per cent for the range of temperature +34° to −37°, which occurred on July 11, 1914. This error would tend to diminish the results by 1 per cent.

5. HORIZONTAL THERMOMETER STEM AND CALIBRATION

A difficulty was encountered in the experiments of 1913, for, owing to the horizontal position of the thermometer stem, the mercury thread sometimes separated, and failed to return after a rise of temperature. This was overcome by drilling a hole into the upper bulb, just before the flight, so that air pressure came upon the mercury column. In 1913, this worked perfectly satisfactorily, but in 1914 the mercury column became foul in every case but that of No. 5 pyrheliometer, owing probably to the creep of the lubricant used in drilling the glass. This prevented the use of pyrheliometers Nos. 1 and 2, and required several washings with benzol and alcohol before the bore of Nos. 3 and 4 was clean enough to be used. Even then the upper temperatures were unavailable, so that no use could be made of records at low altitudes in the flights of July 9 and July 11, 1914.

The reader will perhaps wonder why there was not left a small gas pressure above the mercury column in the original construction. This was not done, for we were required to calibrate the thermometer stems because their bores were not uniform. We could most readily do so by breaking the mercury thread and moving a short column from place to place in the bore, observing its length-changes. This we did for all the thermometers, and have corrected our results accordingly. In view of our experience we should now prefer to introduce gas pressure in the original construction, and calibrate the thermometers in baths of known temperatures.

6. OTHER CORRECTIONS

The aluminum disk, during the highest flight, differed slightly in its mean temperature from that which it had during calibration. Owing to change in the specific heat of aluminum with change of temperature, a correction of 0.5 per cent should be deducted for this.

The suspending wires in their rotation shaded the disk. A correction of 0.2 per cent should be added for this.

Variations in the absorption of the disk by deterioration of the blackened surface between July and December are thought to require a correction of somewhat less than 1 per cent to be deducted.

Variations in reflecting power of the copper diaphragms used in the calibrations are thought to require an additive correction of 0.25 per cent.

While the effect of the downward current of air seems to be nearly negligible, as indicated above, it may be possible that the considerable difference of temperature between the disk and the air during recording at highest altitudes tended to alter or change the sign of this error.

In consideration of all circumstances, it seems to us that the various small positive corrections, including the error below mentioned in determining the angle of the cone of rotation, but not that for clock rate or for inclination, may be regarded as balancing the various small negative corrections. We consider, therefore, in what follows, only the direct results of the exposures, the calibration at Washington, the correction for effective solar zenith distance, the correction to mean solar distance, the correction for clock rate, and the probable correction to reduce to outside the atmosphere.

CIRCUMSTANCES OF OBSERVATION

The following circumstances attended the balloon pyrheliometer flights at Omaha: Observers: For the Smithsonian Institution, L. B. Aldrich; for the U. S. Weather Bureau, Dr. Wm. R. Blair, B. J. Sherry, and Mr. Morris.

India rubber balloons, imported by the Smithsonian Institution from Russia in July, 1913, were used. They were 1.25 meters in diameter, inflated with hydrogen gas, and were sent up in groups of three attached as shown in figure 7.

It was expected that after two of the balloons had burst by expansion, at high altitudes, the third would bring down the apparatus in safety. A reward was offered for the safe return of the apparatus by the finder.

In addition to the barometric element, as a means of measuring heights reached, the balloons were observed by two theodolites, separated by a known base line.

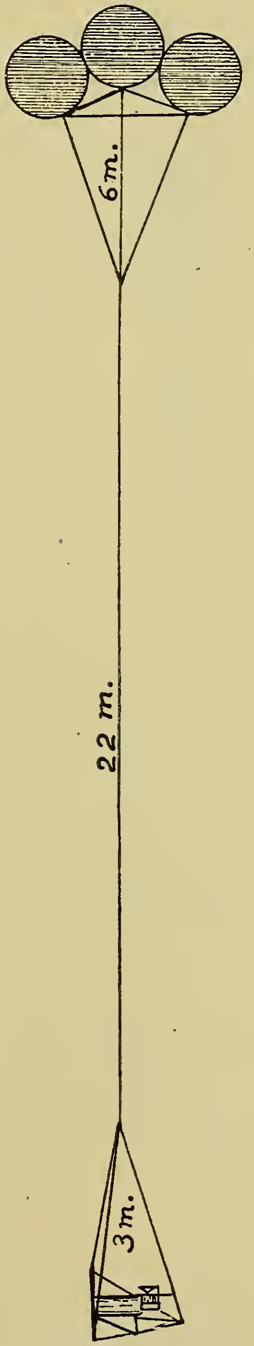


Fig. 7.—Method of Suspending Balloon Pyrheliometer.

JULY 1, 1914. NIGHT ASCENSION

Balloon launched with No. 5 pyrheliometer at 11^h 26^m p. m. in clear sky. Moon half full and setting. Wire, 22 meters long, plus 3 meters, plus 2 meters. Total, 27 meters. Electric flash light attached, but could be followed only a few minutes with theodolite at Fort Omaha, and was not seen from the second station. The apparatus was found July 3, 6.30 a. m., at Harvard, Iowa, two balloons still inflated. The instrument was somewhat damaged, but the record not harmed.

JULY 9, 1914

Balloon launched with No. 4 pyrheliometer at 10^h 8^m a. m. Balloons followed by theodolites at both stations for 1^h 5^m, and at one station for 2^h 16^m. One balloon burst after 42^m, another after 2^h 4^m. The apparatus was found at Omaha after 20 days, but the record was spoiled by light and water, and the instrument greatly damaged.

JULY 11, 1914

Balloon launched with No. 3 pyrheliometer at 10^h 30^m a. m. Sky fairly clear, save for cirri near the horizon. All clear near the sun. Balloons followed by theodolites at both stations for 35 minutes, and at one station for over two hours. Two balloons burst nearly simultaneously, after 1^h 47^m. Pyrheliometer A. P. O. 9 was read immediately after the launching as follows: At 10^h 35^m, 1.147 cal.; at 10^h 39^m, 1.161 cal. Apparatus found 3½ miles northwest of Carson, Iowa, on July 11, at 5 p. m., and received entirely uninjured at Mt. Wilson, California. It was later carried uninjured to Washington, and tested in various ways during the following winter.

Weights of apparatus and accessories:

	Grams
Three balloons, at 2,880 grams each	8,640
Pyrheliometer	1,250
Water in jacket	170
Silk, feathers, and cotton wrapping	370
Wire	50
Total	10,480

DISCUSSION OF RECORDS

1. THE NIGHT RECORD

In figure 8 is given a reproduction of the record obtained in the night flight made at Omaha on July 1, 1914. A_1 A_2 A_3 A_4 is the barometric record, B_1 B_2 B_3 the pyrheliometer record. As shown, the lighting current was cut off intermittently to prevent premature exhaustion of the battery. Unfortunately the mechanism failed to make electrical contacts in the region A_2 A_3, so that the pyrheliometer record is missing there. It does not show in the last part of the record corresponding to A_3 A_4, from which we infer that the electrical heating proved insufficient to hold the temperature of the disk above about —15°, corresponding to the position C, and that the record

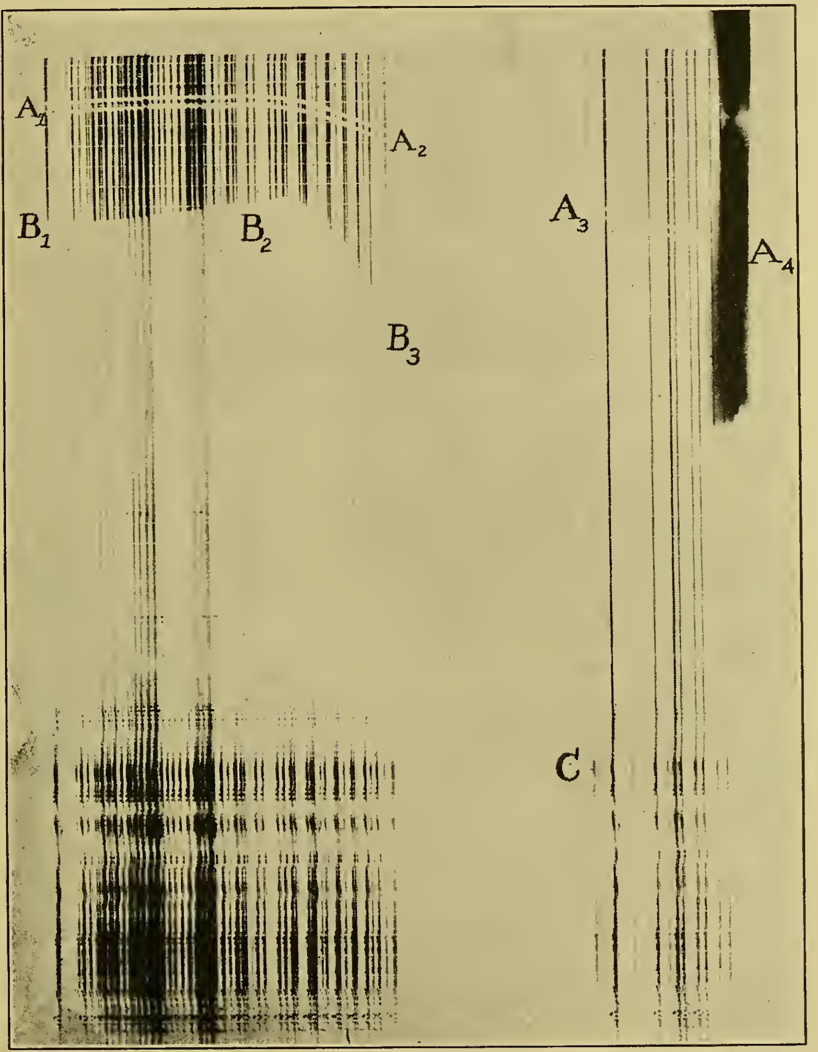


FIG. 8.—Night Record with Balloon Pyrheliometer.

is lost in stray light somewhere below *C*. But from B_2 to B_3 is a period of 20 minutes, during which there were 2½ complete rotations (5 swings) of the shutter, and the apparatus rose about 3,000 meters.

Apart from the slight fall of temperature shown at B_2, when the instrument was removed from the balloon shed, there is no appreciable sudden change of temperature, but only the gradual march attending increasing altitude. No periodic change attributable to the opening and closing of the shutter is discernible. From this we conclude that no considerable error is caused by the current of air due to the uprush of the balloons, which it was thought might cool the disk unequally, depending on whether the shutter is open or not.

2. THE DAY RECORD

The record obtained in the day flight of July 11, 1914, was on solio paper. It was read up while still unfixed, and was at that time very clear and good. Unfortunately it was submitted to the process of toning, without being first photographed, and became so faint that it is quite impossible to reproduce it, although it is still readable.

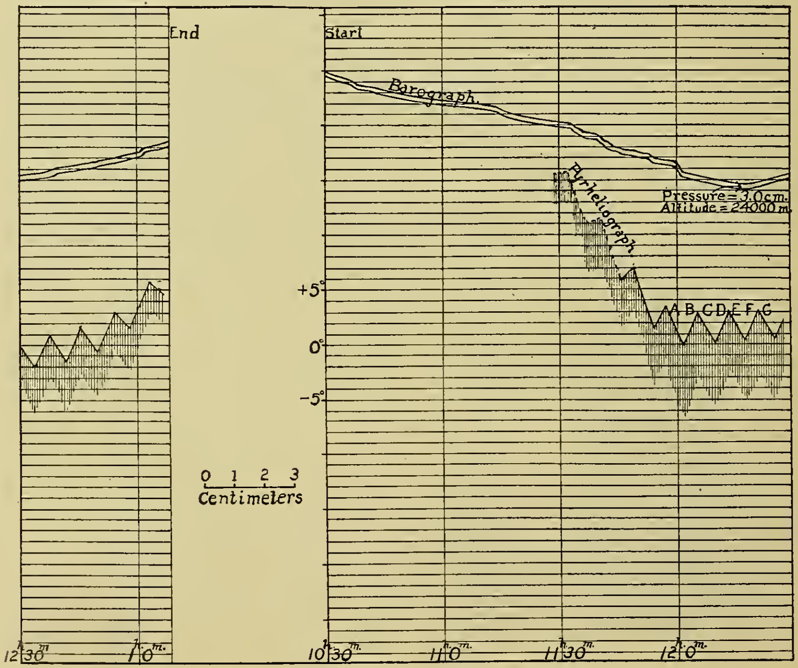


FIG. 9.—Balloon Pyrheliometer Record, July 11, 1914. (From a Tracing.)

Accordingly we give merely the readings made upon the original, and their reduction. Figure 9 is from a tracing made to represent the march of the record.

The pyrheliometer record consists of a series of zigzag reaches of shading corresponding to the up and down marches of the mercury column. We shall principally confine attention to those marked *A, B, C, D, E, F, G,* which represent the solar radiation measured just before the instrument reached maximum elevation. We do this because: (1) As stated above, the earlier part of the records are of little value owing to the bore of the thermometer being foul for temperatures above +10°. (2) A defect in the record occurs just after the balloons began to descend, first owing to a jerkiness, and then owing to crossing the seam in the paper, which renders the next two following readings doubtful. (3) There is doubt as to the elevation at the time of the last descending records, because the barometer arm did not work quite free. (4) The record is finally lost in clouds. All readable records are, however, given for what they may be worth.

CORRECTION TO REDUCE TO VERTICAL SUN

The extreme width of the degree marks on the record during heating *B, D, F,* was measured and found 1.40 millimeters. Inclining the pyrheliometer, first 15.5° N., then 15.5° S., when exposed to the sun, was found to shift the degree marks through a total range of 0.89 mm. Subtracting width of trace, 0.31 mm., and dividing by 2, we find the record sheet is within the pyrheliometer at a distance X, such that X tangent $15.5° = 0.29$ mm. Hence $X = 1.04$ mm. From this it follows that the tangent of the half angle of the cone swept through by the sun rays was $\frac{1.40 - 0.31}{2 \times 1.04}$. Hence the half angle of the cone is 27° 40′. At Omaha, on July 11, at noon the sun's zenith distance was 19° 5′. Hence the pyrheliometer was swinging in a cone whose half angle was $27° \; 40' - 19° \; 5' = 8° \; 35'$.

From these data it follows that the mean value of the cosine of the inclination of the sun's rays upon the pyrheliometer disk at noon was 0.934. But if the instrument had been stationary this value would have been 0.945. Hence the conical rotation produced a change of 0.011. This value has been applied as a correction to the values of cosine Z, corresponding to the several sun exposures. It is probable that the correction is a little too small, because the record of the degree marks is naturally less wide than it would have been if time had been allowed for full photographic effect at the extremes of the swing.

READINGS ON BEST THREE RECORDS OF JULY 11, 1914

	Cooling A	Heating B	Cooling C	Heating D	Cooling E	Heating F	Cooling G
	2.53	1.34	1.78	1.90	1.96	2.10	1.65
	2.22	1.45	1.77	1.78	1.86	2.00	1.53
	2.39	1.33	1.84	1.77	1.97	1.90	1.40
	2.64	1.50	1.88	1.75	1.92	1.98	1.50
	2.40	1.34	1.90	1.88	1.82	1.82	1.61
	2.55	1.52	1.91	...	1.84	1.78	...
Means	2.45	1.41	1.85	1.82	1.89	1.91	1.54
		2.15		1.87		1.715	
Corrected heating........		3.56		3.69		3.625	

SUMMARY OF READINGS AND REDUCTIONS

Watch time	Corrected hour angle East	Cosine Z	Cosine Z corrected for rotation	Pyrheliometer reading	Reading $\times\frac{0.451}{\cos z}$
$11^h 55^m$	$0^h 34^m$	0.936	0.925	3.56	1.736
12 04	0 25	.940	.929	3.69	1.791
12 12	0 17	.942	.931	3.625	1.756
12 20	0 09	.943	.932	3.225	1.561
	West				
12 36	0 07	.945	.934	3.11	1.501
12 44	0 15	.944	.933	3.58	1.730
12 52	0 23	.941	.930	3.09	1.499

The solar radiation indicated by the mean value of the first three records, which are by far the best, is 1.761 calories per sq. cm. per minute. Reduced to mean solar distance and adding 1 per cent for clock rate, it becomes

1.84 calories per sq. cm. per minute.

As will be shown, the mean altitude at this time was about 22,000 meters, and the corresponding pressure about 3 centimeters. In our opinion an increase of about 2 per cent would be a proper allowance for the extinction in the atmosphere above this altitude, considering atmospheric scattering as 1 per cent, and atmospheric absorption 1 per cent.

BAROMETRY AND ALTITUDE

The following results are given by the observations of the U. S. Weather Bureau, as indicated in communications quoted:

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
OFFICE OF THE CHIEF,
WASHINGTON, D. C., MARCH 15, 1915.

Dr. C. D. Walcott,
Secretary, Smithsonian Institution,
Washington, D. C.

DEAR SIR:

Replying to your letter of March 13, 1915, no readings of pressure and temperature were taken preceding the morning ascension of July 11, 1914. However, a reading was taken after the ascension, at 1 p. m., and another just preceding the second ascension, at 4 p. m. These readings were:

	Pressure	Temperature
At 1 p. m.	732.5 mm.	32.3° C.
At 4 p. m.	732.0 mm.	33.1° C.

The values at the Weather Bureau Station in Omaha at these hours were:

	Pressure	Temperature
At 1 p. m.	730.8 mm.	35.6° C.
At 4 p. m.	730.2 mm.	35.6° C.

Applying these differences, +1.8 mm. for pressure and —2.8° C. for temperature, to the value at 10.30 a. m. at Omaha, viz., 731.5 mm. and 32.2° C., we get 733.3 mm. and 29.4° as the probable values at Fort Omaha just preceding the first ascension, or 10.30 a. m.

Very respectfully,
C. F. MARVIN,
Chief of Bureau.

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
OFFICE OF THE CHIEF,
WASHINGTON, D. C., MARCH 9, 1915.

Dr. C. D. Walcott,
Secretary, Smithsonian Institution,
Washington, D. C.

DEAR SIR:

I inclose herewith the data for July 11, 1914, requested by you in your letter of January 29, 1915. They include, for the first ascension, when the balloon pyrheliometer was taken up, altitudes each minute as long as the balloons could be observed at both stations; for the second ascension, in the afternoon, temperatures at those levels in which the temperature-altitude relation changed, and interpolated values at 500-meter levels up to 5,000 meters, and at 1,000-meter levels above 5,000 meters. Pressures also are given, wherever it was possible to compute them. A considerable portion of the record has been rubbed off, by reason of its having lain in a mud pond for some days. There were several pounds of mud in the instrument when it was received. All altitudes were computed from the two-station theodolite observations.

The ascensional rates for the two ascensions are almost identical up to 6,000 meters. *Assuming* that they continue in this relation, a curve extended for the first ascension, as shown in the accompanying chart [not here shown], indicates an altitude of 25,600 meters at the time one of the balloons burst.

Very respectfully,
C. F. Marvin,
Chief of Bureau.

TEMPERATURES AT DIFFERENT ALTITUDES IN BALLOON ASCENSION, JULY 11, 1914, P. M.

Time p. m.	Altitude *m.*	Pressure *mm.*	Temp. °*C.*	Remarks
4:02	312	732.0	33.1	Balloon launched.
......	500	.....	33.2	
4:04.4	631	706.4	33.3	
4:07.3	962	681.0	29.8	
......	1,000	.....	29.7	
4:11	1,503	640.1	26.0	
......	2,000	.....	21.7	
4:18.2	2,493	.....	17.5	
......	3,000	.....	14.0	
......	3,500	.....	10.8	
4:25.3	3,645	.....	9.9	
......	4,000	.....	9.6	
4:28.8	4,447	.....	9.1	
......	4,500	.....	8.6	
4:32.2	4,976	431.5	4.8	
......	5,000	.....	4.7	
......	6,000	.....	— 1.7	
......	7,000	.....	— 7.9	
4:44.1	7,592	309.9	—11.5	
......	8,000	.....	—13.4	
4:46.8	8,597	280.5	—16.0	
4:49	8,930	265.3	—17.9	
......	9,000	.....	—18.3	
......	10,000	.....	—24.8	
4:55.1	10,442	220.3	—27.6	
......	11,000	.....	—31.8	
5:01.8	11,572	185.5	—35.9	
......	12,000	.....	—38.7	
......	13,000	.....	—45.2	
5:08.7	13,348	145.5	—47.0	
......	14,000	.....	—48.8	
5:13.7	14,641	.....	—52.0	Lowest temperature.
......	15,000	.....	—51.5	
5:15.7	15,026	.....	—51.5	
5:19.2	15,457	.....	—48.3	
......	16,000	.....	—48.3	
5:22.4	16,855	.....	—48.3	
......	17,000	.....	—46.6	
5:24.3	17,106	.....	—45.2	Clock stopped.
5:28	18,164	.....	....	Balloon burst.

ALTITUDES OF BALLOON, DETERMINED FROM THEODOLITE READINGS AT TWO STATIONS, JULY 11, 1914, A. M.

Time a. m.	Altitude	Remarks
10:30.3	312	Balloon launched.
10:32	720	
10:33	1,016	
10:34	1,286	
10:35	1,392	
10:36	1,606	
10:37	1,760	
10:38	1,900	
10:39	2,022	
10:40	2,166	
10:41	2,280	
10:42	2,424	
10:43	2,585	
10:44	2,688	
10:45	2,898	
10:46	2,982	
10:47	3,178	
10:48	3,358	
10:49	3,568	
10:50	3,718	
10:51	3,876	
10:52	3,970	
10:53	4,159	
10:54	4,270	
10:55	4,528	
10:56	4,682	
10:57	4,950	
10:58	5,052	
10:59	5,122	
11:00	5,218	
11:01	5,538	
11:02	5,492	
11:03	5,825	
11:04	6,122	
11:05	6,006	Balloon disappeared from view of observers at Creighton College.
p. m. 12:17.7		Balloon burst.

CALIBRATION OF THE BAROMETRIC RECORD OF JULY 11, 1914

This record is marred by the sticking of the aluminum arm at middle deflections, both in rising and falling flight. Fortunately the arm appears to have been free at maximum elevation, as shown by the perfectly normal inflection of the record at precisely the time when the two balloons were observed to burst. Accordingly while no suspicion attaches to the record at maximum elevation, it is worthless at intermediate elevations.

The barometer element was calibrated by enclosure of the whole instrument in a brass box from which air could be exhausted, and of which the temperature was regulated by immersion in a stirred bath of gasoline cooled by expansion of liquid carbon dioxide. In one set of experiments the sensitiveness of the element to change of pressure was determined at several constant temperatures ranging from +34° C. to — 49° C., and the change of zero with change of temperature was determined as a correction. In another set of experiments, both temperature and pressure were simultaneously lowered to correspond with the temperatures and pressures indicated by the foregoing results of the Weather Bureau observers.

We assume that at the time of launching at Omaha, the instrument, being shone upon by the sun, was 5° in excess of the air temperature, and hence at +34° C. We assume that at the maximum elevation the instrument was at — 37° C.

From experiments of December 26, 1914, and February 1 and 4, 1915, we find that the zero of the barometric element changed linearly at the rate of 0.123 mm. per degree, in the sense to diminish the barometric deflection attending falling pressure. Hence for a fall of 71° the correction is 8.7 mm.

From the record of July 11, 1914, the barometric deflection is 37.8 mm. at highest altitude. Corrected deflection, 46.5 mm. From numerous experiments at various constant temperatures, 76.4 cm. mercury pressure corresponds to a deflection on our record of 50.3 mm. Hence for July 11, 1914, the change of pressure was $\frac{46.5}{50.3} \times 76.4 = 70.7$ cm. Hg. The barometer reading at Fort Omaha was 73.33 cm. Hence, by these experiments, the pressure at maximum elevation was 2.63 cm. Hg.

Again, on March 18, 1915, a change of pressure of 72.3 cm. Hg., and accompanying change of temperature from +34.8° to — 30°,[1] gave a barometric deflection of 40.0 mm. Hence, from +34° to — 37° would have given a deflection of 39.1 mm. Hence, the change of pressure on July 11 was $\frac{37.8}{39.1} \times 72.3 = 70.0$.

Hence, by these experiments the pressure at maximum elevation was 3.33 cm. Hg. As a mean result, we decide that at maximum

---

[1] Here the carbon dioxide used for cooling purposes was exhausted.

elevation the barometric pressure was 2.98 cm. Hg., or in round numbers, 3.0 cm. Hg. From our examination of the records of various balloon flights at Omaha and Avalon, we suppose this would be regarded as corresponding to an elevation of 24,000 meters, which is in good agreement with the results obtained by theodolite work.

COMPARATIVE RESULTS OF PYRHELIOMETRY AT REDUCED ATMOSPHERIC PRESSURES

In a recent publication, Prof. H. H. Kimball gives the highest value of solar radiation ever observed at Washington, for zenith distance 60°, as 1.51 calories per cm.^{2} per min., observed on December 26, 1914. Reduced to vertical sun and mean solar distance, this result would have been about 1.58 calories.

The highest values observed on Mt. Wilson are those of November 2, 1909, and yield to a similar reduction 1.64 calories, at mean solar distance and vertical sun.

For Mt. Whitney, for the maximum obtained on September 3, 1909, the reduced value is 1.72 calories at mean solar distance and vertical sun.

In balloon flights of August 31, September 28, and October 19, 1913, Dr. A. Peppler of Giessen observed with an Ångström pyrheliometer at great altitudes. On September 28 the results were, in his opinion, vitiated by a defect of the apparatus. On August 31, the highest result, as reduced by Peppler to the Smithsonian scale of pyrheliometry, was 1.77 calories, obtained at zenith distance 45°, altitude 5,900 meters, air pressure 36.5 cm. This result, however, is not a complete Ångström measurement depending on "left, right, left" readings, and therefore may be vitiated by galvanometer drift. Moreover, it stands very high as compared with others of that date, and, indeed, much higher than others of that date obtained at greater altitudes. On October 19, the highest complete result was 1.67 calories, obtained at zenith distance 61°, altitude 7,500 meters, air pressure 29.8 cm. This result is in good agreement with the others of that date. Peppler regards the results of October 19 as his best. When reduced to zenith sun and mean solar distance, the result of October 19 comes out about 1.755 calories per cm.^{2} per minute.

These direct observations from manned balloons are very meritorious, and of course entitled to far greater weight than those obtained at similar altitudes in our free balloon work at Avalon, in 1913. Hence, although our results there were in complete accord with Peppler's, we have not thought it worth while to give them.

Peppler intended to repeat the work in 1914 at greater altitudes, but we fear this may have been one of the valuable things cut off by war.

In figure 10 we give a plot of the pyrheliometer results at various altitudes, as just collected. It seems to us that, with the complete accord now reached between solar constant values obtained by the spectro-bolometric method of Langley, applied nearly 1,000 times in 12 years, at four stations ranging from sea level to 4,420 meters, and from the Pacific Ocean to the Sahara Desert; with air-masses ranging from 1.1 to 20; with atmospheric humidity ranging from 0.6 to 22.6 millimeters of precipitable water; with temperatures ranging from 0° to 30° C.; with sky transparency ranging from the glorious dark blue above Mt. Whitney to the murky whiteness of the volcanic ash filling the sky above Bassour in 1912, it was superfluous to require additional evidence.

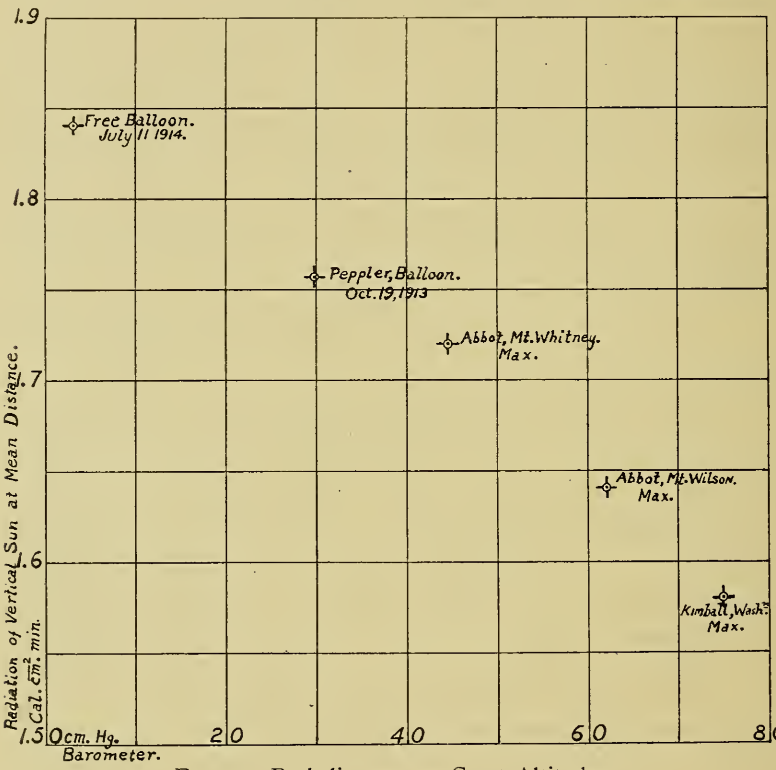


FIG. 10.—Pyrheliometry at Great Altitudes.

But new proofs are now shown in figure 10. This gives the results of an independent method of solar constant investigation. In this method the observer, starting from sea level, measures the solar radiation at highest sun under the most favorable circumstances, and advances from one level to another, until he stands on the highest practicable mountain peak. Thence he ascends in a balloon to the highest level at which a man may live. Finally he commits his instrument to a free balloon, and launches it to record automatically the solar radiation as high as balloons may rise, and where the atmospheric pressure is reduced to the twenty-fifth part of its sea level value. All these observations have been made. They verify the former conclusion; for they indicate a value outside the atmosphere well within the previously ascertained limits of solar variation.

Our conclusion still is that the solar constant of radiation is 1.93 calories per sq. cm. per minute.