SMITHSONIAN MISCELLANEOUS COLLECTIONS
VOLUME 66, NUMBER 5

Hodgkins Fund

ON THE DISTRIBUTION OF RADIATION OVER THE SUN'S DISK AND NEW EVIDENCES OF THE SOLAR VARIABILITY

(WITH ONE PLATE)

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

(PUBLICATION 2412)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
MAY, 1916

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

Fig. 1


Brightness Distribution Along Sun's Diameter
For Different Colors
Infra-red
λ= 1.55μ
Infra-red
λ = .986μ
Red
λ = .670μ
Blue-green
λ = .503μ
Ultra-violet

Fig. 2

Hodgkins Fund

ON THE DISTRIBUTION OF RADIATION OVER THE SUN'S DISK AND NEW EVIDENCES OF THE SOLAR VARIABILITY

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

(With One Plate)

Referring to the Annals of the Astrophysical Observatory,[1] we gave there the results of earlier investigations of the distribution of radiation over the sun's disk, and some indications of a variability of this distribution which might be associated with variation of the sun's total radiation. This work was done in Washington prior to the year 1908. When the new observing station of the Smithsonian Institution was constructed upon Mt. Wilson in 1909, provision was made for the erection of a tower to be used for a tower telescope for the continuation of such observations. It proved impossible to equip a tower telescope until the autumn of the year 1913, when apparatus was hastily arranged and operations were begun on September 9, 1913. The tower was improved both in its rigidity and in the mountings of the apparatus for the research in 1914 and 1915, and is now regularly used on all days when solar-constant observations are made.

In figure 1 (pl. 1) is given a general view of the tower telescope upon the observing station at Mt. Wilson. Owing to the bold situation of the station, it is impossible to get a photograph of the apparatus except by climbing a tall pine tree at some distance away, and the trees intervening are some obstacle to a satisfactory presentation of the installation.

Figure 3 is a diagram of the construction of the tower telescope and its relation to the spectro-bolometer. *A* and *B* are the mirrors of the coelostat, from which a beam of sunlight passes downward to the 30-centimeter (12-inch) concave mirror *C* of 23 meters (75 feet) focal length. Thence the beam passes up to the plane mirror *D*, which reflects the image to focus at *E* near the floor of the observing chamber. At *F* is a small plane mirror at the angle of 45°, which reflects the beam through the slit *G* of the spectro-bolometer *G H I*. At *J K*, outside the observing chamber, is the coelostat used for the ordinary solar-constant observations.

[1] Vol. 2, Pt. 3, and Vol. 3, Chap. 7.

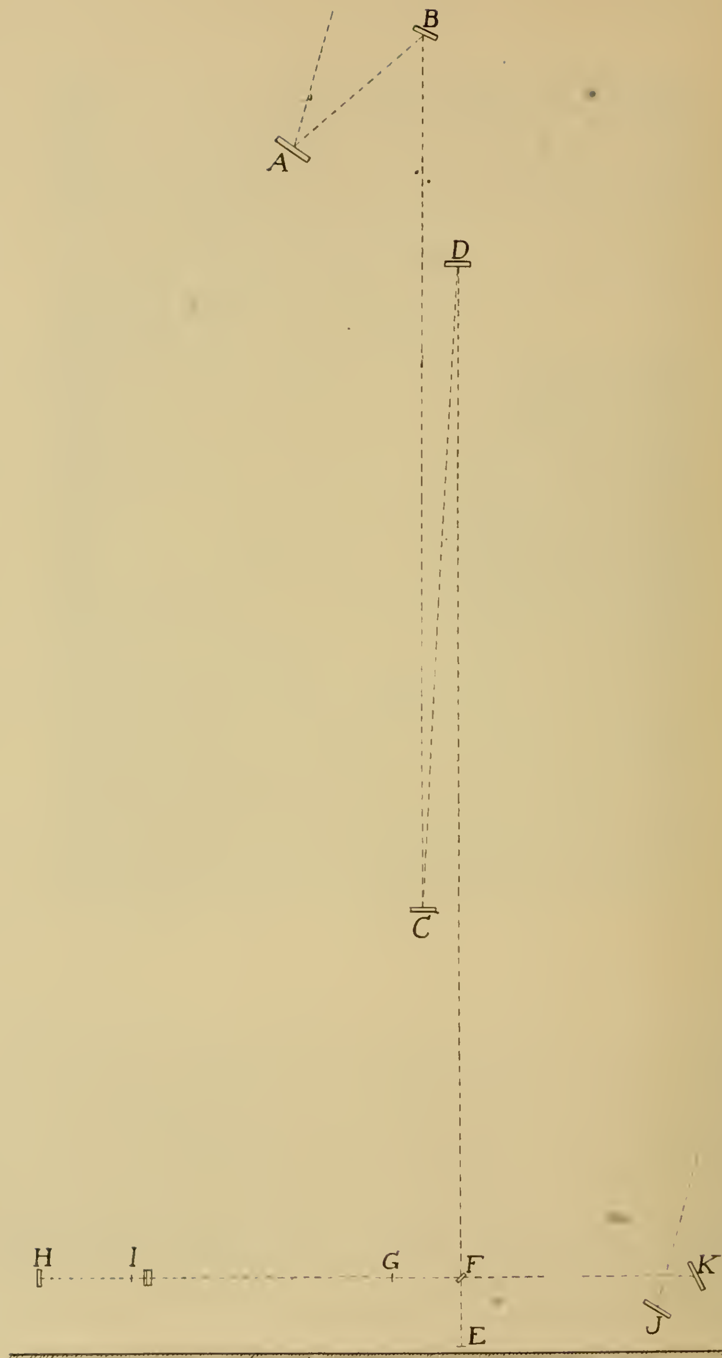


FIG. 3.—Diagram of tower telescope and spectro-bolometer

The reader will understand that the beam from the coelostat *A B*, or that from the coelostat *J K*, may be brought to the spectro-bolometer, according as the 45° mirror *F* is in place or withdrawn. The former is the condition for observing the distribution of light over the sun's disk, the latter the condition for observing the solar constant of radiation.

As explained in the publications already cited, we allow the sun's image to drift across the slit of the spectro-bolometer by the diurnal motion of the earth, thus avoiding all sources of error associated with inequalities of the transmission of the optical apparatus of the tower telescope. For it is obvious that during a single such period of drift the telescope is always directed to the same point of the sky, and treats whatever object passes that point with impartiality, whether it be the sun's limb, center, or the light of the sky itself. We regard this feature as very favorable for exact results, and much preferable to the arrangement used by some investigators, in which the observing apparatus is shifted about from part to part of the solar image, and the results may be affected by inequalities of transmission of the optical apparatus to these different parts of the image.

On the other hand, we are thereby limited to an east and west course across the sun's disk, and this hardly ever coincides with the solar equator. However, it seems clear that a comparison of the mean of a great number of observations taken during a large part of one year with that of a great number of similar observations covering the same part of another year, would certainly be fairly comparable irrespective of the various presentations of the sun during these intervals. It is by no means so clear, without further investigations which we hope to undertake next year, that short-period changes of the distribution of radiation along a solar diameter may not be associated with changes of distribution depending on latitude in the sun. Such investigations as have been made on this point heretofore relate, we think, only to total brightness or total radiation. Pickering's[1] experiments indicated that the contrast of visual brightness along a polar diameter exceeds that along the equatorial, so that for total visual brightness at 95 per cent out on the radius the equator is brighter in the ratio of about 56 to 53. Pickering expressed doubt as to whether this difference is solar or from experimental error. The more numerous investigations of Langley[2] seem to have shown clearly that differences of contrast in total radiation between the equatorial and polar diameters of the sun are negligibly small, probably

[1] Proc. Amer. Acad. Arts Sci., Vol. 10, p. 428, 1874.

[2] Comptes Rendus Sept. 6, 1875.

far less than 1 per cent. Hence it seems probable that the influence of changes in the inclination of the solar equator as affecting our investigations is inappreciable.

Figure 2 (pl. 1) shows a number of drift curves at selected regions of the spectrum chosen to indicate the differences of form which are found, depending on wave lengths. As discovered by earlier investigators, and hitherto abundantly confirmed by ourselves, the contrast of brightness between the center and the edge of the sun is greatest for short wave lengths, and diminishes as one comes to the red and infra-red.

We have two principal objects in this research: First, to repeat our earlier determination of the distribution of light along the diameter of the solar image; second, to detect fluctuations of distributions from year to year and from day to day, if any, and to compare them, if found, with fluctuations of the radiation of the sun as determined in our solar-constant investigations.

On each day of observation we are accustomed to take 14 drift curves, two each at seven different wave lengths, as follows: 0.3737μ, 0.4265μ, 0.5062μ, 0.5955μ, 0.6702μ, 0.8580μ, and 1.008μ. In the reduction of observations, we proceed as stated on pages 154 and 155 of Vol. 3 of our Annals, from which we quote as follows:

"We have determined the rate of descent in the plate carrier of the photographic plates on which the curves are recorded, and have determined from the Nautical Almanac the time required for the sun's disk to pass the meridian. From these data we have determined the distance along the plate corresponding to the width of the sun's diameter. This distance has been regarded as the true width of the U-shaped curve, and all the measurements of ordinates of this curve have been made at certain round-numbered fractions of the corresponding solar radius.

"To illustrate: On June 8, 1908, the sidereal time required for the sun's semidiameter to pass the meridian was 1^m 8.72^s. The corresponding mean solar time for the passage of the diameter is 2.284^m. On this date the photographic plate descended 3.978 centimeters per minute. Hence, the diameter of the sun expressed on the photographic plate is 9.086 centimeters. Measurements were made at the center and at 10 places on either side of it, making 21 places in all, at distances from the center of the U-shaped curve which correspond to certain fractions of the solar radius from the center of the sun's disk.

"In further reduction of the observations, the mean values of the measurements on each curve for the advancing and following limbs of the sun were taken. Then, in order to standardize the observations (for it is to be remembered that the bolographic curves depend for their ordinates on the sensitiveness of the galvonometer, the clearness of the sky, and the sun's zenith distance, all of which vary from day to day), the sums of the mean measurements at the center (given half weight) and at 2/10, 4/10, 55/100, and 65/100 radius, were taken. All the measurements were divided by this sum and thus expressed in terms of a unit five times the mean height of the central part of the **U**-shaped curve.

"For illustration: On June 8, 1908, the following measurements were made on a curve corresponding to wave length 0.501μ. Taking the sum, 40.96, of the first five places (giving the central place half-weight) and dividing this sum into the mean values at the several places on the curve, we have the following values:

TABLE (53) 1.—*Illustrative of reduction of drift curve observations*

Distances from center:	*cm.*										
Linear....................	0.00	0.91	1.82	2.50	2.95	3.41	3.75	3.98	4.18	4 32	4.41
Fractional...............	0.00	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95	0.97
Heights:											
Advancing limb.........	9 80	9.69	9.16	8.74	8.41	7.61	6.96	6.35	5.65	4.70	3.60
Following limb..........	....	9.69	9.26	8.81	8.36	7.68	7.03	6.37	5.58	4.78	4.16
Mean....................	2×4.90	9.69	9.21	8.775	8.385	7.645	6.995	6.36	5.615	4.74	3.88
Ratio, mean height to 40.96	.1196	.2366	.2249	.2142	.2047	.1866	.1708	.1553	.1371	.1157	.0947
Ratio to central height[1]..	1.0000	.9862	.9379	.8932	.8536	.7781	.7123	.6476	.5717	.4825	.3949

[1] The lowest line of the table is added in view of its interest, but is not used in the reductions. It is based on the standard central value .1199 found from 104 curves. It will be further explained.

"The following table contains the standard reduction values for many wave lengths. It corresponds to the next to the last line of table above, represents the mean of many days of observation, and is used in preparation of the tables which follow it.

AUXILIARY STANDARD REDUCTION VALUES

TABLE (54) 2.—*Mean distribution of radiation along radius of solar disk*

Wave length	Number of observations	Distance from center as fraction of radius									
		0.00[1]	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95
μ											
0.386	3	0.1233	0.2417	0.2283	0.2110	0.1953	0.1750	0.1560	0.1367	0.1190	0.1030
0.433	39	.1227	.2400	.2275	.2126	.1978	.1789	.1588	.1430	.1251	.1104
0.456	89	.1207	.2380	.2273	.2136	.2007	.1826	.1644	.1487	.1298	.1136
0.481	74	.1201	.2371	.2267	.2141	.2018	.1851	.1683	.1532	.1359	.1198
0.501	104	.1199	.2362	.2267	.2145	.2026	.1864	.1704	.1559	.1397	.1240
0.534	104	.1192	.2353	.2265	.2150	.2041	.1888	.1736	.1602	.1443	.1306
0.604	72	.1182	.2339	.2262	.2158	.2062	.1929	.1798	.1679	.1533	.1403
0.670	41	.1173	.2324	.2255	.2168	.2081	.1965	.1844	.1737	.1596	.1476
0.699	64	.1171	.2319	.2255	.2169	.2085	.1970	.1856	.1751	.1618	.1492
0.866	51	.1160	.2302	.2248	.2178	.2113	.2021	.1926	.1837	.1726	.1621
1.031	30	.1149	.2293	.2246	.2185	.2126	.2042	.1955	.1875	.1775	.1677
1.225	43	.1148	.2284	.2240	.2188	.2139	.2068	.1987	.1914	.1824	.1737
1.655	26	.1138	.2268	.2235	.2198	.2163	.2111	.2051	.1996	.1928	.1856
2.097	25	.1134	.2260	.2236	.2202	.2169	.2123	.2075	.2024	.1965	.1900

[1] On half the scale of other columns.

"The values in the table just given are a standard of reference, and the values obtained at these wave lengths on any day of observation are comparable with them as soon as reduced to the form given in the next to the last line of table 53.

MEAN DISTRIBUTION OF RADIATION ALONG THE SOLAR RADIUS FOR DIFFERENT WAVE LENGTHS

"The following tabular summary of the distribution of brightness of different wave lengths along the diameter of the sun's disk has been obtained in the manner just described from numerous observations made between November 1, 1906, and January 1, 1908. Profs. Schwartzchild and Villager determined the distribution of radiation along the diameter of the sun for the very short wave length, $\lambda = 0.323\mu$, by photographic observations made after silvering the objective of their telescope.[1] In this way they observed only with the ultra-violet rays transmissible by silver. The following table includes the mean of observations of Schwartzchild and Villager:

Table (55) 3.—*Mean distribution of radiation along radius of solar disk*

[Intensity at center as unit.]

Wave length	Number of observations	Distance from center as fraction of radius									
		0.00	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95
μ											
0.323	......	1.0000	0.960	0.897	0.835	0.775	0.690	0.600	0.530	0.452	0.382
0.386	3	1.0000	.9797	.9258	.8556	.7920	.7097	.6326	.5543	.4826	.4177
0.433	39	1.0000	.9780	.9271	.8663	.8060	.7290	.6471	.5827	.5098	.4499
0.456	89	1.0000	.9857	.9416	.8848	.8314	.7564	.6810	.6160	.5377	.4706
0.481	74	1.0000	.9871	.9438	.8914	.8401	.7706	.7007	.6378	.5658	.4988
0.501	104	1.0000	.9850	.9454	.8945	.8449	.7773	.7106	.6501	.5826	.5171
0.534	104	1.0000	.9870	.9499	.9018	.8561	.7919	.7282	.6720	.6053	.5478
0.604	72	1.0000	.9894	.9568	.9129	.8722	.8160	.7606	.7102	.6485	.5935
0.670	41	1.0000	.9906	.9612	.9241	.8769	.8376	.7860	.7404	.6803	.6292
0.699	64	1.0000	.9902	.9629	.9261	.8903	.8412	.7925	.7476	.6909	.6371
0.866	51	1.0000	.9922	.9690	.9388	.9108	.8711	.8302	.7918	.7440	.6987
1.031	30	1.0000	.9978	.9774	.9508	.9251	.8886	.8507	.8159	.7904	.7298
1.225	43	1.0000	.9948	.9779	.9530	.9316	.9007	.8654	.8336	.7944	.7565
1.655	26	1.0000	.9965	.9820	.9657	.9504	.9275	.9012	.8770	.8471	.8155
2.097	25	1.0000	.9965	.9858	.9709	.9563	.9361	.9149	.8924	.8664	.8374"

We now give the mean distribution of radiation along the solar radius for different wave lengths as found by the observations of 1913. The tables here given are conformable to tables 54 and 55 of Vol. 3 of the Annals. They relate, however, to other wave lengths.

---

[1] Astrophysical Journal, Vol. 23, pp. 284 to 305, 1906.

TABLE 4.—*Auxiliary standard reduction values of 1913*

Wave length	Number of observations	Distance from center as fraction of radius										
		0.00	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95	0.97
0.3737	84	0.1219	0.2401	0.2278	0.2 23	0.1978	0.1781	0.1589	0.1413	0.1217	0.1053	0.0852
0.4265	81	.1218	.2399	.2282	.2124	.1978	.1787	.1595	.1431	.1245	.1084	.0946
0.5062	87	.1193	.2360	.2269	.2147	.2032	.1878	.1717	.1576	.1410	.1262	.1126
0.5955	82	.1179	.2335	.2261	.2161	.2065	.1935	.1802	.1681	.1536	.1402	.1276
0.6702	83	.1168	.2319	.2258	.2170	.2086	.1972	.1856	.1747	.1617	.1495	......
0.8580	82	.1156	.2297	.2247	.2182	.2118	.2027	.1932	.1847	.1741	.1642	......
1.0080	78	.1152	.2290	.2246	.2186	.2126	.2046	.1960	.1881	.1781	.1689	......

TABLE 5.—*Standard distribution of radiation along radius of solar disk, 1913*

Wave length	Number of observations	Distance from center as fraction of radius										
		0.00	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95	0.97
0.3737	84	1.0000	0.9841	0.9344	0.8708	0.8113	0.7305	0.6518	0.5796	0.4992	0.4319	0.3495
0.4265	81	1.0000	.9848	.9368	.8719	.8120	.7336	.6548	.5874	.5111	.4450	.3883
0.5062	87	1.0000	.9891	.9510	.8998	.8516	.7871	.7196	.6605	.5909	.5289	.4719
0.5955	82	1.0000	.9902	.9589	.9165	.8757	.8206	.7642	.7129	.6514	.5946	.5411
0.6702	83	1.0000	.9927	.9666	.9289	.8930	.8442	.7945	.7479	.6922	.6400	......
0.8580	82	1.0000	.9935	.9719	.9438	.9161	.8767	.8356	.7989	.7530	.7102	......
1.0080	78	1.0000	.9939	.9748	.9488	.9227	.8880	.8507	.8164	.7730	.7331	......

CHANGES OF DISTRIBUTION FROM YEAR TO YEAR

We have compared the distribution for 1907 with that for 1913. It was at once apparent that a change of distribution had occurred. Inasmuch as the year 1913 was a year of absolute minimum of sun spots such as has not been equaled for almost a century, it seemed well to use the distribution obtained in 1913 as a standard of reference.

Imagine tables to be formed for other years, similar to that which we have just given for 1913. Imagine, further, that we divide each number of the table for another year by the corresponding number of the table for 1913. There results, for each wave length, a series of values. Having adjusted the values so that smooth curves to represent them would give zero departures at the center of the sun's disk, the actual values, starting near unity at the center of the sun's disk, run to numbers slightly smaller or larger than unity as we approach the edge of the disk, according as the distribution in the given year shows a greater or a less contrast of brightness between the center and the edge than that which prevailed in the standard year 1913.

In the following table (6) are given the results of such comparisons for the years 1907 and 1914. It was necessary to reduce the observations of 1907 to the wave lengths employed in 1913 and 1914. This was accomplished by plotting the tabular values on a very large scale and interpolating for the proper wave length. The 67 observations of 1914 which are here represented were obtained between June 12 and October 5. Other observations of 1914 are not as yet reduced.

TABLE 6.—*Comparison of distribution values of other years with results of 1913*

Year	Wave length	Distance from center as fraction of radius									
		0.00	0.20	0.40	0.55	0.65	0.75	0.825	0.875	0.92	0.95
1907	0.4265	1.0033	0.9996	0.9966	0.9992	0.9992	0.9981	0.9967	0.9929	0.9903	0.9918
1907	0.5062	1.0017	.9991	.9970	.9978	.9968	.9930	.9936	.9920	.9926	.9888
1907	0.5955	1.0005	.9997	.9976	.9971	.9956	.9928	.9919	.9915	.9902	.9909
1907	0.6702	1.0018	.9989	.9958	.9953	.9938	.9916	.9892	.9898	.9837	.9840
1907	0.8580	1.0000	1.0000	.9978	.9956	.9946	.9930	.9922	.9904	.9865	.9809
1907	1.0080	.9986	1.0012	.9991	.9986	.9990	.9966	.9962	.9936	.9933	.9906
	Mean	1.0010	0.9997	0.9973	0.9973	0.9965	0.9942	0.9950	0.9934	0.9894	0.9878
1914	0.3737	1.0005	0.9990	0.9983	0.9977	0.9963	0.9957	0.9939	0.9955	0.9943	0.9926
1914	0.4265	.9998	1.0002	.9987	.9985	.9983	.9973	.9962	.9966	.9946	.9939
1914	0.5062	1.0002	.9996	.9994	.9990	.9984	.9973	.9972	.9976	.9964	.9956
1914	0.5955	1.0000	1.0000	.9997	.9995	.9992	.9987	.9978	.9977	.9966	.9975
1914	0.6702	1.0006	.9999	.9991	.9988	.9985	.9977	.9966	.9968	.9961	.9970
1914	0.8580	.9996	.9998	.9999	.9989	.9983	.9985	.9981	.9979	.9975	.9990
1914	1.0080	.9997	1.0000	.9999	.9996	.9997	.0992	.9990	.9991	.9992	1.0008
	Mean	1.0001	0.9998	0.9993	0.9988	0.9984	0.9978	0.9970	.9975	0.9964	0.9966

The results just given are indicated graphically in figure 4. Ordinates are ratios of the mean ordinates of drift curves for 1907 and 1914 compared to those of 1913 taken as standards. Abscissæ are positions along the solar radius, starting from zero at the center of the disk and running to 1.000 at the limb.

It appears that greater contrast prevailed in the years 1907 and 1914 than that which prevailed at sun-spot minimum in 1913; because when all the curves are reduced to equality at the center of the solar disk, they indicate lower values at the limb in the years 1907 and 1914 than in 1913. The differences are exceedingly small, although so unmistakable. Thus the average departure at 92 per cent on the radius is but 1 per cent in 1907 and but 0.36 per cent in 1914.

We have considered whether these differences are due to experimental error, but three considerations seem to us to oppose this view. First, no significant change in the apparatus or methods of experiment occurred between 1913 and 1914. Second, the fluctuations of contrast from day to day are correlated with fluctuations of the solar constant from day to day, as will appear below from very numerous cases occurring in 1913 and 1914. This being so, it is reasonable to expect also a fluctuation of contrast from year to year, if the solar radiation fluctuates from year to year. Greater values of solar radiation prevailed in 1907[1] and 1914 than those prevailing in 1913. Hence it is not surprising to find that the contrast of brightness was greater in both the years 1907 and 1914 than it was

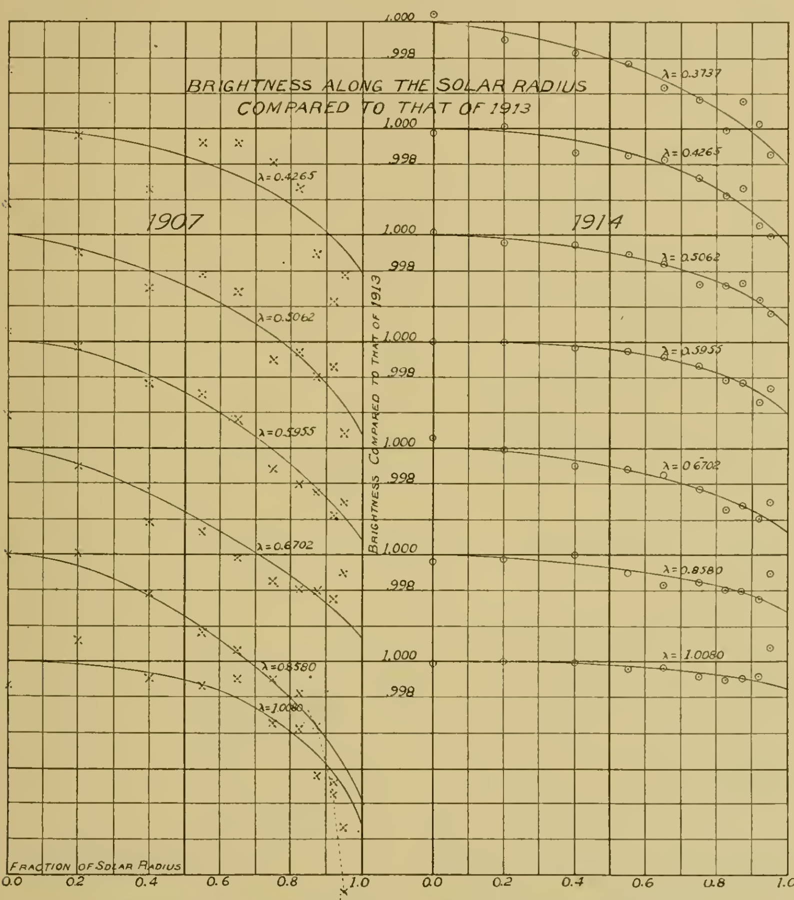


FIG. 4.—Variability of distribution of sun's brightness from year to year

in the year 1913. Third, there seems to be a correlation of change of contrast with change of wave length. This relation does not appear clearly from the results of 1907, but figure 4 shows that these results are subject to large experimental error compared with the

[1] This statement regarding 1907 is based on the dependence between solar-constant values and sun-spot numbers indicated by figure 16 of Vol. 3 of our Annals. Few solar-constant determinations were made in 1907.

results of 1914. A slightly different weighting of two discordant points on each of the curves for wave lengths 0.4265, 0.5062, 0.6702, and 1.008 μ in the curves for 1907 would bring them all (excepting that at wave length 0.8580 μ) into harmony with the conclusions about to be stated. Confining attention to the more accurate observations of 1914, the change of contrast is greater for short wave lengths than for longer ones, in the proportions indicated by the following table (7):

TABLE 7.—*Deviations of contrast of mean results of 1914 from standard form of 1913. (Derived from mean curves)*

Wave length	μ 0.3737	μ 0.4265	μ 0.5062	μ 0.5955	μ 0.6702	μ 0.8580	μ 1.0080
Fraction of radius.							
0.50	0.0020	0.0010	0.0009	0.0004	0.0010	0.0007	0.0002
0.90	0.0062	0.0046	0.0035	0.0026	0.0035	0.0023	0.0010

Figure 5 shows graphically the dependence of the 1914 departures of contrast on the wave length. The evidence of future years will be required to show whether the irregularities of the curves of figure 5

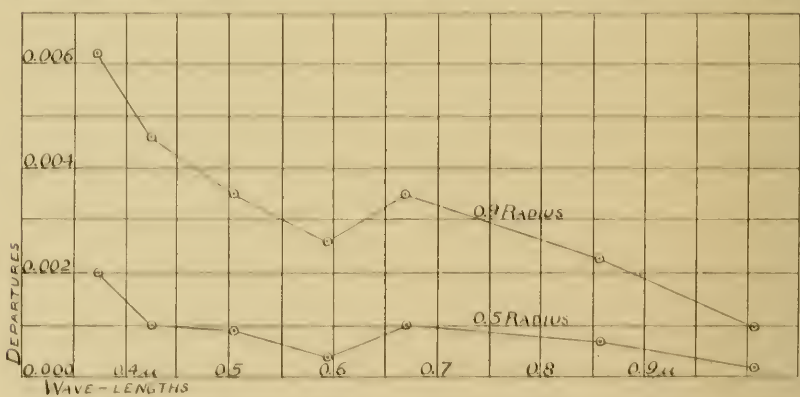


FIG. 5.—Dependence of brightness variability on wave length

are accidental or solar, but of the reality of the increase of departures attending decrease of wave length there seems to be little question.

CHANGES OF DISTRIBUTION FROM DAY TO DAY

We now pass to a consideration of changes of contrast from day to day. Still using the mean distribution of 1913 as a standard, we took logarithms of the values and subtracted these from the corresponding logarithms for the individual days. We then plotted the resulting logarithms as ordinates, and the positions on the solar disk radius as abscissæ. In this way we obtained for each day of observation seven plots, or pairs of plots, in which the slant of the representative lines indicated the departure from the standard mean condition of solar contrast, at seven different wave lengths. In the 1913 reductions we combined the pairs of check values before plotting, but kept them separate in the 1914 reductions.

Figure 6 shows the results of two days of comparison which are typical of the two different classes of results obtained on the various days. On September 22, 1913, the curves run generally upward, indicating a less contrast than the mean, while on October 20, 1913, the lines run generally downward, indicating a greater contrast than the mean. Some curves on each day, to be sure, run counter to the general trend of the day, but these divergences are reasonably to be regarded as often due to accidental error. A change of atmospheric transparency of 1 per cent during the single minute of time at which the central part of the sun's disk is crossing the slit of the spectroscope would account for the divergences shown by wave lengths 0.6702 and 1.008 μ on September 22. Still more probably the discrepancy may be accounted for by a temporary shift of less than a millimeter in the zero of the bolometric curve either at the beginning, middle, or end of the runs.

We desired to obtain for each day's observation a single value which would be typical of each day's departure of contrast from the general mean. While logarithmic curves of departures are not always smooth, and while there is no physical reason on which to base a prediction of the form which they ought to assume, still in general the curves are tolerably represented by straight lines. We have regarded the inclination of the best representative line for each logarithmic plot as a fair indication of the departure of contrast for that day and that wave length. There are seven wave lengths observed on each day of observation, and we might have taken the simple mean value of the tangents of the inclination of the logarithmic lines as the index of the departure for the given day. But it appeared that the departures were greater, the smaller the wave lengths, so much so that the simple mean would give entirely too much weight to the shortest wave length of observation. Accordingly, a system of weights has been determined by comparing the magnitudes of the departures at the different wave lengths. The numbers for 1913 and 1914 were obtained independently from the data for those two

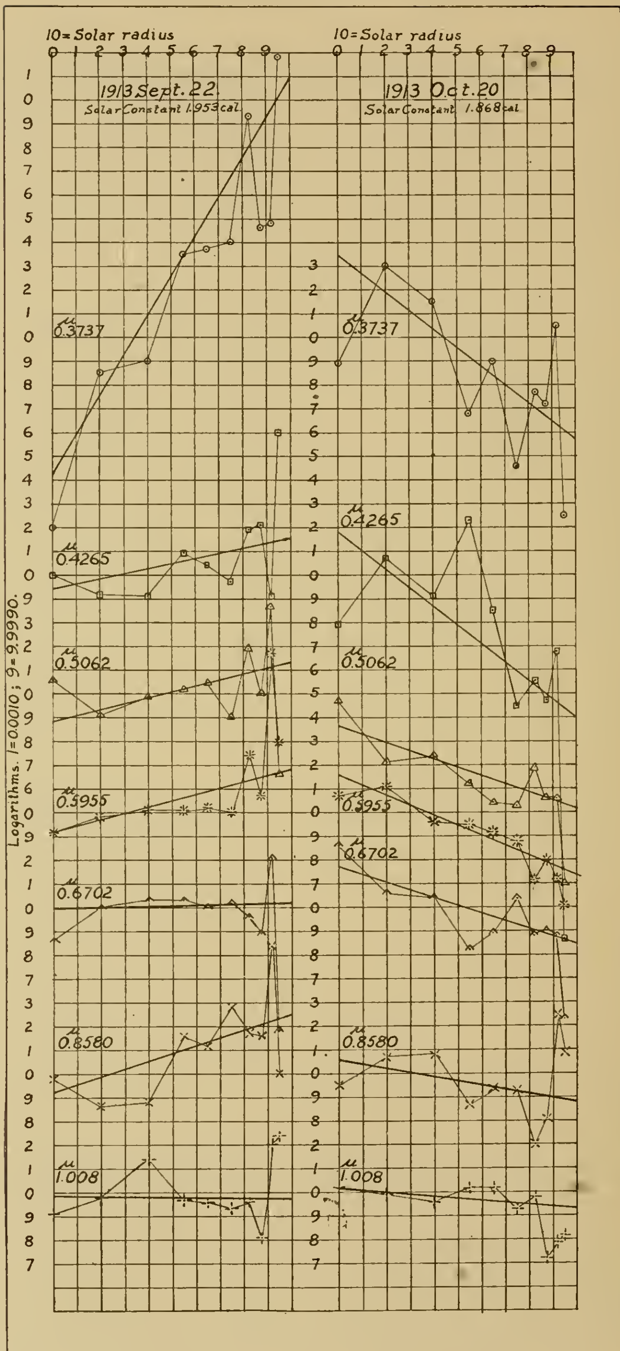


FIG. 6.—Variations of solar contrast from day to day

years, and they differ somewhat from each other.[1] The weights for the two years were not smoothed by wave lengths. They are as follows:

Table 8.—*Adopted weights*

Wave length	0.3737	0.4265	0.5062	0.5955	0.6702	0.8580	1.0080
1913 values	0.33	0.79	1.39	1.00	1.32	1.47	2.17
1914 values	0.42	0.59	0.62	1.00	0.63	1.00	1.67

For the purpose in view, the differences between the two sets of weights are of little significance. The numbers are, on the whole, very like those which might be derived from figure 5.

We have made two different reductions of the data. In one, we multiplied the tangents for each day by the appropriate multiplier taken from the preceding table, and having taken the mean of the weighted tangents, we thus obtained for the given day a value representing the average weighted departure from the standard condition of distribution, as determined by observations at seven different wave lengths. In another reduction, we omitted the wave lengths 0.3737 and 1.008 μ and took the simple mean of the tangents for the other wave lengths. We omitted these two wave lengths in consideration of the fact that the accidental error at 0.3737μ is unduly large, owing to the smallness of galvanometer deflections there; and also that the changes of contrast at wave length at 1.008μ are relatively small compared with the accidental error there.

The following tables (9 and 10) give the solar-cônstant and solar-contrast numbers for the years 1913 and 1914. The values given must be regarded as preliminary and subject to minor changes before final publication.

As so much depends upon the values for 1913, a great deal of attention has been paid to the remarkable decrease of the solar-constant values which occurred on and after September 24, 1913. Not only did the solar-constant values fall off at this time, but also a change in the contrast values occurred. If we divide all the days in which solar-contrast values were obtained in 1913 into two groups,

[1] It may be significant in view of what follows to note that the weights obtained for 1913 depended on the relative amounts of the deviations of individual wave lengths on different days, while the weights obtained for 1914 depended rather on the relative deviations for these wave lengths found from the year as a whole, compared to 1913 as a whole.

TABLE 9.—*Observations of the year 1913*

Date	Solar Constant	Grade	Solar Contrast			
			All λs	Grade	Omitting λ= .3737μ and λ=1.008 μ	Grade
July 16	1.928	Vg+	....	....	....	....
23	1.935	Vg−	....	....	....	....
24	1.911	Vg+	....	....	....	....
Aug. 3	1.928	E	....	....	....	....
4	1.916	E−	....	....	....	....
5	1.958	E	....	....	....	....
6	1.913	Vg−−	....	....	....	....
9	1.957	E−	....	....	....	....
10	1.954	Vg−	....	....	....	....
11	1.921	Vg−	....	....	....	....
12	1.940	Vg	....	....	....	....
13	1.927	Vg	....	....	....	....
14	1.955	E−−	....	....	....	....
15	1.922	E−	....	....	....	....
16	1.877	Vg+	....	....	....	....
17	1.913	E	....	....	....	....
18	1.958	Vg+	....	....	....	....
19	1.859	Vg+	....	....	....	....
20	1.987	Vg+	....	....	....	....
21	1.910	Vg−	....	....	....	....
28	1.968	G+	....	....	....	....
Sept. 2	1.963	G	....	....	....	....
3	1.933	E+	....	....	....	....
4	1.907	G−	....	....	....	....
5	1.905	Vg	....	....	....	....
6	1.901	Vg+	....	....	....	....
7	1.950	Vg++	....	....	....	....
8	1.897	Vg++	....	....	....	....
9	1.936	Vg+	+ 38	P+	+33	P
10	1.930	E−	+ 12	G	−13	G+
11	1.912	E	− 21	Vg−	0	Vg
14	1.907	E−	+ 42	G	+38	G
15	1.899	Vg+ ?	+ 48	G	+39	G
16	1.912	Vg −	+101	P	+54	G−
17	1.938	G+	+ 83	G	+79	G+
18	2.000	Vg	+ 47	Vg−	+67	Vg−
19	1.954	Vg+	+ 62	G	+29	G
P. M. 21	1.915	Vg++	+ 29	G−	+19	P
22	1.953	Vg	+ 49	Vg−	+46	G+
P. M. 24	1.928	E	+138	Vg−	+43	(Omitting λ=.5062) Vg
25	1.881	Vg	+ 28	G+	+12	G+
26	1.849	E	− 15	G+	−05	Vg−
27	1.894	E	− 23	G−	−26	G
28	1.855	E+	+ 18	Vg	−13	Vg
29	1.882	E+	− 54	Vg	−49	Vg+
30	1.907	G+	+ 11	P	−19	P
Oct. 1	1.869	Vg	....	....	....	....
3	1.966	Vg−	+ 11	G+	+19	Vg−
6	1.835	Vg	−107	G+	−68	Vg−
7	1.878	E	− 51	G−	−62	Vg−
8	1.804	G+	− 28	G	−25	G
9	1.806	G	....	....	....	....
11	1.852	E+	− 36	G	−24	G+
12	1.893	E+	− 07	Vg−	+ 4 or −24	G+
13	......	......	....	....	....	....
14	1.861	E	+ 03	Vg−	+16	Vg−
15	1.831	E	− 43	G	−20	G
17	1.907	E−	− 43	G	−29	G+
19	1.873	E+	− 30	G−	−38	G−
20	1.868	E	− 81	G+	−88 or −64	G+
21	1.912	E−	− 02	G−	+04	G−
22	1.893	Vg+	+ 24	G−	+30	G−
23	1.871	E	+ 22	G	+01	G
24	1.882	E	0	Vg−	+16	Vg−
25	1.850	E	− 01	G+	−26	G+
26	1.871	Vg+	+ 29	G+	+20	G
27	1.914	G	− 22	G	−27	G
28	1.830	E−	+ 04	G	+15	G+
31	1.867	Vg+	+ 52	G−	+44	G−
Nov. 4	1.852	E+	+ 65	P+	+09	P+
5	1.818	E+	− 13	G	−43	G
7	1.888	Vg+	− 34	G	−11	G
8	1.902	E	+ 53	G+	+31	G
9	1.918	Vg−	+ 35	G−	+27	G−

TABLE 10.—*Observations of the year 1914*

	Date	Solar Constant	Grade	Solar Contrast: All λs	Grade	Omitting λ= .3737μ λ=1.008 μ	Grade
	June 12	1.977	G+	....	....	....	....
	13	1.943	E−	− 14	G	− 51	G−
	14	1.944	E−	− 52	G+	− 65	G+
	15	1.979	E+	− 13	Vg	− 72	G+
	16	1.938	E	− 21	Vg−	− 40	G+
	19	1.916	Vg	− 34	G	− 43	G+
	20	1.954	E−−	− 38	G	− 54	G−
	21	1.918	E	− 40	E−	− 57	Vg+
	22	1.975	E−	− 16	Vg−	− 37	Vg−
	23	1.943	E+	+ 2	Vg−	− 27	Vg
	24	1.936	Vg−−	− 38	G+	− 32	G+
	25	1.958	Vg	+ 17	Vg−	+ 8	Vg
	26	1.966	E	− 7	G	− 21	G
	30	1.981	Vg+	− 9	Vg−	− 17	G+
	July 1	1.973	E	− 48	G+	− 55	G+
	2	1.947	E−	− 37	G−	− 65	G−
	17	1.932	E	− 13	Vg−	− 34	G+
	18	1.901	E	− 64	G+	− 83	G+
	19	1.951	Vg+	− 64	G+	− 34	G+
	20	1.949	Vg−	− 39	Vg−	− 47	Vg−
	21	1.968	E	− 60	G	− 87	G
	22	1.950	E+	− 55	Vg	− 33	Vg
	23	2.004	Vg+	− 41	G+	− 36	G+
	26	1.934	Vg++	− 11	G+	− 24	G
	P. M. 27	1.948	E−	− 25	G+	0	G
	28	1.968	Vg+	− 39	Vg+	− 66	Vg+
	29	1.921	Vg−−	− 59	G+	− 82	G+
a	30	2.031	Disturbed	− 46	Vg	− 46	Vg
a	Aug. 1	2.062	weather	− 56	G	− 45	G
a	2	1.966	Sky streaked	+ 3	Vg−	+ 6	G+
a	P. M. 5	2.099	with cirri	− 20	G	− 12	G
	7	1.989	Vg	− 56	G	− 30	G
a	8	1.945	Exceptional humidity	+ 6	G	+ 13	G
	9	1.987	E−	− 25	Vg	− 49	Vg
	10	1.949	E	− 88	G+	−104	G+
	11	1.987	E+	− 27	Vg−	− 26	Vg
	12	1.962	E−	− 38	G−	− 70	P
	14	1.952	Vg+	− 49	P	− 79	P
	17	1.923	E−	− 80	Vg	− 63	Vg−
	18	1.937	Vg	− 23	P+	− 34	P+
	19	1.935	E−	− 43	G−	− 76	G−
	20	1.969	G	− 32	G−	− 56	G−
	21	1.947	E+	− 34	G	− 59	G
	22	1.942	E	− 40	Vg	− 73	Vg
	23	1.975	E+	− 43	G−	− 77	P+
	24	1.928	G−	− 59	G−	− 78	G−
	26	1.934	E	− 37	G	− 81	G
	27	1.951	Vg+	− 27	G−	− 26	G
	28	1.940	E	− 38	G	−118	G
a	29	1.779	Disturbed weather	− 27	G−	− 48	G−
a	30	2.057	Sky streaked				
a	31	1.987	with cirri	−130	G−	−133	G−
	Sept. 1	1.915	E	−106	Vg−	−134	Vg−
	2	1.948	E	− 63	G+	− 81	G−
	3	1.942	E	−107	Vg	−121	Vg−
	4	1.949	E+	− 86	G	−108	G+
	6	1.921	E+	− 82	G	−109	P+
	7	1.944	G+	− 81	G	−109	G
	8	1.958	E−	− 53	G−	− 93	G−
?	9	1.932	Vg	−109	G	−174	G
a	10	1.954	E−	− 87	P	−119	P+
	11	1.946	Vg	− 18	G−	− 54	G−
	12	1.936	Vg	− 44	G	− 86	G
	13	1.922	E+	− 22	G	− 53	G
	14	1.954	E	− 58	Vg	− 69	Vg
	15	1.965	E−	− 34	G+	− 46	G
	16	1.951	E+	− 53	G−	− 73	G−
?	19	1.921	Exceptional humidity	− 18	Vg	− 36	Vg−
	20	1.936	E	− 19	Vg−	− 65	Vg
	21	1.960	E	− 62	G+	− 90	G+

Table 10.—*Observations of the year 1914* (Continued)

Date	Solar Constant	Grade	Solar Contrast: All λs	Grade	Omitting λ= .3737μ λ=1 008 μ	Grade
Sept. 22	1.915	Vg+	− 24	G	− 58	G
23	1.985	E	....	....	....	....
28	1.941	E+	− 48	G+	− 98	G+
Oct. 2	1.956	G−	....	....	....	....
? 4	1.939	E(?)	− 48	G	− 44	G
9	1.947	E	− 17	G−	− 24	G−
10	1.961	G	....	....	....	....
11	1.940	E	....	....	....	....
12	1.951	Vg+	....	....	....	....
13	1.946	E+	....	....	....	....
14	1.933	Vg	....	....	....	....
15	1.973	Vg+	....	....	....	....
16	1.946	Vg	....	....	....	....
18	1.960	E−	....	....	....	....
19	1.949	E	....	....	....	....
20	1.955	E+	....	....	....	....

prior to and succeeding September 23, respectively, we find as follows:

Table 11.—*Comparison of results before and after Sept. 23, 1913*

Observation Period	Solar-constant numbers: Above 1.895 cal.	Solar-constant numbers: Below 1.895 cal.	Solar-contrast numbers: Positive	Solar-contrast numbers: Negative
Sept. 9 to Sept. 22	11	0	10	1
Sept. 24 to Nov. 9	8	24	15	17

Not only was this date critical with regard to solar-contrast and solar-constant values, but a marked change in the distribution and total amount of the water vapor in the atmosphere took place. The values of precipitable water in the atmosphere determined by Fowle's method were far above the normal until September 23, and from then to the end of the period of observation generally about normal or a little below. A similar change is indicated, but not in so great a degree, by the observations with the wet and dry thermometers. The temperature also fell at the same critical time. These changes are shown by the following table (12):

Table 12.—*Mean Mt. Wilson precipitable water, pressure of aqueous vapor and dry bulb temperatures during observing periods*

Observation Period	Precipitable Water	Pressure Aqueous Vapor	Temperatures
	mm	*mm*	*c*
Sept. 9 to Sept. 22..........	10.5	5.52	23.0
Sept. 24 to Oct. 7...........	5.2	3.52	13.6
Oct. 8 to Oct 21	5.2	3.22	15.4
Oct. 21 to Nov. 9...........	5.0	4.30	17.1

It is to be regretted that at this very time, when all these changes were occurring, we made a radical change in the observing apparatus, for on September 23 we substituted for the bolometer which had been in use on Mt. Wilson since 1905 the bolometer which was employed in the Mt. Whitney and Algerian expeditions. We made this change because the Algerian bolometer was less subject to prejudicial influence from wind. But had we known how many other changes were occurring at the same time, it is certain that we would not have made a change of apparatus too. We have thought it necessary, on account of this, to investigate very thoroughly the merit of the solar-constant determinations succeeding September 23, and we find the following facts to verify their accuracy.

First, empirical determinations of the solar constant from pyrheliometry and psychrometry at Arequipa in Peru[1] indicate that the values subsequent to September 23 were lower than those prior to that date, and by about the same amount as do the Mt. Wilson observations. Second, we have determined an empirical formula for the solar constant from Mt. Wilson pyrheliometry and psychrometry. This formula has been worked out solely by the use of observations of 1910, 1911, and 1912, and does not depend in any way on bolometric observations of 1913, except that we chose days of the earlier years for which the precipitable water had values comparable with those of 1913. This formula gives the same change in solar-constant values at about September 23 that is indicated by the bolometric work itself. Third, we felt a suspicion that the determinations of the water-vapor absorption in the bolographic work might be interfered with by some change in the excellence of the definition of the spectroscope. Instead of employing with the usual constants Mr. Fowle's method of determining these absorption effects in the bolographs, from measurements on the band $\rho\sigma\tau$, the areas of the absorption bands were actually measured on many plates, just as we did formerly in all our bolographic reductions, and we thus determined new constants applicable to the last part of 1913. But no substantial change occurred in our conclusion regarding the fall of the solar-constant values on and after September 24.

We therefore see no reason to doubt that the days from September 9 to the end of 1913 are as homogeneous as any other series of our measurements, and we believe that the great drop of the solar-constant which is indicated to have occurred just after September 23 is a real one.

---

[1] See "Arequipa Pyrheliometry," Smith. Misc. Coll., Vol. 65, No. 9.

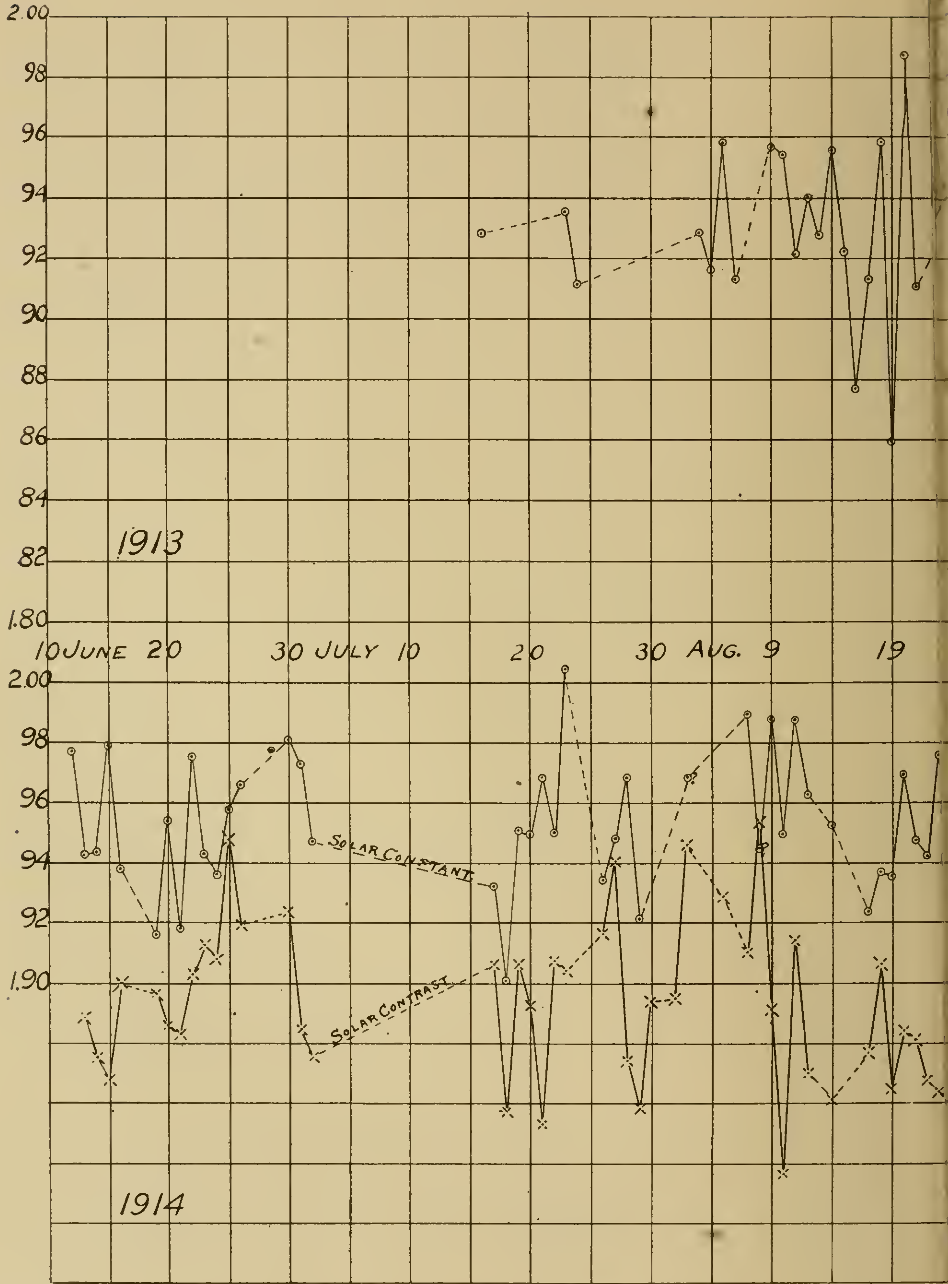
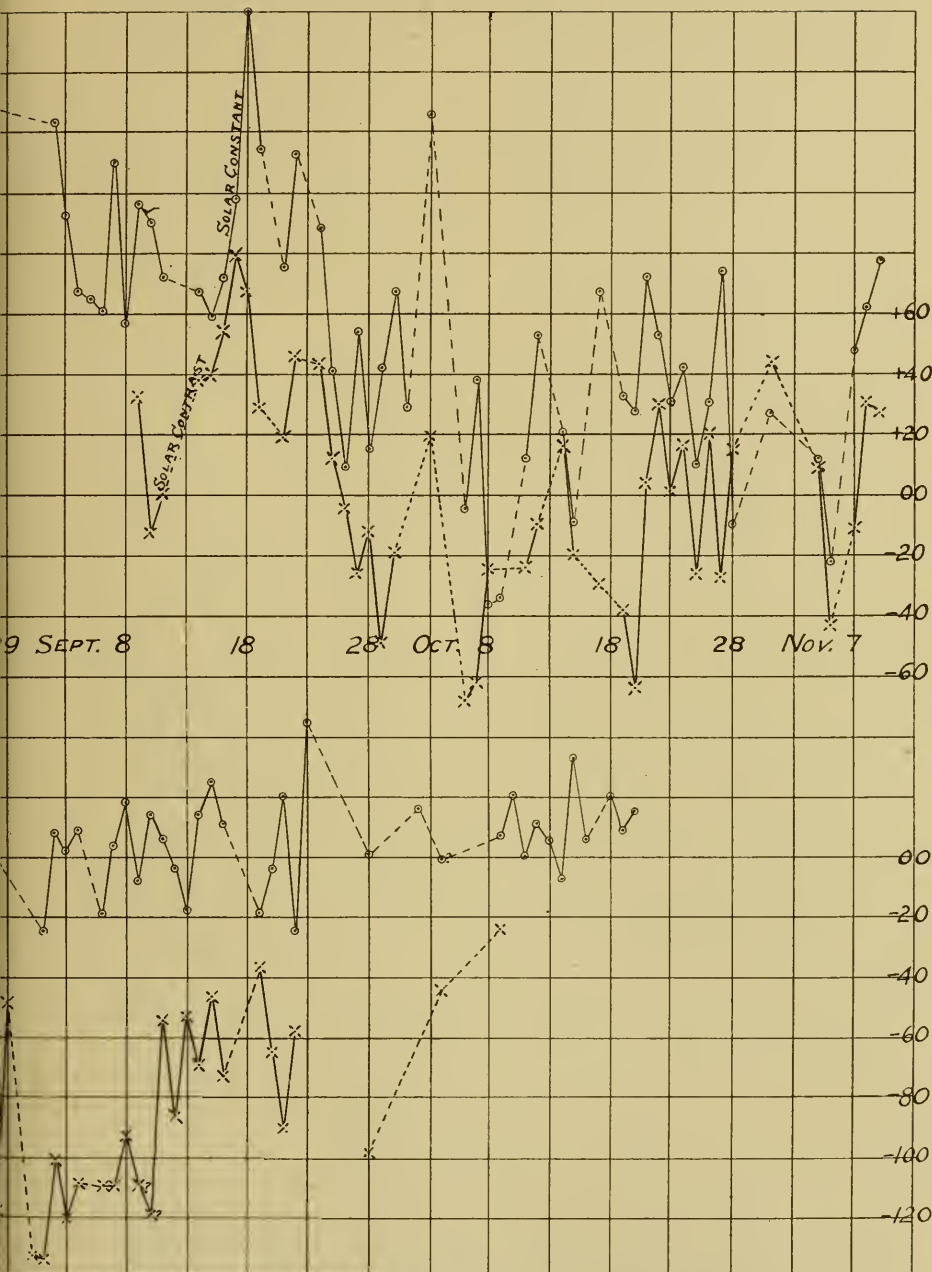


FIG. 7.—Variability of the sun in the years 1913 and 1914. Circles represe



ily solar-constant values. Crosses represent daily solar-contrast numbers

Figures 7, 8, and 9 show the solar-constant values and the solar-contrast values of 1913 and 1914 plotted as functions of the time and also as functions of each other. From figures 8 and 9 the

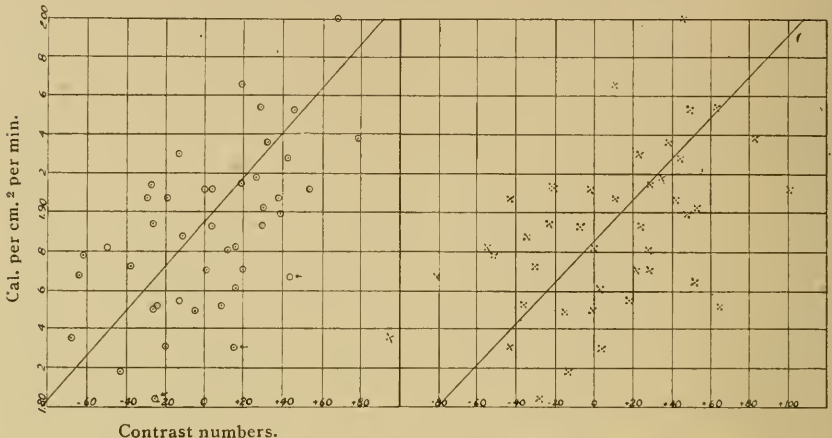


FIG. 8.—Variations of solar constant and solar contrast in 1913[1]

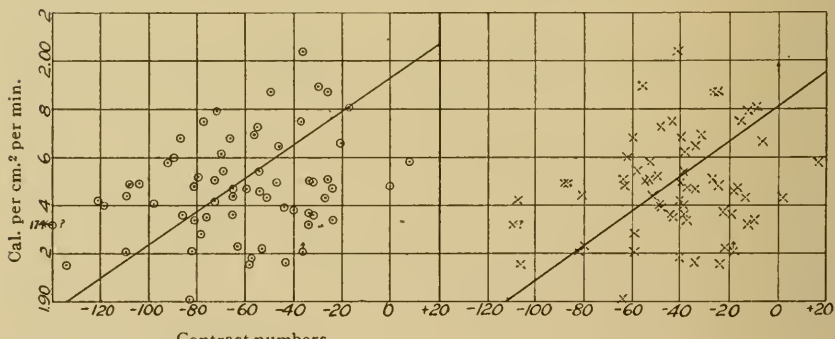


FIG. 9.—Variations of solar constant and solar contrast in 1914[1]

increase of the solar-constant values by 1 per cent corresponds to an increase of solar-contrast values of 1913 and 1914 as follows:

Year	Change of Solar Constant	Change of Solar-Contrast Number
1913:	+1 per cent :	+17
1914:	+1 per cent :	+29

[1] Circles represent simple mean contrast numbers, omitting wave lengths 0.3737 and 1.008μ. Crosses represent weighted means of all wave lengths. Arrows indicate that a certain probability exists that the points marked should be moved in the direction shown.

The factors of correlation (omitting $\lambda=0.3737$ and 1.008) are as follows:

$$1913: r=0.601\pm0.067$$
$$1914: r=0.213\pm0.080$$

The reader will recall that the method of deriving these contrast values is such that algebraically increased contrast numbers correspond really with decreased solar contrast.

Let us now restate these logarithmic results in ordinary terms. Imagine that the spectroscope was dispensed with, and that the contrast of brightness was determined for the solar radiation as a whole, and not for particular wave lengths. Let us further suppose that all the drift curves so obtained during 1913 and 1914 were reduced to unit intensity at the center of the solar disk. We should then find, still confining ourselves to a consideration of the short-period variations, that in 1913 an increase of 1 per cent in the solar constant of radiation corresponds with a decrease of the ordinate of the drift curve at 92 per cent out on the radius of 0.35 per cent.

The results of 1914 indicate a larger ratio of change of contrast compared to change of solar constant than those of 1913. This may be possibly a real difference caused in the sun, but it should be noted that the range of variation in 1914 was so small that the error of the determination of this ratio is much larger than it was in 1913. It is probable that the numerous values which will be found from observations of 1915 will enable us to give a more satisfactory conclusion on this point.

We now come to the consideration of the question why the ratio of change of contrast from year to year with respect to change of solar constant differs in its sign from the ratio of change of contrast from day to day with reference to the corresponding change in the solar constant. As stated above in years when the solar constant was high the solar contrast was greater than usual, while, as just stated, during 1913 and 1914 short-period temporary increases of the solar constant of radiation were attended by decrease in the solar contrast. This indicates two causes at work in the sun. We are inclined to suggest the following hypothesis.

Attending the long-period changes of solar activity indicated by prevalence of sun spots, faculæ, prominences, etc., there is, it may be assumed, a change of the effective solar radiating temperature. Higher effective radiating temperatures should prevail at times when increased solar activity brings faster the hot material to the surface to radiate. It is clear that if the solar temperature was zero, the contrast of brightness would be zero, and the higher the temperature, the higher the contrast and the higher the solar constant of radiation.

Turning now to a consideration of the short-period changes, it was the older view that the difference of brightness between the center and the edge of the solar disk was produced by an absorbing atmosphere or envelope. We prefer, however, to regard the decrease of brightness toward the edge of the sun as mainly a consequence of decreased effective temperature of the radiating surface. We suppose that the depth to which one looks at the center of the solar disk is very considerable, and that the limit of it is reached when the molecular scattering cuts off the ray. The same quantity of molecular scattering will be found in a very much less radial depth near the edge of the sun, because the line of sight there is oblique, so that a comparatively thin layer viewed obliquely will furnish the necessary number of molecules to cut off the radiation.

But while holding these views, we admit that the escape of radiation depends also on the transparency of the outer solar envelope. If now the transparency of this envelope increases, the solar constant of radiation must increase also; but the percentage increase of the intensity of solar rays will be greatest near the edge of the sun, where the path in these imperfectly transparent layers is longest. Thus it would happen that increased transparency of the outer solar layers would produce at the same time increased values of the solar constant of radiation and decreased contrast of brightness between the center and edge of the sun.

The two contrary effects we have been discussing may sometimes neutralize each other, but it is not to be expected that they will exactly neutralize each other for all wave lengths. Hence, we may find, with very high values of the solar constant of radiation, a contrast almost exactly, on the whole, equal to that which prevailed in the mean in the year 1913, but the different wave lengths may differ slightly in their behavior, some indicating a greater contrast than the mean of 1913, others less.

In our former publications on this subject (see Vols. 2 and 3 of the Annals) we have already considered the possibility of short-period irregular fluctuations of contrast and arrived at opposite conclusions from the two sets of data then published. Both sets of data, however, are so far inferior in accuracy to those we are now publishing that we withdraw altogether those former conclusions in favor of the ones which we now advance.

SUMMARY

We have repeated at Mt. Wilson, in 1913 and 1914, with improved apparatus, the determinations of the distribution of brightness along the solar diameter described in Vols. 2 and 3 of the Annals of the Astrophysical Observatory. More than 40 days' determinations were secured in 1913 and more than 80 in 1914.

The results agree closely with those obtained at Washington in 1907 for all wave lengths for which a comparison is possible.

There are, however, slight but significant differences between the mean results of different years. Taking 1913 as the standard year, greater contrast of brightness between the sun's center and edge was found in 1907 and 1914 than in 1913. We incline to connect these changes with solar activity, greater contrast prevailing along with greater solar radiation at times of high solar activity.

Besides these long-period changes there appear to be small changes of contrast from day to day, correlated with the changes of the solar radiation heretofore discovered by us. For this type of changes increased contrast is associated with decreased solar radiation.

We are thus led to consider two causes of change existing in the sun. One, going with increased solar activity, we regard to be increased effective solar temperature, which naturally produces increased radiation and increased contrast. The other, altering from day to day, we regard to be increased transparency of the outer solar envelopes, which naturally produces increased radiation but decreased contrast.

All these changes are greater for shorter wave lengths.

APPENDIX

A correction.—In a recent letter to Mr. Abbot, Professor F. H. Bigelow has called attention to the misrepresentation of his views in foot-note 1 on page 28 of our paper "New Evidence on the Intensity of Solar Radiation Outside the Atmosphere."[1] Professor Bigelow states that he has carefully avoided using Wien's displacement law as the basis of an estimate of the solar temperature. He has used instead a consideration of the general form of the solar spectrum energy curve.

We regret having made this error. The note as it now stands seems to us to represent fairly the position of Mr. F. W. Very.[2] In order to adapt it to Professor Bigelow's position we should require to make the following changes:

In lines 4 and 5 of our note strike out the words "they determine the wave length of maximum energy, and from it."

In line 16 strike out the words "position of the maximum of energy" and substitute the words "form of the solar energy curve outside the atmosphere."

In lines 26 and 27 strike out the words "position of maximum energy in its spectrum," and substitute the words "form of its energy spectrum distribution."

Strike out lines 32 to 41, inclusive.

As thus modified the main thesis of our note is as follows: Estimates of the solar constant of radiation based on estimates of the solar temperature involve: (1) The extrapolation of radiation laws thousands of degrees beyond the temperature to which they have been experimentally verified; (2) the assumption that the sun radiates like a "black body" in the face of experimental evidence that it does not; (3) dependence on the accuracy of the determination of the form of the solar-spectrum energy curve outside our atmosphere, which is a result of difficult and uncertain investigation. In short such estimates are not determinations of the solar constant, but are merely elaborate tissues of speculation. On the other hand we base our determination on sound and simple theory checked and verified at every point and applied nearly a thousand times under the most diverse circumstances, with closely agreeing results.

[1] New Evidence on the Intensity of Solar Radiation Outside the Atmosphere. By C. G. Abbot, F. E. Fowle, and L. B. Aldrich. Smith. Misc. Coll., Vol. 65, No. 4, June 19, 1915.

[2] Am. Jour. Sci., 4th Ser., Vol. 36, 609, 1913.