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THE DISTRIBUTION OF ENERGY IN THE SPECTRA OF THE SUN AND STARS

BY

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Until recently, one could form an estimate of the temperatures prevailing in the sun and other stars only by a determination of the distribution of energy in their spectra and the application of the laws of the perfect radiator or absolutely black body. Although recent advances in the physics of the atom point to a new method of approach to this subject, the form of the energy curve still remains of great theoretical interest.

In the measurement of the solar constant of radiation by the method of Langley, it requires us to determine the ratio of the areas of the energy curve of the sun at the earth's surface and outside the atmosphere, and knowledge of the distribution of intensities of the solar rays is indispensable. To be sure, the values come in merely as a series of weights in forming a pair of sums, one in the numerator, the other in the denominator of the fraction which gives the ratio of the solar energy outside the atmosphere to the solar energy within it. Hence no very high degree of accuracy is needful for this purpose. This is fortunate, for so far as our experiments have gone we have never succeeded in obtaining so high a degree of accuracy as would satisfy us from the workmanlike point of view.

This comes out clearly if one compares the results of our various determinations of the form of the solar energy curve as published in Volumes III and IV of the *Annals of the Astrophysical Observatory*. The divergence in these values is considerable, and when in 1920 the experiments for the determination of the form of the sun's energy curve were repeated, a still wider discrepancy appeared, so great that although these experiments of 1920 were ready at the time of printing of Volume IV of the *Annals* we hesitated to include them until they should be checked by other independent determinations.

These proposed new determinations have been made at Mount Wilson during the summer of 1922, and form the first part of the present communication. The latter part includes the application of them to the spectra of ten of the brightest stars observed with a

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special bolometric outfit by Messrs. Abbot and Aldrich at Mount Wilson in 1922. The work was done in connection with the 100-inch telescope.

We here return our thanks for the aid and encouragement furnished in the stellar work by Dr. Hale, Dr. Adams, and many of the staff of the Mount Wilson Solar Observatory.

SOLAR SPECTRUM ENERGY CURVE

A statement of the method adopted for the observations may be found in Volume II of the *Annals of the Astrophysical Observatory,* pages 24, 50-57. Briefly, it is this:

At each of a number of wave lengths in the solar spectrum it is required to determine: (1) The intensity of the spectrum observed in the bolometer; (2) the selective transmission of the spectroscope; (3) the selective reflection of the coelostat; (4) the transmission of the atmosphere. The bolograph indicates the first, and the measurements on a series of bolographs taken at different zenith distances of the sun furnish the means of computing the last. The reflection of the coelostat is determined by taking bolographs (*a*) with the ordinary pair of mirrors, (*b*) with a substitute pair of mirrors, (*c*) with a combination of both regular and substitute mirrors. The selective transmission of the spectroscope is determined by first passing the ray through an auxiliary spectroscope, selecting certain wave lengths and observing their intensity, (*d*) as transmitted by the auxiliary spectroscope, (*e*) as transmitted by both spectroscopes.

The observation (*d*) is made by setting the bolometer to occupy the position usually occupied by the slit of the usual spectroscope. In this position a number of settings of the auxiliary spectroscope are made, so as to determine the intensity of its radiation at a sufficient number of wave lengths. Then the slit of the usual spectroscope is restored to its proper position so as to permit nearly monochromatic beams of light to pass through the usual spectroscope after having been sorted out by the auxiliary one. The relative intensities of these nearly monochromatic beams are determined by taking bolographic energy curves of them. The areas included in these bolographic energy curves give the relative amounts of energy remaining in these wave lengths after having suffered absorption in the usual spectroscope. Thus the galvanometer deflections with the bolometer at the slit divided by the areas of the corresponding energy curves formed by the bolometer in its usual position, give numbers inversely proportional to the transmission of the usual spectroscope, and suitable to correct its losses.

It will be noted that the procedure thus outlined takes no account of selective absorption by the bolometer for different wave lengths. If, for example, the bolometer should only absorb 50 per cent of the rays in the ultra-violet while it absorbed 95 per cent of the rays in the infra-red, the form of the energy curve would be quite erroneous. We confess that in even our present experiments the possibilities of error from this cause have not been eliminated, but as will appear we have at least shown that with several different bolometers, some camphor smoked, some painted with lamp-black, some in atmospheric pressure, and some in high vacuum, there is no certain difference beyond the experimental error, and we continue here, as heretofore, tacitly to make the assumption that the bolometer absorbs a uniform proportion of the rays throughout the region of spectrum we are concerned with, namely, from 0.3μ to 3μ. Our position is strengthened by the fact that Ångström, Coblentz, and others estimate the absorption coefficient of blackened surfaces for total solar radiation as high as 97 or 98 per cent. This leaves little room for selective absorption.

Observations of 1920.—The determination of the transmission of the spectroscope was repeated in 1920 with new stellite mirrors, those used in 1917 and 1918 having gone to Chile. There is nothing new in the method employed, but the work was done with all possible care and with independent adjustments on July 16, 17, and 19, and August 18 and 19, 16 determinations in all. Ten points in the spectrum were observed in July and nine others alternating with them in August. The average probable error of the determination of relative spectroscopic transmission at these 19 points was 1.2 per cent. The results run as shown in table 1.

Combining these results with the determination of the reflecting power of the stellite-mirror coelostat made in 1918, and determinations of the form of the energy curve at the earth's surface and of atmospheric transmission accompanying made at Mount Wilson on 10 satisfactory days of 1920, of which five gave high, five low solar constants, we obtained the distribution of solar energy in the spectrum outside our atmosphere. These values will be given below.

Observations of 1922.—All the apparatus used in 1920 having been removed to Mount Harqua Hala, we used an entirely new outfit. The coelostat mirrors were silvered but the main spectroscope had new stellite ones.

In repeating the work, we were well convinced that the principal uncertainty rested on the determination of the absorption of the spectroscope. So many closely agreeing observations have been made in former years of the transmission of the atmosphere, the results of which fall in so well with the theory of Rayleigh on the molecular scattering, that we could not doubt that the atmospheric transmission coefficients obtained on excellent days were abundantly accurate for the purpose here in view. At least this is true for the wave lengths greater than 0.4μ. In the ultra-violet, we are well aware that there is contamination of the spectrum by stray light from longer wave lengths, so that the atmospheric transmission coefficients determined for that region are too high, and the magnitude of this error increases

TABLE 1.—*Spectroscopic Transmission. Observations of 1920*

Place by counter..........	193 18	194 00	194 45	195 30	196 15	196 45	197 20
Prismatic deviation from ω_1	224.6′	210.6′	195.6′	180.6′	165.6′	155.6′	144.0′
Wave length μ............	.355	.370	.391	.412	.441	.463	.492
Relative transmission	194	243	297	291	314	328	343
Probable error, per cent...	3.2	3.0	1.8	0.4	1.4	0.7	0.9

Place by counter..........	198 00	198 35	199 15	200 12	200 30	201 10	201 45
Prismatic deviation from ω_1	130.6′	119.0′	105.6′	86.6′	80.6′	67.2′	55.6′
Wave length μ............	.533	.578	.650	.798	.859	1.040	1.215
Relative transmission	372	378	362	348	335	295	291
Probable error, per cent...	1.1	1.1	0.9	1.2	0.3	0.9	0.7

Place by counter	202 00	203 00	203 30	205 00	205 50
Prismatic deviation from ω_1	50.6′	30.6′	20.6′	−9.4′	−26.0′
Wave length μ............	1.297	1.594	1.733	2.118	2.310
Relative transmission	324	365	383	351	186
Probable error, per cent...	1.0	1.2	0.5	0.4	2.3

as the wave length diminishes. If that were the only effect of the stray light, it would tend to diminish the intensities of the solar energy spectrum outside the atmosphere in the region of the ultra-violet rays, but there are also two additional effects of stray light, both of which tend in the other direction.

The first of these is the building up of the bolographic energy curve at the earth's surface in the ultra-violet by these same stray radiations which, as we have just said, tend to raise the atmospheric transmission coefficients. Obviously the effect of this building up tends to make the ultra-violet too high.

The third effect of stray light is in the determination of the transmission of the spectroscope. If the reader will go over the summary of procedure for that purpose, which has just been stated, he will perceive that the auxiliary spectrum which falls at the slit of the main spectroscope will be subject to contamination by the stray light. Monochromatic beams of energy result at the usual position of the bolometer, after the passage of the light through both spectroscopes, in which the stray light will be practically eliminated. Consequently in the ultra-violet the auxiliary spectrum will be relatively too bright, owing to the influence of stray light, while in the final spectrum represented by the little energy curves, the stray light will be eliminated. Hence, the ratios of the bolometric deflections at the focus of the auxiliary spectrum divided by the bolographic areas observed in the usual spectrum will be too large in the ultra-violet, indicating a greater absorption in the spectroscope than actually exists, and this will tend to make the ultra-violet part of the solar spectrum outside the atmosphere too high. We shall recur to this question of stray light a little later, and introduce an estimate of the combined effect of these three different influences.

In considering the best means of assuring a trustworthy result, it seemed to us that great advantage would come from using several different prisms, both in the auxiliary and in the usual spectroscope, so that we could carry through the whole determination of the solar energy curve outside the atmosphere with instruments of very different dispersion characteristics. In order to get these as decisively different as possible and at the same time to use materials of high transmissibility throughout the region of the spectrum we were concerned with, it occurred to us to use prisms of rock salt in substitution for the ultra-violet crown glass prisms we usually employ. Moreover, as the work of 1920 and some previous years had been done with ultra-violet crown glass prisms in both the auxiliary and usual spectro-

TABLE 2.—*Circumstances of the Observations*

1922 Date	Object	Prisms		Bolometer	Type of blackening	Spectrum places	No. of tests	Notes
		1st spectroscope	2d spectroscope					
Aug. 28	Spectroscope absorption	Great flint	U. V. Crown.	New vacuum	Lamp-black paint.	First set	2	1. Part of plates melted.
" "	" "	" "	" "	" "	" " "	Second set	2	2. " " " "
" 29	" "	" "	" "	" "	" " "	" "	1	3. Bolometer wiggles.
" "	" "	" "	" "	Old air	Camphor smoke	" "	1	4. Correction for shutter.
" 30	" "	" "	" "	" "	" "	" "	1	5. Shutter changed.
" "	" "	" "	" "	" "	Lamp-black paint.	" "	2	6. Bolometer wiggles much.
" "	" "	" "	" "	" "	" " "	" "		7. Bolometer wiggles much.
" 31	Test of bolometers	" "	None	Old vacuum in air	" " "	" "	2	8. Bolometer of 1916.
" "	" " "	" "	"	Old air	" " "	" "	1	9. Same as Aug. 30.
Sept. 1	" " "	" "	"	Old vacuum exhausted	" " "	" "	2	10. On these days many experiments alternately with and without air.
" "	" " "	" "	"	" " in air	" " "	" "	2	
" 2	" " "	" "	"	" " exhausted	" " "	" "	1	
" "	" " "	" "	"	" " in air	" " "	" "	1	
" "	" " galvanometer scale	None	"	" " " "	" " "	None	1	11. Varied shunt.
" "	" " sectors	"	U. V. Crown.	" " " "	" " "	Selected	1	12. Eye observations.
" "	" " bolometers	Great flint	None	" " " "	" " "	Second set	1	13. First spectroscope re-silvered.
" "	" " "	" "	"	New vacuum repaired	" " "	" "	1	14. Strips resoldered and re-evacuated.
" "	Spectroscope absorption	" "	U. V. Crown.	" " "	" " "	" "	2	15. Excellent conditions.
" 3	" "	" "	" "	" " "	" " "	First set	2	" "
" 5	Solar energy spectrum distribution.	None	" "	" " "	" " "	Bolographs	10	16. Cloudless.
" "	Spectroscope absorption	Great flint	Rock salt	" " "	" " "	Combined set.	1	17. See final discussion.
" 6	Solar energy spectrum distribution.	None	" "	" " "	" " "	Bolographs	10	18. Cloudless, good sky.
" "	Spectroscope absorption	Great flint	" "	" " "	" " "	Combined set.	1	19. Excellent conditions.
" "	Test of bolometers	" "	None	Old vacuum in air	" " "	" "	1	20. Compare Sept. 2.
" 9	Spectroscope absorption	U. V. Crown.	Rock salt	Old air repaired	" " "	" "	1	21. Little value.
" 11	Bolographs great wave-lengths	None	" "	" " "	" " "	Bolographs	4	22. Eye observations also.
" "	Test of sector values	"	" "	" " "	" " "	Selected	3	23. Bolographic.

NOTES.—1, 2, Wash water too hot. Only half plates saved. One of each set. 3, Progressive increase of bolometer disturbance led finally to resoldering of connections and reevacuating the bolometer. 4, No glass being in front of bolometer the shutter gave a deflection due to its difference of temperature from surroundings. Noted magnitude and applied corrections. 5, Shutter moved over in front of slit instead of in front of bolometer. Correction avoided. 6, 7, In painting the bolometer strip it was slightly torn. Hence bad wiggles spoiled this work. Rejected. 8, 9, 10, 20, This bolometer was connected to mercury vapor pump and used alternately with and without vacuum of less than 0.001 mm. mercury on Aug. 31, Sept. 1, 2, and 6. Readings in the auxiliary spectrum by eye observations at galvanometer compared with and without air, and with old air bolometer repainted and with new vacuum bolometer repaired. 11, Observed by eye the galvanometer deflections for increasing bolometer shunt by 1, 2, 3, 4, 5, 6, 7 ohms from 1930 ohms originally. First swings were 31.3, 61.0, 91.0, 122.0, 152, 181, 211 mm. No corrections seem required for inequalities of galvanometer scale. 12, A few trials of deflections at the same spectrum points with different rotating sectors. Better determinations later. 14, The new vacuum bolometer returned from Pasadena resoldered and reevacuated with liquid air trap. 15, Results of highest weight. 16, Atmospheric transmission coefficient and absorption of coelostat mirrors entirely determined. 17, Changed to rock salt prism. Good determination. 18, Same remark as 16. 19, Good determination. 21, The old bolometer No. 20, used for many years at Washington (See *Annals*, Vol. I) had been broken as per note 6. New coarse strips of only 0.7 ohms resistance were now inserted. The purity of the spectrum with these and U. V. prism in first spectroscope insufficient. 22, Used sifting train of salt for eye observations. Observed to 14 microns. 23, Excellent sector determination.

scopes, we determined to substitute in the auxiliary spectroscope a prism of ordinary flint glass which, as is well known, produces a far greater relative dispersion in the ultra-violet than the ultra-violet crown glass.

It seemed to us that when these various modifications of the experiments had been made, namely, the use of bolometers in air, bolometers in vacuum, bolometers painted with lamp-black, and bolometers smoked with camphor smoke; when we had employed several different types of prisms; and when we had independently set up the apparatus with the greatest possible care on several different occasions; then, if the results of all these modifications should agree among themselves and should agree either with the work of 1920 or with the work of the earlier years, as reported in Volumes III and IV of the *Annals of the Astrophysical Observatory,* the final result, supported by such far-reaching agreements, ought to be entitled to confidence.

We now proceed to give in table 2 in abbreviated form the data of the observations and their results.

As noted above, the measurements of the degree of uniformity of the galvanometer scale do not indicate appreciable corrections to be necessary. For though the increase of deflection for successive steps of one ohm diminishes slightly with increasing deflection, yet there should be a small change in this direction depending on the fact that a change of one ohm on a shunt of 1,937 ohms about a Wheatstone's bridge coil of 56 ohms produces less current in the galvanometer than 1 ohm change on 1,930 ohms. With allowance for this, the readings differ by less than their probable error from linear relations.

The deflections are governed by rotating sectors. As determined with automatic recording of deflections in numerous series, the deflections for sectors are as follows:

Sector No.	3	2	1	0
Deflection	1.000	3.159	9.161	26 677
Deflection	0.3748	1.184	3.434	10.000

From this we derive factors of reduction:

To reduce	3 to 0	2 to 0	1 to 0	0 to 0
Factor	26.68	8.445	2.913	1.000

To reduce	3 to 3	2 to 3	1 to 3	0 to 3
Factor	1.000	0.3166	0.1092	0.03748

Table 3.—*Ratios of Deflections of Various Bolometers as Reduced to Nearly Equal Scales*

A = old bolometer No. 20 in air, camphor-smoked.
B = old bolometer No. 20 in air, lamp-black-painted.
C = 1916 bolometer in air, lamp-black-painted, glass plate in front.
D = 1916 bolometer in vacuum, lamp-black-painted, glass plate in front.
E = 1922 bolometer in vacuum, lamp-black-painted, glass plate in front.

Spectrum place	Wave length *microns*	A/C	B/C	D/C	D/C	D/C	D/C	D/C Mean	E/C
06 : 00	0.37	89	105	107	105	99	103	1.035	94
04 : 30	0.40	100	91	100	106	103	104	1.032	108
03 : 15	0.46	100	100	104	101	100	99	1.010	106
02 : 00	0.53	103	106	95	90*	99	105	.997	102
00 : 45	0.65	102	100	102	88*	95	100	.992	99
99 : 50	0.86	110	100	105	100	98	101	1.010	100
98 : 15	1.22	106	99	108	100	99	101	1.020	100
97 : 00	1.60	111	109	89*	99	93	95	.970	103
95 : 00	2.12	110	105	100	102	93	98	.982	100

* Omit.

These figures perhaps show that the camphor-smoked bolometer No. 20 read low in the visible and ultra-violet spectrum as compared with the infra-red, but this result may have been produced by changes of sky between the two series of observations, which in this instance were not made on the same day. In all the other cases we incline to think there is nothing definite shown, and the fluctuations were due to slight differences of wave length between settings, or to changes in sky between observations, as well as to accidental errors of galvanometer readings, which latter were sometimes no doubt more than 1 per cent. The change between air pressure and evacuated condition of the 1916 bolometer seemed to us at one time real, but looking at the individual determinations we now incline to doubt it. In vacuum the 1916 bolometer was about five times as sensitive as in air. The observations in vacuum in each case were taken immediately preceding those in air, and at high sun.

Reduction of the observations of spectroscopic absorption.—As a sample of the work we give the observations and reductions for September 2, first series.

TABLE 4.—*Sample of Spectroscopic Absorption Work*

Place by second spectroscope	Sector-free deflections and times				Sector-free areas and times		Sector-free mean deflection	Spectroscopic absorption. Arbitrary units
	Deflection	Time	Deflection	Time	Mean measures	Time		
	cm.		*cm.*		*cm.*^{2}			
06 : 00	0.77	3^h 07^m	0.52	3^h 54^m	1.97	3^h 29^m	0.645	327
04 : 30	5.54		4.95		16.19		5.25	325
03 : 15	15.10	3^h 09^m	14.15	3^h 56^m	48.5	3^h 35^m	14.62	302
02 : 00	30.51		28.89		112.1		29.70	265
00 : 45	56.58		54.89		204.5		55.73	273
99 : 50	85.29	3^h 11^m	86.15	3^h 59^m	323.0	3^h 39^m	85.72	266
98 : 15	91.20		90.20		330.5		90.70	275
97 : 00	60.63		61.16		236.2		60.90	258
95 : 00	17.61	3^h 14^m	17.61	4^h 01^m	51.7	3^h 46^m	17.61	341

Working along in this way, and reducing all of the ratios, deflection divided by area, proportional to spectroscopic absorption, to the same scale of arbitrary units, we come at length to the following tables:

TABLE 5.—*Collected U. V. Glass Spectroscopic Absorption. First Places*

Place by second spectroscope	Dates of observation			Mean values	Per cent probable error
	Aug. 28	Sept. 3–I	Sept. 3–II		
05 : 15	518	431	417	455	4.2
03 : 45	495	480	484	486	0.6
02 : 40	448	446	437	444	0.4
01 : 25	403	427	432	421	1.3
99 : 48	384	409	422	404	1.6
98 : 30	...	428	425	426	..
98 : 00	...	437	420	428	..
96 : 30	416	405	398	406	0.7
94 : 10	...	703	735	419	..

Similarly for the other set of spectrum places we obtained:

Table 6.—*Collected U. V. Glass Spectroscopic Absorption. Second Places*

Place by second spectroscope	Dates of observation						Mean values	Per cent probable error
	August 28	August 29-I	August 29-II	August 30	Sept. 2-I	Sept. 2-II		
06:00	500	541	507	496	515	544	517	1.0
04:30	508	458	495	368	507	547	480	3.0
03:15	466	461	452	400	471	473	454	1.3
02:00	410	433	426	397	412	440	420	1.0
00:45	490	445	450	436	426	421	445	1.2
99:50	408	413	400	428	413	385	408	0.8
98:15	433	428	419	422	426	436	427	0.3
97:00	...	377	370	481	402	398	406	2.5
95:00	...	553	591	630	532	569	575	1.7

In the same manner we arrived at the following results for the spectroscopic absorption values in arbitrary units applicable to the case of the rock salt prism replacing the U. V. crown glass prism in the second spectroscope. As we had no reason to expect absorption bands introduced by rock salt it was unnecessary to investigate so many places in the spectrum as were used for the U. V. crown glass prism which has several such bands. Eleven places were chosen including all the wave lengths of the "Second Places" above and in

Table 7.—*Collected Rock Salt Spectroscopic Absorption*

Place by U. V. spectroscope	Dates of observation			Mean values	Per cent probable error
	Sept. 5	Sept. 6	Sept. 9		
06:00	699	644	693	679	1.5
05:15	582	567	513	554	2.1
04:30	522	539	476	512	1.6
03:15	451	438	412	434	1.6
02:00	411	391	384	395	1.2
00:45	349	352	368	356	1.0
99:50	313	305	327	315	1.2
98:15	264	271	281	272	1.0
97:00	239	260	270	256	2.1
95:00	215	227	223	222	0.9
94:10	203	208	...	210	..

addition two others from the " First Places." For clearness we give the spectrum settings which the U. V. crown glass prism would have required at these wave lengths, so as to compare with those in the preceding tables.

These determinations of spectroscopic absorption for the U. V. glass and for the rock salt spectroscopes were plotted on a large scale and smooth curves drawn to fix the best values to use for the absorption coefficients at the wave lengths where bolographic ordinates are measured. These results will appear in a later table.

Reductions of observations of coelostat absorption.—On September 5, and again on September 6, bolographs were taken to determine coelostat absorption. Thus, for instance, on September 5, after a series of four bolographs beginning at $6^h 36^m$ and finishing with the bolograph at $8^h 13^m$ taken to determine atmospheric transmission coefficients, two additional silvered mirrors were employed in connection with the bolographs as follows:

Time of observation	$9^h 45^m$	$10^h 01^m$	$10^h 20^m$	$10^h 39^m$	$10^h 49^m$	$11^h 03^m$
Mirror arrangement	4 mirrors	Usual	4 mirrors	2 substitutes	2 substitutes	Usual

These bolographs of the solar spectrum having been marked with smoothed curves as usual, were measured in ordinates at the usual places as in solar-constant determinations. The results were then combined in the following manner:

From the usual bolographs taken at $8^h 13^m$, $10^h 01^m$, and $11^h 03^m$, it was determined what would have been the usual ordinates at the various times when four mirrors and two substitute mirrors were employed, and thus the whole body of data could be brought to a common time and air mass. Mean values of ordinates for the four mirrors and for two substitutes were determined. Let A, B, and C be directly comparable ordinates at a certain wave length with usual, substitute, and four mirrors, respectively, then the correcting factor for the combined absorptions of the usual mirrors at this wave length is B/C. If that for the substitute mirrors was desired, it would be A/C.

Proceeding thus in effect, we obtained the correcting factors for the absorption of the usual mirrors over the whole spectrum for both September 5 and September 6. The latter day's values were obtained for slightly different wave lengths as observed with the rock salt prism. But the values were readily convertible to a comparable basis, and were thus compared by plotting on a large scale. The two sets of data were in satisfactory accord throughout, but were mutually helpful in smoothing out accidental errors. This being done, smoothed curves were drawn for each day separately and applied independently in the final computations of the energy curves of the two days. From inspection of the results it is believed that the determinations of coelostat reflection are surely correct to within 1 per cent, except as far as they may be affected systematically in the violet by stray light as already referred to above.

TABLE 8.—*The Solar Energy Curve. U. V. Glass Prism. September 5, 1922*

Prismatic deviation from ω_1	Wave length μ	Dispersion coefficient	Coelostat reflection	Spectroscope coefficient	Prismatic energy curve outside atmosphere	Normal energy curve outside atmosphere
230′	0.3504	1104	0.545	632	394	435
220	0.3600	990	0.616	580	506	501
210	0.3709	887	0.667	530	615	546
200	0.3853	788	0.705	490	825	650
190	0.3974	692	0.734	480	980	678
180	0.4127	605	0.760	480	1445	875
170	0.4307	529	0.784	487	1820	963
160	0.4516	460	0.807	470	2350	1081
150	0.4753	397	0.829	450	2960	1175
140	0.5026	338	0.850	436	3390	1146
130	0.5348	282	0.870	420	3806	1073
120	0.5742	230	0.890	420	4500	1035
115	0.5980	206	0.899	428	5002	1030
110	0.6238	183	0.907	440	5650	1034
105	0.6530	162	0.915	444	6000	972
100	0.6858	144	0.923	435	6400	922
95	0.7222	127	0.930	420	6380	810
90	0.7644	112	0.936	410	6270	702
85	0.8120	98.8	0.941	407	6250	618
80	0.8634	86.5	0.945	410	6165	533
75	0.9220	76.8	0.949	413	5910	454
70	0.9861	71.5	0.953	418	5620	402
65	1.062	68.0	0.957	422	5248	357
60	1.146	66.0	0.960	426	4760	314
55	1.225	66.0	0.963	429	4400	290
50	1.302	66.0	0.966	428	3850	254
45	1.377	66.0	0.970	424	3312	218
40	1.452	66.0	0.973	418	2880	190
35	1.528	66.4	0.975	411	2460	163
30	1.603	67.3	0.977	406	2164	146
25	1.670	68.1	0.978	405	2013	137
20	1.739	69.6	0.979	408	1774	123
10	1.870	72.3	0.979	430	1390	100
0	2.000	76.8	0.980	495	1088	84
—10	2.123	83.0	0.980	574	662	55
—20	2.242	90.5	0.981	660	378	34

TABLE 9.—*The Solar Energy Curve. Rock Salt Prism. September 6, 1922*

Prismatic deviation from *A*	Wave length μ	Dispersion coefficient	Coelostat reflection	Spectroscope coefficient	Prismatic energy curve outside atmosphere	Normal energy curve outside atmosphere
200′	0.3749	1585	0.676	630	199	313
190	0.3820	1484	0.699	592	193	286
180	0.3881	1384	0.717	562	231	321
170	0.3975	1280	0.735	543	335	429
160	0.4057	1193	0.751	526	420	500
150	0.4145	1113	0.766	508	447	496
140	0.4242	1036	0.781	492	461	477
130	0.4350	958	0.796	476	524	502
120	0.4463	886	0.811	463	620	549
110	0.4590	817	0.825	450	672	549
105	0.4652	785	0.831	443	676	530
100	0.4720	750	0.839	436	745	558
95	0.4790	714	0.845	430	826	590
90	0 4860	679	0.852	424	867	589
85	0.4937	642	0.858	419	880	565
80	0.5017	607	0.865	414	917	555
75	0.5105	571	0.871	408	951	544
70	0.5199	534	0.877	402	974	521
65	0.5290	500	0.882	396	1020	510
60	0.5400	466	0.888	392	1088	507
55	0.5513	434	0 893	388	1165	506
50	0.5638	404	0.898	384	1228	496
45	0.5767	377	0.902	379	1307	493
40	0.5905	351	0.907	374	1426	501
35	0.6052	323	0.910	368	1436	464
30	0.6212	294	0.914	362	1482	435
25	0.6380	267	0.917	355	1517	404
20	0.6557	243	0.920	348	1648	400
15	0.6784	222	0.923	341	1743	386
10	0.7037	199	0.927	334	1843	366
5	0.7302	174	0.930	326	1965	342
0	0.7604	152	0.933	318	2087	317
—5	0.7957	135	0.935	307	2170	293
—10	0.8321	117	0.937	298	2261	265
—15	0.8788	975	0 939	290	2396	234
—20	0.9322	820	0.941	282	2514	206
—25	0.9970	670	0.943	272	2676	179
—30	1.093	527	0.945	262	2831	149
—35	1.202	402	0.947	250	2897	117
—40	1.332	300	0.949	242	2961	89
—45	1.500	245	0.951	232	2947	72
—50	1.751	216	0.953	222	2821	61
—55	2.070	208	0.954	212	1657	35

In further reduction we now include the mean result of 1920, the U. V. glass prism result of 1922, and the rock salt prism result of 1922, with the object of comparing these several determinations, getting from them the best general representative values, and finally comparing these with the earlier results of 1903 to 1910, and 1916 to 1918, respectively, given in Table 58 of Volume IV, *Annals Astrophysical Observatory*. In order to do this we first reduced the results of 1922 to the scale of those of 1920. In the following table we do not retain the individual wave lengths observed for rock salt, but have read off from a large scale plot the values which the rock salt work would indicate for the wave length places used in U. V. glass work.

We give in figure 1 the individual values found for the different wave lengths for the work of 1920 and the U. V. glass and rock salt prisms in 1922. As will be seen by inspection of the plot, when we consider all circumstances, particularly the wide differences in dispersion characteristics, the agreement of the rock salt work of 1922 with the U. V. glass work of 1920 is little less than remarkable over the whole extent of spectrum covered. Agreement even descends to the details in the solar bands near wave lengths 0.386, 0.425, and 0.535 micron. There are moderate divergences central at wave lengths 0.65 and 1.3 microns. The discrepancy beyond 1.7 microns is not surprising in view of the difficulty introduced by the water-vapor bands, and the approaching opacity of U. V. crown glass.

Turning to the U. V. glass work of 1922, its agreement with 1920 between wave lengths 0.5 and 1.7 microns is nearly perfect. At greater wave lengths than 1.7 it lies between the 1920 work and the rock salt work. For wave lengths less than 0.5 micron there is a pretty wide divergence, the 1922 U. V. glass work running smaller. The departure does not much exceed 10 per cent until the wave length is less than 0.40 micron.

We incline to attribute this ultra-violet discrepancy to the inferiority of the day, September 5, 1922, as indicated by the logarithmic plots of atmospheric extrapolation. These indicate that the sky was growing less transparent towards noon, for the computed coefficients of atmospheric transmission in the infra-red are all closer to unity than they ought to be. This mediocre character, and the excessively high transmission coefficients, would scarcely affect the form of the energy curve for wave lengths greater than 0.6 micron, because here the atmospheric transmission is always above 90 per cent, so that changes of it affect the form of curve only slightly. But supposing the sky

TABLE 10.—*Comparison of Normal Solar Energy Curves*

Wave length ω_1	U. V. glass deviation from μ	Energy curves outside the atmosphere						
		1920	1922 U. V.	1922 R. S.	1903–10	1903-10 omitting quartz work	1916–18	Weighted mean, 1920–22
0.3415	240′	262	...	...	226	...	263	262
0.3504	230	307	200	...	272	...	304	281
0.3600	220	330	230	...	310	...	330	297
0.3709	210	340	251	325	342	...	353	318
0.3853	200	304	299	300	344	...	385	301
0.3974	190	343	312	350	413	...	411	340
0.4127	180	484	403	513	506	500	567	480
0.4307	170	482	443	495	535	506	518	479
0.4516	160	569	497	548	610	567	580	548
0.4753	150	570	540	575	625	569	622	566
0.5026	140	558	527	553	604	548	566	546
0.5348	130	515	493	509	578	515	530	506
0.5742	120	498	476	493	538	484	508	489
0.5980	115	487	474	493	505	464	482	485
0.6238	110	466	475	430	472	434	450	457
0.6530	105	446	447	400	424	400	423	431
0.6858	100	419	424	384	384	370	391	409
0.7222	95	373	373	350	333	340	351	366
0.7644	90	332	323	315	293	310	313	323
0.8120	85	287	284	279	256	275	278	283
0.8634	80	244	245	244	227	245	247	244
0.9220	75	212	209	211	198	220	212	211
0.9861	70	191	185	191	172	200	187	189
1.062	65	182	164	162	144	180	165	169
1.146	60	150	144	135	119	153	135	143
1.225	55	133	133	113	102	125	118	126
1.302	50	113	117	96	89	96	101	109
1.377	45	97	100	84	78	85	87	94
1.452	40	87	87	76	68	75	75	83
1.528	35	77	74	72	59	67	65	74
1.603	30	68	67	68	52	57	57	68
1.670	25	60	63	63	45	51	50	62
1.738	20	53	57	61	42	46	45	57
1.870	10	40	46	51	33	38	31	46
2.000	00	28	39	42	25	26	23	36
2.123	—10	18	25	32	18	...	15	25
2.242	—20	16	16	...	14	...	12	16
2.348	—30	20	...	...	12	...	10	20

was actually growing worse, the effect on the wave lengths less than 0.6 micron would be more and more serious, as indeed the energy curves of figure 1 indicate.

The second day, September 6, is not subject to this criticism. The work of 1920 rests on many good days of observation. Accordingly we decided to give the 1920 work and the 1922 rock salt work each double weight for wave lengths less than 0.5 micron, and all three curves equal weight for greater wave lengths. With this convention we compute the weighted mean of table 10 as plotted in heavy full line in figure 1.

This new result, namely the weighted mean of the 1920 and 1922 observations, given in table 10 and in the heavy full line of figure 1, we regard as our best determination of the form of the solar energy curve outside the atmosphere.

It rests principally on our very careful work of 1920, which, however, on account of its divergence from our previously published work of 1903 to 1910 we had hesitated to publish until further tested. Now it is confirmed beautifully by the rock salt work of 1922, a determination as absolutely different as possible. The principal differences are: Silver in place of stellite at the coelostat; new stellite mirrors in the usual spectroscope; a flint glass prism of high dispersion in place of the low dispersion U. V. crown prism in the auxiliary spectroscope; a rock salt prism of excessively different dispersion in place of the U. V. crown glass prism in the usual spectroscope; a new bolometer and new galvanometer. Also the U. V. crown glass work of 1922 is in almost perfect agreement over the whole range of longer wave lengths, and where it differs in the visible and ultraviolet it differs in the opposite sense to the 1903 to 1910 work.

We place little confidence in our work of 1916 to 1918 on the form of the energy curve, for a reason already explained in Volume IV of the *Annals*. To avoid confusion we have not plotted it, although its mean result is given in table 10. The mean value of 1903 to 1910 is given there and plotted in figure 1. As it rests on a great number of observations at different stations, and as these individual determinations differ widely among themselves, as given in the *Annals*, Volume III, table 62, it is interesting to examine them separately and see if any class of the individual determinations would have tended to agree better with the new work. We are at once struck by the fact that it is the quartz prism work at Mt. Wilson and Mt. Whitney which has given most of the divergence, excepting of course the three short-wave values at the top of column 4 of the above cited

Table 62 of *Annals,* Volume III. These are very likely vitiated by stray light. The quartz prism was very imperfect, being greatly blemished by interior striae and a tinge of smokiness, and its definition was so abominable that hardly any lines could be distinguished in its solar spectrum. Very possibly the determinations with quartz ought therefore to be rejected.

If we should reject all of them, there would result the following modification of Table 62 of *Annals,* Volume III:

Wave length	0.42	0.43	0.45	0.47	0.50	0.55	0.60
Percentage correction by determinations 1, 2, 3, 4	−3.7	−4.8	−6.1	−8.7	−9.3	−10.5	−10.1
Corrected intensities	506	506	566	570	550	503	453

Wave length	0.70	0.80	1.00	1.30	1.60	2.00
Percentage correction by determinations 1, 2, 3, 4	−1.6	+5.4	+2.8	+0.9	+6.2	+3.2
Corrected intensities	358	280	171	90.6	56.5	25.5

These corrected values are given in table 10 and are much closer to the new determination, indeed they are mainly in very good agreement. We therefore are the more confirmed in our view that the new values, the weighted mean of 1920 and 1922, are good, and that the old ones called "Mean 1903 to 1910" were vitiated by the inclusion of the numerous quartz prism determinations.

In figure 1 we have given in dot and dash lines the distribution of energy in the spectrum of the perfect radiator or "black body" at 6,000° absolute centigrade. It is apparent that closer agreement exists between this and the new curve of 1920 and 1922 than exists between it and the old one of 1903 to 1910. But still the observed solar energy curve is far from being of the "black body" form. In order to match the two from 0.6 to 2.0 microns, a higher "black body" temperature than 6,000° would be required, and then the visible and ultra-violet parts of the observed curve would lie far beneath the computed one.

We have explained this kind of phenomenon by a double hypothesis. First, because we see deeper into the sun the longer the wave length, because long-wave rays are less scattered. Hence the infra-red region is supplied by a hotter, because deeper lying, layer. Secondly,

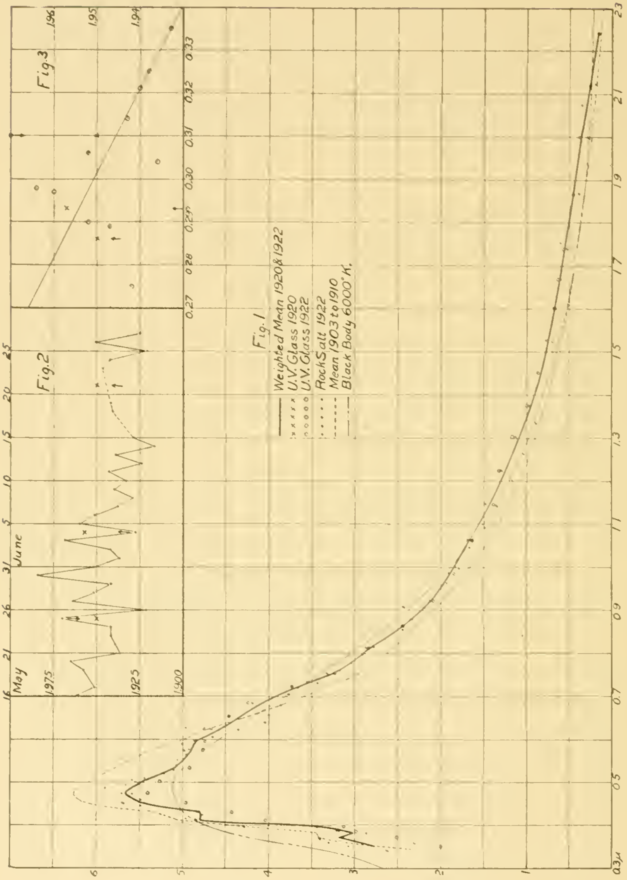
Fig. 1
Weighted Mean 1920 & 1922
U.V. Glass 1920
U.V. Glass 1922
Rock Salt 1922
Mean 1903 to 1910
Black Body 6000° K.
0.3μ
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
1
2
3
4
5
6
Fig. 2
May
June
16
21
26
31
5
10
15
20
25
1.975
1.950
1.925
1.900
Fig. 3
0.27
0.28
0.29
0.30
0.31
0.32
0.33
1.96
1.95
1.94

FIGS. 1, 2, AND 3.

the profusion of Fraunhofer lines in the visible, and still more in the ultra-violet solar spectrum, must cut this part down very greatly. The purity of our spectrum does not suffice to enable us to restrict our measurements to spaces between the lines, as was done by Fabry and Buisson in their beautiful studies of the ultra-violet.[1] They find even for the ultra-violet solar spectrum between wave lengths 0.394 and 0.292 micron, the corresponding "black-body" temperatures between 6,020° and 5,970° K. These measurements, however, relate to the center of the solar image, while ours include the rays as mixed in ordinary sunlight and coming from all parts of the sun's image. Ours is therefore a cooler source than theirs.

Fabry and Buisson draw attention to our over-estimate of the transparency of the earth's atmosphere for rays in this region, which indeed we have already admitted. As they point out, it is impossible to determine the atmospheric transmission correctly in this region without screening out stray light arising in the more intense spectrum regions.

We may remark, however, that the high altitudes of our observing stations, as they tend strongly to build up the ultra-violet compared to other parts of the spectrum, are favorable to diminishing this source of error below what might appear from a mere inspection of Fabry and Buisson's sea-level atmospheric transmission coefficients.

As we have stated at the beginning, we have tried to estimate the effects of the three kinds of errors stray light produces in our work on the form of the ultra-violet solar energy curve outside the atmosphere. Two of these tend to make our values in the ultra-violet too high, and the third acts oppositely. Assuming for the moment that the spectroscopic correction factor is right, suppose the true ordinate of the energy curve outside the atmosphere for a wave length λ in the ultra-violet should be e_t, but that in the ordinary bolographic work we determine this ordinate from observations as e_c. The discrepancy is caused by stray light coming from another part of the spectrum, which increases the intensity observed at the wave length λ, and also increases the apparent atmospheric transmission coefficient because the stray light being of longer wave length is of higher real transmission coefficient than the ray in question. Let e_s be the intensity of the stray light outside the atmosphere, and a_s, a_c, and a_t be the true atmospheric transmission coefficient for stray light, the falsified computed one, and the true one for the wave length λ.

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[1] *Astrophysical Journal,* December, 1921, and *Comptes rendus t.* 175, p. 156, 1922.

Then for air masses 2 and 1, respectively, the observed intensities will be:

$$\left\{e_t a_t^2 + e_s a_s^2\right\} \text{ and } \left\{e_t a_t + e_s a_s\right\}.$$

Therefore $$\frac{e_t a_t^2 + a_s a_s^2}{e_t a_t + e_s a_s} = a_c \text{ and } e_c a_c = e_t a_t + e_s a_s.$$

Whence $$\frac{e_t}{e_c} = \frac{a_c}{a_t} \left\{\frac{a_s - a_c}{a_s - a_t}\right\}.$$

Judging from the visible appearance in the eyepiece of the bolometer, when the spectroscope is set for infra-red rays, where there is properly no visible light, the stray radiation there, and presumably in the ultra-violet region as well, represents impartially the whole spectrum, for it appears in the infra-red as white light. If so, we may reasonably assign for a_s the value 0.90. Other lesser values, 0.80, 0.70, may also be used for illustrative purposes.

Take now a wave length in the ultra-violet for which a_c is 0.60. This in ordinary Mt. Wilson observing is about $\lambda = 0.35\mu$. In the following table we give values of the expression $\frac{e_t}{e_c}$ corresponding to assumed values of a_s and a_t, a_c being 0.60 in all cases.

Table 11.—*Comparison of True and Measured Radiation Outside Atmosphere. Specimens of ratio* $\frac{e_t}{e_c}$.

Stray light transmission	True transmission coefficient		
	0.55	0.50	0.40
0.90	0.93	0.90	0.90
0.80	0.87	0.80	0.75
0.70	0.73	0.60	0.50

These illustrations indicate that for the more probable conditions the ratio of real to bolographically determined radiation outside the atmosphere, so far as this depends on daily observations, is between 0.8 and unity. It is of course easy to see why the ratio falls rapidly when the stray light is assumed to have nearly the same transmission coefficient as that observed, for it must then require a far greater dilution with the stray light to change equally the transmission coefficient of the combination.

Returning now to its influence on the spectroscopic correction factors, we have already pointed out that it tends to make this correction factor too large, but just how much we cannot tell. However, as it works in the same sense as the combined effects just tabulated, we can finally say that the complete tendency of stray light is to cause the ultra-violet region of our spectrum energy curve to be too high. The real values would be such as to give smaller intensities in the ultra-violet than our curve indicates. In other words, the real curve would deviate still further below the "black-body" curve in the ultra-violet than figure 1 indicates.

That the error is not so large as the figures of table 11 indicate, or as readers of Fabry and Buisson's paper might suppose, seems apparent from computations by Fowle of the Rayleigh atmospheric transmission coefficients based on the number of molecules of air above Mt. Wilson. For comparison we give observed transmission coefficients of a good day, September 20, 1914, when we observed from sunrise until noon and also the mean of many good days of the years 1909 to 1912.[1]

TABLE 12.—*Atmospheric Transmission Coefficients. Mt. Wilson*

Wave-length in microns	0.342	0.350	0.360	0.371	0.384	0.397	0.413
Computed	——	0.617	0.650	0.684	0.719	0.751	0.784
Observed Sept. 20, 1914.....	0.615	0.600	0.618	0.681	0.681	0.743	0.764
Observed mean of many days	0.604	0.605	0.635	0.656	0.686	0.726	0.741

Wave-length in microns	0.431	0.452	0.475	0.503	0.535	0.574
Computed	0.815	0.845	0.872	0.897	0.919	0.939
Observed Sept. 20, 1914.....	0.794	0.820	0.859	0.881	0.893	0.889
Observed mean of many days	0.784	0.812	0.841	0.865	0.882	0.887

Our observed transmission coefficients actually fall below the computed values for all wave lengths given in the table, which shows that even with the blue skies of excellent days on Mt. Wilson there is still some effect of haziness additional to molecular scattering. But we do not see that it is necessary to suppose that our observed values are greatly erroneous, at least for wave lengths above 0.350 micron.

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[1] See *Annals Astrophysical Observatory,* Vol. IV, p. 243, and Vol. III, p. 138.

Before leaving the subject of our solar work and its relations to the ultra-violet solar observations of Fabry and Buisson, we give in the following table 13 Fabry and Buisson's determinations of atmospheric ozone for 14 days of the year 1920, and corresponding solar-constant values as determined by Smithsonian observers at Calama, Chile. In giving the solar-constant observations we add for three days corrected values. They are determined by drawing, in figure 2, a smoothed curve following the run of the numbers from day to day. In figure 3 we plot Fabry and Buisson's ozone values as abscissae, with solar-constant numbers as ordinates. The observed values are given as circles, the corrected values as crosses. We believe readers who examine figure 2 will scarcely hesitate to think the three corrected values (the crosses) are probable ones. If that is admitted, we think the run of observations in figure 3 gives some indication that increasing values of the solar constant are associated with decreasing quantities of atmospheric ozone.

TABLE 13.—*Ozone and the Solar Constant*

Date 1920	Ozone value Fabry and Buisson	Solar constant, Calama	
		Observed	Smooth curve
	cm.	*cal.*	
May 21	0.304	1.936	
25	0 310	1.970	1.950
27	0.298	1.964	
28	0.290	1.952	
29	0.275	1.942	
31	0.306	1.952	
June 4	0.293	1.929	1.957
5	0.297	1.960	
7	0 325	1.938	
9	0.321	1.940	
10	0.335	1.933	
11	0.314	1.943	
21	0.286	....	1.950
23	0.289	1.947	

If this is so, the important infra-red ozone band[1] at a wave length of about 10.4 microns, falling exactly in the region where terrestrial radiation is otherwise most freely transmitted by the atmosphere, very likely changes greatly its absorbing power for outgoing earth rays along with changes in the solar radiation, but in the sense to

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[1] See figure 41, *Annals Astrophysical Observatory*, Vol. IV, p. 285.

diminish terrestrial temperatures as solar radiation increases. This, if true, must be an important meteorological consideration. We hope soon to make an investigation of this ozone problem.

STELLAR SPECTRUM ENERGY CURVES

By invitation of Dr. Hale, given in the year 1916, we devised a spectro-bolographic outfit for obtaining spectrum energy curves of images of the brighter stars focused by the 100-inch telescope of the Mount Wilson Solar Observatory. The experiments were unavoidably postponed until the summer of 1922. We do not give here an extended account of them because we hope to repeat them with improvements in sensitiveness and accuracy. We are convinced that though we succeeded in making a vacuum galvanometer of 11 ohms resistance with which we measured 5×10^{-12} amperes, and though in combination with the vacuum bolometer we measured with it a change of temperature of 1×10^{-8} degrees Centigrade, satisfactory stellar spectrum energy observations demand at least tenfold more sensitiveness with fivefold less disturbance than we could achieve in this way. Hence, although we observed roughly the distribution of energy in the spectra of 10 of the brighter stars, including nearly all of the principal Harvard classes, we propose to employ new devices in further experiments.

Without the aid furnished by Dr. Stratton and the Bureau of Standards, Dr. Thomson and the General Electric Laboratory, at Lynn, Dr. Nichols and the Nela Research Laboratory, and especially Dr. Hale, Dr. Adams, and the staff of the Mount Wilson Solar Observatory, we could not have obtained these preliminary results.

Figure 4 gives a general view of the arrangement of apparatus successfully employed after a failure of preliminary experiments at the Newtonian focus of the great telescope, due to electrical and temperature disturbances. The rays *ab* coming from the star were reflected from *b* backwards towards the focus of the 100-inch mirror and were reflected a second time at *c* by a convex mirror whose property it was to increase the focal length from 40 to 250 feet. There was a third reflection by a plane mirror at *d,* so that the rays came at length to the so-called Coudé focus at *e,* in the southern prolongation of the equatorial axis of the telescope.

Here the rays entered the nearly constant temperature room *q,* whose roof, walls, floors, and piers are so massively built of cement as almost to remind one of Egyptian pyramids. The star rays diverged to the concave mirror *f* (at 6 meters distance beyond the

Coudé focus) which brought them a second time to focus over a meter distant at the slit *g*. Thence they diverged to the collimating mirror *h*, of 45 centimeters focus, proceeded parallel to the 18° ultra-violet crown glass prism *i*, and were returned nearly over the same path by a reflecting coat of silver on the back of the prism so that they came at last to focus on the special vacuum bolometer close to the slit *g*.

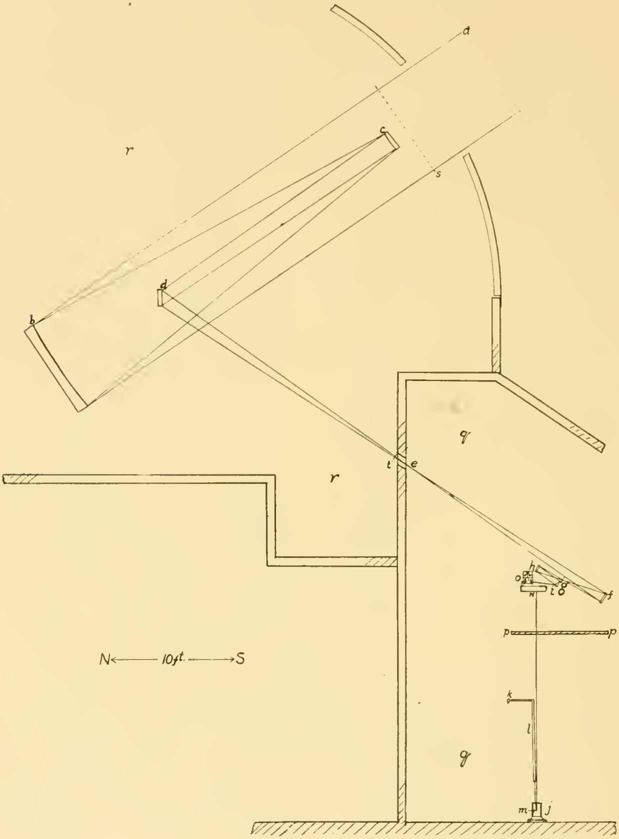

FIG. 4.

Electrical connections led from the spectrobolometer situated 6 meters above the floor (but conveniently adjustable from the platform *p, p*) to the special magnetically shielded galvanometer *j,* whose tiny platinized mirror, *m,* reflected a beam of light from the brilliant special incandescent lamp *k* up to the photographic plate carrier *n,* where bolographs of the stellar spectra were to be taken. The astronomical clock *o* was connected so as to move the prism and photographic plate simultaneously for this purpose.

In practise we found that owing (1) to a slow but persistent drift of the galvanometer due to temperature changes, and (2) to a continual oscillation of the galvanometer light spot over a range of from 1 to 5 millimeters, occasioned apparently by electrical oscillations induced by power and light circuits, it was inadvisable to use the photographic recorder. All of our results were obtained by eye observing upon a ground glass scale drawn with luminous paint, and resting on the platform *p, p,* at 5 meters from the galvanometer.

The procedure of observing was as follows: A selected star having been brought into focus at *c* by the night assistant at the telescope in the dome, *r, r,* the mirror, *f,* was adjusted so as to form its image centrally within the slit at *g.* The prism, previously set by means of a sodium flame exposed at *c* so that the *D* line fell upon the bolometer, was then rotated by turning the driving shaft which connected to the clock *o* through a certain number of turns sufficient to go beyond the region of spectrum where sensible heat could be observed. Then one observer (Mr. Aldrich) made successive settings of whole turns down through the star spectrum, and recorded the other observer's (Mr. Abbot's) galvanometer readings at these settings. Arrived at the other end of the spectrum region where sensible deflections were observed, a return series of settings was made at places half-way between those of the first series. Exposures in the spectrum were made by pulling a cord which lifted a shutter at *t* near the Coudé focus. Frequently the slit *g* was inspected from a distance by a telescope so as to correct if necessary the position of the star image within its jaws.

All of the observations of stellar spectra were made when the stars observed were within less than 50° of the zenith, so that the air-mass never exceeded 1.5. For the purpose of eliminating in one operation the selective losses in the atmosphere, the telescope, and the spectroscope, so far as necessary for such rough measures, it was contrived to observe near midday with the same apparatus an image of the sun whose energy spectrum is known. For this purpose a screen, *s,* with eight symmetrically distributed quarter-inch holes was placed over the top of the telescope tube, and a diaphragm of $\frac{1}{8}$-inch aperture inserted at t. These reductions of the solar intensity sufficed, with a little series resistance added in the galvanometer circuit, to permit the solar spectrum to be observed on nearly equal terms with those of the stars. The factor of reduction to bring the sun down to about the intensity of Capella proved to be as expected a little more than 26 magnitudes.

Employing these solar comparisons together with the 1920 determination of the forms of the sun's energy curve outside the atmosphere both for the prismatic and the normal spectra, we have eliminated selective effects of absorption from the stellar spectra which follow.

On various accounts we are unable to claim much accuracy for our results. They are to be regarded merely as a preliminary feeling-out of the problem. Better knowledge of the distribution of these stellar spectra has, we believe, already been obtained by Coblentz with his method of absorbing screens, also being employed by Pettit and Nicholson. But of course if the employment of a prism could be made satisfactorily, its results would be far preferable to those of absorption methods. Our experiments show us just what must be done to bring this about, and we now have great hope of succeeding in new experiments with modified instruments.

In our experiments of 1922 the principal defects are these:

1. Insufficient sensitiveness. It was impossible to measure the radiation, as weakened by increasing prismatic dispersion and increasing atmospheric and instrumental absorption, far enough towards the violet to follow with any accuracy the normal spectra of stars of types *G, F, A,* and *B* to their maxima.

2. Insufficient accuracy of wave length. With the moderate dispersion of what was practically a 36° crown glass prism, the wanderings of the star image in the wide slit of the spectroscope were sufficient to produce uncertainties of wave length amounting roughly to as much as the distance from D to B in the orange-red of the spectrum. This defect could have been reduced greatly had we been able to continue the experiments one or two more nights, and will easily be made small hereafter by better following devices.

3. Insufficient accuracy of intensity measures. Owing to bad following the image wandered sometimes partly onto the slit jaw before it was corrected. This would, of course, have been prevented had the work gone on. But more serious, because incessant, were the oscillations of the galvanometer light-spot on the scale, through amounts which, for some stars, were nearly as great as the observed maximum deflection in the spectrum. Though every deflection re-

TABLE 14.—*Original Observations of Intensities in Stellar Spectra*

Galvanometer deflections in millimeters

Spectrum place		Name of star observed, its magnitude and spectrum class													
Shaft turns from *D*	Wave length	ϵ Orionis 1.8, *Bo*	β Orionis 0.3, *B8p*	α Lyræ 0.1, *Ao*	α Can. Maj. -1.6, *Ao*	α Aquilæ 0.9, *A5*	α Aurigæ 0.2, *Go*		Sun -26.5, *Ga*	α Tauri 1.1, *K5*		β Pegasi Var., *Ma*	α Herculis Var., *Mb*	α Orionis Var., *Ma*	
		(2)	(2)	(3)	(3)	(3)	(2)	(3)	(1)	(2)	(3)	(2)	(2)	(1)	(3)
—3.0	0.477	0	...	...	...	...	0	1	...	..	..	...	...	..	..
—2.5	0.465	...	...	...	...	0	1	..	3	..	..	...	...	..	..
—2.0	0.484	0	0	...	1	...	2	1.5	...	..	1.5	...	...	..	..
—1.5	0.505	0	0	...	...	2.5	3	..	13	0	5	...	...	..	..
—1.0	0.529	0.5	1.5	...	10	...	3	4	...	..	3	...	0	..	1
—0.5	0.557	4	6	0	9	2	7	..	20	2	7	...	...	..	..
0.0	0.589	4.5	2	6	15	...	5	7	37	3	7	...	0.5	0.5	9
+0.5	0.628	5.5	1	1.5	13	6	4	..	34	3	10	...	...	1.5	0
1.0	0.674	1	5	4	11	5	7	10	43	5	13	0	5	3	16
1.5	0.729	...	0	5	17	5	6	..	45	4	14	...	...	6.5	11
2.0	0.797	...	0	4	6	2	6	14	45	9	17	4?	9	9	18
2.5	0.874	...	...	6	...	1.5	6	..	45	4	15	...	...	12.5	26
3.0	0.966	...	...	2.5	1	...	5	15	36	12	15	5?	7	9	33
3.5	1.088	...	...	3	...	...	1	8.5	41	7	..	...	...	6	30
4.0	1.204	...	...	0	...	...	1	7	30	10	13.5	0.5?	7	3	23
4.5	1.320	...	...	...	...	...	..	6	30	10	..	...	...	2.5	29
5.0	1.434	...	...	...	...	...	..	2	18	10	14	0	5	2	16
5.5	1.544	...	...	...	...	...	..	..	13	4	..	...	...	2	20
6.0	1.652	...	...	...	...	...	..	..	15	0	3.5	0	1	1	28
6.5	1.755	...	...	...	...	...	..	..	11	0	..	...	...	..	11
7.0	1.855	...	...	...	...	...	..	..	4	0	0	0	0	..	7
7.5	1.954	...	...	...	...	...	..	..	...	..	..	...	...	..	5
8.0	2.048	...	...	...	...	...	..	..	...	..	..	...	...	..	12
8.5	2.141	...	...	...	...	...	..	..	...	..	..	...	...	..	0
9.0	2.230	...	...	...	...	...	..	..	...	..	..	...	...	..	0.5

(1) Observations of August 19, 1922. (2) Observations of September 13, 1922. (3) Observations of September 14, 1922.

corded is the mean of several trials, it cannot be hoped that these relatively large disturbances are eliminated satisfactorily. Moreover, the uncertainties of wave-length settings mentioned above aggravate the errors of intensities, because the deflections, even if true, might have related to wave lengths somewhat different from those supposed. If the experiments on each star had been repeated several times on later nights very much greater accuracy could doubtless have been had in the final means. But, after all, the sensitiveness available was not adequate ever to give satisfactory results, and it would have been a waste of time to go on with the apparatus as it was in 1922. With these remarks we give the observations. We have arranged the stars in order of the Harvard spectrum classification, although the order of observing followed approximately the order of their right ascensions.

The scale of galvanometer deflections differs on the three nights of observation and even at different hours of the same night according to the time of swing which was practicable at the time. Wherever there are two observations on one star we have reduced the smaller deflection data to the scale of the larger approximately and have given the observations of larger deflection greater weight in drawing smoothed curves. In view of what has been said of the sources of error always present, readers will not be surprised at the irregularities which the data present.

As the work is altogether rough and preliminary we shall not take space to detail what steps were necessary to reduce the direct observations for the selective losses in the atmosphere and the apparatus, merely repeating that these reductions depended on the solar-spectrum observations of 1920 taken together with those made on August 19, 1922, with the great telescope and stellar spectro-bolometric outfit.

In figure 5 we have given in smooth curves as well as we can the stellar distribution outside the atmosphere on the scale of the 36° ultra-violet crown glass prism, and in figure 6 the corresponding curves reduced to the normal or wave-length scale. In drawing the normal curves we were immediately made conscious that for the stars of types *B, A, F, G,* the original very small deflections in the shorter wave lengths lacked a sufficient degree of accuracy to warrant multiplying them by the very large prismatic dispersion factors. Such results would have had no meaning and would have been apt to mislead. Accordingly we cut off all of these normal curves beyond wave length 0.5 micron, and omitted four stars of types *B* and *A* for which the observed deflections at maximum ordinate in the prismatic spectrum did not exceed 5 millimeters.

Obviously in order to determine at all satisfactorily by heat methods the spectrum distribution for stars of types *B*, *A* and *F*, it will be necessary to use apparatus of a decidely higher order of sensitiveness than ours.

On the whole the positions of maximum ordinates in the prismatic spectra shift with spectrum type much as we should have expected.

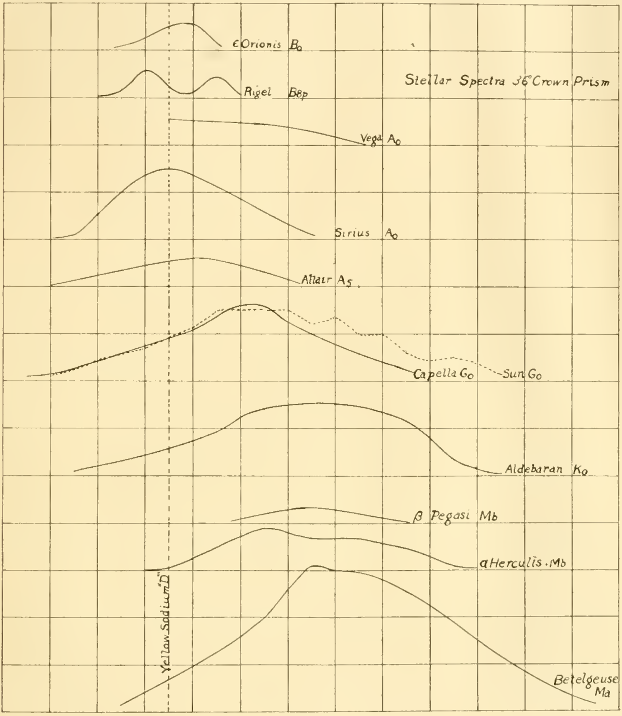

FIG. 5.

It is satisfactory that the curves for the sun and Capella agree so well. The several depressions in the infra-red of the solar curve are most likely real, as they coincide closely with great infra-red water vapor bands. The stellar curves would doubtless have shown them too if there had been enough energy so that they had been equally as accurate.

We attribute little weight to the circumstance that the maximum in the normal spectrum curve of α Herculis falls to the violet of that of α Orionis. That Aldebaran gives its maximum at shorter wave lengths than either, we think is real, but we do not feel confidence in the exact places for any one of the three. Greater accuracy is essential if real deductions as to star temperatures and their approach to "black body" conditions are to be made.

Though we have not concealed the shortcomings of these stellar observations, they cost a great deal of effort. Fatalities seemed to lurk about the work to surprise us so that we were almost ashamed to meet any one on Mount Wilson lest he should ask what new things had gone wrong that day. We made a list of all the serious mishaps, and they numbered nearly 30, some requiring a whole week to repair. But we feel after all that a decided step was made to have gotten from 10 to 30 millimeters deflection in the fairly extended spectra of four of the brightest stars. For it was not many years ago that Boys failed to recognize stellar heat, and Nichols observed but one or two millimeters in the total radiation of such stars. Naturally our success, such as it was, depended largely on the great size of the Mount Wilson telescope, but besides that it indicates a large gain in sensitiveness of apparatus. Furthermore, the experience gained clarifies the problem so exactly that plans for future experiments may now be laid with great certainty.

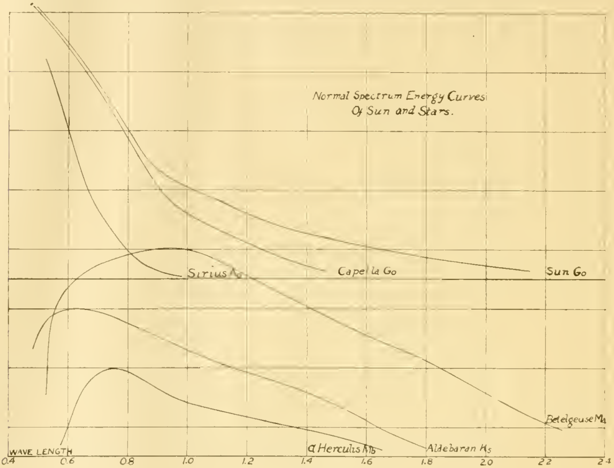

FIG. 6.