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THE RADIATION OF THE PLANET EARTH TO SPACE

(With Two Plates)

BY
C. G. ABBOT

(Publication 3028)

CITY OF WASHINGTON
PUBLISHED BY THE SMITHSONIAN INSTITUTION
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THE RADIATION OF THE PLANET EARTH TO SPACE

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In an illuminating series of papers, G. C. Simpson recently has approached the subject of terrestrial and atmospheric radiation to outer space. The first of these papers is entitled " Some Studies in Terrestrial Radiation."[1] Here Simpson makes the unsatisfactory assumption that the atmospheric water vapor behaves like a " grey body " in absorbing radiation. That is, he assumes that general coefficients of absorption and of transmission may be employed, without regard to the wave length of the radiation considered. Arriving in this way at unexpected and questionable results, Simpson then modified his procedure in a second paper entitled " Further Studies in Terrestrial Radiation."[2] Here he makes the following important assumptions: (a) The stratosphere contains 0.3 mm. of precipitable water. (b) The absorptive properties of atmospheric water vapor may be regarded as so similar to those of steam that Hettner's[3] observations of the absorption of a layer of steam may be taken as representing the coefficients of absorption of atmospheric water vapor between wave lengths 4μ and 34μ.[4] (c) " The stratosphere absorbs all radiation between wave lengths $5\frac{1}{2}\mu$ and 7μ, and from wave length 14μ to the end of the spectrum."

As the Smithsonian Institution has hitherto published considerable evidence relating to these three subjects, it has occurred to me to see whether the use of our independently derived data would check well the

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[1] Mem. Roy. Meteorol. Soc., Vol. 2, No. 16, 1928.

[2] *Ibid.*, Vol. 3, No. 21, 1928.

[3] Hettner, G., Ann. Physik. Leipzig, 4th Folge., Band 55, p. 476, 1918.

[4] Simpson nevertheless calls attention to the incomplete similarity between the absorption of concentrated and unconcentrated vapors, and therefore corrects Hettner's curve between 8μ and 11μ from other data derived from atmospheric experiments.

results of Simpson in this important field. Fowle[1] carried on for several years, 1908 to 1917, experiments on the absorption of radiation of long wave lengths by the atmosphere contained in tubes of large diameter and up to 800 ft. in length. These tubes were laden with water vapor ranging from 0.2 up to 2.5 mm. of precipitable water, and of carbon dioxide content ranging from 7 grams up to 160 grams per meter cross-section at normal temperature and pressure.

In his early experiments, Fowle had established means for determining the quantity of precipitable water in atmospheric air by means of measurements on the bands $\rho\sigma\tau$, ϕ, and ψ of the upper infra-red solar spectrum. These experiments are fortunately very definite as to the determination of water vapor equivalent to 0.3 mm. of precipitable water.

In the summer of the years 1909 and 1910, Abbot observed the infra-red solar spectrum from Mount Whitney, California, altitude 4,420 m. Bolographs of the spectrum were obtained, having very satisfactory quality as far as the delineation of the bands $\rho\sigma\tau$, ϕ, and ψ is concerned.[2] From these, Fowle determined the quantity of total precipitable water in a vertical path of atmosphere above Mount Whitney. On August 14, 1910, he observed 0.6 mm. Considering the moderate altitude and the summer season, this small observed water-vapor content hardly prepares one to accept Simpson's assumption that the stratosphere, which begins at 12,000 m., and is at a temperature about 50° C. lower than that which prevailed at the summit of Mount Whitney on that occasion, can contain half of the precipitable water above that station. We have other evidence leading to the same view.

At Mount Montezuma, Chile, altitude 2,710 m., we have observed spectroscopically the total precipitable water in a vertical column above the station almost daily for about 10 years at all seasons. The following table gives average values for the 12 months, and also extreme values for each of these months, together with associated surface temperatures.

In illustration of the great alterations in the appearance of the solar energy spectrum depending on the quantity of atmospheric humidity, we give reproductions of two days' observations at Montezuma, plates 1 and 2. Note the bands $\rho\sigma\tau$, ϕ, ψ and Ω.

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[1] Fowle, F. E., Ann. Astrophys. Observ., Vol. 4, pp. 274-286. Astrophys. Journ., Vol. 38, p. 393, 1913; Vol. 42, p. 394, 1915. Smithsonian Misc. Coll., Vol. 68, No. 8, 1917.

[2] See Annals, Vol. 4, fig. 50.

TABLE I.—*Monthly Mean Results at Montezuma, Years 1923 to 1928*

Month	Temp. for year 1924 Mean dry bulb 8 o'clock a. m.	Precipitable Water in Centimeters									Surface pressure aqueous vapor
		Mean of years 1923–1928	Total no. of days	Mean of absolute minima	Year of absolute minimum	Mean of absolute maxima	Year of absolute maximum	Absolute daily minimum	Absolute daily maximum	No. of days values less than 0.10 cm.	
		cm.		cm.		cm.		cm.	cm.		mm.
Jan.	17.0	0.89	114	0.34	1924	1.44	1927	0.08	2.16	2	3.0
Feb.	14.7	1.04	108	0.41	1928	1.84	1925	0.16	2.38	0	4.9
Mar.	13.5	0.80	140	0.36	1923	1.52	1927	0.19	2.13	0	4.2
Apr.	13.7	0.46	140	0.12	1924	1.12	1925	0.06	1.73	2	2.9
May	9.2	0.31	140	0.10	1924	0.76	1925	0.04	1.40	8	1.9
June	9.1	0.30	130	0.08	1923	0.64	1923	0.03	1.14	9	1.8
July	8.7	0.23	149	0.05	1926	0.74	1926	0.02	0.97	24	1.4
Aug.	9.0	0.23	137	0.05	1924	0.64	1926	0.04	0.93	26	1.9
Sept.	12.0	0.26	138	0.07	1928	0.71	1924	0.05	0.87	12	1.9
Oct.	14.0	0.29	159	0.07	1924	0.68	1926	0.03	1.02	10	2.1
Nov.	14.9	0.37	145	0.12	1924	0.87	1923	0.05	1.24	7	2.3
Dec.	15.7	0.65	122	0.22	1924	1.33	1927	0.10	1.54	0	3.3

Numbers of days observed of precipitable water

Total 1923 to 1928	With values less than 0.10 cm.	With values in centimeters:							
		0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
1622	100	3	7	12	9	19	17	21	12

From the tabular data, it is clear that values of total precipitable water are frequently observed at Montezuma closely approaching the value assumed by Simpson for the stratosphere. These values are found in winter, with a surface air temperature of +9° C., on the edge of the tropics at 2,710 m. altitude.

In view of these observations at Montezuma, and considering the rapid decrease of humidity with temperature (the vapor pressure at −50° and 0° C. being respectively 0.03 and 4.58 mm.) and also the fact that three-fourths of the superincumbent atmosphere lies between Montezuma station and the bottom of the stratosphere, one is forced to conclude that the value of the precipitable water contained by the stratosphere is vanishingly small, rather than 0.3 mm. as assumed by Simpson. This materially affects his argument, especially that part which relates to cloudy skies.

As an independent approach, instead of Simpson's two other basic assumptions, which we have designated as (b) and (c), we have employed Fowle's two summaries of the results obtained in his long-tube experiments.[1] To make these results of Fowle's applicable to the problem of atmospheric radiation and absorption, as set by Simpson, we have prepared a large scale plot, reproduced in reduced size in figure 1. From this plot we take table 2. In choosing the quantities of precipitable water to be used, we have doubled the values given by Simpson for successive layers in the table he designates as "Fig. I," page 72, of his paper "Some Studies in Terrestrial Radiation." This doubling we do because of the following consideration.

We are proposing to ascertain the radiation which certain layers of the free atmosphere, containing natural loads of water vapor and carbon dioxide, will send upwards in all directions within a solid angle filling a complete hemisphere. We assume, as does Simpson, that for monochromatic rays the emission of such a layer bears the same proportion to the emission of the perfect radiator that the absorption of the layer in question bears to unity. While some rays are emitted vertically, most rays are emitted obliquely, so that the average emission and absorption of a layer exceeds that which corresponds to the precipitable water vapor and carbon dioxide found in a vertical path. It is readily proved by performing the integration over a complete hemisphere that the average upward path is double the vertical one. Hence we have doubled Simpson's figures for the precipitable water contained in the layers he has chosen. These data appear in table 2.

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[1] See Annals, Vol. 4, Table 102, p. 286; also Smithsonian Physical Tables, 7th Rev. Ed., 4th reprint, p. 308.

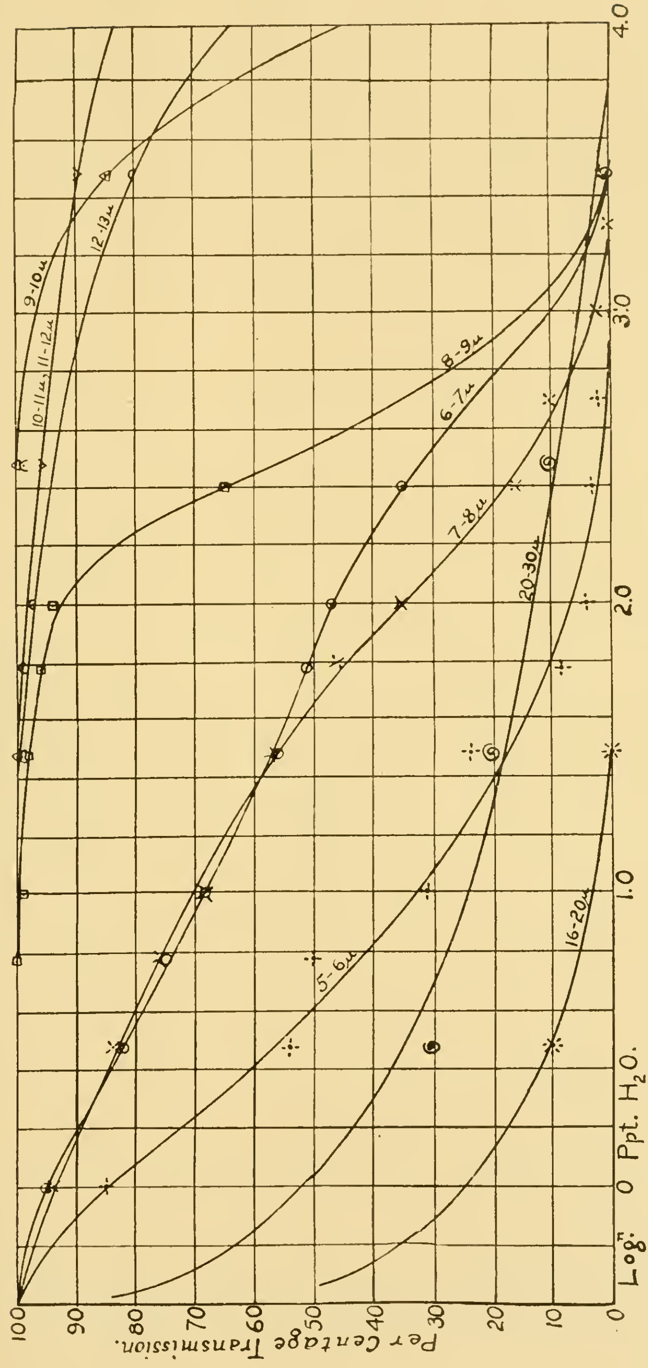

FIG. 1.—Absorption and Transmission of Radiation by Air Laden with Water Vapor and Carbonic Acid Gas. (After Fowle.)

As a second step, we consider the spectral distribution and intensity of emission of the perfect radiator at different temperatures.[1] By interpolation on large scale plots we have prepared table 3. This gives the approximate[2] intensity of emission of the perfect radiator at temperatures corresponding to the mean temperatures of Simpson's layers, and to those of his selected latitudes of the earth's surface.

Multiplying the values in table 2 by corresponding ones in table 3, we obtain the emission of radiation outwards from each Simpson atmospheric layer towards a complete hemisphere. The values are given in table 4.

Again interpolating in the plots (fig. 3) we next obtained the transmission coefficients for each superincumbent atmospheric mass lying above the respective Simpson layers. Allowance is made for the ozone absorption between 9μ and 11μ. These values are given in table 5.

Multiplying these values by corresponding ones in tables 3 and 4, we obtained the contributions of the Simpson atmospheric layers and also of the earth's surface[3] at the latitudes 90°, 70°, 60°, 50°, 40°, and 0° to the intensity of emission of the earth as a planet towards outer space.[4] These results are given in table 6.

All of these results apply to cloudless skies. We now assume, with Simpson, that the earth is 50 per cent cloudy; that the clouds totally absorb all radiation arising from beneath them; that they radiate quite as efficiently as the perfect radiator; and that their upper surfaces maintain the same average temperature as the earth at 70° latitude. We are not able to compute their radiation in Simpson's manner, since we have shown reasons to believe that the stratosphere is almost destitute of water vapor, instead of containing 0.3 mm. of precipitable water as he supposes. We simply assume that the combined emission of clouds and atmosphere during one-half the time at all latitudes is the same as that of the earth's surface and the superincumbent atmosphere at latitude 70°. That is: For the atmosphere 0.151 cal. per $\overline{\text{cm}}.^2$ per min.; for the cloud surface 0.100 cal., giving a total for completely overcast sky of 0.251 cal. During the other half of the time,

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[1] See Smithsonian Physical Tables, p. 248.

[2] We do not guarantee these values to within 2 per cent.

[3] We assume, with Simpson, that the earth's surface may be regarded as a perfect radiator.

[4] Notwithstanding our previous evidence that the water-vapor content of the stratosphere is vanishingly small, we have thought best to estimate 30 per cent of black-body efficiency as applicable to the stratospheric radiation in the wave-length region 13μ to 50μ, where water vapor is so very active. We have allowed 16 per cent of black body efficiency to the ozone band, 9μ to 11μ.

TABLE 2.—*Percentage Emission of Simpson Layers (after Fowle) Compared to Perfect Radiator = 100*

Simpson Layer	Precipitable H_2O (Doubled)	Log. ppt. H_2O × 1000	Wave lengths, microns											
			5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–16	16–20	20–30	30–40	40–50
	cm.														
— 3	.0002	$\bar{1}.30$	1	3	1	0	0	0	0	0	100	15	10	100	100
— 2	.0006	$\bar{1}.78$	3	9	3	0	0	0	0	0	100	45	30	100	100
— 1	.0012	0.08	8	20	7	0	0	0	0	0	100	78	52	100	100
+ 1	.0020	0.30	13	33	13	0	0	0	0	0	100	85	60	100	100
2	.006	0.78	26	58	24	0	0	0	0	0	100	94	72	100	100
3	.012	1.08	34	70	32	0	0	0	0	0	100	98	77	100	100
4	.024	1.38	41	79	41	2	0	0	0	0	100	100	80	100	100
5	.048	1.68	47	87	51	4	0	1	1	2	100	100	84	100	100
6	.092	1.96	53	93	63	7	0	2	2	3	100	100	87	100	100
7	.172	2.24	59	96	75	18	0	3	3	4	100	100	89	100	100
8	.312	2.49	68	98	85	44	0	4	4	6	100	100	91	100	100
9	.548	2.74	78	99	93	68	1	6	6	8	100	100	93	100	100
10	.910	2.96	89	100	97	84	3	7	7	11	100	100	95	100	100
11	1.456	3.16	95	100	99	93	6	8	8	14	100	100	96	100	100
12	2.280	3.36	99	100	100	99	11	10	10	17	100	100	98	100	100
13	3.540	3.55	100	100	100	100	20	11	11	22	100	100	99	100	100

TABLE 3.—*Energy Distribution in Spectra of Perfect Radiator*
(To reduce to cal. per $\overline{\text{cm.}}^2$ per min., multiply by .0001)

Simpson Layer	Temperature Absolute C	Wave lengths, microns												
		5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–16	16–20	20–30	30–40	40–50
—3	205	...	3	24	33	51	60	60	60	210	261	396	162	60
—2	211	3	6	30	42	60	75	75	75	246	291	435	174	63
—1	217	3	12	36	57	75	90	90	90	285	324	474	186	69
+1	223	6	21	48	72	90	105	105	105	324	357	513	198	75
2	229	9	30	60	87	108	120	120	120	360	390	555	210	81
3	235	12	39	75	102	123	138	138	138	402	420	594	225	87
4	241	18	51	90	120	144	156	156	156	441	453	630	237	90
5	247	27	63	108	141	165	174	174	174	480	486	669	249	96
Pole	250	30	72	119	152	176	186	187	187	503	506	690	256	99
6	253	33	81	129	162	186	198	198	198	525	525	711	261	102
7	259	39	99	150	186	210	222	222	219	573	561	750	273	108
Lat. 70°	262	47	110	164	198	225	234	234	230	598	581	768	281	111
8	265	54	120	177	210	240	246	246	240	624	600	786	288	114
Lat. 60°	268	58	132	189	225	254	258	258	251	650	617	807	292	117
9	271	63	144	201	240	267	270	270	261	675	633	828	300	120
10	277	84	171	231	270	297	300	300	285	732	681	870	312	126
Lat. 50°	280	95	186	248	287	315	316	315	297	762	703	888	320	129
11	283	105	201	264	303	333	336	330	309	792	726	906	327	132
Lat. 40°	286	119	216	282	325	353	354	345	324	825	753	925	333	135
12	289	132	231	300	348	372	372	360	339	858	780	945	339	138
13	295	165	270	345	396	420	411	396	369	930	834	987	354	144
Equator	298	180	288	372	426	444	432	414	390	960	864	1005	360	150

TABLE 4.—*Radiation of Layers of Atmosphere Depending on H_2O and CO_2*

(To reduce to cal. per $\overline{\text{cm.}}^2$ per min., multiply by .0001)

Simpson Layer	Wave lengths, microns												
	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–16	16–20	20–30	30–40	40–50
—3	0	0.1	0.2	0	0	0	0	0	210.0	39.1	39.6	162.0	60.0
—2	0.1	0.5	0.9	0	0	0	0	0	246.0	130.9	130.5	174.0	63.0
—1	0.2	2.4	2.5	0	0	0	0	0	285.0	252.7	246.5	186.0	69.0
+1	0.8	7.0	6.2	0	0	0	0	0	324.0	303.4	307.8	198.0	75.0
2	2.3	17.4	14.4	0	0	0	0	0	360.0	366.6	399.6	210.0	81.0
3	4.0	27.3	24.0	0	0	0	0	0	402.0	411.6	457.4	225.0	87.0
4	7.4	40.3	36.9	2.4	0	0	0	0	441.0	453.0	504.0	237.0	90.0
5	12.7	54.8	55.1	5.6	0	1.7	1.7	3.5	480.0	486.0	562.0	249.0	96.0
6	17.5	75.3	81.3	11.3	0	3.9	3.9	5.8	525.0	525.0	618.6	261.0	102.0
7	23.0	95.0	112.5	33.5	0	6.7	6.7	8.7	573.0	561.0	667.5	273.0	108.0
8	36.3	117.6	150.4	92.4	0	9.8	9.8	14.4	624.0	600.0	715.3	288.0	114.0
9	49.1	142.6	186.9	163.2	2.7	16.2	16.2	20.9	675.0	633.0	770.0	300.0	120.0
10	74.8	171.0	224.1	226.8	8.9	21.0	21.0	31.3	732.0	681.0	826.5	312.0	126.0
11	100.0	201.0	261.4	281.8	19.9	26.9	26.4	43.3	792.0	726.0	869.8	327.0	132.0
12	131.0	231.0	300.0	344.5	40.9	37.2	36.0	57.6	858.0	780.0	926.1	339.0	138.0
13	165.0	270.0	345.0	396.0	84.0	45.2	43.6	81.2	930.0	834.0	977.1	354.0	144.0

TABLE 5.—*Percentage Transmission through Superincumbent H_2O, O_3 and CO_2 (after Fowle)*

(Absorption of ozone, 9–11μ, from Fig. 41, Annals, Vol. 4)

Simpson Layer	Superincumbent ppt. H_2O (Doubled)	Log. H_2O	Wave lengths, microns												
			5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–16	16–20	20–30	30–40	40–50
	cm.														
—3......	.0002	—.70	99	97	99	100	84	84	100	100	0	85	90	0	0
—2......	.0008	—.10	94	89	96	100	84	84	100	100	0	40	70	0	0
—1......	.0020	+.30	87	67	87	100	84	84	100	100	0	14	40	0	0
+1......	.0040	.60	79	51	80	100	84	84	100	100	0	8	32	0	0
2......	.0100	1.00	68	33	70	100	84	84	100	100	0	3	24	0	0
3......	.024	1.38	59	21	59	99	84	84	100	100	0	1	19	0	0
4......	.048	1.68	53	12	49	97	84	83	99	98	0	0	16	0	0
5......	.096	1.98	47	7	36	93	84	82	98	97	0	0	13	0	0
6......	.188	2.27	39	3	23	78	84	82	97	95	0	0	10	0	0
7......	.360	2.56	29	1	12	48	84	80	95	93	0	0	8	0	0
8......	.672	2.83	17	0	5	25	82	79	94	91	0	0	6	0	0
9......	1.22	3.08	7	0	2	10	81	77	92	88	0	0	4	0	0
10......	2.13	3.33	2	0	0	2	76	76	91	83	0	0	3	0	0
11......	3.59	3.55	0	0	0	0	67	75	89	78	0	0	1	0	0
12......	5.87	3.77	0	0	0	0	55	73	87	72	0	0	0	0	0
13......	9.41	3.97	0	0	0	0	38	70	83	63	0	0	0	0	0

TABLE 6.—*Atmospheric and Surface Radiation Reaching Outer Space through Cloudless Sky*

(To reduce to cal. per $\overline{\text{cm.}}^2$ per min., multiply by .0001)

Simpson Layer	Wave lengths, microns													Totals
	5–6	6–7	7–8	8–9	9–10	10–11	11–12	12–13	13–16	16–20	20–30	30–40	40–50	
Stratosphere	......	......	......	......	9.6	9.6	......	......	63.2	78.3	118.8	48.6	18.0	346.1
—3	0.0	0.1	0.2	0	0	0	0	0	0	33.2	35.6	0	0	......
—2	0.1	0.4	0	0	0	0	0	0	0	52.3	91.5	0	0	......
—1	0.2	1.6	2.2	0	0	0	0	0	0	35.3	98.8	0	0	......
1	0.6	3.5	4.9	0	0	0	0	0	0	24.3	98.6	0	0	......
2	1.6	5.6	10.0	0	0	0	0	0	0	11.0	96.0	0	0	......
3	2.4	5.7	14.2	0	0	0	0	0	0	4.1	86.8	0	0	......
4	3.9	4.8	18.1	2.4	0	0	0	0	0	0	80.6	0	0	......
5	6.0	3.7	19.8	5.2	0	1.4	1.7	3.4	0	0	73.1	0	0	......
Pole:														
Atmosphere	14.8	25.4	70.3	7.6	9.6	11.0	1.7	3.4	63.2	238.5	779.8	48.6	18.0	1291.9
Surface	14.1	5.0	38.9	141.4	147.8	152.5	183.3	181.4	0	0	89.7	0	0	954.1
														2246.0
6	6.8	2.2	18.7	8.8	0	3.2	3.8	5.6	0	0	61.9	0	0	......
7	6.7	1.0	13.5	16.0	0	5.4	6.5	8.1	0	0	53.4	0	0	......
Lat. 70°:														
Atmosphere	28.3	28.6	102.5	32.4	9.6	19.6	11.9	17.1	63.2	238.5	895.1	48.6	18.0	1513.4
Surface	13.6	1.1	19.7	95.0	189.0	187.2	222.3	213.9	0	0	61.4	0	0	1003.2
														2516.6
8	6.0	0	7.5	23.1	0	7.7	9.2	13.1	0	0	42.9	0	0	......
Lat. 60°:														
Atmosphere	34.3	28.6	109.5	55.5	9.6	27.3	21.1	30.2	63.2	238.5	938.0	48.6	18.0	1622.4
Surface	9.9	0	9.4	90.0	208.3	203.8	242.5	228.4	0	0	48.4	0	0	1040.7
														2663.1
9	3.5	0	3.7	16.3	2.2	12.5	14.9	18.4	0	0	30.8	0	0	......
10	1.5	0	0	4.5	6.8	16.0	19.1	26.0	0	0	24.8	0	0	......
Lat. 50°:														
Atmosphere	39.3	28.6	113.2	76.3	18.6	55.8	55.1	74.6	63.2	238.5	993.6	48.6	18.0	1823.4
Surface	1.9	0	0	5.7	239.4	240.2	286.6	246.5	0	0	26.6	0	0	1046.9
														2870.3
11	0	0	0	0	13.3	20.2	23.5	33.8	0	0	8.7	0	0	......
Lat. 40°:														
Atmosphere	39.3	28.6	113.2	76.3	32.9	76.0	78.6	108.4	63.2	238.5	1002.3	48.6	18.0	1923.9
Surface	0	0	0	0	236.5	265.5	307.0	252.7	0	0	9.2	0	0	1070.9
														2994.8
12	0	0	0	0	22.5	27.2	31.3	41.5	0	0	0	0	0	......
13	0	0	0	0	31.9	31.6	36.2	51.2	0	0	0	0	0	......
Equator:														
Atmosphere	39.3	28.6	113.2	76.3	87.3	134.8	146.1	201.1	63.2	238.5	1002.3	48.6	18.0	2197.3
Surface	0	0	0	0	161.9	302.4	343.6	245.7	0	0	0	0	0	1053.6
														3250.0

the values at different latitudes are as given in table 6 for clear skies. For half-cloudy skies we take the mean of the two conditions.

We are now prepared to assemble our results and compare them with those of Simpson (table 7).

It is clear that our employment to a considerable extent of independent data and methods has made no very great difference in the totals from those of Simpson. The range of our totals for half-cloudy sky is indeed considerably greater than his as between the equator and the poles. Our method has enabled us to segregate the contributions of the atmosphere and of the earth's surface, which in Simpson's second paper are not computed separately. We find the earth's surface almost equally contributing at all latitudes, but the atmosphere, which contributes much more than half the total (even more than two-thirds the total on cloudless days at the equator) emits very much lesser proportions as we approach the poles. The two sources are very different as regards wave lengths of principal contribution; the atmosphere emitting mostly in the region exceeding 16μ in wave length, the surface emitting principally in the region 9μ to 13μ.

TABLE 7.—*Radiation of Earth and Atmosphere to Space*
Calories per $\overline{\text{cm}}.^2$ *per min.*

Latitude	Smithsonian results						Simpson results		
	Clear sky			Half-cloudy sky			Atmosphere plus surface		
	Atmosphere	Surface	Total	Atmosphere	Surface or cloud	Total	Clear	Overcast	Half-cloudy
0°	0.220	0.105	0.325	0.186	0.102	0.288	0.316	0.213	0.264
40°	0.192	0.107	0.299	0.171	0.103	0.274	0.307	0.243	0.275
50°	0.182	0.105	0.287	0.166	0.102	0.268	0.291	0.249	0.270
60°	0.162	0.104	0.266	0.156	0.102	0.258	0.274	0.252	0.265
70°	0.151	0.100	0.251	0.151	0.100	0.251	0.253	0.253	0.253
90°	0.129	0.096	0.225	0.140	0.098	0.238	....	....	0.245

If we sum up the results in the seventh and tenth columns, which represent our own and Simpson's totals for half-cloudy sky, and assign weights to them proportional to the areas of earth which they respectively represent, we find that the earth as a planet radiates averages of 0.277 or 0.265 cal. per square centimeter per minute according as our results or Simpson's are taken. If we compute the same quantity from the solar constant, 1.94 cal., and Aldrich's albedo, 43 per cent, the result is $\frac{1.94}{4} \times 0.57 = 0.276$ cal. The discrepancies are very small and far within the probable error of the determinations.


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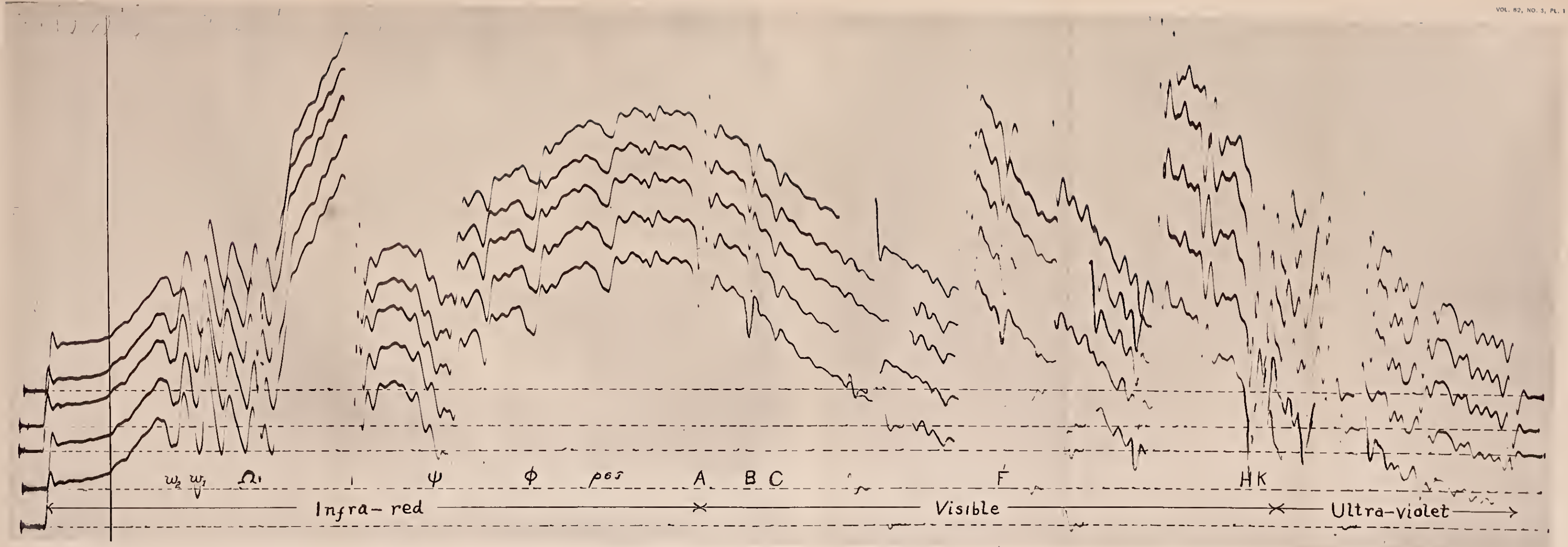
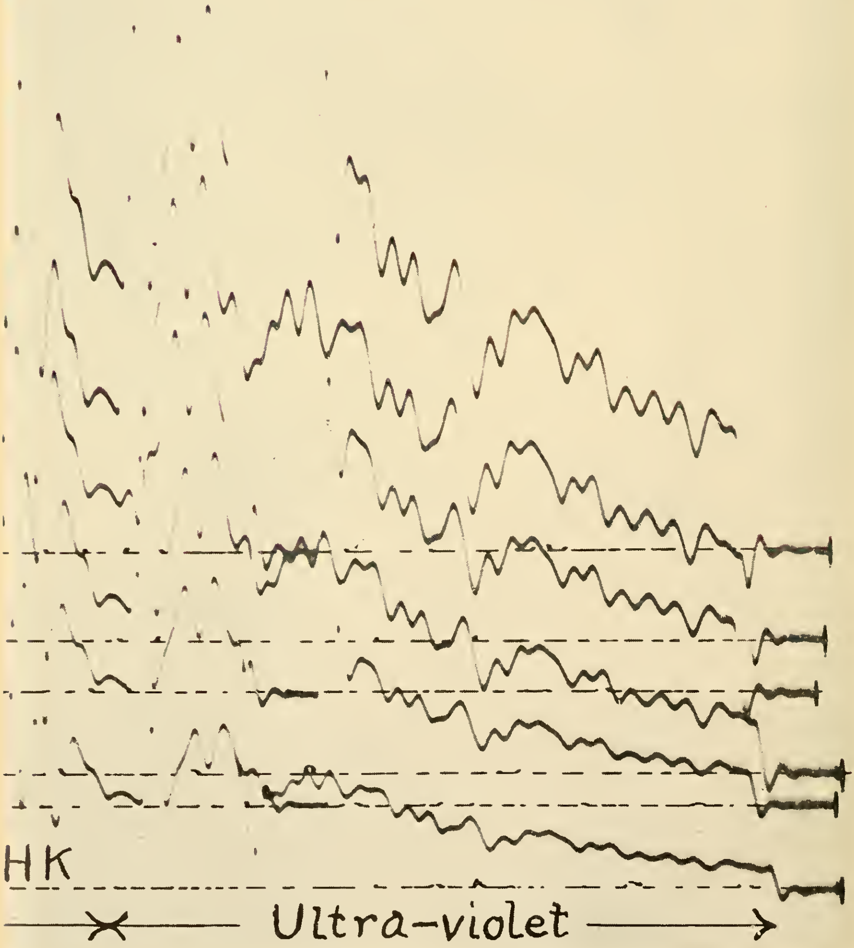


Bolographs of the Solar Energy Spectrum. Observed at Montezuma, Chile, July 7, 1924.
Precipitable water, 0.03 centimeters.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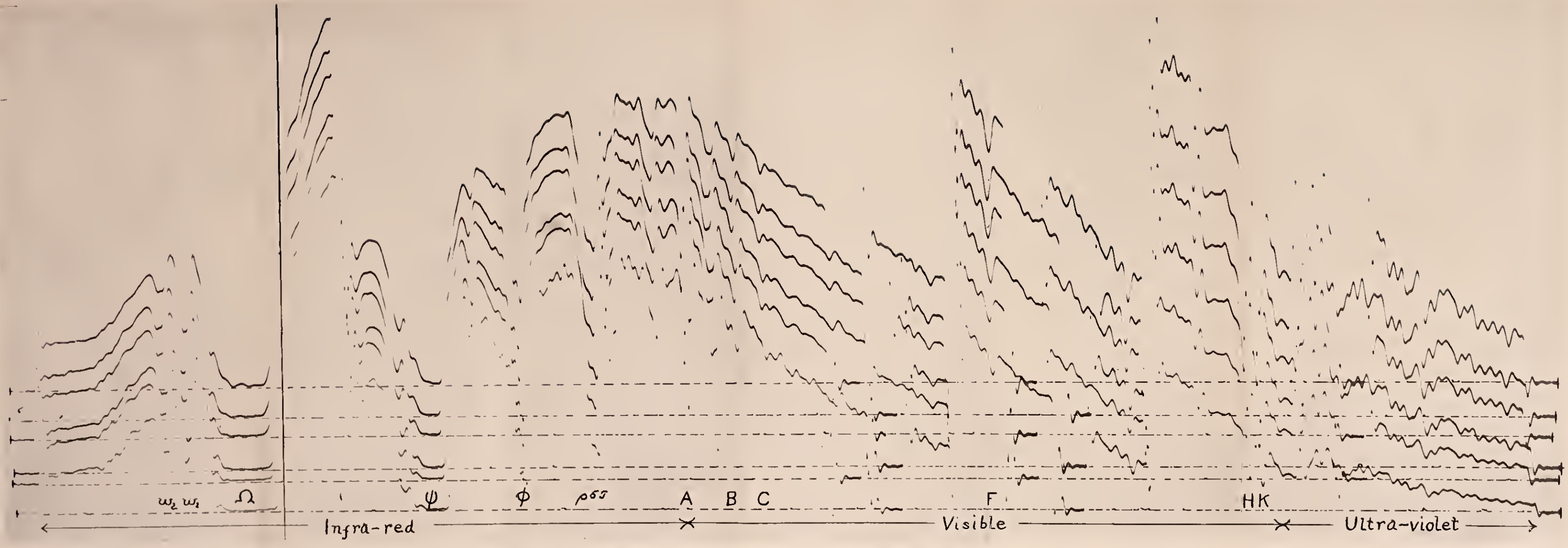
Ultra-violet



Bolographs of the Solar Energy Spectrum. Observed at Montezuma, Chile, March 18, 1925.
Precipitable water, 1.37 centimeters.