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MAGNETIC STORMS, SOLAR RADIATION, AND WASHINGTON TEMPERATURE DEPARTURES

(With Two Plates)

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Occasionally the earth's magnetic condition is greatly disturbed. At such times large sunspot groups are usually visible near the center of the solar disk. From studies of the aurora, radio transmission, and other electrical phenomena of the atmosphere, it is concluded that the earth is being bombarded by showers of electric ions at times of magnetic storms. These ions appear to emanate most copiously from sunspots.

For many years the Smithsonian Institution has made daily measurements, whenever possible, of the heat equivalent of the energy of solar radiation. It lies mainly in the wave-length region from 0.33 to 2.5 microns (thousandths of a millimeter). This embraces ultraviolet, visible, and infrared rays. The measurements are made in such a way that the losses caused by the earth's atmosphere may be estimated. On each day of observation it is computed what the intensity of the sun's heat would be if one could observe at mean solar distance outside the atmosphere. The values thus obtained are termed measures of "the solar constant of radiation." The average value of the solar constant is about 1.94 calories per square centimeter per minute. Fluctuations in solar-constant values occur, but the range of them is small, seldom exceeding 1 percent of the total.

The earth's atmosphere on a cloudless day diminishes the intensity of solar heat of the direct sun beam reaching the earth's surface in several ways: First, by the scattering exerted by the molecules of oxygen, nitrogen, and other gases of the atmosphere; second, by the scattering and absorption produced by dust particles floating in the atmosphere, and seen as haze; third, by the absorption of rays of certain wave lengths by oxygen, carbon dioxide, water vapor, ozone, and other gases and vapors which produce true absorption of radiation with conversion of radiant energy into heat. About 1880 Lord

Rayleigh proved that the scattering by particles (such as molecules and very small dust particles) which are small compared to the wave length of light is proportional inversely to the fourth power of the wave length. Thus it happens that the sky is blue, because the blue rays, being of shorter wave length than the red or yellow rays, are much more scattered out of the direct sun beam by the molecules of the atmospheric gases.

If now, as stated above, the earth is being showered at times of magnetic storms by multitudes of electric ions, which certainly are small compared to the wave length of light, the direct sun beam, shining 93 million miles through these showers, must be weakened by Rayleigh scattering. The only question is how much. This paper gives the results of an investigation of that question.

Our first experience of such a phenomenon came to us in the year 1920. About March 20 to 23, 1920, there was an enormous sunspot group central on the sun's disk, as shown in plate 1. There was also a severe magnetic storm on the earth, accompanied by fine auroral displays. The storm was most severe on March 22 and March 23. Smithsonian observations of solar radiation made at Calama, Chile, followed the course shown in the upper curve of figure 1. The phenomena of central passage of the great sunspot group included a diminution of the observed values of the solar constant of radiation of the order of 5 percent, reaching the minimum value on March 23. Possibly the very low value of March 23 may have been made unduly low by experimental error, but the value of March 24, nearly as low, is of quite as high a grade as most of the Montezuma values of that year.

Critics may suggest that these low values of the solar constant were caused, not by Rayleigh scattering from electric ions along the 93-million-mile path of sun rays through space, but rather by a hazing of the earth's atmosphere, produced by the adherence of water-vapor molecules to the ions, after they entered the atmosphere; in other words, that the solar-constant values were erroneous. This suggestion, however, runs counter to the observations. For though the lower curve in figure 1, which traces the march of values of atmospheric transmission coefficients for green light at wave length 0.511 micron, does show that the atmosphere became less transparent[1] during the passage of the sunspot through the central position on the sun's disk, that change alone, if it were not countered by other factors in determining the solar constant—factors also affected by atmos-

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[1] This change will be accounted for when we consider figure 3 below.

pheric conditions—would have tended to *raise,* not to depress, the solar-constant values. At that time the solar constant was being determined at Calama, Chile, by the fundamental, or "long," method of Langley. The less transparent the atmosphere the greater would have been our estimate of the losses it produced in the solar ray, and the larger the computed solar-constant value outside the atmosphere. But this tendency is counterbalanced exactly by lower observed pyrheliometer readings when the atmosphere is less clear. The solar-constant values would be too low only if the transparency of the atmosphere was erroneously observed too high.

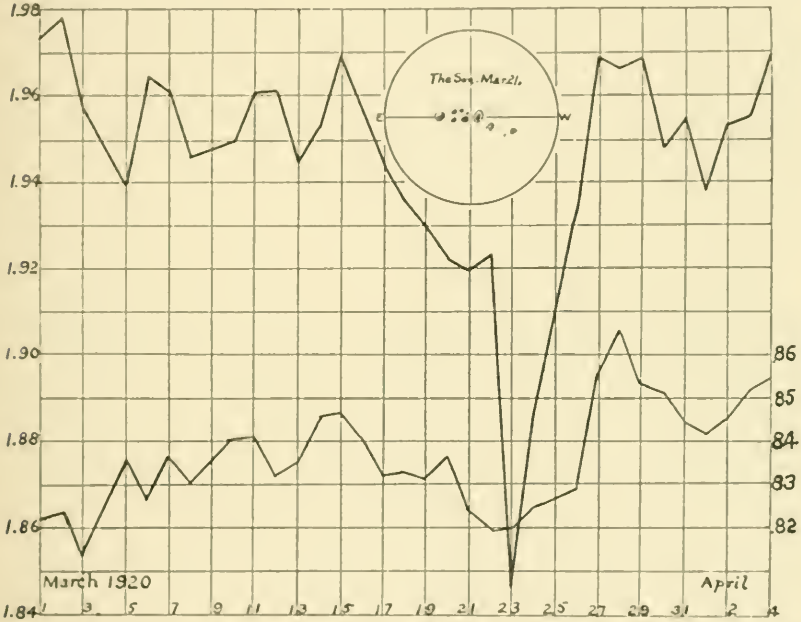

FIG. 1.—Solar constant March-April 1920, upper curve; atmospheric transmission green light, lower curve.

Other critics have suggested to me that the observed change of the solar constant of March 1920 might have been produced erroneously by a change of the absorption of solar rays by ozone, assuming that the solar outburst of electrified ions produces large changes of the concentration of atmospheric ozone. I reply that all solar-constant values done by the long method, as in 1920, take account of such effects because the atmospheric transmission coefficients are necessarily appropriately modified owing to the method of obtaining them. All solar-constant values done by the short method since 1923 are specifically corrected for absorption of atmospheric ozone, as explained in volume 5 of Annals of the Smithsonian Astrophysical Observatory, pages 124 to 131. Hence this suggestion of critics applies neither to the work of 1920, nor to the work subsequent to 1923.

In conversation with Dr. Nicholson of Mount Wilson Observatory, in September 1947, I asked him if he knew of other occasions when great sunspot groups passed centrally through the sun's disk. If so, I proposed to see if a similar depression of solar-constant values occurred. In reply he suggested that sunspots were "like shotguns, rather than like rifles," when they pepper space with electric ions. Hence it might well be that *whenever a severe magnetic storm occurs* there will be generated a shower of ions embracing our line of sight and introducing Rayleigh scattering through the 93 million miles of space between the earth and the sun.

MAGNETIC STORMS, 1923 TO 1946

I undertook to test this hypothesis. The phenomena of March 1920, are so exceptional that I omitted them in a general tabulation. From the journal "Terrestrial Magnetism" I found over 70 occasions in the years 1923 to 1946 when very severe magnetic storms were reported. Not being very familiar with the terms used by the observers at the magnetic stations, I am not sure that I found all the dates of severe magnetic storms during this interval. Moreover, the magnetic observers, if they see this paper, may not regard all the storms I selected as severe. There was, indeed, some discrepancy between the estimates of severity from different magnetic stations reporting in "Terrestrial Magnetism." Whatever may be the incompleteness or inexactness of my selection, I feel sure that experts will agree that all the storms included in table 1, which follows, were strong, if not always deserving the description severe.

The magnetic storms continued from 2 to 10 days. It was often uncertain which day to take as representing the height of the storm, that is, the day most likely to be the day when the shower of ions was densest. All the several tabulations of the data which I made showed clearly a depression of the solar constant at or near the height of the magnetic storm. Hence I thought it fair to select as zero day that day during the height of the storm when the solar constant was most depressed.

SOLAR-CONSTANT OBSERVATIONS

Unfortunately I could not use all the storm dates selected. Our observations of the solar constant made at Montezuma and at Mount

St. Katherine are so much more accurate than any others that the results from other stations must be ignored in a study of small changes of this kind. That restriction cuts off a great many dates, because the sequences of solar-constant values, at and near the storm dates, were often too incomplete to be used. With the utmost liberality of selection, I could find but 53 storm dates from 1923 to 1946 when solar-constant sequences observed at Montezuma or St. Katherine were complete enough to be fairly used in the tabulation. Even among those sequences retained, many were so imperfect as hardly to deserve employment. I therefore made two reductions, one employing the whole group of 53 dates, the other employing 22 of them, when the sequences were at least two-thirds complete, and were not broken badly near the zero dates. However, the mean results of the complete tabulation of 53 and the tabulation of the 22 most satisfactory sequences are in almost perfect agreement. Hence it may be said that two independent tabulations, one of 22 cases, the other of 31 cases, yield practically identical results as to the influence of severe magnetic storms on the solar constant.

My solar-constant data, 1923 to 1939, are taken from table 24, volume 6, Annals of the Astrophysical Observatory of the Smithsonian Institution. From unpublished daily results, those of 1939 to 1946 were kindly put at my disposal by Director L. B. Aldrich of the Observatory. In quoting from the Annals I have used the direct mean values from Montezuma or St. Katherine, and not the "preferred" values. I have come to distrust the method used to obtain "preferred" values, and it has not been used in the reductions of 1939 to 1946. Furthermore I have ignored "grades." They are more or less liable to personal bias, and especially to a tendency to discredit apparently wild values. It is very clear from the present research, and from another I have made on hurricanes, that some wild values are caused by cosmic conditions, not by errors of observation.

EFFECT OF MAGNETIC STORMS ON THE SOLAR CONSTANT

With these explanations given, I now ask attention to table 1. It enumerates the 53 dates retained.[2] Corresponding to each one is a sequence, more or less complete, of solar-constant values from Montezuma or Mount St. Katherine. It extends from 10 days before to 10 days after the date marked zero, when the magnetic storm appeared to be at its height. The table has 53 more or less complete lines of 21

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[2] The phenomenon of March 22, 1920, is of so much greater range of severity that I have treated it separately above, and do not include it in table 1.

columns. Two additional lines give the number of values per column and their mean values. To save printing, the first two places of the solar constant are omitted. The reader must therefore remember that where, for instance, "32" is printed, 1.932 is to be understood.

Although, as stated above, about 20 storm dates had been omitted, because the corresponding sequences of solar-constant values were too defective, there still remain many very incomplete sequences in the table. I therefore thought it good, as I have said, to pick out a smaller number of occasions when the sequences, especially those near zero day, were nearly full. These selected dates, 22 in number, are indicated by asterisks in the table. Their mean values and the numbers of observations entering into these means, are given in the last lines of table 1.

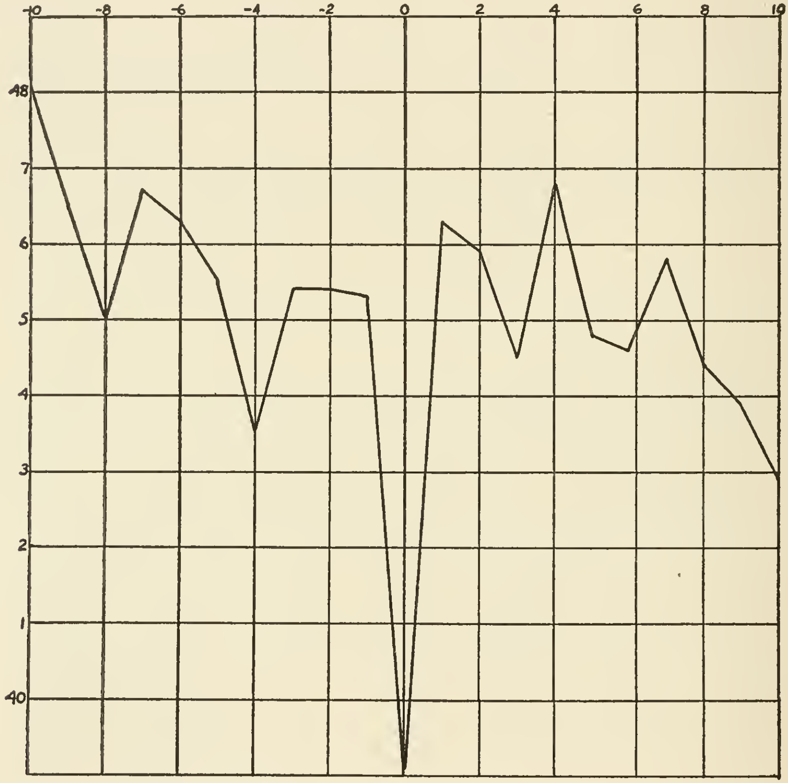

Fig. 2.—Depression of solar constant attending severe magnetic storms. Abscissae, days before and after height of storm; ordinates, solar constant (to be prefixed by 1.9).

It is satisfactory to see that the mean results from 53 cases and the mean results from the preferred 22 cases are nearly identical. Hence we may infer that the 31 incomplete sequences, printed without asterisks in table 1, independently confirm closely the results obtained from the 22 preferred cases. It is seen that a very sudden drop of about 0.0062 calorie, or ½ percent, occurred on zeroth day. There is a slight, but perhaps not significant, depression of the solar constant

TABLE 1.—*Effect of magnetic storms on solar-constant values*

Dates	−10	−9	−8	−7	−6	−5	−4	−3	−2	−1	0	1	2	3	4	5	6	7	8	9	10
1923: 9, 27	32	45	60	54	53	58	49	47	70	..	..	51	52	52	49	46	43	40	50	40	29
10, 14*	40	50	40	29	56	—	48	41	35	47	47	..	..	41	..	49	37	45	51	52	43
12, 22	..	..	32	46	..	49	47	..	43	..	29	30	34	26	..	35	30	28	..	21	33
1924: 1, 29*	48	48	37	54	37	..	..	38	51	54	45	47	50	26	51	29	49	24	..	..	40
2, 16*	48	46	53	58	54	46	..	37	34	..	20	..	33	56	40	45	43	36	47	..	40
5, 21*	48	41	45	..	45	59	..	..	55	52	49	53	..	45	48	55	53	54	49	53	47
6, 10	47	53	55	61	54	..	..	55	..	57	53	..	44	41	..	..	45	65	..	51	55
9, 23	51	47	50	..	46	..	55	49	44	45	23	24	..	54	50	47	..	58	..	..	..
10, 22*	54	..	61	49	..	50	50	48	50	48	52	61	58	46	57	59	44	51	44	61	..
1925: 5, 3	..	..	..	..	..	..	32	42	41	42	42	..	46	44	..	55	49	48	48	46	41
10, 24*	44	..	56	50	46	..	..	..	47	46	38	53	49	45	..	40	51	43	38	..	..
11, 9*	51	43	38	..	..	..	..	39	47	42	37	49	45	44	45	53	44	45	43	55	63
12, 6	..	45	51	..	..	43	55	42	54	51	44	53	43	49	48	..	..	..	..	..	..
12, 28	42	..	51	48	56	46	..	..	..	..	44	56	46	52	53	47	42	..	..	47	42
1926: 1, 23	64	40	49	..	..	56	..	50	42	..	34	50	48	..	21	..	..	..	..	..	38
1, 27	..	56	..	50	42	..	34	50	48	..	21	..	..	..	..	..	38	..	..	..	..
3, 5	..	..	40	..	..	..	34	..	47	44	38	51	45	..	..	44	54	60	..	40	..
10, 15*	34	..	26	29	39	47	41	47	46	41	34	42	39	42	45	41	43	52	37	..	26
1927: 1, 8	..	..	..	..	38	36	40	39	30	47	44	42	41	..	41	32	34	..	..	..	..
4, 14	..	47	..	..	..	..	41	42	47	48	40	44	52	..	53	49	45	47	..	26	..
5, 4*	..	43	46	46	42	42	39	41	42	41	44	53	..	39	..	39	42	..	38	42	48
7, 22*	..	38	40	43	46	50	50	41	..	50	42	45	43	46	56	48	43	38	45	43	36
8, 25*	46	43	39	44	36	40	28	46	41	46	41	49	42	51	45	49	48	39	36	38	42
10, 13	45	44	47	53	52	..	..	50	42	48	43	..	..	45	..	..	..	41	51	45	38
1928: 7, 8*	39	..	..	45	47	49	50	37	41	49	42	46	40	40	..	..	43	..	38	..	46
10, 18	52	42	41	45	50	..	46	59	..	..	43	49	..	..	..	..	50	44	40	33	33
1929: 7, 9*	45	44	36	46	42	..	33	35	..	37	39	50	45	48	40	41	43	37	32	..	42
11, 3	..	..	..	37	40	..	..	..	43	..	37	34	34	41	39	50	51	48	41	42	..
1930: 9, 30	..	..	..	..	..	35	44	..	..	46	44	49	52	50	52	33	45	..	38	39	50
12, 3	..	..	..	..	55	54	48	57	52	50	59	60	48	55	59	50	50	51	48	55	56
1932: 10, 16*	27	39	42	55	44	..	..	40	..	..	29	29	25	33	30	39	34	..	..	..	32
1936: 6, 19*	53	47	47	49	46	44	47	55	52	54	43	53	55	49	46	53	..	..	47	53	42
11, 28*	48	58	..	..	58	53	51	53	..	41	37	46	51	52	60	..	..	51	55	52	46
1937: 2, 3*	46	45	..	..	46	47	48	50	59	50	48	48	48	47	57	53	50	42	55	47	43
4, 26	34	48	46	46	42	38	42	28	48	47	45	..	48	40	46	34	32	..	..	37	..
8, 23*	51	49	49	45	54	35	49	45	50	47	41	48	45	46	53	46	50	45	47	42	48
1938: 1, 21	..	62	..	57	50	53	53	57	47	48	..	..	..	..	..	..	48	53	55	..	..
4, 17*	38	43	46	46	..	..	..	49	42	44	..	38	43	43	43	..	47	50	49	..	50
5, 13	49	43	46	52	49	43	41	44	..	44	41	..	47	37	39	44	..	..	..	43	43
1939: 2, 6	37	..	..	43	43	43	39	..	46	43	39	..	..	43	44	..	..	..	..	..	..
3, 27	58	44	38	..	..	..	..	41	40	45	42	47	50	49	48	..	48	51	44	47	40
8, 23	..	..	36	..	34	38	..	..	38	41	38	41	..	38	..	..	48	51	39	46	54
10, 13	35	54	38	..	..	..	53	..	..	31	33	50	51	..	..	52	42	39	46	..	38
1940: 3, 24	38	46	39	30	29	32	30	..	34	41	36	38	..	41	..	..	39	51	..	..	..
1941: 3, 1	..	..	59	61	..	59	..	63	63	49	..	..	64	63	..	52	..	..	51	..	..
9, 18	..	..	58	45	54	51	..	..	..	50	48	56	54	..	66	..	..	..	..	..	..
1943: 8, 31*	50	54	53	52	54	52	48	57	52	43	27	45	47	47	51	51	49	51	43	39	..
1946: 1, 3*	..	..	40	33	38	43	32	46	35	43	31	46	42	31	..	43	35	27	34	..	44
2, 7	54	..	..	44	44	29	..	..	42	38	36	..	..	..	..	..	..	..	39	33	..
3, 24	39	41	34	..	..	33	37	27	..	34	38	41	..	..	..	..	56	51	47	42	47
4, 22	44	..	..	..	51	49	..	..	43	..	34	36	43	..	40	30	50	50	..	46	..
7, 27*	52	47	47	49	55	..	45	40	39	39	34	..	..	42	31	31	41	..	43	..	46
9, 7	..	..	..	39	37	..	..	..	40	45	48	51	46	44	46	49	..	41	46	49	39
	35	33	38	35	39	33	34	38	41	43	49	40	34	41	34	36	41	36	35	32	35
Mean of 53 cases	481	465	450	467	463	455	435	454	454	453	391	463	459	445	468	448	446	458	444	439	429
	Mean of first 9 = 458											Mean of last 9 = 448									
	19	17	19	17	19	14	15	20	18	20	21	20	18	22	17	19	20	17	20	12	18
Mean of 22* cases	454	458	443	451	466	469	439	443	454	457	390	476	444	436	469	455	445	429	436	481	430
	Mean of first 9 = 453											Mean of last 9 = 447									

as between the means of the first 9 and the last 9 of the solar-constant values of the sequences.

In order to illustrate the variation in effect of magnetic storms on solar radiation depending on the magnitude of sunspots and their location on the sun's disk, I ask the reader to compare plate 2 with plate 1. Plate 2 includes direct photographs of the sun taken at Mount Wilson on November 28, 1936, and February 3, 1937. On these dates there was no central sunspot group, as on March 22, 1920. On November 28, 1936, two large sunspot groups were at about 20° solar latitude both north and south of the center of the sun's disk and another near the sun's limb. On February 3, 1937, there were many small spot groups upon the disk, and one very large one near the sun's limb, but none near the center of the disk. Accordingly we see from the solar-constant records a very large depression in March 1920 (see fig. 1), a conspicuous depression in November 1936, and scarcely any depression in February 1937 (see table 1), at the times of severe magnetic storms.

MAGNETIC STORMS AND SKY CONDITIONS

Thus the magnitude of the Rayleigh depression of solar radiation resulting from 93 million miles of ionic shower proves measurable. Since these ions invade the earth's atmosphere, we may look for two meteorological effects. First, the captured ions are likely to act as centers of condensation of water molecules and dust, and thereby increase the haziness and the brightness of the sky. Second, the surface temperatures of the earth might be affected.

From table 24, Annals, volume 6, and unpublished later records, I collected for 30 magnetic-storm dates the pyranometer measures at air mass 2.5 of the brightness of the sky near the sun. The mean values for these dates and the 10 days before and 10 days after, together with the numbers of observations entering into each mean, are given in table 2 and graphically in figure 3.

It appears that the haziness of the sky increased suddenly on the storm day,[3] and sky brightness near the sun averaged 10 percent higher for the 10 last days of the sequences than for the first 10 days. As could be expected, the graph, figure 3, is rather irregular. It must be considered that the principal causes of sky haziness lie in the lower layers of the atmosphere, and are subject to great fluctuations as dust and humidity float about in the changing air currents. Hence the

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[3] This tends to explain the drop in atmospheric transparency shown in figure 1.

relatively minor effects of the invasion of ions, at times of magnetic storms, are superposed on large variations of sky brightness due to other causes.

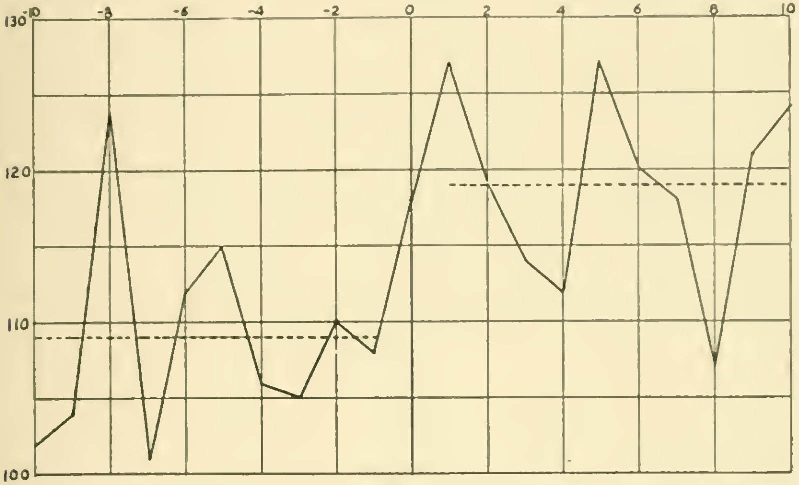


FIG. 3.—Increased sky brightness after severe magnetic storms. Abscissae, days before and after height of storm; ordinates, pyranometer observations of sky brightness.

TABLE 2.—*Effect of magnetic storms on sky brightness. Pyranometer observations*

Days from zero day.....	—10	—9	—8	—7	—6	—5	—4	—3	—2	—1	0	1	2	3	4	5	6	7	8	9	10
No. of observations......	19	19	19	21	24	21	19	24	23	23	23	22	19	24	22	23	23	19	19	21	19
Mean pyranometer	102	104	124	101	112	115	106	105	110	108	118	127	119	114	112	127	120	118	107	121	124

Mean of first 10 = 109 Mean of last 10 = 119

MAGNETIC STORMS AND WASHINGTON TEMPERATURE

It remains to trace the effects of ionic bombardment on temperature at the earth's surface. The departures from normal temperatures at Washington from 9 days before zeroth day to 9 days after have been tabulated for 73 severe magnetic storms occurring from 1923 to 1946. In this tabulation no vacancies occurred in the sequences. Hence I give only the mean results in table 3 and figure 4.

Washington temperature fell sharply, beginning 1 day before the magnetic storm, and reaching a level on storm day 3° below that of the mean of temperatures from 9 to 2 days before the storm. After the storm the temperature rose sharply, but averaged 0.8° lower from the second to the ninth day after the storm than the mean value before it.

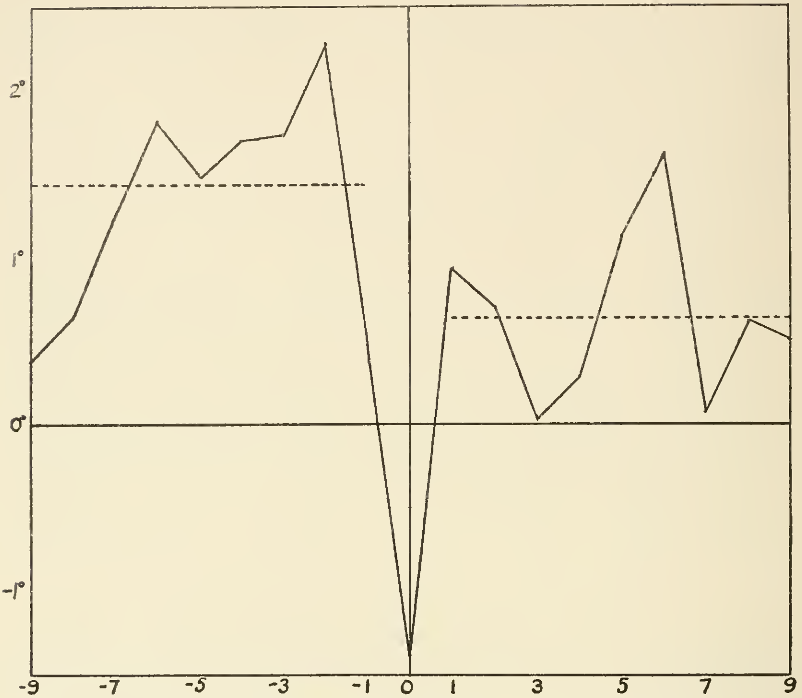


FIG. 4.—Washington temperatures depressed by severe magnetic storms. Abscissae, days before and after height of storm; ordinates, degrees centigrade of departures from normal.

TABLE 3.—*Effect of magnetic storms on Washington temperature*

Days from zero day.	—9	—8	—7	—6	—5	—4	—3	—2	—1	0	1	2	3	4	5	6	7	8
Mean departure from normal temperature.	0°.37	0°.63	1°.25	1°.81	1°.48	1°.70	1°.74	2°.28	0°.47	—1°.38	0°.93	0°.70	0°.04	0°.29	1°.12	1°.60	0°.07	0°.61

Mean of first 8 = 1°.41 Mean of last 8 = 0°.64

OTHER CASES OF TEMPERATURE CHANGE CAUSED BY VARIATION OF SOLAR RADIATION

Simpson, in his classical investigation of the temperature of the earth's atmosphere, and its relation to radiation, computed the theoretical effect of a rise of 1 percent in the solar constant. For eastern North America he found that such a rise in radiation would depress temperatures at the earth's surface. Clayton, by statistical studies of actual changes in solar radiation to temperature, had also arrived at the same result. Indeed his isothermal lines, corresponding to a rise of 1 percent in the solar constant, very nearly map out the extension of Pleistocene glaciation in North America. See, for instance, figure 21, Smithsonian Miscellaneous Collections, volume 77, No. 6, 1925.

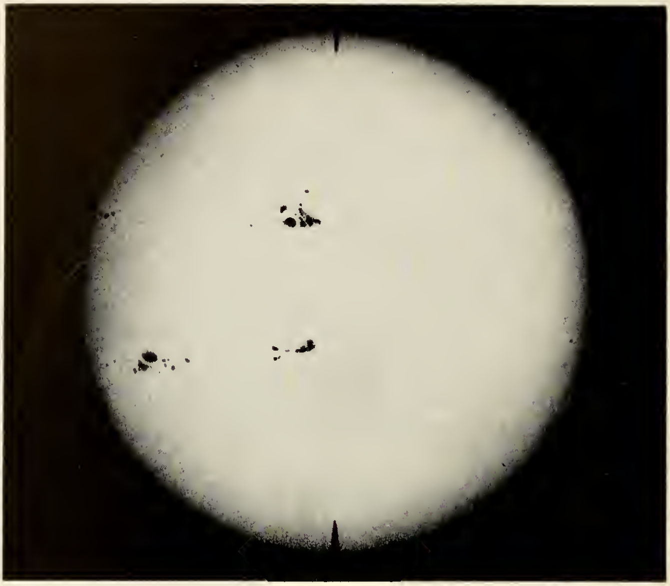
As stated above, I find the opposite trend in temperature at Washington to that found by Simpson and Clayton. For I find a depression of temperature following a sudden obscuration of the planet earth, caused by its bombardment by electric ions. The circumstances, however, are not parallel. Those authors treated of a relatively permanent increase of solar radiation. The larger part of the range of the magnetic storm effect is very short-lived, less than 2 days. Moreover, there is no change of atmospheric transparency to be assumed in the investigations of Simpson and Clayton, except as increased earth temperature presently gives rise to increased atmospheric humidity and greater cloudiness. The magnetic storm, on the contrary, immediately diminishes atmospheric transparency. Any change of cloudiness, which might eventually follow, would doubtless be delayed more than the 9 days after the storm covered by my tabulation. So it seems to me there is no unexplained contradiction between these results and those of Simpson and Clayton.

NUMBER OF IONS IN A SHOWER

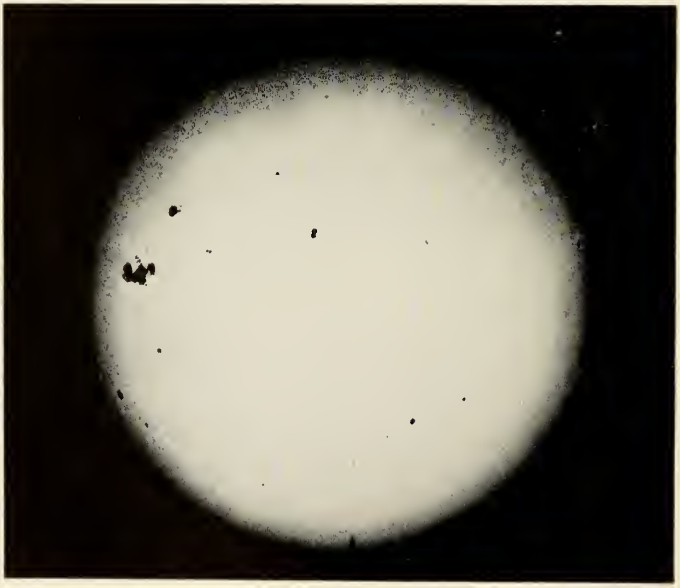
One other point of some interest is an inquiry as to the average density of the shower of electric ions for the 53 cases of severe magnetic storms covered by table 1. The effect produced was to diminish the solar constant by $\frac{1}{3}$ percent. Referring to Annals, volume 6, figure 11, page 166, the center of gravity of a solar-constant change associated with Rayleigh scattering may be set at about wave length 0.40 micron. On very clear days above Montezuma, with air mass 1.0, the solar radiation may be observed as high as 1.65 calories per square centimeter per minute, or $\frac{0.29}{1.94} = 15$ percent lower than the solar constant. If readers think it worth while, they may compute from Rayleigh's equations, and the above data, the numbers of particles involved under the two sets of circumstances. But roughly estimating, one might say that the 93 million miles of space contained $\frac{0.34}{15} = 0.023$ as many particles as would be contained of molecules in the atmosphere above Montezuma, where the barometric pressure is about 590 mm. mercury. These figures relate, however, to cases when the great sunspot groups were not central on the sun's disk. The great group of March 1920, produced about 10 times as great an effect on the solar constant as the average of the 53 cases of 1923 to 1946.

Using Humphrey's estimate of atmospheric densities, Millikan's figure for the number of molecules per cubic centimeter at sea level, I compute that the number of molecules in a column of air of 1 square centimeter cross section above Montezuma is approximately 1.4×10^{25}. If there are 0.023 times as many ions in the ionic showers accompanying average severe magnetic storms, it follows that the average increase of density in ions per cubic centimeter in space between the earth and the sun on such occasions is $\frac{1.4 \times 10^{25} \times 0.023}{15 \times 10^{12}} = 2 \times 10^{10}$, or 10 times the number of the earth's inhabitants, approximately. On March 23, 1920, the figure was approximately 10 times larger still.

SOLAR PHOTOGRAPH, MARCH 20, 1920 (MT. WILSON)



1. SOLAR PHOTOGRAPH, NOVEMBER 28, 1936 (MT. WILSON)



2. SOLAR PHOTOGRAPH, FEBRUARY 3, 1937 (MT. WILSON)