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FURTHER EXPERIMENTS ON THE UNIFORMITY OF DISTRIBUTION OF THE COSMIC RADIATION

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ABSTRACT

More careful and prolonged observations on the small, daily variation before reported in the measured intensities of the cosmic rays, the new observations being made under such conditions as to eliminate the possibility of a slight temperature effect suggested by Bowen and Millikan's recent explanation of ionization-pressure relations in high-pressure electroscopes, yield the definite result that *within the limits of the author's present observational uncertainty which is of the order of a third of a percent, the sun has no direct influence on cosmic-ray intensities.* New evidence is presented that if observed and apparently systematic variations of the order of a third of a percent are in fact real they are best interpreted as the result of small changes in the blanketing effect of the earth's atmosphere due to air currents.

IN OCTOBER, 1930[1] I published briefly the results of a long series of tests designed to bring to light minute effects of the sun or the milky way or of other celestial objects on the intensity of the cosmic radiation. These experiments brought to light no evidence for any such effects, indeed definite evidence aaginst their existence; but they did reveal a slight daily period of the order of a percent and of such character as to be best interpretable in terms of daily changes in the thickness of the atmosphere through which the rays must pass to reach the earth's surface.

These observations were taken for the most part out-of-doors and at different altitudes up to 14,000 feet with a sensitive, high-pressure, cosmic-ray electroscope but in such a way as to eliminate completely the possibility of a temperature effect upon the elastic constants of the electroscope. Nevertheless there were other possibilities of temperature effects and since the just discernable maximum in the values of the comsic ray intensities seemed invariably to coincide with the period of maximum daily temperature as well as of minimum barometric pressure, I undertook during the past summer to repeat some of these measurements under conditions in which the temperature of the electroscope could be held very nearly constant.

A further reason for studying these daily variations with great care is

[1] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).

found in the fact recently brought to light by Bowen and myself[2] that the lack of linearity in the ratio between pressure and ionization in high pressure electroscopes is due to the impossibility of obtaining saturation with ordinary potentials in the use of such instruments. Thus if the same beta-ray, for example, passes first through an electroscope at one atmosphere and second through a similar electroscope at thirty atmospheres, in the latter instance the detached electrons are separated from their mother atoms, let us say, one thirtieth as far as in the first instance. However the forces causing them to reunite vary rapidly with the distance apart and therefore become so huge in the second instance that it is impossible to obtain saturation with potentials anything like those which produce it easily at one atmosphere. In some experiments of my own less than half of the ions were caught at 30 atmospheres although with the use of potentials between 100 volts and 300 volts the currents had the appearance of saturation, i.e., they were practically independent of the applied potential between these limits.

This explanation which Bowen and I have recently given of pressure-ionization effects obviously carries with it the conclusion that in such a high-pressure, unsaturated electroscope a somewhat larger number of ions will be carried to the electrodes at high temperatures than at low, since increased energy of agitation will obviously prevent a certain number of ions from reuniting that would otherwise do so. At 30 atmospheres this effect of temperature on current is not large for differences of temperature of say ten or fifteen degrees centigrade such as will sometimes occur between night and day; but in refined measurements it should be appreciable. It is a fundamental source of weakness in the use of high-pressure electroscopes. For measuring *relative* ionizations at constant temperature such high-pressure electroscopes are satisfactory, but for very fine measurements made at different temperatures they may lead to serious errors. This is presumably the cause of some of the differences in the results obtained by different observers on the variation of cosmic-ray intensities with the positions of celestial objects, inadequate precautions having been taken to avoid this effect of temperature on the measured ionization currents.

My own experiments made on Pike's Peak (altitude 14,100 feet) in both 1928 and 1930, (continued however through but two days) failed to reveal any daily period there; but they were made in a heated room of reasonably constant temperature while my experiments made out-of-doors both at Pasadena and at Gem Lake and on Mount Manitou (continued however over a period of many days and hence giving more significant mean values) showed clearly a maximum in the afternoon of the order of one per cent.

I therefore repeated during the past summer (July and August) the Pasadena measurements as follows. I divided the day into four equal six hour periods: (1) 6 A.M. to noon, (2) noon to 6 P.M., (3) 6 P.M. to midnight and (4) midnight to 6 A.M., these periods being purposely taken long so as to eliminate as far as possible the random fluctuations to be expected. The first series

[2] Bowen and Millikan, Nature, Oct. (1931).

of measurements was made in Throop Hall, California Institute, with several feet of concrete both above (in the floors) and in the side walls, but with the temperature varying but slightly, in general not more than one degree centigrade during the different periods. The second series was taken in the basement of my house at 1640 Oak Grove Avenue, Pasadena, with equally constant temperatures but with only wood above the instrument. The results are shown in Tables I to IV.

TABLE I. *Cosmic-ray intensity measurements in Throop Hall, Pasadena, July 11th to August 16.*

	Morning ions cc/sec.	Barometer inches	Afternoon ions cc/sec.	Barometer inches	Evening ions cc/sec.	Barometer inches	Night ions cc/sec.	Barometer inches
7/11	—	—	27.54	*29.06*	27.36	*29.06*	27.37	*29.07*
7/12	27.29	*29.06*	27.69	*29.03*	27.69	*29.04*	27.15	*29.05*
7/13	27.17	*29.04*	27.26	*29.02*	27.48	*29.01*	27.41	*29.03*
7/14	27.50	*29.04*	27.52	*29.00*	28.10	*29.03*	27.65	*29.04*
7/15	27.45	*29.03*	27.63	*29.02*	27.77	*29.09*	27.57	*29.09*
7/16	27.54	*29.07*	27.40	*29.09*	27.41	*29.12*	27.47	*29.12*
7/17	27.36	*29.11*	28.00	*29.06*	27.61	*29.03*	27.63	*29.04*
7/18	27.67	*29.02*	28.01	*28.99*	28.09	*28.98*	27.58	*28.99*
7/19	27.34	*28.99*	27.52	*28.98*	27.42	*29.00*	27.59	*29.04*
7/20	27.09	*29.03*	27.27	*29.00*	27.24	*28.99*	27.72	*29.02*
7/21	27.54	*29.03*	27.40	*29.00*	27.23	*29.00*	27.39	*29.02*
7/22	27.34	*29.01*	27.95	*28.99*	27.11	*28.98*	27.31	*29.00*
7/23	27.39	*28.98*	27.86	*28.95*	27.47	*28.93*	27.41	*28.95*
7/24	27.22	*28.95*	27.42	*28.93*	27.40	*28.94*	27.51	*27.97*
7/25	27.44	*28.96*	27.50	*28.95*	27.26	*28.96*	27.41	*28.97*
7/26	27.30	*28.97*	27.43	*28.92*	27.06	*28.93*	27.25	*28.97*
7/27	27.73	*28.95*	27.11	*28.95*	27.46	*28.98*	27.50	*29.01*
7/28	27.04	*29.02*	—	—	—	—	27.41	*29.04*
7/29	27.37	*29.03*	28.08	*29.02*	27.81	*29.04*	27.26	*29.07*
7/30	27.51	*29.06*	27.50	*29.04*	27.40	*29.06*	27.21	*29.09*
7/31	28.02	*29.08*	27.67	*29.04*	27.61	*29.05*	27.44	*29.08*
8/1	27.21	*29.06*	27.99	*29.03*	27.31	*29.02*	27.33	*29.03*
8/2	27.32	*29.03*	27.39	*29.00*	27.16	*29.02*	27.65	*29.05*
8/3	27.69	*29.05*	27.34	*29.04*	27.36	*29.06*	27.18	*29.10*
8/4	27.23	*29.09*	27.17	*29.08*	27.50	*29.09*	27.15	*29.11*
8/5	27.36	*29.11*	27.41	*29.08*	27.58	*29.09*	27.19	*29.14*
8/6	27.17	*29.15*	27.29	*29.12*	27.57	*29.15*	27.72	*29.19*
8/7	27.14	*29.17*	27.06	*29.19*	27.29	*29.14*	27.28	*29.18*
8/8	—	—	—	—	—	—	27.14	*29.20*
8/9	27.38	*29.20*	27.63	*29.16*	27.19	*29.17*	27.57	*29.24*
8/10	27.40	*29.22*	27.52	*29.17*	—	—	—	—
Means	27.387	*29.051*	27.528	*29.030*	27.461	*29.035*	27.415	*29.062*

It will be seen from Table 1 for example, that the divergence of the individual readings from the mean is in general less than a percent. It should be said too that these readings of about 27 ions per cc per second represent essentially pure cosmic-ray intensities, the local radiation, which itself was found to be here very constant, being practically all screened out by the completely encircling lead envelope, 7.6 cm in thickness. The zero reading of the electroscope is 1.2 ions per cc per sec. The readings in Tables I and III are uncorrected for changes in barometric height, but the mean barometer reading during each period is given in the column immediately to the right of the intensity reading in question.

The barometric height remains remarkably constant during the month of observations represented in Table I and the eight days of observation represented in Table III; but the barometer goes through a small minimum each afternoon and a small maximum in the morning hours. In other words the mean barometric heights during the periods from midnight to 6 A.M. and 6 A.M. to noon are always higher than during the periods from noon to 6 P.M. or from 6 P.M. to midnight; but the cosmic-ray intensities show just the in-

TABLE II. *Cosmic-ray readings, July 11 to August 10, Reduced to barometer of 29.04 inches.*

	Morning	Afternoon	Evening	Night
7/11	—	27.58	27.38	27.38
7/12	27.31	27.68	27.69	27.16
7/13	27.17	27.24	27.41	27.40
7/14	27.50	27.47	28.09#	27.65
7/15	27.44	27.61	27.83#	27.63
7/16	27.50	27.34	27.31	27.37
7/17	27.45	27.98#	27.60	27.63
7/18	27.65	27.95#	28.01#	27.52
7/19	27.28	27.45	27.36	27.59
7/20	27.08	27.22	27.18	27.70
7/21	27.50	27.35	27.18	27.37
7/22	27.30	27.89#	27.04#	27.26
7/23	27.32	27.75	27.33	27.30
7/24	27.11#	27.28	27.28	27.44
7/25	27.34	27.39	27.16#	27.32
7/26	27.21	27.28	26.92#	27.16
7/27	27.62	27.00#	27.39	27.46
7/28	27.02#	—	—	27.41
7/29	27.36	28.06#	27.81#	27.30
7/30	27.49	27.50	27.40	27.17
7/31	28.07#	27.67	27.62	27.49
8/1	27.22	27.98#	27.29	27.32
8/2	27.28	27.34	27.14#	27.64
8/3	27.70#	27.34	27.38	27.23
8/4	27.29	27.22	27.56	27.24
8/5	27.45	27.46	27.65	27.31
8/6	27.31	27.39	27.71#	27.91#
8/7	27.30	27.18#	27.41	27.46
8/8	—	—	—	27.34
8/9	27.58	27.78	27.35	27.77#
8/10	27.62	27.68	—	—
Means	27.394	27.515	27.446	27.331

verse of these relations. In both Tables I and II the afternoon mean-cosmic-ray-intensity is the highest, though only of the order of a third of a percent or less, while also in both tables the period 6 A.M. to noon shows the *minimum* mean intensity.

Both tables give indications that the differences in the means result from slight changes in the thickness of the atmospheric blanket due to the air currents set up by the daily heating of the earth's surface by the sun's rays. Indeed the differences cannot possibly be due to a *direct* influence of the sun since in both tables the maximum and the minimum mean readings both occur while the sun is up. The lag in all the effects after the period of maximum heating or cooling is indicated in both Tables I and III, the columns giving both barometric readings and ionization readings in the period 6 P.M. to midnight showing apparently that the atmospheric currents with their consequent changes in the atmospheric blanket, which reach their maximum in the afternoon, hold over also into the evening period (6 P.M. to midnight)

TABLE III. *Cosmic-ray measurements in basement of 1640 Oak Grove Avenue, Pasadena, August, 11–20, 1931.*

	Morning	Barometer	Afternoon	Barometer	Evening	Barometer	Night	Barometer
8/11	28.27	*29.27*	28.77	*29.25*	28.43	*29.28*	28.23	*29.29*
8/12	28.74	*29.29*	28.42	*29.29*	28.30	*29.30*	28.37	*29.32*
8/13	28.38	*29.32*	28.56	*29.32*	28.10	*29.33*	28.71	*29.34*
8/14	28.23	*29.34*	28.68	*29.29*	28.73	*29.28*	28.52	*29.30*
8/15	28.41	*29.26*	28.73	*29.24*	28.26	*29.26*	28.58	*29.28*
8/16	28.30	*29.27*	28.24	*29.24*	28.69	*29.24*	28.85	*29.27*
8/18	28.65	*29.23*	28.71	*29.20*	28.77	*29.22*	28.70	*29.24*
8/19	28.55	*29.23*	28.25	*29.20*	28.68	*29.21*	28.28	*29.26*
Means	28.441	*29.276*	28.546	*29.254*	28.494	*29.265*	28.530	*29.285*

while the quieter conditions which establish themselves between midnight and morning also seem to hold over into the period from 6 A.M. to noon.

For reasons which I have before given[1] the reduction of the readings in Tables I and III to a particular value of the barometric pressure cannot be expected completely to wipe out the differences in the means of the ionization

TABLE IV. *Cosmic-ray readings, August 11–20 reduced to barometric height of 29.26 inches.*

	Morning	T °C	Afternoon	T °C	Evening	T °C	Night	T °C
8/11	28.25	*24.8*	28.75	*24.7*	28.46	*24.5*	28.28	*24.2*
8/12	28.79	*24.4*	28.45	*18.6*	28.36	*24.5*	28.46	*24.1*
8/13	28.47	*24.4*	28.65	*24.3*	28.22	*24.1*	28.83	*24.1*
8/14	28.35	*24.3*	28.75	*24.5*	28.77	*24.3*	28.62	*23.9*
8/15	28.41	*24.3*	28.71	*24.9*	28.26	*24.5*	28.61	*24.0*
8/16	28.30	*24.6*	28.21	*25.1*	28.66	*24.4*	28.85	*23.6*
8/18	28.60	*24.2*	28.62	*24.8*	28.70	*23.9*	28.66	*23.0*
8/19	28.50	*23.4*	28.19	*24.6*	28.54	*24.5*	28.26	*23.6*
Means	28.459		28.541		28.496		28.571	

at different periods since the barometer must respond somewhat to both static and dynamic influences,[3] while if the incoming rays are actually constant, a cosmic-ray electroscope should reflect merely the total mean thickness of the blanket or air-wave interposed at a given time between the recording instrument and the rays coming in over the whole celestial dome, independently of whether the atmosphere is in motion or at rest. Tables II and IV represent such reduction of all readings to a common pressure. This is seen to reduce somewhat the differences between the means without however wiping them out. The relative positions of all the means in Table II remain the same as in Table I and this is true also of the morning, afternoon and evening means of Table IV but the "night mean" in Table IV has risen a trifle above that of the afternoon mean. This raises perhaps a little doubt as to whether all the differences may not be accidental, but the evidence on the whole seems to be rather in favor of a very slight afternoon maximum and a morning minimum occasioned by atmospheric currents due to solar heating.

[3] Chapman, Proc. Royal Soc., June (1931) concludes from theoretical considerations that these differences cannot amount to as much as one percent, while these new observations of mine show experimentally that they do not amount to more than about a third of a percent.

I have noted a bit of further evidence in this direction in Table II. The fluctuations in the individual readings seem in general to be somewhat less in the period from midnight to 6 A.M. than during the other three periods, and this is the period in which the atmosphere is normally most quiet. In Table II, I have starred every reading which differs from the mean at the bottom of its column by as much as 1 percent. If the fluctuations are all due to changes in the thickness of the atmospheric blanket the "night" column should show the smallest number of such stars as it will be seen to do in Table II. There is definite evidence however, brought to light both by Steinke in Germany and by Carl D. Anderson in Pasadena for occasional wholly random bursts of ionization due to something like catastrophic nuclear disintegrations and it is therefore at least a possibility though not a likelihood that all of the apparent regularities in the mean differences (Tables II and IV) are accidental.

The only *certain* conclusion that I can draw from the whole set of observations is then that *within* the *limits of my own observational uncertainty, which has now been reduced to about a third of a percent, the sun has no direct influence upon the intensity of the cosmic rays.* I can make the same assertion on the basis of other only partially published data with respect to the milky way and also with respect to the nearest spiral nebula, Andromeda. The foregoing result is also in complete agreement with the extraordinarily careful and exact observations of Hoffman in Halle. The foregoing statement is the same as that which Cameron and I made as a result of our observations in Bolivia and on the Pacific Ocean between Los Angeles and Mollendo Peru, in 1926, but the limit of our uncertainty was then estimated at 6 percent while it has now been reduced to about a third of one percent. With this precision attained and with the great difficulty, if not the entire impossibility, of making dependable allowances for the effect of small waves in the atmosphere as well as for the effect of random fluctuations in ionization, great caution must clearly henceforth be exercised in interpreting any results as showing minute variations either with solar or with sidereal time.