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Diurnal Variation of Cosmic Rays

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The intensity of cosmic rays at an altitude of 3900 meters was measured hourly over a consecutive period of 240 hours. The procedure eliminated the effects due to the variations of the temperature and possible variations of pressure of the gas in the chamber. The ionization was about 1.5 ± 0.25 percent more between 8 A.M. and 4 P.M. than between 8 P.M. and 4 A.M. If the variation is due to the soft component of the cosmic rays, these results are in satisfactory agreement with the results of other observers. Analysis of the data suggests that the portion of the space in the neighborhood of the sun may emit cosmic rays more copiously than the remote regions. This makes doubtful the inference that the energy in the universe in the form of cosmic rays is comparable with that in the form of light.

SOME of the earlier investigators of cosmic rays reported considerable variations in the intensity of these rays as measured at different times of day. More extensive observations have indicated that these variations were probably statistical fluctuations which did not indicate any significant changes in the intensity of the cosmic rays. There have, however, recently been found very small but consistent differences between day and night.[1] In previous papers[2] we have reported the discovery that the ionization in a pressure ionization chamber increases with increasing temperature. A review of the recent experiments showed that although in some of them the temperature of the apparatus was held constant, in others diurnal temperature changes might have affected the observed ionizations. We have therefore carried through a new series of measurements of cosmic rays over a period of 240 consecutive hours, in such a way that changes of ionization with temperature cannot influence our results. The suggestion has been made that the more absorbable portion of the cosmic rays shows the greater diurnal variation. This more absorbable component is however almost completely absent at sea level. Our work was accordingly done at a much higher altitude (3900 m) than any previous long series of observations.

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[1] A good summary of this work is given by G. Hoffmann, Zeits. f. Physik **69**, 703 (1931).

[2] A. H. Compton, J. C. Stearns, and R. D. Bennett, Phys. Rev. **38**, 1565 (1931); **39**, 873 (1932).

APPARATUS AND PROCEDURE

A diagram of the apparatus employed is shown partly in section, in Fig. 1. The ionization chamber is a steel sphere, approximately 10 cm internal diameter, filled with air at 30 atmospheres pressure. The ionization current is measured by a Lindemann electrometer, operating at about 50 divisions per volt. By applying an arbitrary potential to the grounding key, the sensitivity of the electrometer can be determined, and the needle can be made to move over any desired portion of the scale. The ionization current was approximately saturated when 144 volts from a dry battery were applied to the chamber. Surrounding the ionization chamber may be placed cylindrical shells of 2.5 cm of copper, and 5 successive layers of lead, each 2.5 cm thick, a total mass of about 800 kg. The equipment was housed in a motor bus, which had a wooden roof too thin to absorb any appreciable cosmic radiation.

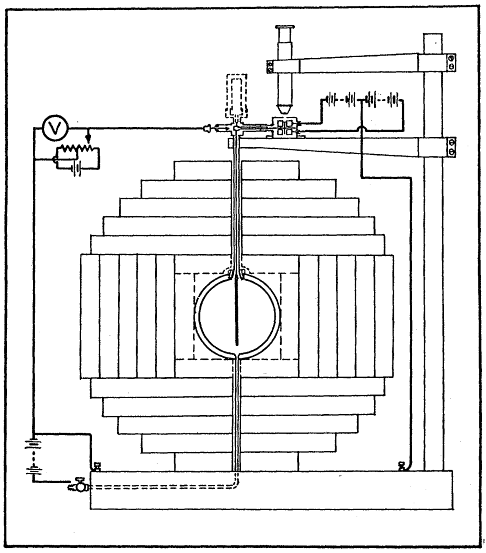

Fig. 1. Cross section of ionization chamber with shield.

The readings consisted in comparing the time required for the electrometer needle to move 10 microscope scale divisions when cosmic rays alone were used with the time when a tube of 0.941 milligrams of radium enclosed in 1 cm of lead, was brought to standard position at about 22 cm from the center of the chamber. All measurements were made with 2.5 cm of copper and 5 cm of lead surrounding the chamber. Auxiliary tests showed that when the radium was removed, the ionization due to the local radiation traversing this shield was less than 3 percent of that due to the cosmic rays. Thus the ratio of the readings is a measure of the cosmic rays in terms of the gamma rays from the radium standard.

In our previous paper we showed that the ratio of gamma ray to cosmic ray ionization is independent of pressure. According to the theory of the effect of temperature on ionization developed there, the ratio of the ionizations must thus be independent also of the temperature. Thus neither gas leaks nor temperature changes should affect our measurements of the radium equivalent of the cosmic rays.

EVIDENCE FOR A DIURNAL VARIATION

The results of the measurements are summarized in Table I and are shown in detail in Fig. 2. In Table I the values of $i_c/i_{c+\gamma}$ are the averages, over 10 days for the hours indicated, of the observed ratios of the ionization due to cosmic rays alone and due to cosmic rays plus the gamma-rays, measured as described above. The values of $I=i_c/i_\gamma$ are calculated from the observed values of $i_c/i_{c+\gamma}$ from the algebraic relation,

$$\frac{a}{b}=\frac{a}{a+b}\Big/\left(1-\frac{a}{a+b}\right).$$

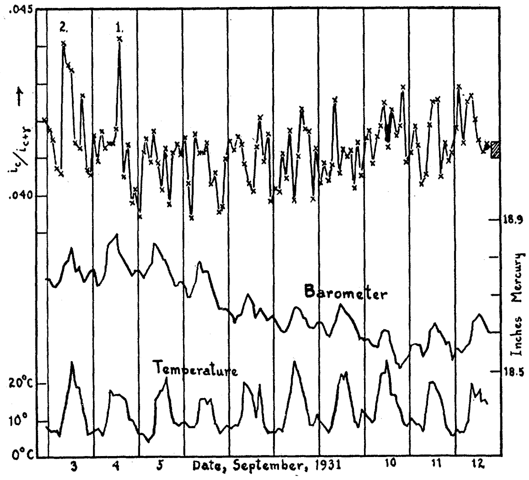

Fig. 2.

TABLE I. *Diurnal variation of cosmic rays at 3900 meters, 39°N 106°W, September 2–12, 1931.*

Hour	$i_c/i_{c+\gamma}$	$I=i_c/i_\gamma$	Temp. °C	Bar., inch	δI_T	δI_P	Chauvenet	I_0
6– 8A	0.04113	0.04289	9.0	18.663	−0.00002	−0.00024	—	0.04263
8–10	.04184	.04366	17.2	18.704	−.00024	+.00003	−0.00025	.04320
10–12	.04140	.04319	19.4	18.717	−.00013	+.00011	—	.04317
12– 2P	.04140	.04319	20.0	18.718	−.00010	+.00011	—	.04320
2– 4	.04179	.04361	17.7	18.687	−.00003	−.00008	−.00032	.04318
4– 6	.04106	.04282	15.4	18.673	.00000	−.00017	—	.04265
6– 8	.04119	.04296	9.8	18.657	+.00016	−.00027	—	.04285
8–10	.04092	.04267	7.8	18.651	+.00009	−.00031	—	.04245
10–12	.04082	.04256	8.4	18.663	+.00004	−.00024	—	.04236
12– 2A	.04106	.04282	8.4	18.666	+.00006	−.00022	—	.04266
2– 4	.04126	.04303	7.9	18.645	+.00007	−.00035	—	.04275
4– 6A	.04098	.04273	7.3	18.649	+.00008	−.00032	—	.04249

Probable error of bi-hourly mean value of $I=\pm0.00019$.
Probable error of bi-hourly mean value of $I_0=\pm0.00014$.
Mean value of $I_0=0.04280\pm0.00005=85$ ions per cc per sec. at 30 atmospheres.

The ratio I is thus a measure of the ionization due to the cosmic rays in terms of the ionization due to the γ-rays as unity. The temperature and barometric pressure are likewise ten day averages taken over the hours indicated.

CORRECTIONS FOR TEMPERATURE AND PRESSURE VARIATIONS

These values of I are subject to a small correction due to the variation of the battery voltage with the temperature; for a change of the potential applied to the ionization chamber induces a charge on the collecting electrode. It was found that a change of potential of 2.5 volts on the ionization chamber was sufficient to move the electrometer needle over the 10 scale divisions used in taking the readings. Thus if δV_T is the change in the battery potential during the reading, the correction to be applied is

$$\delta I_T = I\delta V_T/2.5.$$

The fluctuations δV_T during a single 10 minute reading were too small to be measured (of the order of 1 part in 30,000) with our field apparatus. They could be calculated, however, from the observed rate of temperature change and measurements of the electromotive force at different temperatures. These measurements were made on another dry battery of similar construction, using the Lindemann electrometer as an electrostatic voltmeter. When a battery potential of about 80 volts was applied to the plates of the electrometer, changes as small as 0.01 volt could be detected.

It was found that two types of voltage changes occur. The first is an increase of e.m.f. of about 0.015 percent per degree Centigrade, which follows closely the changes of the battery temperature. The second is a slow change, requiring more than 12 hours to come to equilibrium. This is an increase at the rate of about 0.003 percent per hour per degree change in temperature. The corrections to be applied due to these voltage changes are indicated in Table I by δI_T.

The rate at which the cosmic-ray intensity varies with the barometric pressure can be calculated from data showing the intensity at different altitudes. Using the values given by Millikan and Cameron[3] for the ionization inside lead screens, observed at different altitudes under conditions closely similar to ours, we find for barometric pressure of 18.7 inches, $(1/I)(dI/dP) = -0.147$ per inch of mercury. This enables us to standardize our intensity values by reducing them to 18.7 inches pressure. The appropriate corrections are indicated in Table I as δI_p.

The probable error of each bi-hourly value of I was calculated from the variations between the 10 daily readings which make up the average. The mean value of the 12 probable errors thus calculated is $r = \pm 0.00019$. With this probable error, it is found by applying Chauvenet's criterion that it is improbable that in 120 data there should be departures from the mean as great as those shown in Fig. 2 as points (1) and (2). By neglecting these data we thus get more reliable mean bi-hourly values, whose probable error is now reduced to $r_c = \pm 0.00018$.

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[3] R. A. Millikan and G. H. Cameron, Phys. Rev. **37**, 242 (1931).

Changes in barometric pressure on successive days introduce a fluctuation in the bi-hourly values of I of $r_p = \pm 0.00011$. Similarly, due to the difference in the temperature changes on successive days, there is a fluctuation of $r_t = \pm 0.00002$. When the intensity is corrected for pressure and temperature changes, the probable error of the mean I_0 values thus becomes

$$r_0 = (r_c^2 - r_t^2 - r_p^2)^{1/2} = \pm\ 0.00015.$$

It will be noted from Table I and Fig. 3 that the variations in the bi-hourly values of I are hardly more than is to be expected from the probable error. On the basis of this evidence, we stated in a preliminary report of this work[4] that our readings "showed no variations in intensity greater than were to be expected from purely statistical considerations." However, when the corrections due to the daily changes in barometric pressure are applied, there appears a marked difference between the intensity of the rays in the daytime and at night. During these experiments, the ionization was about 1.5 ± 0.25 percent more intense between 8 A.M. and 4 P.M. than between 8 P.M. and 4 A.M. There is only one chance in about 10^4 that this variation of 6 times the probable error should result from statistical fluctuations.

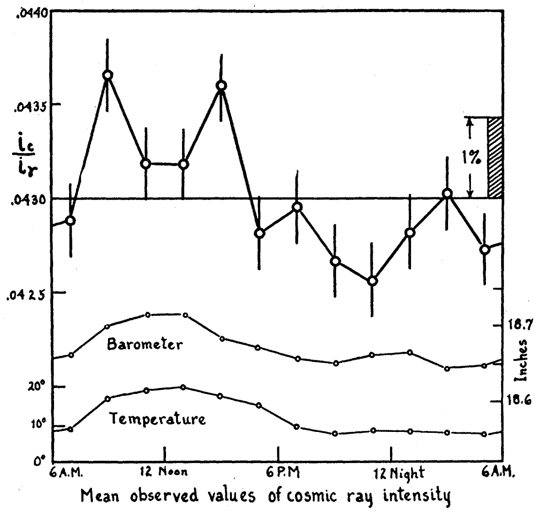

Fig. 3. Mean observed values of cosmic-ray intensity.

The existence of this diurnal variation, as well as the effect on the data of changes in the barometer, are shown graphically in Figs. 3 and 4. In Fig. 4, the dotted circles are calculated including the datum points (1) and (2) of Fig. 2 in calculating the average. In these figures the probable error of the data is represented by the length of the line drawn through each datum point. It will be noted that whereas before correction for barometric changes, 7 of the 12 points lie within the probable error of the mean position, after this correction only 3 of the 12 points lie within the probable error of the mean. In

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[4] R. D. Bennett, J. C. Stearns and A. H. Compton, Phys. Rev. **38**, 1566 (1931).

Fig. 2 the "barometer effect" shows itself by the gradual rise of the mean intensity of the cosmic rays as the daily average of the barometer readings falls.

Diurnal variations similar to that here reported have been noted by other observers. Recently Lindholm[5] and Hess[6] have shown that an analysis of the data taken by Hoffmann and Lindholm[7] at 2450 m shows a diurnal change larger than the probable error, and about 0.5 percent of the whole cosmic-ray intensity. Likewise Hess and Pforte[8] from their own data at 100 m elevation find an intensity which is on the average 0.33 percent greater during the day than at night. This is precisely the magnitude of the effect reported by Millikan[9] in his most recent sea level measurements, though Millikan doubts whether the difference he observed was greater than the experimental error. Hoffmann[10] also notes an effect (at about sea level) "due to the sun" of the same order of magnitude as Millikan's, but of questionable reality.

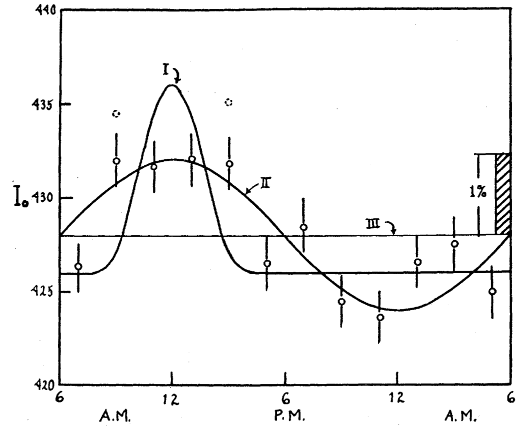

Fig. 4. Cosmic-ray ionization as function of time of day. Corrected for effects of temperature and pressure variations.

A possible explanation of the greater magnitude of the diurnal variation which we have found is that the variation occurs only in the soft component of the cosmic rays ($\mu =$ *ca.* 0.8 per meter of water). At 3900 m this constitutes about 65 percent of the whole cosmic radiation, whereas at sea level it amounts to only 8 percent. Thus our average difference of 1.0 percent between the 12 daylight hours and the 12 night hours would correspond to a difference of 0.12 percent at sea level or 0.7 per cent at 2450 meters. These values are in reasonably satisfactory agreement with those cited above.

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[5] F. Lindholm, Gerlands Beitrage zur Geophysik **22,** 141 (1929).

[6] V. F. Hess, Naturwiss **18,** 1094 (1930).

[7] G. Hoffmann and F. Lindholm, Gerlands Beitrage zur Geophysik **20,** 12 (1928).

[8] V. F. Hesse and W. S. Pforte, Zeits. f. Physik **71,** 171 (1931).

[9] R. A. Millikan, Phys. Rev. **39,** 391 (1932).

[10] G. Hoffmann, reference 1.

SIGNIFICANCE OF THE DIURNAL VARIATION

Two alternative types of diurnal variations may be anticipated. The first would be due to rays coming directly from the sun. In this case the intensity of the "solar component" would be a maximum at noon, falling gradually to zero at sunset as the rays penetrate greater and greater thickness of the atmosphere. Curve I of Fig. 4 is calculated on this hypothesis, assuming that the solar component has the same absorption coefficient (*ca.* 0.8 per meter of water) as the soft component of the cosmic rays. The calculation is made for latitude 39°36′N, and sun's declination of 5°30′N.

The second alternative would be that cosmic rays are emitted more abundantly from the portions of space in the neighborhood of the sun than at remote distances. This would give rise to a gradual change, with a maximum at noon and a minimum at midnight, following approximately a sine curve, as indicated by curve II of Fig. 3.

If we represent by 1 the mean square departure of the data from the true value as calculated from the probable error, the mean square departure from curve I is found to be 1.9, from II is 0.8 and from III is 2.5. That is, curve II is much more probable than curve I or the straight line III, and agrees satisfactorily with the experimental data. It should be added that if a curve similar to I is calculated assuming the absorption of the solar component to be the same as of the total cosmic-ray beam it agrees considerably better with the experiments than does the curve I as here drawn. Such an assumption seems however to be ruled out by the fact noted above that at low altitudes the diurnal variation is much less prominent than at high altitudes.

Thus the evidence favors the view that the diurnal variation follows approximately a sine curve, with the maximum at noon and minimum at midnight. Unless this effect is due to some obscure atmospheric phenomenon, it suggests that the portion of space in the neighborhood of the sun emits cosmic rays more copiously than the more remote regions. It can be simply shown that the effective radius of the region from which the rays come should be approximately,

$$r = 2a/\delta$$

where a is the radius of the earth's orbit, and $\delta = (I \text{ noon} - I \text{ midnight})/I$. Thus if δ for the soft component of the cosmic rays is 0.02, r becomes 100 times the radius of the earth's orbit, or about twice the radius of the orbit of Pluto.

Millikan and Cameron have shown that the energy received by the earth as cosmic rays is comparable with that received as star-light. If the cosmic rays which we receive are a fair sample of those existing in interstellar space, this means that the energy in the universe in the form of cosmic rays is of the same order as that in the form of light. Curve II which these experiments confirm is however based on the assumption that the part of space near the sun emits cosmic rays more copiously than the more remote regions. That is, these experiments support the view that we do not receive a fair sample of the cosmic rays. This makes it difficult to form any reliable estimate of the energy of cosmic rays in interstellar space.

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