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A Geographic Study of Cosmic Rays

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Data are given from measurements of the intensity of cosmic rays by 8 different expeditions at 69 stations distributed at representative points over the earth's surface. Each set of apparatus consisted of a 10 cm spherical steel ionization chamber filled with argon at 30 atmospheres, connected to a Lindemann electrometer, and shielded with 2.5 cm of bronze plus 5.0 cm of lead. Measurements were made by comparing the ionization current due to the cosmic rays with that due to a capsule of radium at a measured distance, the radium standards used with the several sets of apparatus having been intercompared. The method of detecting and correcting for the following disturbing effect is discussed: insulation leak and absorption, local gamma-radiation, radioactive contamination of the ionization chamber, and shielding from cosmic rays by roof and horizon. Intensity *vs.* barometer (altitude) curves are given for various latitudes. These show not only the rapid increase with altitude noted by previous observers, but also the fact that at each altitude the intensity is greater for high latitudes than near the equator. At sea level the intensity at high latitudes is 14 ± 0.6 percent greater than at the equator; at 2000 m elevation, 22 percent greater; and at 4360 m, 33 percent greater. This variation follows the geomagnetic latitude more closely than the geographic or the local magnetic latitude, and is most rapid between geomagnetic latitudes 25 and 40 degrees. Consideration of the conditions necessary for deflection of high-speed electrified particles by the earth's magnetic field indicates that if the cosmic rays are electrons, they must originate not less than several hundred kilometers above the earth. The data can be quantitatively explained on the basis of Lemaitre and Vallarta's theory of electrons approaching the earth from remote space. Acknowledgment is made of the cooperation of more than 60 physicists in this program, 25 of whom are named.

IN the summer of 1930, Professor R. D. Bennett, then of the University of Chicago, Professor J. C. Stearns of the University of Denver, and the writer initiated a coordinated study of the geographical distribution of cosmic rays. While it will be some years before this study is completed, the results already obtained give information whose publication should not be delayed. The present paper is thus a progress report[1] on the findings of our associated expeditions, and gives data which we hope to amplify in subsequent communications.

Previous studies of the relative intensity of the cosmic rays in different parts of the world have been made by J. Clay,[2] who made several trips between Java and Holland, and who found consistently a lower intensity near the equator; Millikan and Cameron,[3] who found but small

[1] Earlier reports of the work of these expeditions have appeared as follows: A. H. Compton, R. D. Bennett and J. C. Stearns, Phys. Rev. **38**, 1565, 1566 (1931); ibid. **39**, 873; **41**, 119 (1932). R. D. Bennett, Technology Review, July, 1932; A. H. Compton, Phys. Rev. **39**, 190; **41**, 111 and 681; **42**, 904 (1932); Scientific Mon., Jan., 1933. A. H. Compton and J. J. Hopfield, Phys. Rev. **41**, 539 (1932). J. C. Stearns, W. P. Overbeck and R. D. Bennett, Phys. Rev. **42**, 317 (1932). R. D. Bennett, J. L. Dunham, E. H. Bramhall and P. K. Allen, Phys. Rev. **42**, 446 (1932).

[2] J. Clay, Proc. Amsterdam Acad. **30**, 1115 (1927); **31**, 1091 (1928).

[3] R. A. Millikan and G. H. Cameron, Phys. Rev. **31**, 163 (1928).

differences between Bolivia and California in their measurements in mountain lakes, and no difference[4] between Pasadena and Churchill, close to the north magnetic pole; Bothe and Kolhörster,[5] who carried a counting tube from Hamburg (53°N) to Spitzbergen (81°N) and back, and who detected no variations in the cosmic rays larger than their rather large experimental error; Kennedy, who under Grant's direction[6] carried similar apparatus from Adelaide, Australia to Antarctica, and likewise found no measurable change; and Corlin,[7] who on going from 50°N to 70°N in Scandinavia found some evidence of a maximum at about 55°N. The prevailing opinion regarding the significance of these measurements has thus been expressed by Hoffmann[8] in a recent summary; "The results so far have on the whole been negative. Most of the observers conclude that within the errors of experiment the intensity is constant and equal, and those authors who do find differences give their results with certain reservations."

In view of the strong indication from the Bothe-Kolhörster double counter experiment[9] that the cosmic rays are high-speed electrical particles, this failure to find a variation of cosmic-ray intensity with latitude was of unusual interest. If the negative results of the experiments could be established with higher precision, it would mean that the cosmic rays could not be electrical particles coming from outside the earth's atmosphere, unless these particles had an unsuspectedly high energy. If, on the other hand, further experiments should confirm the tentative findings of Clay and Corlin, it might be found that a consistent theory of cosmic rays could be built on the assumption of high-speed electrical particles entering the earth's atmosphere.

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

[5] W. Bothe and W. Kolhörster, Berl. Ber. p. 450 (1930).

[6] Kerr Grant, Nature **127**, 924 (1931).

[7] A. Corlin, Lund Medd. No. 121 (1930).

[8] G. Hoffmann, Phys. Zeits. **32**, 633 (1932). Hoffmann mentions also (without reference) that in their airship flight over the north pole, Malmgrön and Behounek observed the normal cosmic-ray intensity throughout the flight.

[9] W. Bothe and W. Kolhörster, Zeits. f. Physik **56**, 751 (1929).

Organization and Location of the Observing Stations

In order to get as extensive data as possible in the minimum possible time, several expeditions were organized to go into different parts of the world. Seven similar sets of apparatus were constructed, and measurements by the different observers were made with essentially the same procedure. The work has been done not only at sea level, but also at as great a variety of altitudes as possible, in order to learn whether the intensity-altitude relation was independent of the location.

Eight of these associated expeditions have so far reported data. They have been under the direction of:

1. J. C. Stearns and A. H. Compton, working in Colorado and Switzerland.
2. A. H. Compton, in Hawaii, New Zealand, Australia, Panama, Peru, Mexico, northern Canada, Michigan and Illinois.
3. R. D. Bennett, Massachusetts Institute of Technology, in Alaska, California, Colorado and Cambridge.
4. E. O. Wollan, University of Chicago, in Chicago, Spitzbergen and Switzerland.
5. Allen Carpe, of New York City, in Alaska.
6. S. M. Naude, University of Capetown, in South Africa.
7. J. M. Benade, Forman Christian College, Lahore, in India, Ceylon, Malaya, Java, Ladakh.
8. P. G. Ledig, Division of Terrestrial Magnetism, Carnegie Institution of Washington, in South America.

The locations of the major stations where measurements have been made and reported are shown in Fig. 1.

Apparatus

In designing the measuring apparatus, the two main characteristics kept in mind were freedom from sources of systematic error and portability. An ionization chamber was used rather than a counting tube, because of the better reproducibility and the lower statistical error of its readings. The chamber was made small, 10 cm diameter, in order that the weight of the pro-

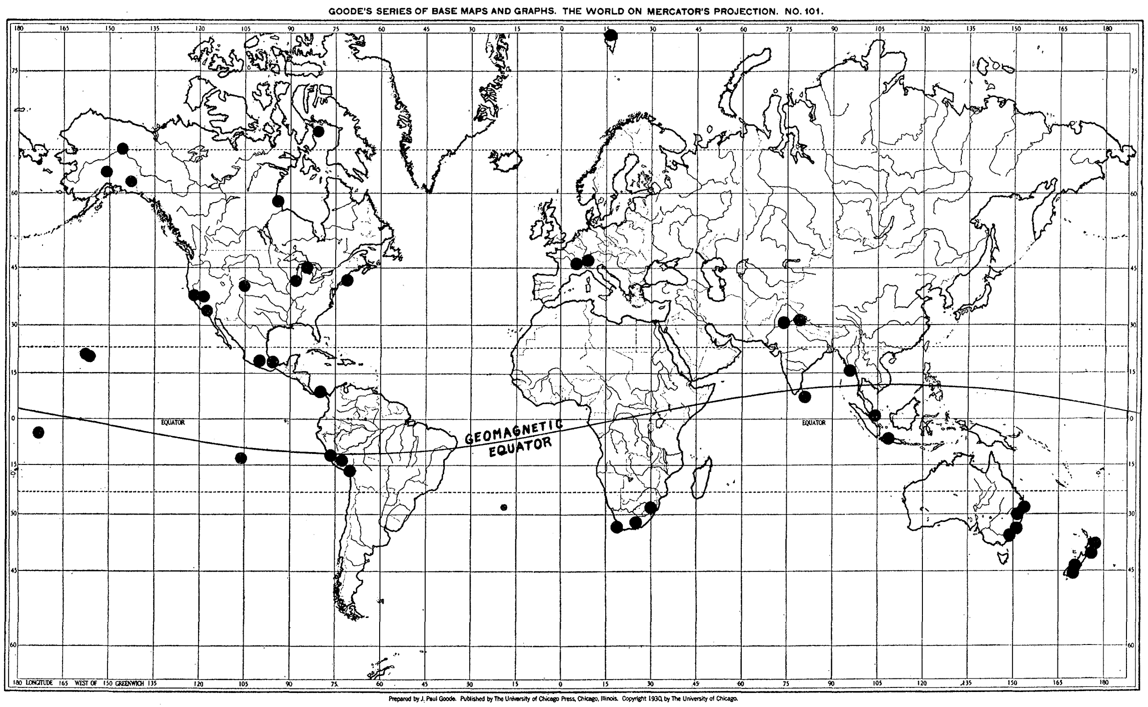

FIG. 1. Map showing location of our major stations for observing cosmic rays.

tecting shields should not be too great for transport by pack trains or porters. By filling the chamber with argon[10] at 30 atmospheres the ionization current was made large enough to be conveniently measurable with a Lindemann electrometer. At each station the ionization due to the cosmic rays was compared with that due to a standard radium capsule. Our measurements were thus independent of the pressure of the gas in the chamber, or of the sensitiveness of our electrical instruments, the reliability of our comparison between different stations depending rather upon the constancy of the radium capsule.

A partly diagrammatic plan of the apparatus is shown in Fig. 2. The ions produced in the argon-filled chamber are collected by a steel rod electrode, which conducts the ionization current to the needle of the electrometer. This electrode is insulated by an amber cone from the brass tube through which it passes. The brass tube serves as a support for the ionization chamber, and remains at ground potential. The chamber containing the key and the connection to the electrometer, though at atmospheric pressure, is kept nearly air-tight with a sponge rubber gasket *G*, and is dried with a phosphorus pentoxide tube. The electrometer is similarly dried by using a modified form of drying tube. The pressure chambers have shown little if any leak while in service in the field. The various battery potentials indicated in the diagram are supplied by commercial dry batteries. Spherical shells of bronze and of antimony lead encased in thin steel are fitted around the ionization chamber. These shells, each 2.5 cm thick, are sufficient to reduce the intensity of the local gamma-rays to about 5 percent of the cosmic-ray intensity.

For standardizing the instrument, a capsule containing about 1.3 mg of radium enclosed in about 1 cm of lead is placed with its center 1 meter from the center of the ionization chamber. The absolute magnitude of the ionization current due to the radium in this position was measured by the help of a standard cylindrical condenser, which is screwed in place of the grounding key *K*. This condenser has two pairs of concentric cylinders which may be used alternately. The difference in capacity between the larger and the

[10] Cf. A. H. Compton and J. J. Hopfield, Phys. Rev. **41**, 539 (1932).

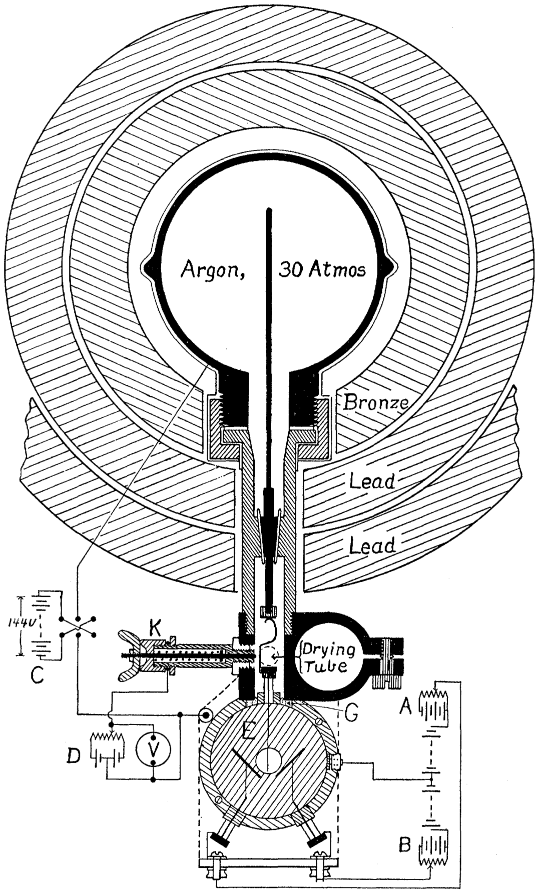

FIG. 2. Cosmic-ray ionization chamber, electrometer, and electrical connections.

smaller pair can be calculated from the dimensions as 14.95 cm. By comparing the rate of drift of the electrometer needle with and without the condensers, the capacity of apparatus No. 7, for a needle sensitivity of 0.01 volt per division, was found to be 12.72 cm. The ionization current due to the laboratory radium standard at 1 meter produced a potential change of 4.14×10^{-5} volts per second, when the chamber was filled with dry air at 741 mm pressure and 24.5°C, corresponding to 4.626×10^{-5} volts per second filled with air under standard conditions. The volume of the chamber was 430.8 cc. Thus the ionization in standard air due to the laboratory radium standard at 1 meter, through the lead and bronze shields, is,

$$I_s=\frac{1}{300}\times\frac{12.72\times4.626\times10^{-5}}{4.77\times10^{-10}\times430.8}=9.53 \text{ ions cm}^{-3}\text{ sec.}^{-1}. \quad (1)$$

Each of the 7 sets of apparatus has with it its own secondary radium standard, which was compared with the laboratory standard before the equipment was sent out for use. These secondary standards were found to produce respectively in standard air at 1 meter, per cm^3 per sec., the values given in Table I.

THE MEASUREMENTS

Each complete set of measurements at a given station consisted of two parts: (1) the determination of the ratio i_2/i_r of the ionization with the radium at a great distance to the ionization with the radium at 1 meter from the center of the ionization chamber, by using both lead shields; and (2) measurement of the ratio i_1/i_2 of the ionization with no radium present when only 1 lead shield surrounds the chamber to that with two lead shields in place. From these two data and the value of I_γ given in Table I can be

TABLE I. *Ionization by radium capsules.*

Capsule No.	Expedition No.	Ionization (I_γ)
1	3	11.05 ions
2	7	11.8
3	6	12.2
4	5	11.95
5	2 and 8	11.6
6	9	11.55
7	4 and 3	11.85

calculated the ionization due to the cosmic rays (through both lead shields), and the intensity of the local gamma-rays which enter the chamber.

Let i_r be the observed ionization current in arbitrary units, through 2 lead shields, radium at 1 meter; i_1 the ionization through 1 lead shield, radium absent; i_2 the ionization through 2 lead shields, radium absent. The ratio of the ionization due to cosmic and local rays to that due to the gamma-rays alone is then,

$$R_2=i_2/(i_r-i_2)=(i_2/i_r)/(1-i_2/i_r). \quad (2)$$

Also, the ratio of the cosmic rays with 1 shield to the gamma-rays with 2 shields is,

$$R_1=(i_1/i_2)R_2. \quad (3)$$

To correct for the effect of the local radiation we use the formulas,

$$C = [a/(a-b)](R_2 - bR_1)I_\gamma \qquad (4)$$

$$L = R_2 I_\gamma - C. \qquad (5)$$

Here C is the ionization through both lead shields, due to the cosmic rays alone, and I_γ is the ionization by the gamma-rays, so that if I_γ is expressed in ions per cc per second in standard air, C is expressed in the same units.[11] a is the ratio of the ionization due to the cosmic rays when 2 lead shields are used to that when 1 shield is used, and has a value of about 0.9. b is the same ratio for the local gamma-rays, and has a value of 0.286. L represents the ionization due solely to the local rays.

The derivation[12] of Eq. (4) involves the assumption that the ionization due to radioactivity in the chamber itself is negligible. This has been tested with three of our sets of apparatus by placing them in deep tunnels (one in Colorado, one in Thibet and one in Peru). If the assumption is justified, the calculated intensity of the cosmic rays inside the tunnel should be zero. In the Colorado and Thibet measurements it was found to be respectively about 0.2 and 0.1 percent of the intensity outside the tunnel, whereas in the Peruvian measurements there appeared an ionization of about 2 percent, which may have been due to temporary radioactive contamination.

The value of b was determined by using the radium capsule as the source of gamma-rays. In regions where thorium is abundant the resulting value may not be wholly reliable, but approximate tests on the local radiation inside a tunnel in Peru have confirmed the value obtained with radium within experimental error. It was found that the value of a varies so rapidly with altitude that it was necessary to adjust this constant according to the barometric pressure. The values of a used in calculating our results are given in Fig. 3. These values are somewhat arbitrary.

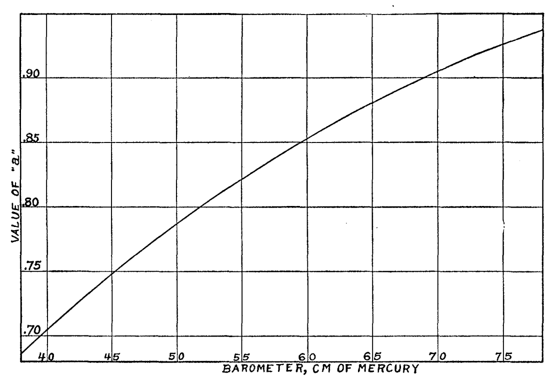

FIG. 3. a as a function of barometric pressure.

Approximate values of a have been determined by measurements of the relative ionization with 1, 2, and 3 shields. Such determinations are however unreliable because the cosmic rays are not exponentially absorbed by the shields. The values given in Fig. 2 are so chosen that the correction for local radiation is on the average about the same for different altitudes. Errors in the value of a will introduce errors in the absolute ionization by the cosmic rays, and in the

[11] This statement assumes that the value of R_2 will be independent of the nature and pressure of the gas in the ionization chamber. Its independence of pressure when air or CO_2 is used has been tested and confirmed by Stearns (Phys. Rev. **39**, 881 (1932)), Millikan (Phys. Rev. **39**, 397 (1932)) and Steinke and Schindler (Naturwiss. **20**, 15 (1932)), though Broxon working with nitrogen (Phys. Rev. **40**, 327 (1932)) and Hopfield using argon (Phys. Rev. **42**, 904A (1932)) find slight differences. If such differences exist, they will require a revision of our *absolute* cosmic-ray intensities, though not of our relative intensities at different altitudes and latitudes.

[12] Let C_1 and L_1 be the intensities of the cosmic rays and the local rays respectively through 1 shell of lead, C_2 and L_2 be the intensities through 2 shells of lead. Then

$$I_1 = C_1 + L_1 \qquad (6)$$

and

$$I_2 = C_2 + L_2 \qquad (7)$$

are the total observed intensities in the two cases, when no radium is present. Also, $a = C_2/C_1$ and $b = L_2/L_1$ are the fractions of the cosmic and the local rays respectively transmitted by the second shell of lead. Thus $C_2 = aC_1$ and $L_2 = bL_1$. Writing Eq. (7) as

$$I_2 = aC_1 + bL_1, \qquad (8)$$

and combining with (6) we find,

$$C_1 = [1/(a-b)](I_2 - bI_1),$$

or, since $C_2 = aC_1$

$$C_2 = [a/(a-b)](I_2 - bI_1). \qquad (9)$$

However, I_2 is the same as the $R_2 I_\gamma$, and $I_1 = R_1 I_\gamma$. Also, C_2 is identical with the C of Eq. (4). Hence,

$$C = [a/(a-b)](R_2 - bR_1)I_\gamma, \qquad (10)$$

which is Eq. (4) of the text.

relative ionization at different altitudes. They will not affect however the relative ionization as calculated at different latitudes.

In any case, since the corrections introduced by Eqs. (3) and (4) for the local radiation are of the order of only 5 percent of the observed intensity, small errors in this correction are not serious.

A typical series of readings consists of: (A) Measurements with the bronze and both lead shields, with and without radium, and with the ionization chamber alternately at +144 and −144 volts. This serves to determine i_2/i_r. (B) Measurements with the bronze and one lead shield, without radium, and with the ionization chamber alternately at +144 and −144 volts. Comparison with A gives i_1/i_2.

Measurements of type A and B are made alternately over a period of from 8 hours to 240 hours, and then averaged. Most of the data reported for a given station represent about 30 hours of readings.

Corrections

In addition to the correction for local radiation, small corrections were necessary also for the absorption by the roof—if any—protecting the apparatus, and for the shielding due to neighboring mountains or buildings. The roof correction was made by adding to the observed barometric pressure an equivalent to the average weight per cm^2 of the roof. The maximum correction thus applied amounted to 5.3 mm of mercury. Wherever possible an unprotected site was of course chosen. In no case was the shielding by neighboring buildings significant. In many cases, however, neighboring mountains shielded the apparatus appreciably. A panorama of the altitude of the horizon was then made, and the loss from the shielded zones estimated from Table II. The maximum correction as thus estimated for any station was 10 percent. Since

Table II.

Degrees from zenith	Normal contribution
0–45°	0.6578
45–60°	0.2105
60–75°	0.1100
75–85°	0.0210
85–90°	0.0007

the angular altitude distribution of cosmic rays is known to depend on the elevation, this correction is of course only approximate.

Several kinds of electrical troubles were encountered. Among these should be mentioned, leakage across the insulation supporting the electrode and the electrometer needle, dielectric absorption by this insulation, ionization in the air filling the electrometer and the tube connecting the electrometer to the ionization chamber, and insulation failures in the auxiliary battery box. Trouble with the batteries could introduce no systematic errors into our measurements, but occasionally reduced their precision. By drying the battery box and connections either with heat or with calcium chloride, the insulation could be kept in satisfactory condition in the dampest weather. Small leaks along the electrometer insulation and ionization in the connecting tube produced effects which average out when a complete series of readings as outlined above is taken. It can be shown that if the resistance of this insulation leak obeys Ohm's law, the average rate from −10 to +10 differs from the rate at 0 by less than 1 percent if the time from 0 to +10 does not exceed that from −10 to 0 by more than 20 percent. Under normal operating conditions the difference was much less than this, and any insulation leak was thus of negligible importance. Tests for such leaks were however a part of our regular routine.

Dielectric absorption showed itself by a faster rate of deflection just after reversing the potential of the sphere than after some minutes had elapsed. The effect could be reduced by careful drying of the air near the electrometer insulation. By using a "null method" of reading, for which each apparatus was wired, the effect of dielectric absorption could be completely eliminated. This method consisted in changing the voltage of the battery C continuously through 6 volts by means of a potentiometer, and thus inducing on the electrode a current which would just balance the ionization current, thus keeping the electrometer needle at zero. In this case the time was noted for which a change of 6 volts was required. This method was however used very little, since the direct deflection method was simpler, and no difference could be detected in the results of the two methods when suitable care was taken.

We have occasionally noted also that the readings taken immediately after changing the lead and copper shields have shown a slightly higher ionization than occurs after standing for 30 minutes or more. This may be due to a temporary active deposit falling on the outside of the electrically charged chamber when the shields are removed. This may have influenced some of the data taken at Summit Lake in Colorado. The effect is at most a few percent, and seems to be of short duration.

It will be especially noted that the value of the cosmic-ray intensity observed in the field does not depend at all upon the sensitivity of the electrometer nor the precision of our voltmeter, nor, within wide limits, upon the perfection of the insulation. We have relied rather upon the constancy of the radium sample as our only standard.

For measuring the barometric pressure, Paulin barometers and aneroids were chiefly used. Wherever possible, these instruments were compared with mercury barometers, and some boiling point tests were made. On the high mountain measurements, however, it is probable that our barometric errors are more serious than our errors in the cosmic-ray data.

Data

In Table III are recorded the data which have been reported before the end of 1932. All the measurements that have been made are included, except one in Australia, and several near Ceylon and Singapore, for which insulation troubles due to high humidity made the results highly erratic. The tabulated values of i_2/i_r and of i_1/i_2 are merely the averages of the observations, taken as described above, without any corrections. The horizon correction is calculated from Table II, and the values of I_γ are taken from Table I. For expedition 1, the laboratory standard capsule was used at a much shorter distance, thus accounting for the high value of I_γ. The values of C and L are then calculated from these data by using Eqs. (3) and (4). No corrections for radiation from the chamber walls have been applied in the tabulated values of C.

In Fig. 4 are plotted the values of the cosmic-ray intensity C as a function of the barometric pressure, including all the data given in Table III. The circles represent data obtained in the northern hemisphere, and the squares those from the southern hemisphere. The solid dots are values from geomagnetic latitudes[13] higher than 40 degrees, the open dots are between 25°S and 25°N, and the half shaded dots for intermediate latitudes.

In plotting these data, the values of C found by expeditions 1 and 4 have been adjusted so that they can be compared with those from the other expeditions. Expedition 1 used a somewhat larger ionization chamber, filled with air at 30 atmospheres instead of argon, and cylindrical instead of spherical shields. A reliable comparison of the data with the two sets of apparatus is however made possible by comparing the value of $C=6.10$ ions obtained from 240 hours readings at Summit Lake with apparatus number 1 in 1931 with the value of $C=5.70$ ions obtained from a series of readings of equal length at the same location with apparatus number 3. Thus all of the data obtained by expedition 1 have been multiplied by the factor $5.70/6.10=0.935$ to reduce them to the same basis as those obtained by the other expeditions. Expedition 4 used an ionization chamber with which a variety of auxiliary tests had been made over a period of four months. Just before its final filling with argon, it was noted that the residual ionization (radium re-

[13] By geomagnetic latitude we mean the latitude relative to the pole of the earth's uniform magnetization. The north geomagnetic pole, according to Bauer (Terrestrial Magnetism **28**, 1 (1923)), is at 78°32′N, 69°08′W. This is not identical with the north "magnetic pole" (90° dip), which Amundsen places at 71°N, 96°W (1903–6). The geomagnetic latitudes here used are calculated by the formula,

$$\sin \lambda = \sin \psi \cos \theta \cos \varphi + \cos \psi \sin \theta, \quad (11)$$

where λ is the geomagnetic latitude, ψ is the colatitude of the north pole of uniform magnetization, θ is the geographic latitude of the point, and $\varphi + 69°08'$ is the west longitude of the point.

The "magnetic latitude," as commonly used in papers on terrestrial magnetism, is commonly defined by the formula,

$$\tan \mu = \tfrac{1}{2} \tan \delta, \quad (12)$$

where μ is the magnetic latitude and δ is the inclination or dip of the magnetic needle.

Thus the magnetic latitude is a function of the local magnetic field at the point, whereas the "geomagnetic latitude" depends upon the earth's resultant magnetic moment.

TABLE III. *Cosmic-ray intensities at various locations.*

Expt.	Expd.	Place	Lat.	Long.	Bar. (cm)	i_2/i_r	i_1/i_2	Hor. corr.	I_γ	C	L	C_{76}	C_{60}	C_{45}	Geo-mag. Lat.	Date
1	1	Mt. Evans	40N	106W	44.7	——	——	1.00	——	7.32	0.13†			6.69	49N	9/31
2	1	Summit Lake	40N	106W	47.4	0.0430	——	.995	137	6.10	.13†			6.71	49N	9/31
3	1	Denver	40N	105W	62.3	——	——	——	——	2.93	——		3.02		49N	9/31
4	1	Jungfraujoch	47N	6E	50.0	.0371	1.344	.944	137	5.45	.16			6.99	49N	10/31
5	2	Haleakala	21N	156W	54.7	.2264	1.504	.99	11.6	3.00	.42		2.42		21N	4/32
6	2	Idlewild	21N	156W	66.0	.1725	1.449	.99	11.6	2.12	.32		2.61		21N	4/32
7	2	Honolulu	21N	158W	76.4	.1304	1.230	1.00	11.6	1.63	.11	1.65			20N	4/32
8	2	SS Aorangi	4S	173W	75.3	.1391	1.500	1.00	11.6	1.65	.20†	1.64			7S	4/32
9	2	Ball Pass	44S	170E	60.2	.2120	1.249	.99	11.6	3.05	.10		3.08		50S	4/32
10	2	Ball Hut	44S	170E	66.3	.1757	1.281	.970	11.6	2.38	.16		3.01		50S	4/32
11	2	Dunedin	46S	170E	76.4	.1460	1.211	1.00	11.6	1.87	.11	1.88			51S	4/32
12	2	Wellington	41S	175E	75.8	.1464	1.235	.99	11.6	1.86	.14	1.86			44S	5/32
13	2	Sydney	34S	151E	76.6	.1614	1.480	1.00	11.6	1.86	.37	1.88			43S	5/32
14	2	Kosciusko	36S	148E	60.6	.2312	1.511	1.00	11.6	2.98	.50		3.06		45S	5/32
15	2	Brisbane*	28S	153E	76.8	.1444	1.510	1.00	11.6	1.61	.35	1.63			37S	5/32
16	2	Guyra*	30S	152E	64.8	.1893	1.232	1.00	11.6	2.60	.11	1.87			39S	5/32
17	2	Auckland	37S	175E	77.5	.1372	1.186	1.00	11.6	1.76	.08	1.81			42S	5/32
18	2	SS Mataroa	13S	106W	76.2	.1300	1.259	1.00	11.6	1.61	.13	1.61			5S	6/32
19	2	Panama	9N	80W	75.5	.1362	1.324	.995	11.6	1.66	.18	1.64			20N	6/32
20	2	Lima	12S	77W	75.0	.1356	1.313	1.00	11.6	1.65	.17	1.62			1S	6/32
21	2	Chosica	12S	77W	68.8	.1541	1.287	.978	11.6	1.99	.16	1.66			1S	7/32
22	2	Matucana	12S	77W	57.3	.1927	1.243	.924	11.6	2.93	.06		2.64		1S	7/32
23	2	Chicla	12S	77W	48.6	.2596	1.312	.932	11.6	4.32	.03			5.22	1S	7/32
24	2	Galera	12S	77W	42.8	.337	1.368	.976	11.6	6.03	0			5.24	1S	7/32
25	2	Huantapallacu	13S	74W	43.8	.3221	1.402	.995	11.6	5.41	.12			5.07	2S	7/32
26	2	El Misti	17S	71W	37.7	.4245	1.490	1.00	11.6	8.41	.125			5.10	6S	7/32
27	2	Monte Blanco	17S	71W	42.8	.3500	1.441	.980	11.6	6.15	.21			5.39	6S	7/32
28	2	Arequipa	17S	71W	57.6	.2061	1.300	.995	11.6	2.89	.14		2.63		6S	7/32
29	2	Mollendo	17S	72W	76.8	.1266	1.179	1.00	11.6	1.61	.07	1.63			6S	7/32
30	2	Vera Cruz	19N	96W	76.0	.1306	.998	1.00	11.6	1.68	.06†	1.68			29N	8/32
31	2	Orizaba	19N	97W	66.1	.1619	1.066	.995	11.6	2.19	.06†		2.77		29N	8/32
32	2	Mexico City	19N	99W	58.5	.2039	1.264	1.00	11.6	2.87	.10		2.69		29N	8/32
33	2	Nevado Toluco	19N	100W	46.5	.3204	1.386	.981	11.6	5.44	.13			5.95	29N	8/32
34	2	SS Ocean Eagle	67N	80W	75.3	.1400	1.150	.982	11.6	1.86	.06	1.84			78N	8/32
35	2	Churchill*	59N	94W	76.0	.1386	1.186	.99	11.6	1.80	.09	1.80			69N	9/32
36	2	Otsego Lake	45N	85W	73.2	.1469	1.184	1.00	11.6	1.91	.08	1.80			56N	9/32
37	2	Chicago	42N	88W	74.5	.1514	1.205	1.00	11.6	1.96	.10	1.88			53N	10/32
38	3	Fort Yukon	67N	145W	75.1	.1500	1.190	(1.00)	11.05	1.88	.09	1.84			71N	6/32
39	3	Kennecott	62N	143W	61.0	.2092	1.214	(1.00)	11.05	2.88	.06		3.01		66N	7/32
40	3	Berkeley	38N	122W	75.1	.1465	1.220	(1.00)	11.05	1.81	.11	1.78			46N	7/32
41	3	Tioga Pass	38N	119W	53.0	.2788	1.307	(1.00)	11.05	4.18	.13		3.04		46N	8/32
42	3	Pasadena	34N	118W	73.6	.1537	1.250	(1.00)	11.05	1.88	.14	1.79			42N	8/32
43	3	Denver	40N	105W	62.3	.2026	1.271	(1.00)	11.05	2.69	.14		2.96		49N	8/32
44	3	Summit Lake	40N	106W	48.1	.3466	1.372	(1.00)	11.05	5.70	.20			6.96	49N	9/32
45	4	Chicago	42N	88W	74.5	.1838	1.168	1.00	11.85	2.57	.09	1.80			53N	7/32
46	4	Advent Bay	78N	16E	75.5	.1844	1.152	.98	11.85	2.59	.09	1.86			75N	8/32
47	4	Zurich	47N	9E	71.7	.1930	1.184	.995	11.85	2.74	.10	1.82			49N	10/32
48	4	Eiger Gletcher*	47N	8E	57.4	.2460	1.236	.90	11.85	4.21	.07		3.14		49N	10/32
49	4	Wengen	47N	8E	65.5	.2208	1.195	.99	11.85	3.36	.07		3.20		49N	10/32
50	4	Jungfraujoch	47N	8E	50.1	.3246	1.260	.99	11.85	5.68	.06†			6.84	49N	10/32
51	5	Mt. McKinley*	63N	151W	50.0	.333	1.312	.98	11.95	6.00	.10			8.50	67N	5/32
52	6	Capetown	34S	18E	76.0	.1294	1.234	(1.00)	12.2	1.70	.12	1.70			32S	6/32
53	6	Lootsberg	32S	25E	62.2	.1875	1.292	(1.00)	12.2	2.65	.16		2.91		32S	7/32
54	6	Johannesburg	26S	28E	62.6	.1799	1.224	(1.00)	12.2	2.59	.09		2.88		27S	7/32
55	6	Vlakfontein	27S	30E	63.9	.1749	1.328	(1.00)	12.2	2.38	.20		2.75		28S	7/32
56	6	Pretoria	27S	28E	65.6	.1644	1.252	(1.00)	12.2	2.31	.12		2.81		28S	7/32
57	6	Lodewykslust	27S	31E	67.7	.1560	1.290	(1.00)	12.2	2.09	.16	1.69			28S	7/32
58	6	Nat. Park, Natal	29S	29E	64.9	.1674	1.270	(1.00)	12.2	2.31	.14		2.77		30S	7/32
59	6	Mt-aux-Sources	29S	29E	54.5	.2264	1.300	(1.00)	12.2	3.51	.05		2.80		30S	7/32
60	7	Lahore	31N	74E	74.3	.127	1.20	1.00	11.8	1.63	.08	1.59			21N	8/32
61	7	Lal Tibba	30N	78E	58.2	.184	1.27	.98	11.8	2.62	.09		2.44		20N	8/32
62	7	Rohtang La	32N	77E	47.7	.281	1.375	.98	11.8	4.51	.15			5.24	22N	8/32
63	7	Sarchu	33N	78E	46.1	.297	1.37	(1.00)	11.8	4.87	.12			5.21	23N	8/32
64	7	Lachalung La	33N	78E	42.8	.315	1.41	.96	11.8	5.32	.10			4.65	23N	8/32
65	7	Bara Lacha La	33N	77E	42.5	.343	1.42	.99	11.8	6.09	.13			5.21	23N	8/32
66	7	Telekonka*	33N	78E	41.2	.384	1.43	(1.00)	11.8	7.24	.10			5.60	23N	8/32
67	7	Lanyar La	30N	78E	37.7	.421	1.48	.99	11.8	8.58	.07			5.25	20N	8/32
68	8	Lima	12S	77W	74.6	.1306	1.255	1.00	11.6	1.61	.13	1.58			1S	12/32
69	3	Cambridge	42N	71W	76.8	.184	1.140	1.00	11.85	2.55	.12	1.87			53N	12/32

* Values at these stations have low statistical weight, because of either low reproducibility of the data or a small number of readings.

† These values of L are estimated, because of insufficient data for their reliable calculation.

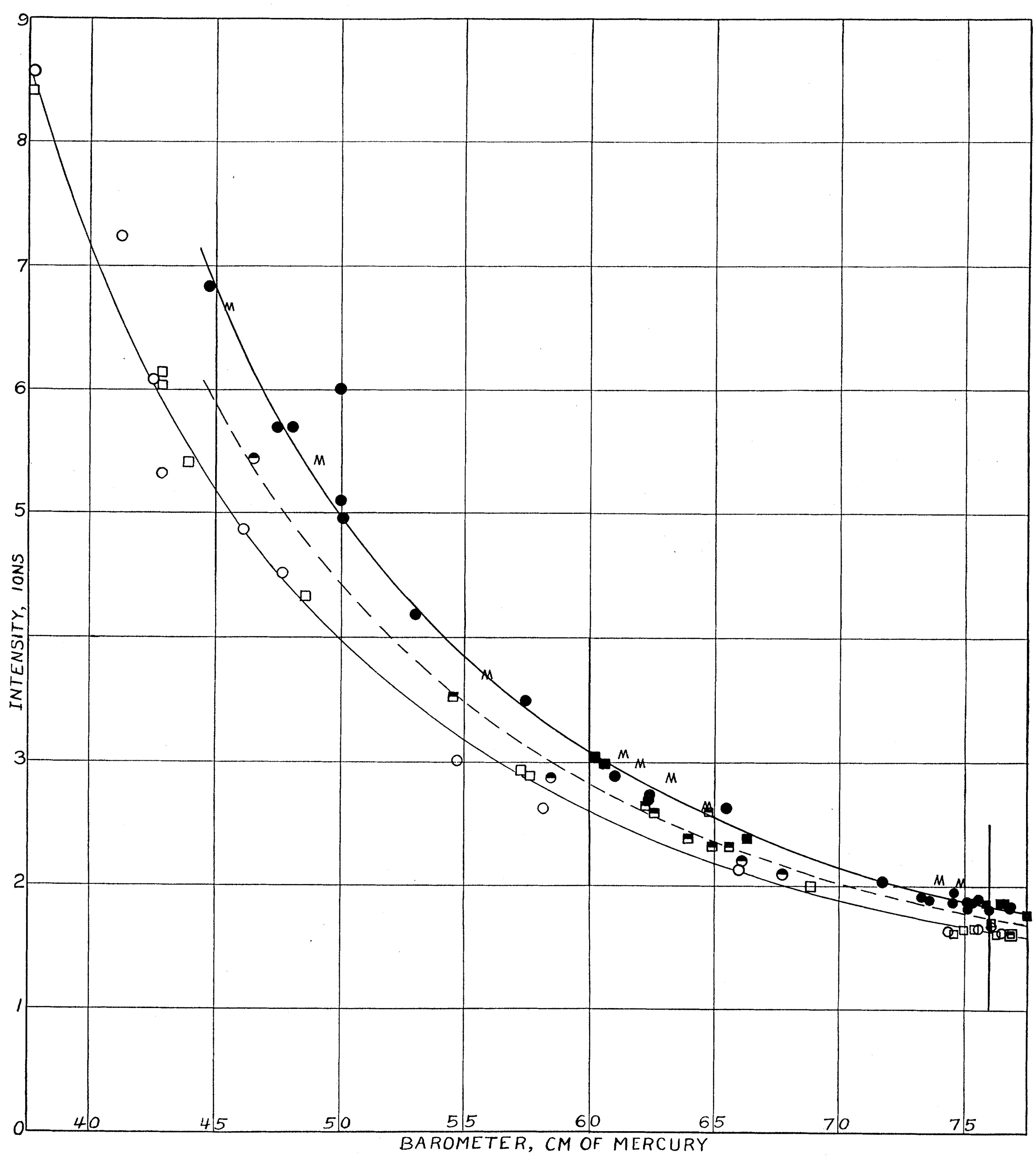

FIG. 4. Cosmic-ray intensity at different elevations. Squares, southern hemisphere. Circles, northern hemisphere. Solid dots, 90° to 40°. Shaded dots, 40° to 25°. Open dots, 0° to 25°.

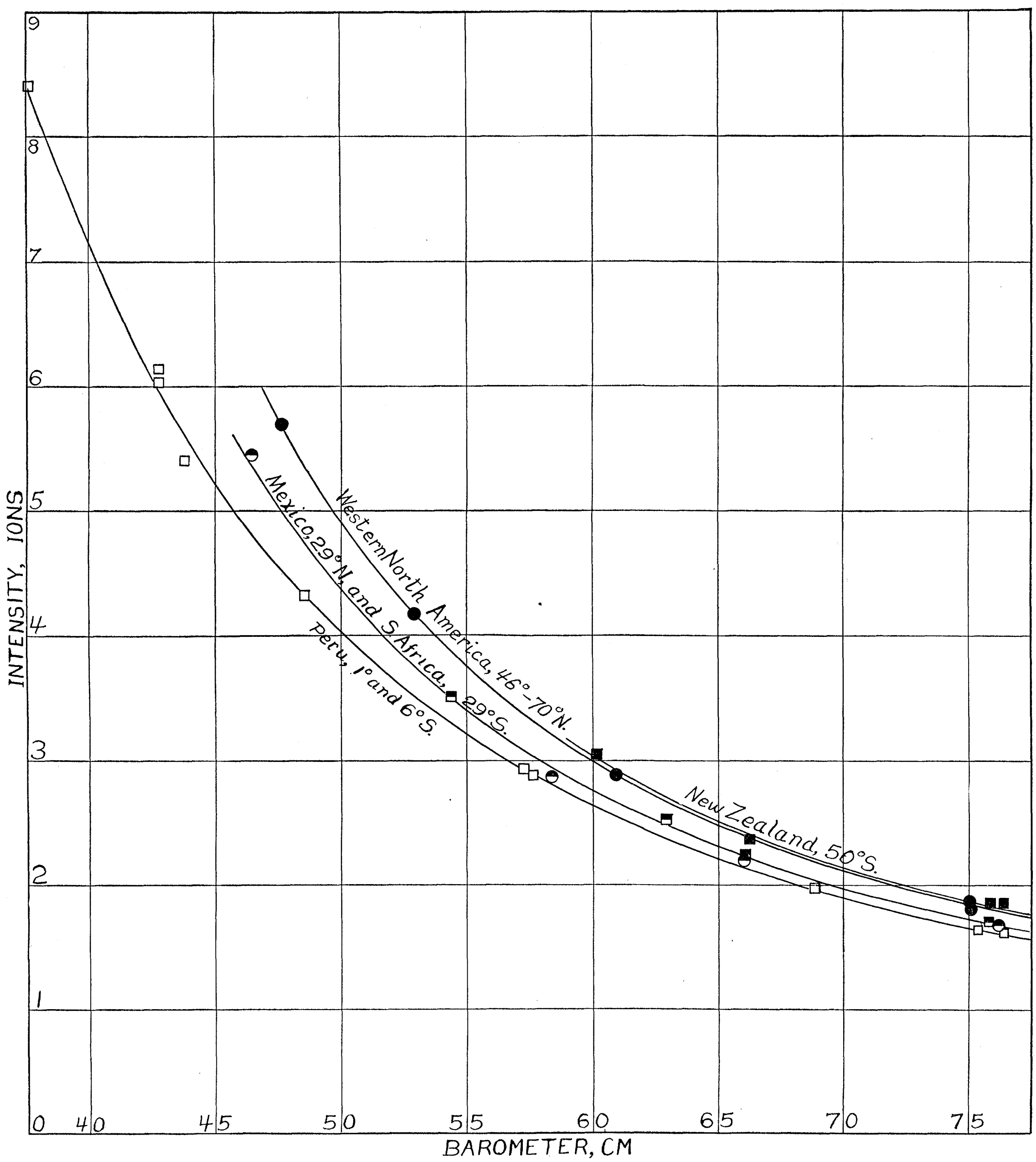

FIG. 5. Typical intensity *vs.* altitude curves for various latitudes.

moved and shields in place) was greater with air at 1 atmosphere than with air at 100 atmospheres. This could only mean an alpha-ray contamination, whose ionization is reduced by pressure. The magnitude of this ionization from the walls has been estimated by comparing the mean value of $C_{76}=2.55$ ions from experiments 45, 46 and 69 (Chicago, Spitzbergen and Cambridge) with the mean value of $C_{76}=1.84$ ions obtained for similar latitudes by expeditions 2 and 3. Thus, by subtracting 0.71 ion from the data obtained with apparatus 4, its results become comparable with those from the other sets of equipment.[14]

On the same figure are plotted the data of Millikan and Cameron,[15] indicated by the symbol *M*. The agreement between their values and ours is satisfactory, in view of the differences in the type of apparatus employed.

In Fig. 4 all of the data are included, without choice on the basis of statistical weight. The fact that all of the solid dots lie higher than the open ones over the whole range of barometric pressures is definite evidence that the cosmic rays are more intense at high latitudes than near the equator. This difference is shown more clearly in Fig. 5, which shows the results of six series of intensity *vs.* altitude measurements, made under favorable conditions, at six different latitudes. Those in New Zealand, Mexico and Peru were taken with apparatus number 2, Western North America with number 3, and South Africa with number 6. The excellent agreement between the New Zealand and the North American data, and between the South African and Mexican data indicates the reliability of our method of measurement. This figure shows also how the difference in intensity between the tropic and polar zones becomes much more prominent at the higher elevations.

Variation of Cosmic-Ray Intensity with Latitude

In order to make a precise comparison of the data for different latitudes, the data plotted in Fig. 4 have been reduced to three standard barometric pressures, by using the smooth curves drawn in this figure as guides in effecting the reduction. All data for pressures over 67.5 cm have been reduced to 76 cm; those between 52.5 cm and 67.5 cm to 60 cm; and those between 37.5 cm and 52.5 cm to 45 cm. The values as thus standardized are given in Table III in columns C_{76}, C_{60} and C_{45}, and are plotted in Fig. 6 as functions of the geomagnetic latitude. In making this graph, the values in brackets in columns C_{76}, C_{60} and C_{45} have been averaged and plotted as a single point, in order to avoid unnecessary complexity. The numbers within the datum points indicate the apparatus with which the different values were obtained.

All the data agree in showing a marked difference between the intensities found within 20 degrees of the magnetic equator as compared with those at a higher latitude than 50° north or south. The increase in going to the higher latitudes averages 14 percent at sea level, 22 percent at 2000 meters (barometer 60 cm), and 33 percent at 4360 meters (barometer 45 cm).

In order to show the sea level values more clearly, they have been plotted in Fig. 7 on a larger scale. There have been added to this figure the data of Millikan,[16] taken at Pasadena and Churchill; and the recent ones of Clay and Berlage,[17] obtained with a set of Steinke recording equipment, compared with a standard at Amsterdam and carried on a ship from Genoa to Singapore. The values in Table IV, read from Clay and Berlage's curve, have been used in

[14] It is probable that there may be wall corrections of a similar type that should be applied to the other sets of apparatus. If so, however, the corrections are certainly much smaller than those for chamber number 4. Lacking exact information regarding the magnitude of these corrections, we have preferred to make none at all for the other sets of equipment. This procedure is partially justified by the small magnitude of the correction as found for the three sets of equipment that have been tested, and by the consistency of the data as here shown. It is probable that an even better agreement will, however, appear when it becomes possible to determine this zero correction by direct experiment. It will be about a year before such tests can be completed. Of course any possible zero correction cannot affect the differences observed at different latitudes and altitudes when using the same set of apparatus.

[15] R. A. Millikan and G. H. Cameron, Phys. Rev. **37**, 235 (1931). The ionization values given in their Table III are divided by the factor 13.80 given by Millikan (Phys. Rev. **39**, 397 (1932)) to reduce their measurements at 30 atmospheres air pressure to 1 atmosphere.

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

[17] J. Clay and H. P. Berlage, Naturwiss. **37**, 687 (1932).

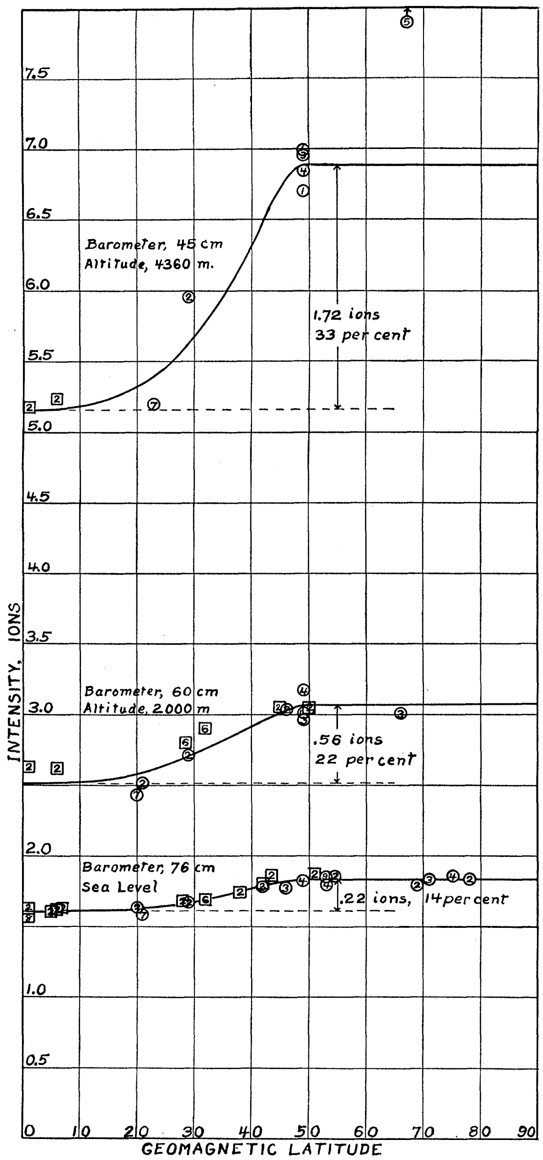

FIG. 6. Intensity *vs.* geomagnetic latitude for different elevations.

Fig. 5. These values have been plotted as crosses without any adjustment of the constants. Millikan's values are given for an ionization chamber pressure of 30 atmospheres; which, as he notes in a later paper,[18] multiplies the ionization by 13.80. With this reduction factor, his value at Pasadena is 2.050 ions for barometer 74.0 cm, and at Churchill is 2.020 ions for barometer 74.8 cm. Reduced to sea level according to the curves of Fig. 4, these intensities become 1.970 and 1.974 respectively. These values have been compared with ours by multiplying by the factor 1.79/1.97, which makes his value at Pasadena and ours at the same place identical. This gives for Millikan's value at Churchill (on our scale) 1.793 ions, plotted as a plus sign, which is to be compared with our value at Churchill of 1.80 ions. Our data are thus in good accord with those of the other observers who have made measurements in the same regions.

It is significant that most of the datum points recorded in Fig. 7 were taken with the same set of apparatus (expedition 2). It was carried from geomagnetic latitude $\lambda = 53$ N to 51 S. After crossing the equator four times at different longitudes it was brought back to 78 N, and then sent once more across the equator with expedition 8.

The 15 experimental points plotted in Fig. 7 for this instrument were all taken under essentially the same conditions, so that we cannot find any source of systematic error that might affect the results. The readings with instruments 3 and 4 confirm the absence of appreciable variation north of $\lambda = 42°$, and comparison with the data from instruments 6 and 7 confirms both the magnitude of the variation observed by instrument 2 and the latitude at which it occurs.

TABLE IV. *Cosmic-ray intensities from Clay and Berlage's curve.*

Place	Lat.	Long.	*C*	Geomag. Lat.
Amsterdam	52 N	5 E	1.87	54 N
Genoa	44 N	9 E	1.79	44 N
At sea	37 N	19 E	1.72	35 N
Suez	30 N	32 E	1.66	27 N
Guardafui	12 N	51 E	1.61	6 N
Colombo	7 N	80 E	1.59	4 S
Singapore	1 N	104 E	1.58	11 S

The average of our 8 datum points taken for geomagnetic latitudes less than 22 degrees is 1.620 ± 0.006 ions. For our 9 datum points at latitudes higher than 48°, the average is 1.839 ± 0.006 ions. The difference between the two latitude ranges is thus 0.219 ± 0.0085 ion; that is, more than 25 times the probable error. This probable error is also approximately that estimated also on the basis of statistical fluctuations in the readings taken under uniform conditions.

[18] R. A. Millikan, Phys. Rev. **39**, 397 (1932).

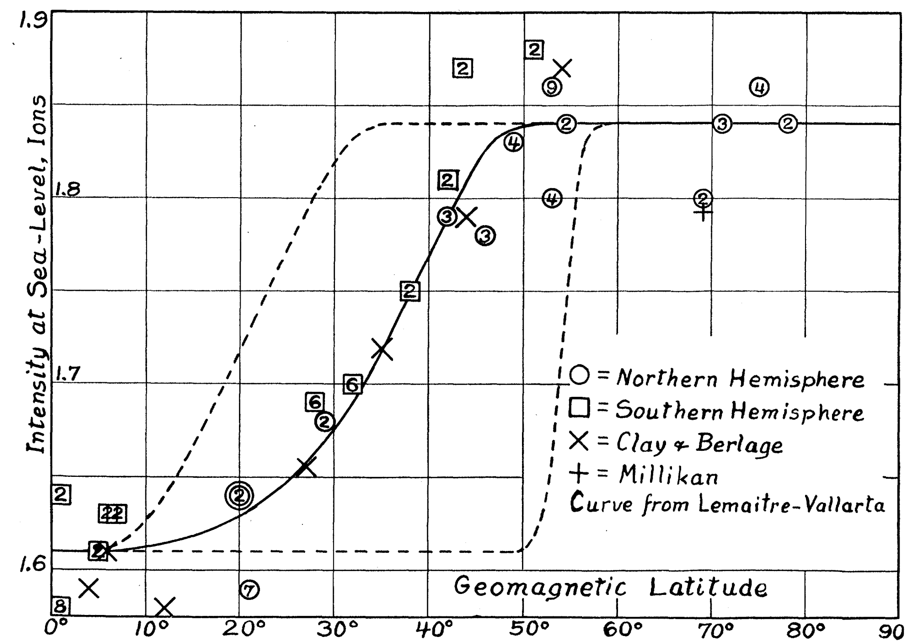

FIG. 7. Intensity *vs.* geomagnetic latitude at sea level, including data of Clay and Millikan.

There is thus no indication of any serious systematic error. From a statistical standpoint, therefore, the probability of the existence of this latitude effect amounts practically to a certainty.

COMPARISON WITH LEMAITRE-VALLARTA THEORY

The sharpness of the increase in intensity between geomagnetic latitudes 25° and 45° is a major feature of these data. This shape of curve is just what may be expected from the new theory of Lemaitre and Vallarta,[19] which considers the effect of the earth's magnetic field on the motion of electrons approaching the earth from remote space. To show that this is true, the smooth curves drawn in Figs. 6 and 7 have been calculated from the Lemaitre-Vallarta theory (by graphical interpolation in their family of $F(x)$ *vs.* latitude curves). The arbitrary constants used for Fig. 7 are: 1.605 ions due to rays unaffected by the earth's magnetic field (neutral rays, or electrons of energy over 4×10^{10} electron-volts), and a band of electrons approaching the earth with energies between 0.5×10^{10} and 1.3×10^{10} electron-volts, which reach the earth at latitudes higher than 50°, producing 0.235 ion, but which fail to reach the earth at the geomagnetic equator.[20] The excellent agreement between this curve and the experimental data means that the variation of cosmic-ray intensity with latitude is that to be expected if a considerable portion of the ionization at high latitudes is due to electrons coming from remote space with energies of about 7×10^{9} electron-volts.

At the higher altitudes, as shown in Fig. 6, the latitude effect is so large as to be unquestionable, even without statistical analysis. Within experimental error, the zone over which the cosmic-ray intensity varies with latitude is the same as that found at sea level. There is one datum, of 8.5 ions at geomagnetic latitude 67 degrees, which perhaps indicates a continued increase in intensity at the higher latitudes at high elevations. This datum, however, is starred in Table III, because it represents a single unchecked result obtained by the ill-fated Carpe expedition[21] on Mt. McKinley. Bennett and his

[19] G. Lemaitre and M. S. Vallarta, Phys. Rev. **42**, 914 (1932).

[20] In calculating the ionization due to this band of rays, 4 equally ionizing groups were assumed, having respectively the following values of Lemaitre and Vallarta's x: 0.30, 0.35, 0.40 and 0.45.

[21] Both observers, Allen Carpe and Theodore Koven, were killed by falling into a crevasse in the Muldrow

coworkers (data here recorded under expedition 3) have concluded from their Alaskan measurements at 1840 meters that the shape of the intensity-altitude curve is the same for geomagnetic latitude 66°N as at 48°N.[22] This is further supported, to much higher altitudes, by Millikan's recently reported[23] airplane measurements at 64°N, which showed the same increase with altitude as did experiments at 55°N. We thus seem justified in neglecting Carpe's datum, and in assuming that, as at lower altitudes, the intensity-latitude curve is flat north of 50°. This means, according to the Lemaitre-Vallarta theory, that there is no marked difference in the energy distribution of the particles responsible for the latitude effect as observed at different altitudes up to 4360 meters.

On the other hand, it will be seen from Fig. 6, that the extra component of cosmic rays which appears at the higher latitudes is more rapidly absorbed than is the main body of the rays. This would be anticipated if the portion of the rays that is unaffected by the earth's magnetic field consists of electrons of greater energy. Other interpretations are however possible. Thus, the uniform background may be due to some electrically neutral ray, such as photons, neutrons, or high speed neutral atoms.

Electrified Particles Bombarding the Earth from Remote Space

We have shown that the variation in intensity with latitude, which our experiments have brought to light, can be accounted for satisfactorily on Lemaitre and Vallarta's theory, which assumes that the rays consist of electrons of high energy coming from remote space, but are deflected by the earth's magnetic field. May there not, however, be alternative explanations?

A guide to possible interpretations is given by plotting the cosmic-ray intensity against the different variables of which it may be supposed to be a function. In Fig. 8 the same data as those used in Fig. 5 are plotted against the geographic latitude. Though there is clearly some correlation, in the intermediate latitudes, such as 30°, the scattering is definitely greater than is to be expected from the probable error of the experiments. Thus, the intensity is probably not a direct function of the geographic latitude.

In Fig. 9 the data are plotted against the local "magnetic latitude."[13] Though the correlation in this case is somewhat better than with the geographic latitude, the scattering in the neighborhood of 40°, where the change is most rapid, is again larger than would be expected from the probable error. This result indicates that the latitude variation is not due to the local magnetic field, which presumably would be effective for several hundred kilometers above the ground. It is thus difficult to attribute the latitude variation to any magnetic effect on the rays which occurs primarily within the earth's atmosphere.

The absence of any systematic variation of the atmospheric electric gradient with the latitude makes it hopeless to attempt to correlate the present effect with the electric field of the earth's atmosphere. Also, there is no systematic difference detectable between the data obtained at sea, such as experiments 5, 6, 7, 8, 18, 34, 46; and those taken at corresponding geomagnetic latitudes in mid-continental stations, such as 25, 28, 32 and 60 at the lower latitudes and 14, 37, 39 and 47 at the higher latitudes. This uniformity of the rays with respect to oceanic and continental areas makes it difficult to ascribe the latitude variation to any kind of atmospheric phenomenon.

It can be shown further that this latitude effect cannot be due to any bending of the cosmic-ray particles within the earth's atmosphere. For an electron moving with a speed nearly equal to that of light, the radius of curvature of the path when crossing a magnetic field of strength H is approximately,

$$R = mc^2/eH. \tag{13}$$

With 0.3 gauss as the value of H at the equator, where the magnetic effect is a maximum, this

Glacier, on which the observation tent was pitched. Some parts of the apparatus, and their notebook, were later recovered, but their Paulin barometer remains on the mountain. Though the cosmic-ray data appear reliable, the unchecked barometer might be in error by enough to bring this point in line with the others.

[22] R. D. Bennett, J. L. Dunham, E. H. Bramhall, P. K. Allen, Phys. Rev. **42**, 447 (1932).

[23] R. A. Millikan as quoted in New York Times, Dec. 31, 1932.

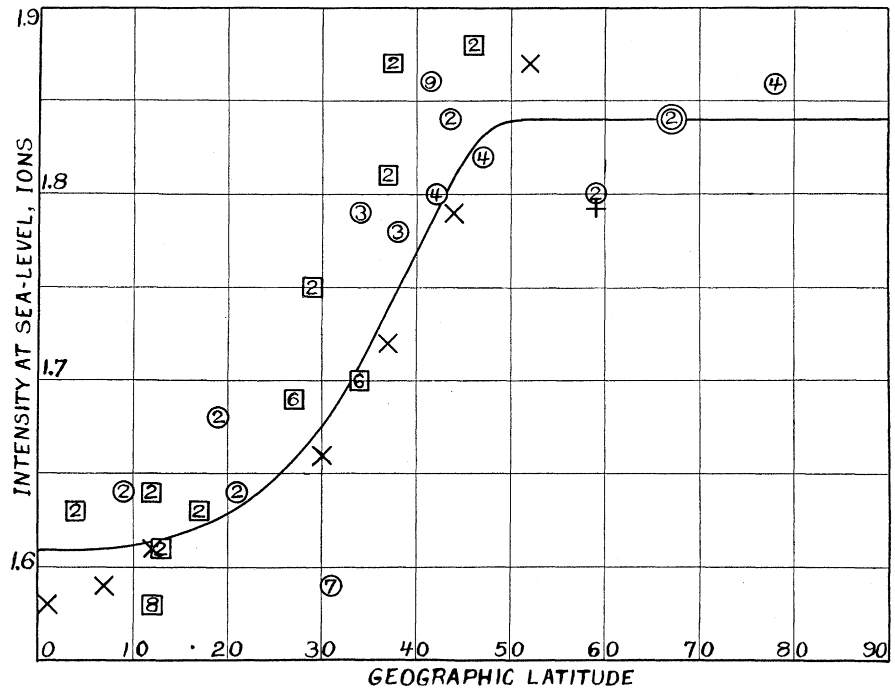

FIG. 8. Intensity *vs.* geographic latitude.

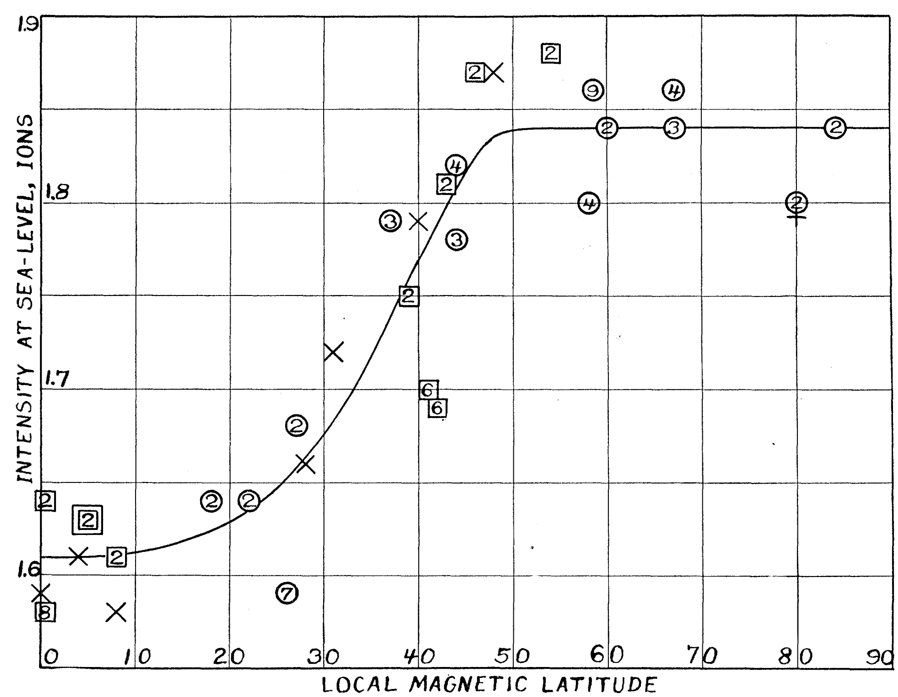

FIG. 9. Intensity *vs.* local magnetic latitude.

becomes,

$$R=6\times10^{30}m \text{ cm}, \tag{14}$$

where m is the mass of the moving particle expressed in grams. The range of beta-particles has been discussed at length by Rutherford, Chadwick and Ellis,[24] chiefly on the basis of Bohr's theory of beta-ray absorption. From their formulas (10), p. 438; and (7), p. 442, the range of a beta-particle in air at atmospheric pressure can be written approximately as:

$$r=0.2\times10^{30}m \text{ cm}, \tag{15}$$

if the mass m of the electron in motion is much larger than the rest mass. That is, the radius of curvature in the earth's magnetic field is at atmospheric pressure, $6/0.2=30$ times the particle's range. Thus, at atmospheric pressure the curvature produced in the path of an electron by the earth's magnetic field is negligible. At an altitude of 25 kilometers, where the density of the earth's atmosphere is about 1/30 of that at sea-level, the range of an electron should be about equal to its radius of curvature, and above this altitude the earth's magnetic field should have an appreciable effect on the particle's range. This means that, if the cosmic rays which are affected by the earth's magnetic field are electrons, they must originate at an altitude of more than 25 km. For other electrified particles, protons, alpha-particles, etc., the limiting altitude as thus calculated is still higher.

Supposing that it is such electrons, originating high in the earth's atmosphere, which are detected by our ionization chambers at the earth's surface; how much energy is necessary to penetrate the atmosphere? If in Eq. (15) we place the range $r=8.0\times10^5$ cm, which is the equivalent of 1 atmosphere if the air were of uniform density equal to that under standard conditions, we obtain $m=4\times10^{-24}$g. Multiplying by the conversion factor, $300c^2/e$, this means an energy of 2.3×10^9 electron-volts.[25] This would be the minimum possible energy for an electron passing vertically through the atmosphere without deflection. For such an electron, however, according to Eq. (14), the radius of curvature is 240 kilometers. This means that, if a beta-particle capable of penetrating the earth's atmosphere is appreciably affected by the earth's magnetic field, it must originate not less than some hundreds of kilometers above the earth's surface. This conclusion supports the comparison of Figs. 7 and 9, which indicated that it is the average rather than the local magnetic field of the earth which is responsible for the latitude variation.

It would seem that an effect due to a magnetic field necessarily implies that the rays thus affected are moving charged particles. If so, our data mean that a portion at least of the cosmic rays consists of high speed particles. But we have seen also that these particles must originate high above the earth. It is accordingly not permissible to assume that these cosmic electrons are secondary beta-rays produced within the earth's atmosphere by some form of electrically neutral rays such as photons. Our experiments seem to require rather that the portion of the cosmic rays which varies with the geomagnetic latitude shall consist of electrified particles approaching the earth from distances of not less than some hundreds of kilometers.

The quantitative agreement of the curve taken from Lemaitre and Vallarta's theory, with the data plotted in Fig. 7, strongly supports this conclusion. Though in fitting this curve to the data several arbitrary constants were available, it is by no means true that any arbitrary set of data could thus be fitted. If the cosmic-ray intensities at the equator and the poles are to be respectively 1.61 and 1.84 ions, the Lemaitre-Vallarta theory requires that the intensities at intermediate latitudes shall lie between the two broken curves of this figure. Of these, that for the higher latitude represents the minimum energy (2.3×10^9 electron-volts) that an electron can have which will penetrate the earth's atmosphere,

[24] E. Rutherford, J. Chadwick, C. D. Ellis, *Radiations from Radioactive Substances* pp. 434–444, 1930.

[25] Neglecting a small correction due to the different ratio of (atomic weight)/(atomic number), this corresponds to an energy loss of 2.5×10^7 electron-volts per cm of lead traversed by a β-particle. This is in substantial accord with the loss of 3.5×10^7 electron-volts per cm of lead as reported recently by C. D. Anderson (Bulletin Am. Phys. Soc. 7, No. 7, p. 15, Dec. 7, 1932). With Anderson's value, the energy lost by an electron traversing the atmosphere would be slightly greater than that here estimated.

superposed on a background of radiation that is unaffected by the earth's field. The curve for the lower latitude represents the maximum energy the electrons can have (3.2×10^{10} electron-volts) if the difference in intensity between the equator and the poles is to be of the specified amount. It would be a surprising coincidence that the experimental curve should fall within the rather narrow limits defined by this theory if the latitude variation has some other origin.

The experimental data thus give very strong support to Lemaitre and Vallarta's theory of the variation of cosmic-ray intensity with latitude. This means that this variation seems to be due to the presence in the cosmic rays of charged particles coming into the earth's atmosphere from remote space with an energy, if they are electrons, of about 7×10^9 electron-volts.

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