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The Variation with Altitude of the Production of Bursts of Cosmic-Ray Ionization*†

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The rate of occurrence of bursts of ionization from 140 pounds of lead shot was measured in a fifty liter, Dowmetal ionization chamber, filled with nitrogen at 14.5 atmospheres pressure, at four elevations between sea level and the summit of Pike's Peak (4300 meters). The ionization chamber was so designed as to minimize the random fluctuations of the cosmic-ray ionization. The increase in the rate of occurrence with elevation was found to be very large, and increasingly greater at higher elevations. The rates of occurrence of all sizes of bursts greater than 1.5×10^6 ions in the chamber increased with elevation in the same manner. The results are discussed in the light of W. F. G. Swann's theory.

THE occurrence of large bursts of ionization in a closed vessel, first noticed by G. Hoffmann[1] in 1927, has since been the object of many investigations. Of vital importance to the understanding of this phenomenon is the question of the nature of the radiation which produces it. The most direct attack upon this question would appear to involve a study of the variation of the rate of occurrence of these bursts with altitude. As part of the general program of investigation at the Bartol Research Foundation concerning burst production, observations have been made at four elevations—at Pike's Peak (4300 m), at Glen Cove (3500 m), at Colorado Springs (1860 m) and at Swarthmore (61 m), the same apparatus being used in all cases.

The bursts of ionization were observed in a fifty liter, spherical chamber cast of Dowmetal. The chamber was made gas tight by means of a close-fitting internal shell of aluminum and was filled with commercial nitrogen to a pressure of 14.5 atmospheres. The electrodes were a series of concentric, spherical shells spaced at an average distance of five centimeters. The change of potential of the electrodes when a burst occurred was measured by a vacuum tube electrometer. Fig. 1 shows the circuit diagram of the apparatus. The galvanometer used had a sensitivity of approximately fifty megohms and a period of three seconds. The voltage sensitivity of the whole apparatus was about 1700 mm/volt, and the charge sensitivity 5×10^5 ions/mm. During the observations the sensitivity was determined at frequent intervals by the application of a known voltage to the control grid of the vacuum tube by means of the dry cell and potentiometer unit in the control box (resistances R_2 and R_3 in Fig. 1.

The observations at Pike's Peak and at Glen Cove were taken visually; those at Colorado Springs and at Swarthmore by photographic registration. The galvanometer spot was allowed to fall upon a horizontal slit placed in front of a moving strip of photographic paper. Fig. 2 shows a section of such a record taken at

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† A preliminary report was made at the Pittsburgh Meeting of the American Physical Society, December 28–29, 1934.

[1] G. Hoffmann, International Conference on Physics, London, October, 1934.

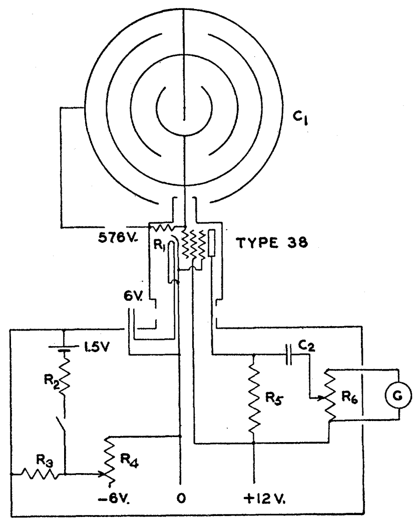

FIG. 1. Circuit diagram of the vacuum tube electrometer.

$R_1=4\times10^{10}$ ohms	$R_5=10^5$ ohms
$R_2=100$ "	$R_6=18{,}000$ "
$R_3=1$ "	$C_1=1.23\times10^{-10}$ farad
$R_4=400$ "	$C_2=8\times10^{-6}$ "

Swarthmore. The upper trace on the paper was taken with no lead above the chamber, and a burst of ionization is indicated by a downward deflection. The lower trace was taken with 140 pounds of lead above the chamber. Here the galvanometer leads have been reversed, and a burst is indicated by an upward deflection. The lead, in the form of shot, was contained in seven heavy canvas bags which were tied onto the top of the sphere. The thickness was not uniform, but its average may be estimated to be equivalent to four centimeters of solid lead. Only bursts of ionization greater than 1.5×10^6 ions were measured.

The smallest size of burst which can be measured with reasonable certainty in an ionization chamber depends upon the magnitude of the statistical fluctuations in the ionization of the cosmic rays passing through the chamber. Let t be the time interval during which a burst of ionization is observed, i.e., the time of collection of the ions. Let r represent the standard deviation of the ionization during unit time. Then the standard deviation in the ionization occurring in the time t is $rt^{\frac{1}{2}}$. The rate of occurrence of a fluctuation of size S ions or greater is given by

$$[1/t(2\pi)^{\frac{1}{2}}]\int_y^\infty e^{-y^2/2}dy \quad \text{where} \quad y=S/rt^{\frac{1}{2}}.$$

The value of r, if it cannot be conveniently measured, may be estimated in the following way. If the cosmic radiation consisted of single, unrelated rays passing through the chamber at random, at the rate of N per second, then r would be $IN^{\frac{1}{2}}$, where I is the average ionization produced by one ray. Since it is known that groups of two and more related rays occur frequently, this value for r must be multiplied by a corrective factor. This factor may be estimated from the cloud-chamber observations of C. D. Anderson[2] to be about 1.5 at sea level. It is greater than this at higher elevations. Any other fluctuations present, such as those caused by alpha-particles, must, of course, be taken into account also. It is to be noted that the rate of occurrence of large fluctuations may be much reduced by reducing the value of t.

In the chamber employed for these observations the collecting time was reduced to a minimum value by reducing the spacing of the electrodes (to 5 cm), by applying a relatively high potential (574 volts) and by using only as high a pressure (14.5 atmos.) as was necessary to eliminate the fluctuations of the alpha-particle ionization. By these means, the value of t was reduced to 0.5 second. If one chooses for the value of N, 2.5×10^{-2} per cm^2 per second;[3] for the mean path of a ray through the sphere, two-thirds of the diameter; for the specific ionization, 60 ions per centimeter;[4] a saturation of 72 percent as estimated from the data of I. S. Bowen;[5] and a pressure of 14.5 atmospheres; the standard deviation in the ionization in the interval of 0.5 second at sea level is 1.3×10^5 ions.[6] It is more difficult to estimate the size of the fluctuations at Pike's Peak. However, the ratio of the fluctuations in a chamber at Pasadena to those at an elevation of 14,700 feet on the magnetic equator has been reported by Evans and Neher.[2] Because of the presence of the magnetically deflected rays at Pike's Peak, the standard deviation in the ionization there will be

[2] C. D. Anderson, Phys. Rev. **44**, 406 (1933). See also R. Evans and V. Neher, Phys. Rev. **45**, 144 (1934).
[3] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).
[4] W. F. G. Swann, Phys. Rev. **44**, 961 (1933).
[5] I. S. Bowen, Phys. Rev. **41**, 29 (1932).
[6] This also involves the assumption that every ionizing ray has sufficient penetrating power to travel across the chamber through the electrodes.

TABLE I.

Size in ions	Rate of occurrence (per hour). Swarthmore	Pike's Peak
5×10^5	0.4	260
10^6	<0.004	1.1
1.5×10^6	<0.004	<0.004

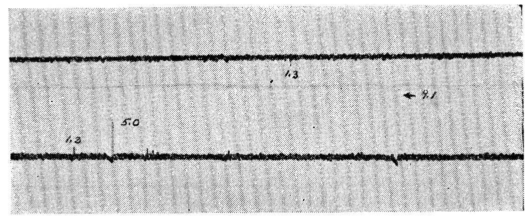

FIG. 2. Sample of photographic record. Lower trace with lead, upper trace without lead. Sizes of bursts in millions of ions.

somewhat larger than that computed from this ratio. Table I gives the rates of occurrence of fluctuations larger than a given size at Swarthmore and at Pike's Peak. It is to be noticed that the fluctuations are well below the chosen lower limit of size of bursts measured, namely, 1.5×10^6 ions.

OBSERVATIONS AND RESULTS

At each of the four stations where observations were taken, an effort was made to have as little material as possible over the apparatus. At Swarthmore, the observations were taken in a building with a thin wooden roof, on the roof of the Bartol Research Foundation Laboratory. In Colorado Springs, the apparatus was placed under a large skylight on the top floor of Palmer Hall at Colorado College. At Glen Cove, the apparatus was located on the first floor of a

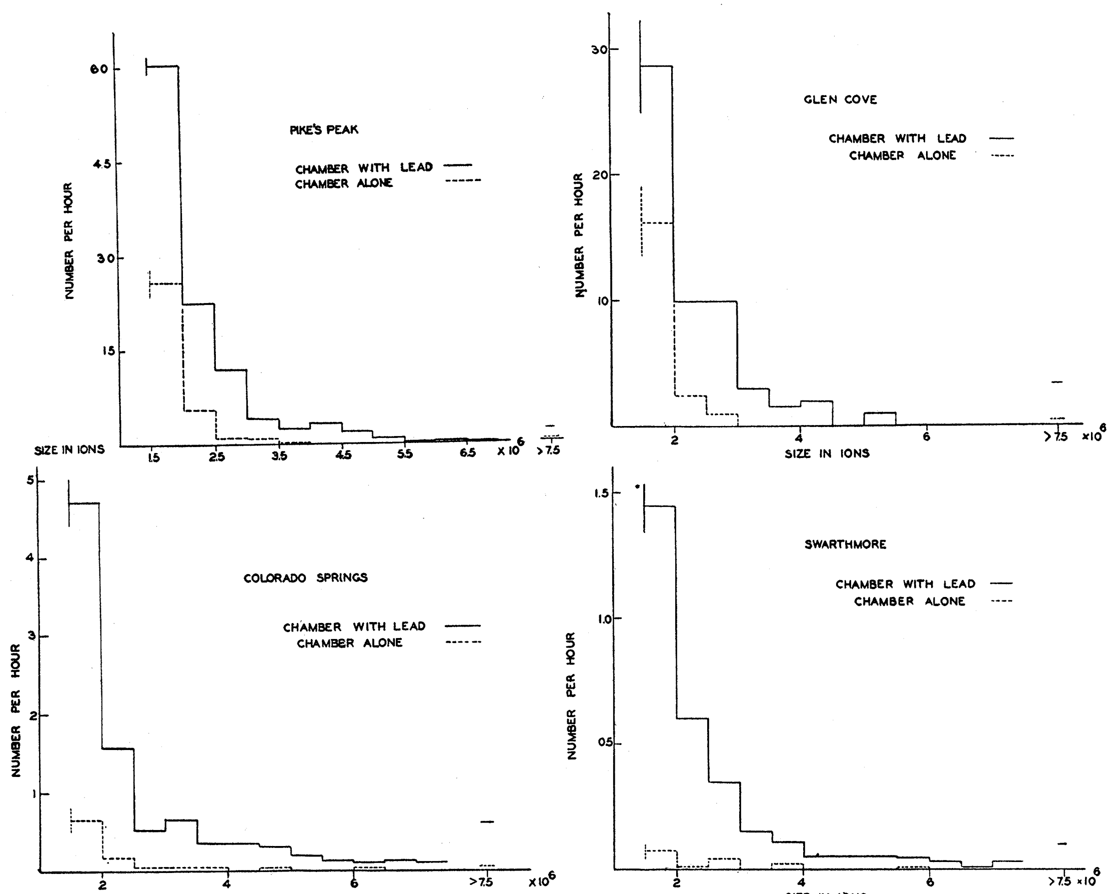

FIG. 3. Frequency distributions of bursts at the four elevations.

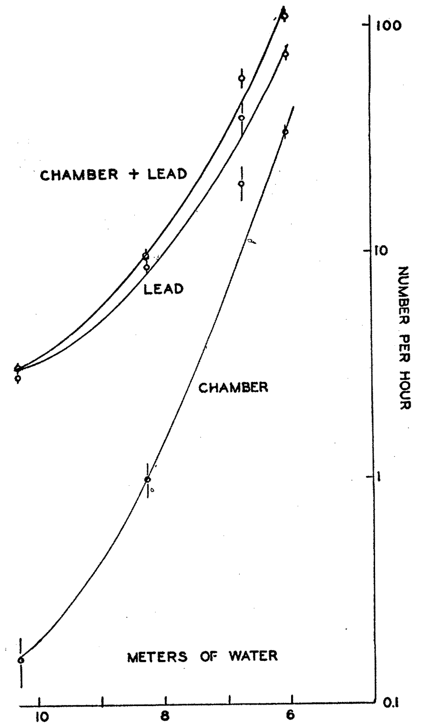

FIG. 4. Variation of rate of occurrence of bursts with altitude.

wooden, two story building, and at Pike's Peak, in the Summit House under a sheet iron roof. Table II gives the elevation data for each station.

TABLE II.

Station	Swarth-more	Colo. Springs	Glen Cove	Pike's Peak
Elevation (m)	61	1860	3500	4300
Barometer (mm Hg)	756	607	494	445
Depth below top of atmos. (m of water)	10.27	8.25	6.73	6.04

The frequency polygons shown in Fig. 3, represent the data taken. The difference between the corresponding ordinates of the polygons representing the data taken with lead over the chamber and without the lead, respectively, is taken to represent the number of bursts which originate in the lead. The vertical lines at the left of each polygon give the standard deviation in the rate of occurrence of bursts between 1.5 and 2 million ions as computed from the square root of the number of such bursts observed. All the bursts greater than 7.5 million ions have been

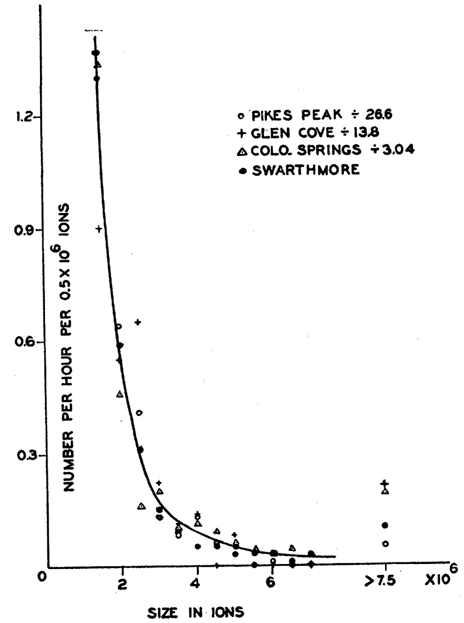

FIG. 5. Frequency distribution of bursts from lead reduced to a common total rate.

classed together and are indicated to the extreme right of each diagram. Bursts greater than twenty million ions would throw the galvanometer off scale, and their size could not be determined, but their occurrence was recorded. It is to be noticed that, although at sea level the bursts without lead present form only a small fraction of the number with the lead, at Pike's Peak they represent about 31 percent of the total.

The variation with elevation of the rate of occurrence of all the bursts greater than 1.5 million ions is given in Fig. 4. The vertical lines again represent the standard deviations of the points. The increase with elevation is surprisingly rapid and much greater than the increase either in the total intensity of the cosmic radiation or in the softest known component of it. The number of bursts with no lead present increases even faster with altitude than the bursts from lead. However, since an appreciable fraction of these bursts might originate in the surrounding walls and roofs, this increase might be ascribed almost entirely to differences in the surroundings of the chamber.

For lead, the increase with elevation seems to be the same for all sizes of bursts measured. This may be seen from Fig. 5. Here the fre-

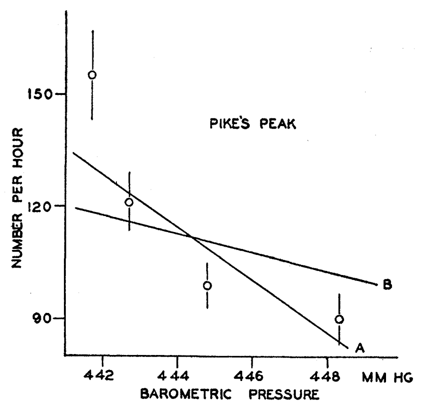

FIG. 6. Barometer effect for bursts with lead on chamber at Pike's Peak. Line A is least squares fit, line B estimated from variation of rate of occurrence of bursts with elevation.

quencies for each size of burst at each elevation are divided by the ratio between the total rate of occurrence of bursts at that elevation and that at Swarthmore, and plotted against the size of burst, the rate for each interval of size being plotted at the beginning of that interval. The smooth curve is drawn through the mean of the Swarthmore, Colorado Springs and Pike's Peak points. Within the accuracy of their determination, all the points are seen to fit this smooth curve. Using the assumptions already stated under the discussion of fluctuations, the number of rays which would be needed to produce the ionizations observed in these experiments is about 51 rays per million ions.

There is an independent check upon the variation in the rate of occurrence of bursts with elevation reported here. The Pike's Peak data were taken during such a time that the change in the number of bursts with barometric pressure could be estimated. Fig. 6 shows the results of this analysis. The line A is the best fit, by least squares, to the four points representing rates of occurrence of bursts greater than 1.5 million ions which occurred when lead was over the chamber. The slope of this line is -7.1 bursts per hour per mm Hg, with a probable error of 2.3 in the same units. The slope of the curve for lead chamber in Fig. 4, at the elevation of Pike's Peak, also gives a value for this "barometer effect," *viz.*, -2.7 bursts per hour per mm Hg. Line B in Fig. 6 represents this estimate. The agreement between the two values is fair considering the paucity of relevant data, the difference being just less than twice the probable error of the first value. From the slope of the same curve (Fig. 4) at the Swarthmore point, a barometer effect of about 0.5 percent per mm Hg may be estimated. This cannot be reconciled with the value 5 percent per mm Hg reported by Steinke, Gastell and Nie,[7] but is not in disagreement with experiments of the authors which showed the effect to be less than 1 percent at Swarthmore.

Discussion

The number of bursts which occur at any elevation should be proportional to the number of burst-producing rays I multiplied by the probability p that such a ray will produce a burst. The observed variation with elevation may be the result of a change in either or both of these quantities.

If we assume that p is independent of the depth below the top of the atmosphere, then Fig. 4 represents the absorption curve of the radiation which produces bursts. We see that this radiation is not exponentially absorbed, but the absorption coefficient, defined as the derivative of the logarithm of the function at the point considered, varies from about 1.8 per meter of water at Pike's Peak to about 0.4 per meter of water at sea level. The actual values of these absorption coefficients will vary considerably with the shape of the curve that is drawn through the points in Fig. 4 and hence express only the general character of the variation. This "component" of the cosmic radiation, however, cannot produce any appreciable ionization, since all the ionization, even at very high elevations, has been accounted for by previously reported components.[8]

On the other hand, the variation with elevation may all be caused by a variation in the probability p. This point of view has been developed by W. F. G. Swann.[9] Swann assumes that the number of nonionizing corpuscular cosmic rays is independent of elevation, but that their energy decreases by the production of showers of rays as

[7] E. G. Steinke, A. Gastell and H. Nie, Naturwiss. **51**, 898 (1933).
[8] I. S. Bowen, R. A. Millikan and V. Neher, Phys. Rev. **44**, 250 (1933).
[9] W. F. G. Swann, Phys. Rev. **46**, 828 (1934).

they pass through the atmosphere. It is the ionization produced by these showers that is measured in an ionization chamber. The ionization increases with altitude because the number of showers increases with the energy of the primary rays. The number of showers produced in air may be expressed as $N_{\text{air}} = f(E)$, where E is the energy of the primary rays. The number of showers which will be produced in lead will be represented by $N_{\text{Pb}} = F(E)$, which may be quite a different function of E from $f(E)$. It is N_{Pb} which is measured in these experiments. The data are fairly well represented by the assumption that $F(E) \propto f^2(E)$. This agreement is illustrated in Table III.

TABLE III.

Station	Swarthmore	Colo. Springs	Glen Cove	Pike's Peak
Relative ionization[8]	1	1.80	3.51	4.78
Relative ionization squared	1	3.24	12.3	22.8
Relative No. of bursts	1	3.04	13.8	26.6

Thus the observations seem to have a simple interpretation from the point of view of Swann's theory. The actual details of the mechanism of burst production may be, of course, much more complicated than is represented above. There may be a number of intermediate steps between the loss of energy by the primary ray and the formation of the ionizing rays of the burst as, for example, the shower producing photons which seem to be necessary in order to interpret the photographs of C. D. Anderson and Blackett and Occhialini.[10]

The authors wish to express their appreciation of the cooperation of President Davies and of Dr. Paul E. Boucher of Colorado College. They are also indebted to Mr. Benjamin Stewart and to Mr. Orrie Stewart of Colorado Springs, who provided space for the apparatus on Pike's Peak and at Glen Cove. To Dr. W. F. G. Swann, without whose helpful advice and continued support of the project these experiments could not have been carried out, the authors are deeply grateful.

[10] See, for example, P. M. S. Blackett, International Conference on Physics, London, October, 1934.

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On the North-South Asymmetry of Cosmic Radiation

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The development of the theory of the latitude and azimuthal effects is reviewed and the significance of Johnson's experiments on the north-south asymmetry is brought out. Störmer's critical remarks are commented on with reference to Lemaitre and Vallarta's paper and to recent papers by Lemaitre and by Bouckaert.

THE theory of the latitude and azimuthal effects of cosmic radiation[1] developed by Lemaitre and Vallarta has now been sufficiently carried through by Bouckaert to lead to precise results for sufficiently high energies ($x_0 > 0.414$ in the energy units defined by Eq. (12) in (I)) and low geomagnetic latitudes. For these energies the allowed cone (*not* a circular cone) has been calculated by Bouckaert except for angles close to the horizon. His results (III) are reproduced in Fig. 1, drawn for positive particles, which gives the orthogonal projection on the horizontal plane of the trace of the cone on the unit sphere, for energies $x_0 = 0.45$, 0.5, 0.6 and 0.7 and geomagnetic latitudes $\lambda = 0°$, 10° and 20°. For positive particles, which alone will be considered for the moment, the cone at the equator opens from the west and is symmetrical with respect to the east-west vertical plane. As the latitude increases the eastern boundary of the cone of a given energy moves towards the east and markedly shifts towards the south. As a conse-

[1] G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 87 (1933); G. Lemaitre, Ann. de la Soc. Sci. de Bruxelles **A54**, 162 (1934); L. Bouckaert, Ann. de la Soc. Sci. de Bruxelles **A54**, 174 (1934). These papers will be referred to here as (I), (II), (III), respectively.

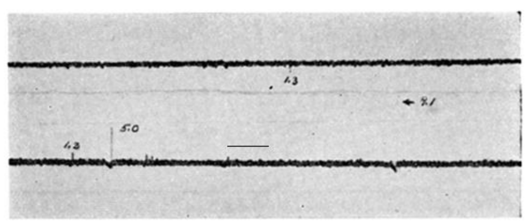

Fig. 2. Sample of photographic record. Lower trace with lead, upper trace without lead. Sizes of bursts in millions of ions.