Correlation of Geomagnetic Cosmic-Ray Effects*

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With the experimental data collected in a B-29 airplane and given in an earlier report, an attempt is here made to correlate several of the well-known geomagnetic effects found in cosmic rays. First, evidence is presented to show that, within the uncertainties of the experimental data and the existing calculations on the behavior of charged particles in the magnetic field of the earth, there are few if any negative primary particles in the momentum range 7 to 23 Bev/Zc compared with positives. Second, under the assumption of no primary negative particles and by correlating experimental data on the latitude effect at different zenith angles with the zenith angle effect in the east-west plane at the equator, it is possible, with the help of calculations of Vallarta *et al.* at the equator, to determine curves of minimum momentum for the primaries as a function of geomagnetic latitude. It is thus possible to plot curves for intermediate latitudes where the calculations are extremely difficult and have not been carried through in detail except in certain special cases. The results are independent of any assumed momentum distribution of, or the magnitude of charge carried by the primary particles.

I. INTRODUCTION

IT has been pointed out by Biehl, Neher, and Roesch[1] that the near-quality in the east-west effect for the penetrating and non-penetrating components at the geomagnetic equator at an air pressure of 235 g/cm^{-2} argues strongly for the same kind of primary particle responsible for both. Analysis of other data taken at the above and other pressure altitudes by these authors at the geomagnetic equator gives further evidence that the same primary particles are responsible for the non-penetrating as well as the penetrating radiation found at the above atmospheric pressure. This is contrary to the conclusion reached by Johnson and Barry[2] from their balloon flights made at 20° geomagnetic north. They found it necessary to assume a mixture of primary protons with positive and negative electrons to account for their measured small east-west effect.

Several attempts to correlate the various geomagnetic effects have been made in the past. Among these may be mentioned that of Johnson.[3] At that time the experimental data were inadequate to permit arriving at definite conclusions. Jánossy[4] finds a correlation between the east-west effect at sea level and the latitude and longitude effects assuming only incident positively charged primaries, but at high altitudes the correlation using the data then existing made it necessary to assume other kinds of primaries.

In what follows an attempt is made to correlate the various geomagnetic effects by using the calculations of Vallarta *et al.* assuming that the primary cosmic rays consists only of positively charged particles. The analysis will be independent of the magnitude of the charge carried by the primary particles and hence applicable to a mixture of positively charged particles such as protons and heavier nuclei.

The experimental data on which the following results are based were published by Biehl, Neher, and Roesch [Phys. Rev. **76**, 914 (1949)]. This article will be referred to hereafter as (A).

II. MOMENTUM OF PRIMARY PARTICLES AT THE GEOMAGNETIC EQUATOR AND LONGITUDE 80°W

On the geomagnetic[4a] equator at geographic longitude 80° W two factors reduce the least momentum of the particles that can reach a given position in the sky compared with that calculated by assuming a magnetic dipole situated at the center of the earth. One of these is due to the fact that the earth's magnetic field can best be represented by a dipole situated approximately 300 km from the center of the earth. The longitude effect found at sea level by Clay[5] and independently by Millikan and Neher[6] is explained by such an eccentric dipole. The other factor affecting the minimum momentum for particles at the equator is the tilt of the earth's magnetic field. It was pointed out by the author[7] in 1935 that the surfaces of equal horizontal intensity of the earth's magnetic field are in general tilted with respect to the surfaces of equal gravitational potential along the geomagnetic equator and that this would tend to reduce the measured east-west effect in Peru and increase it in the region of Africa.

The map published by Millikan and Neher,[8] showing lines of equal cosmic-ray intensity at sea level, agrees with magnetic maps, showing lines of equal horizontal intensity, in placing Peru approximately 60° west of the region where the axis of the equivalent dipole is farthest from the surface of the earth. Using the calculations of Vallarta[9] on the longitude effect, we

* Assisted by the joint program of the ONR and the AEC.
[1] Biehl, Neher, and Roesch, Phys. Rev. **75**, 688 (1949).
[2] T. H. Johnson and J. G. Barry, Phys. Rev. **56**, 219 (1939).
[3] T. H. Johnson, J. Franklin Inst., **226**, 533 (1938).
[4] L. Jánossy, *Cosmic Rays* (Oxford at the Clarendon Press, London, 1948), pp. 308–313.
[4a] Geomagnetic latitude as here used is computed from a dipole situated at the center of the earth.
[5] Clay, van Alphen, and 't Hooft, Physica **1**, 829 (1934).
[6] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 205 (1935).
[7] H. V. Neher, Phys. Rev. **47**, 417 (1935).
[8] R. A. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936).
[9] M. S. Vallarta, Phys. Rev. **47**, 647 (1935).

conclude that as far as eccentricity of the dipole is concerned the minimum momentum required for a particle[9a] with electric charge Z to reach the vertical at the equator at 80° W is 14.2 Bev/Zc instead of 15.0 as calculated for the symmetrical dipole.

Curves giving the tilt of the earth's magnetic field have been published by Vallarta,[10] but for present purposes it is perhaps better to scale off the distances between lines of equal horizontal intensity from available maps. We find by such means that the tilt in the region of Peru is approximately 4° as compared with 3° taken from Vallarta's curves.

To find the effect of this tilt on the minimum momentum of a particle at the equator we use the calculation on the Störmer cones.[11] Assuming, for example, that the effect of tilt in Peru is to decrease the momentum by an amount which corresponds to changing the zenith angle in the east-west plane by 4°, we find that at the vertical the corresponding change in momentum for a particle of charge Z is -0.7 Bev/Zc. The effect of tilt and eccentricity, then, is to reduce the symmetrical dipole value at the vertical from 15 to 13.5 Bev/Zc for the region of Peru. For other zenith angles in the geomagnetic east-west plane we calculate the values shown in Fig. 1.

III. EVIDENCE OF ABSENCE OF NEGATIVE PARTICLES IN PRIMARY RADIATION

Experiments of Hulsizer[12] on burst production under lead at high altitudes indicate that the relative numbers of incident electrons to total particles at geomagnetic latitude 53°N is less than 6 percent. A comparison in reference (A) of the east-west effect with the latitude effect also indicates that the number of negative primaries relative to positives is small in the momentum range 9 to 13.5 Bev/Zc. Because of the importance of this point some further discussion may be justified.

Since the latitude effect depends on the sum of the effects due to primary positive and negative particles while the east-west effect depends on their difference, a comparison of the two constitutes a means of determining their relative numbers.

In a series of experiments reported in (A), cosmic-ray telescopes were carried at 30,000 ft. pressure altitude from 64° N to the equator along longitude 80° W. These telescopes were pointed at zenith angles 45° E, 0°, and 45° W, and included measurements with no added absorber, 10 and 20 cm of lead between the counter trays. Data taken with 10 and 20 cm of lead absorber will be used since the effects of scattering are much less important than without an absorber (see reference (A)). Shown in (A) Figs. 6 and 8 are the counting rates taken as a function of geomagnetic latitude with both 10 and 20 cm of lead for a telescope pointed 45°E as well as 45°W and also at the vertical.

Let: j_{0E} = radiation remaining at 45° E at the equator. Δj_1^+ = change in radiation at 30,000 ft. pressure altitude caused by positive primaries whose momentum lies between the least allowable value at 45° toward the west and 45° toward the east at the equator. From Fig. 1 we find these two values to be 10.3 and 23.5 Bev/Zc. Δj_1^- = similar change caused by any negative particles in this momentum range.

There is some latitude, λ_1, where the momentum for positives at 45° E becomes the same as for positives at 45° W at the equator. In going to this latitude the negatives toward the west change their minimum momentum from 23.5 to 10.3 Bev/Zc, while the positives toward the east change their momentum by the same amount. The change in momentum for negative primaries at 45° E in going from the equator to latitude λ_1 is from 10.3 down to approximately 7 Bev/Zc, the exact value being unimportant at present. This is also the range in momentum of positive particles for this same latitude change at 45°W.

Let: Δj_2^+ = change in radiation caused by positives in this latter momentum range. Δj_2^- = similar change caused by negatives in this same momentum range. Then the ratio of the change from 45°W to 45° E to that remaining at the equator is

$$\rho_1 = \frac{\Delta j_1^+ - \Delta j_1^-}{j_{0E}}. \quad (1)$$

Likewise the ratio of the change in going from the equator to λ_1 as defined above for a telescope pointing

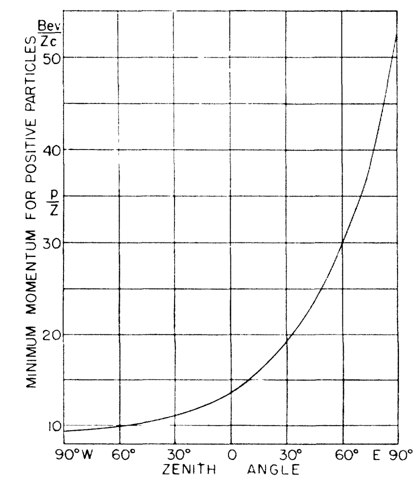

FIG. 1. Minimum momentum per unit charge for positive particles at the geomagnetic equator *vs.* zenith angle at geographic longitude 80° W. Based on calculations of Lemaitre, Vallarta *et al.* on the behavior of charged particles in the magnetic field of the earth but corrected for tilt of the magnetic field and the eccentricity of the dipole.

[9a] Expression momentum in terms of Bev/Zc, where Z is the net number of unit charges carried by the particle, gives a quantity independent of the mass and charge of the particle and the calculations based on unit charge may therefore be used. Since the heavy primary particles appear to be completely stripped of their electrons, Z for this case becomes equal to the atomic number.

[10] M. S. Vallarta, Phys. Rev. **74**, 1937 (1948).

[11] G. Lemaitre and M. S. Vallarta, Phys. Rev. **50**, 493 (1936).

[12] Robert I. Hulsizer, Phys. Rev. **76**, 164(A) (1949).

45° E to that remaining at 45° E at the equator is

$$\rho_2=\frac{\Delta j_1{}^{+}+\Delta j_2{}^{-}}{j_{0E}}. \tag{2}$$

Further, the ratio of the change in radiation at 45° W to 45° E at latitude λ_1 to that remaining at the equator at 45° E is:

$$\rho_3=\frac{\Delta j_2{}^{+}-\Delta j_2{}^{-}}{j_{0E}}. \tag{3}$$

Subtracting (1) from (2) and dividing by the sum of (2) and (3) we get

$$\frac{\Delta j_1{}^{-}+\Delta j_2{}^{-}}{\Delta j_1{}^{+}+\Delta j_2{}^{+}}=\left(\frac{\Delta j^{-}}{\Delta j^{+}}\right)_{7-23}=\frac{\rho_2-\rho_1}{\rho_2+\rho_3}. \tag{4}$$

This gives the ratio of the intensity due to negative primaries in the momentum range 7 to 23 Bev/Zc to that due to positives in the same momentum range in terms of the experimental quantities, ρ. If $\rho_2=\rho_1$, then the contribution measured would be zero. The problem cannot be solved accurately since the calculations on the minimum momentum at intermediate latitudes have not been carried through. The value of ρ_2 (and ρ_3) will depend on the particular latitude at which the minimum momentum for positives at 45° E becomes equal to that at the equator at 45° W. If we choose the lower curve E_1, published by Vallarta,[10] we find this latitude to be 29.3° N. For the average of 10 and 20 cm of lead we find from reference (A) Figs. 6 and 8, $\rho_1=0.33\pm0.02$, $\rho_2=0.27\pm0.08$, $\rho_3=0.22\pm0.03$, where the uncertainties are estimated from the statistics of the counting rates and the individual values for 10 and 20 cm of lead absorber. The chief error lies in the value of ρ_2 which is the relative increase in the counting rate in going from the equator to 29.3° N for the telescope pointing 45° E. For the case of 10 cm of lead the latitude where the cosmic-ray intensity at 45° E becomes equal to that at 45° W at the equator is 28.3° N while the similar latitude for 20 cm of lead is 34.0° N. The reason for this discrepancy is not known and we have taken the average of the data for 10 and 20 cm of lead as representing the best estimate that can be made at the present time.

Using the above experimental values of ρ we find, for the ratio of negative particles to positives in the momentum range 7 to 23 Bev/Zc,

$$(\Delta j^{-}/\Delta j^{+})_{7-23}=-0.12\pm0.15.$$

It is obvious that to be physically significant this ratio must be positive or zero. We shall in what follows assume that all of the primary particles are positively charged. The consistency of the results will be added justification for this assumption.

The procedure to be followed is to take the calculations of Vallarta *et al.* in the east-west plane at the equator as correct (Fig. 1) and then to correlate the measurements in this east-west plane with measurements as a function of some other parameter such as latitude, longitude, or azimuth. We shall use the average of the data with 10 and 20 cm of lead absorber although the accuracy is not as good as with no absorber. The justification for using the lead data is that it was shown in reference (A) that when the telescopes with lead absorber were pointed at an angle to the vertical, the counting rate was the same as when pointed at the vertical provided (a) the intervening mass of air was the same and (b) the primary radiation incident on the top of the atmosphere was the same.

IV. CORRELATION OF LATITUDE EFFECT AND ZENITH ANGLE EFFECT WITH THE CALCULATIONS OF VALLARTA *et al.*

Lemaitre and Vallarta[11] have given the boundaries to the cones for certain minimum momenta of the primary particles at the equator. The particular boundary that passes through the vertical in a north-south direction bends toward the west for increasing zenith angle. An application of Liouville's theorem implies that the primary radiation is constant at all zenith angles along this boundary. Using a lead absorber it was shown in reference (A) that the intensity measured was independent of the zenith angle and depended only on the mass of intervening air for the same incident radiation on the top of the atmosphere. We thus imply from this and from Liouville's theorem that if at two locations where the mass of intervening air is the same and the same intensity is measured, then the incident primary radiation is the same. Thus if at a certain latitude, longitude, air pressure, azimuth angle, and zenith angle a certain intensity of particles is measured that can penetrate the lead absorber, then, if the same intensity is measured at some other latitude, longitude, air pressure, azimuth angle, and zenith angle for the same mass of intervening air, the primary radiation incident

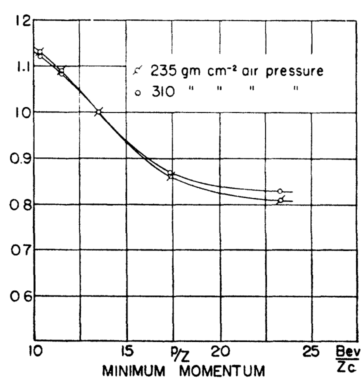

FIG. 2. Experimental values of the ratio of cosmic-ray intensity measured in the east-west plane at the geomagnetic equator to that in a direction of constant momentum through the same mass of air, *vs.* the least allowable momentum for that particular direction. See reference (A) [Phys. Rev. **76**, 914 (1949)] for experimental data.

on the top of the atmosphere is the same. This is again under the assumption that all the incident particles have the same sign of electric charge.

The zenith angle effect, as plotted in Fig. 26 of (A) is for a telescope pointed in the direction of this constant momentum boundary at the equator and hence for primary particles of the same minimum momentum as for the vertical. The ratio of the values for the same zenith angle taken in the east-west plane to those in this constant momentum direction is then different from unity only because of the different primary momentum range included. In Fig. 2 this ratio is plotted, not as a function of zenith angle, but of the least allowable momentum for the particular direction as obtained from Fig. 1. The data are for the average of 10 and 20 cm of lead taken at the atmospheric pressures of 235 and 310 g/cm^{-2}. The values at 310 g/cm^{-2} are computed from data, some of which have not been heretofore published.

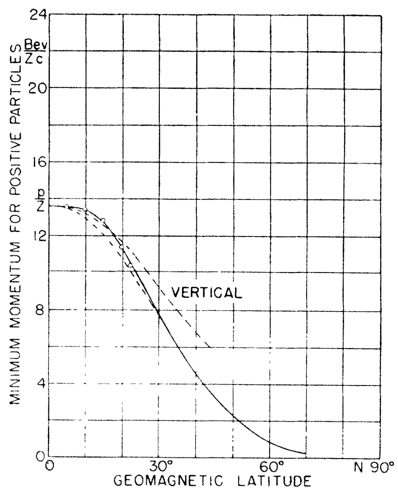

FIG. 3. Assuming only positive primaries a comparison of zenith angle effect given in Fig. 2 with the measured latitude effect at the vertical permits an experimental determination of the minimum momentum *vs.* geomagnetic latitude for the vertical direction.

We note that the asymmetry shown by the points at the greater atmospheric pressure is slightly less than that at greater altitudes as was pointed out in reference (A).

Assuming only positive primary particles, we must therefore expect the same relative increase in the latitude effect at the vertical as we go away from the equator (see reference (A), Fig. 6) as is shown in Fig. 2 when the momentum range covered is the same. We thus have sufficient information to solve parametrically for the minimum momentum of the primary particles *vs.* geomagnetic latitude. This has been done as shown in Fig. 3 down to a momentum of 10.3 Bev/Zc or a latitude of 22.5° N and has not been carried farther because of the increasing importance of atmospheric absorption.

Plotted in the same figure are the two limiting curves

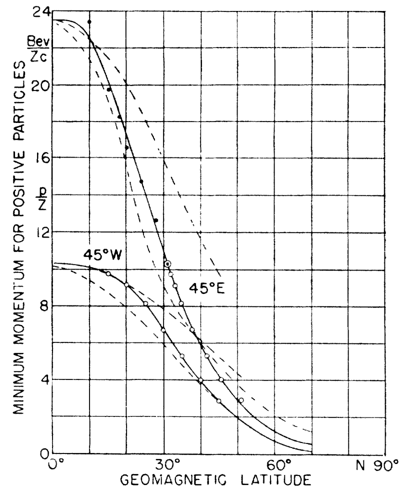

FIG. 4. Further comparison of the data given in Fig. 2 with the latitude effect at 45 E and 45° W permits an experimental determination of the minimum momentum *vs.* geomagnetic latitude for these two zenith angles.

given in a recent summary by Vallarta.[10] These are plotted on a momentum basis and are corrected for tilt of the earth's magnetic field and for the eccentricity of the dipole. The upper broken curve gives the calculated momentum a particle must have in the vertical direction at the geomagnetic latitude given by the abscissa, above which all momenta are allowed by the earth's magnetic field. The lower broken curve gives the least momentum a particle must have in order to penetrate the earth's magnetic field in a vertical direction at the geomagnetic latitude given by the abscissa.

The experimental curve has been extended to higher latitudes by gradually dropping down to the lower curve of Vallarta according to his instructions.

The next comparison we shall make with the calculations of Vallarta *et al.* is using the latitude effect at 45° as given in reference (A), Fig. 6 or 8. We have already used values at 29.3° N and the equator to correlate with the zenith angle values at 45° W and 45° E at the equator to gain some information as to the number of negative primaries compared with positives. We shall now use the intermediate values for intermediate latitudes.

Again, using the average values for 10 and 20 cm of lead absorber, we find that starting at 31° N and going toward the equator at 45° E covers the same momentum range as starting at 45° W at the equator and sweeping across the sky in the vertical plane to 45° E. Solving parametrically the two experimental curves of counting rate *vs.* geomagnetic latitude (reference (A) Fig. 6 or 8) and counting rate *vs.* momentum (Fig. 2) we arrive at the results given by the dots in Fig. 4 for minimum momentum *vs.* geomagnetic latitude.

To carry the comparison of the experimental results with calculations to higher latitudes we note from the lead curves of (A) Figs. 6 and 8 that, beginning with 0°

TABLE I. Pairs of latitudes at which the intensity at 45°W becomes equal to that at 45°E. Average for 10 and 20 cm of lead.

0 and 31.0°N	30 and 37.5°N
15 and 31.5°N	35 and 41.5°N
20 and 33.0°N	40 and 45.5°N
25 and 34.2°N	45 and 51.0°N

and 31° geomagnetic latitude where the intensity at 45° W becomes equal to that at 45° E respectively, there is a latitude where toward the west the intensity is the same as at another latitude toward the east. This means that the minimum momentum must be the same in the two cases. In Table I, pairs of latitudes are given at which these intensities become equal for the average of 10 and 20 cm of lead absorber.

These pairs of points have been plotted in Fig. 4 and shown by the circles. In plotting these we start first with the previous point at 31° N and extend the 45° E curve in such a manner that the corresponding points lying on the 45° W curve gradually drop down to the lower of the two extreme curves (shown dashed) given by Vallarta.[10]

We have thus experimentally determined in Figs. 3 and 4 the relation between minimum momentum for entrance and geomagnetic latitude at zenith angles 45° W, 0°, and 45° E. This is particularly important at intermediate latitudes where the calculations are exceedingly tedious.

It should be remarked that these curves have been strictly determined only along longitude 80° W and are not applicable to other longitudes. It will be noticed that all the experimental curves tend to lie above the upper curve given by Vallarta at low latitudes. This may be due to the peculiar variation of the earth's magnetic field along longitude 80° W.

V. CORRELATION OF AZIMUTHAL EFFECT WITH ZENITH ANGLE EFFECT AT THE EQUATOR

Lemaitre and Vallarta[11] have given curves showing the azimuthal variation of minimum momentum at several latitudes and zenith angles. We have already used their calculations for the boundary to the main cone at the equator that passes through the vertical to find the zenith angle dependence for particles of the same momenta.

A detailed comparison can be made at other azimuth angles by using the experimental values given in Fig. 2 with the curves shown in (A) Figs. 17 or 19. Again we solve the two curves parametrically and find the relation between minimum momentum as a function of azimuth angle. The comparison of these results with the calculations of Lemaitre and Vallarta is shown in Fig. 5 where we have used only the data with lead and zenith angle 45°. Suitable corrections to the ordinate of the calculated curve have been made to allow for eccentricity of the earth's dipole and tilt of the magnetic field as discussed earlier.

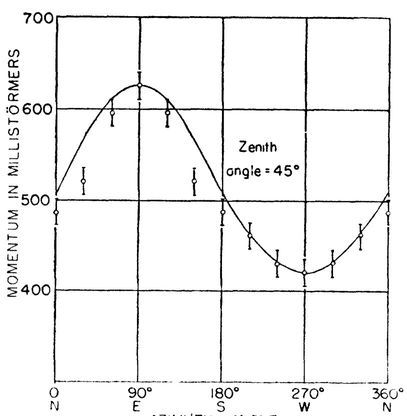

FIG. 5. Comparison of the measured azimuthal effect at zenith angle 45° with the data given in Fig. 2 permits a determination of the minimum momentum *vs.* azimuth angle.

It is apparent that with due regard to the experimental errors involved there is satisfactory agreement between the calculations and the experimental values.

The data may be presented in another way as shown in Fig. 6. Here the latitude effects at the vertical and at 45° E have been plotted as a function of minimum momentum, the latter taken from Figs. 3 and 4. The smoothed experimental data are taken from (A) Fig. 8. Plotted also in Fig. 6 are the data, shown by circles, taken at definite azimuths at the equator with the same absorber. In this latter case we use the calculations of Lemaitre and Vallarta for the dependence of momentum on azimuth.[11] The broken curve is the boundary to the limits of the momentum range covered for any given zenith angle at this altitude. That part of the broken curve to the left of the dotted vertical line corresponds to the telescope pointing toward the west while that to the right of the vertical line corresponds to easterly directions.

The $22\frac{1}{2}$° curve lies below the vertical curve because of the slightly greater atmospheric depth. The agreement between the variation in azimuth at 45° zenith angle with the latitude effect at 45° E, as discussed above, is clearly brought out in Fig. 6.

It is again clear that the close agreement between the latitude and azimuthal curves where the momentum ranges overlap is further substantiation for the assumed absence of negative particles in the primary radiation in the momentum ranges involved.

VI. CORRELATION OF LATITUDE, ZENITH ANGLE AND LONGITUDE EFFECTS

An analysis similar to that carried out at the beginning of this paper gives for the minimum momentum allowable at the vertical in India, 17.0 Bev/Zc after corrections for tilt of the earth's magnetic field and eccentricity of the dipole are taken into account.

Now it was shown in reference (A) that when 10 or 20 cm of lead absorber were used there was a good correlation between the intensity measured at an angle to the vertical and that measured at the vertical provided

(1) the mass of intervening air was the same and (2) the momentum range covered was the same. This agreement is apparently due to the compensating effects of scattering and decay.

From Fig. 6 we may find the longitude effect at certain particular atmospheric depths. At $310\times\sec.22.5°=335$ g/cm^{-2} atmospheric depth we would expect a 13 percent decrease in intensity in going from Peru to India along the geomagnetic equator, where the change in minimum momentum is from 13.5 to 17.0 Bev/Zc. Now the latitude effect in the total radiation as compared with that in the penetrating was shown in (A) to be approximately equal. We would therefore expect the total radiation to have a longitude effect of 13 percent also at about 330 g/cm^{-2} air pressure. It is difficult to compare this with experimental data since similar flights have not been made in Peru and India. There is also the question of variations with time unless the flights are made simultaneously. However the figure of 13 percent is certainly not in conflict with existing experimental data taken at Bangalore and Pishawar,[13] India, and at Acapulco, Mexico,[14] using counter telescopes.

From the lower curve in Fig. 6 we find for the longitude effect at $310\times\sec.\ 67.5°=810$ g/cm^{-2} atmospheric pressure a value of 5 percent. The value found *at sea level* or 1030 g/cm^{-2} in the world survey of Millikan and Neher[15] was 4 percent.

It is of interest to compare the latitued effect at 310 g/cm^{-2} air pressure with that found at sea level. Using the data of (A) Fig. 5 for 10 cm of lead absorber at the higher altitude and that given by Millikan and Neher[15] at sea level along the same longitude (80° W) we find the values given in Table II for the ratios between the latitude effects at the two elevations for certain increments in latitude. A slight extrapolation leads us to expect a longitude effect about 4 times as large at 30,000 ft. as at sea level or a decrease of 16 percent in going from Peru to India along the geomagnetic equator. This is in agreement with the value taken from Fig. 6.

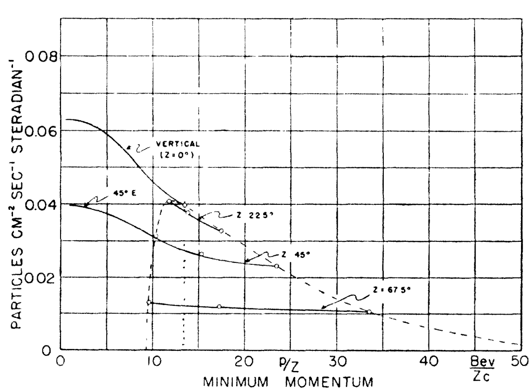

FIG. 6. Plotting intensity *vs.* minimum momentum as given by Fig. 3, 4, and 5 permits a comparison of the latitude effect with the azimuthal effect at the geomagnetic equator.

TABLE II. Latitude effect at 30,000 ft. (310 g/cm^{-2} air pressure) relative to that at sea level along 80°W longitude. 10 cm lead absorber. Sea level values taken with ionization chamber shielded with 10 cm of lead. 30,000 ft. data taken with counter telescope pointing at the vertical with 10 cm of lead absorber between trays of counters.

	Percent increase Sea level	30,000 feet	Ratio
0–20°N	1.5	9.1	6.0
20–25	1.8	7.3	4.1
25–30	2.0	6.3	3.2
30–35	2.0	9.9	4.9
35–40	1.8	6.2	3.4
40–50	1.0	5.7	5.7

To give a more complete picture, Fig. 7 is included which gives the azimuthal data taken with 10 cm of lead absorber in the counter telescope at the two different elevations over Peru. Each curve gives the intensity for given masses of intervening air as a function of minimum momentum of the primary particles.

Also from Fig. 7 the absorption in the atmosphere of the radiation that can penetrate 10 cm of lead due to primaries of a certain minimum momentum may be determined by taking the intersections with vertical lines. Thus the intersections of the curves with the dotted line at 13.5 Bev/Zc should fall on the intensity *vs.* air pressure curve in the vertical direction in Peru taken with 10 cm of lead. Comparison with curve B of reference (A) Fig. 21 shows this to be true.

VII. SUMMARY

The calculations of Vallarta *et al.* on the paths of charged particles in the magnetic field of the earth have shown the general behavior to be expected in the several geomagnetic effects found in cosmic rays. By using experimental data taken on a B-29 flight to Peru it has been possible (1) to say that, within the limits of the uncertainties in the experimental data and in the

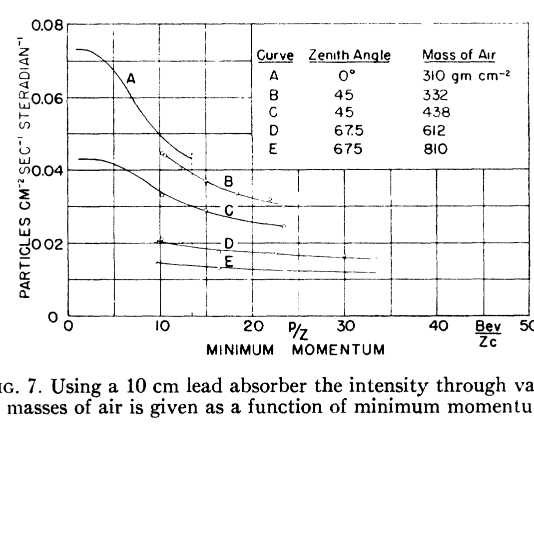

FIG. 7. Using a 10 cm lead absorber the intensity through various masses of air is given as a function of minimum momentum.

[13] H. V. Neher and W. H. Pickering, Phys. Rev. **61**, 407 (1942).
[14] Millikan, Neher, and Pickering, Phys. Rev. **63**, 234 (1943).
[15] R. A. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936).

calculations of Vallarta *et al.* on the behavior of charged particles in the magnetic field of the earth, there are few if any negative primary particles in the momentum range 7 to 23 Bev/Zc compared with the positives, and (2) to find experimentally the minimum momentum for entrance for positive primaries as a function of geomagnetic latitude. This is particularly important at intermediate latitudes where the calculations become extremely difficult and have not been carried through in detail except in particular cases. The experimental determination of these curves is independent of the assumed nature of the primaries (except that they carry a positive charge), the way in which they or their secondaries are absorbed in the atmosphere or their momentum distribution at the top of the atmosphere.

Using the experimental data on the latitude, azimuthal and longitude effects in conjunction with the calculations of Vallarta *et al.*, it has been found possible to correlate all these phenomena. We may therefore say at the present time that within the experimental uncertainties all of these geomagnetic effects fit into a consistent picture.

It is again a pleasure to acknowledge the assistance given by the ONR and to the U. S. Air Forces in providing the facilities and airplane that made possible collecting the data used in this analysis.

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Energy Transfer to Nucleons in Cosmic-Ray Stars at 95,000 Feet*

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The size-frequency distribution of cosmic-ray stars produced in photographic emulsions exposed at 95,000-feet altitude and the energies associated with the non-relativistic prongs of these stars have been determined. A distribution function for the excitation energy of stars with more than 8 prongs is derived.

NUCLEAR disruption ("stars") produced by cosmic rays in photographic emulsions exposed at balloon altitudes are frequently associated with the emission of relativistic singly charged and neutral particles, the majority of which are presumably mesons.[1,2] It is to be expected that all nuclear interactions of cosmic-ray primaries will lead to an excitation of the residual nucleus which gives rise to the low energy evaporation and knock-on star fragments.

At balloon altitudes stars with twenty and more non-relativistic prongs, corresponding to excitation energies of the order of one Bev, are observed not too infrequently. The mechanism by means of which such large excitation energies can be transferred from an incident nucleon to the nucleons of the target is not obvious. By elastic collisions alone a fast nucleon can transfer to a silver nucleus not much more than about 200 Mev.

S. A. Wouthuysen[3] has calculated the probability $p(E)dE$ of an "excitation energy" (including all nucleons with energies less than about 30 to 40 Mev and all heavier fragments) in the interval between E and $E+dE$ for Ag-nuclei bombarded by primary protons, assuming an effective collision cross section equal to about 80 percent of the geometrical cross section. In these calculations nucleon-nucleon collisions are considered to be completely inelastic (leading to meson production) for energies >600 Mev and completely elastic for energies <600 Mev. The assumption of complete inelasticity certainly exaggerates the energy transfer due to the secondary nucleons produced by an energetic incident primary. On the other hand, the mesons are assumed to leave the nucleus without contributing at all to the excitation energy. Whether this assumption is justified or not depends on the nuclear interaction cross section of fast π-mesons, for which no reliable data are as yet available. The result is shown in curve 1 of Fig. 1.

In order to allow a comparison with the actual excitation energy distribution of stars produced by cosmic-ray primaries, we have determined the total energy (kinetic+binding) associated with the "black prongs" ($K/K_{\min}>7$, corresponding to $E_P<40$ Mev) of stars in Ilford C_2 and Eastman NTB3 emulsions, exposed at 95,000-feet altitude at 51°N geomagnetic latitude (curve 1 of Fig. 2). We find that some 30 percent of the black prongs are due to α-particles, at least some 10 percent to deuterons, 3 to 4 percent to H^3 and some 5 percent to fragments heavier than He. The number and energy of neutrons is assumed to be 1.3 times the number and energy of the protons. Since it actually may be quite appreciably larger,[4] the excitation

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[1] U. Camerini *et al.* Phil. Mag. **40**, 1073 (1949).
[2] Kaplon, Peters, and Bradt, Helv. Phys. Acta **23**, 24 (1950).
[3] S. A. Wouthuysen (to be published).
[4] H. A. Bethe, Echo Lake Conference on Cosmic Rays (June, 1949).