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Further Study of Cosmic Rays on the Pacific Ocean

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Records of cosmic-ray intensity obtained on the *R. M. S. Aorangi* during 15 new voyages between Vancouver, Canada, and Sydney, Australia, from July 28, 1937, to September 23, 1938, with a Carnegie model C cosmic-ray meter, are discussed and compared with records taken during 11 voyages on the same route previously reported by Compton and Turner. The observed minimum of cosmic-ray intensity near the equator averages 10.3 percent less than the intensity at Vancouver, in good agreement with the value given by Compton and Turner. The correlation between the cosmic-ray intensity and the atmospheric temperature is confirmed. An atmospheric temperature coefficient is found to be a function of latitude, with its highest numerical value of -0.25 percent per °C for latitudes higher than 40° (N and S). With this variable temperature coefficient a latitude effect (about 8.5 percent) of magnetic origin alone is found. The mean latitude effect curve for 25 trips, corrected for external temperature, is flat beyond the critical latitudes (about 40°N and 38°S). The difference in cosmic-ray intensity between the Northern and Southern Hemispheres beyond the critical latitudes after this temperature correction is found to be 0 ± 0.1 percent (probable error). This is inconsistent with a galactic rotation effect as great as the 0.5 percent predicted by Compton and Getting, but does not definitely rule out a more recent modification of their calculation. The origin of the latitude effect knee is ascribed to the minimum energy required for a primary electron to produce mesotrons capable of traversing the atmosphere. The small magnitude of the latitude effect is shown to supply strong evidence of the secondary nature of mesotrons.

A. H. COMPTON and R. N. Turner have recently described and discussed the records of cosmic-ray intensity obtained on the *R. M. S. Aorangi* during eleven voyages between Vancouver, Canada, and Sydney, Australia, from March 17, 1936, to January 18, 1937, with a Carnegie Model C cosmic-ray meter.[1] The present paper describes the cosmic-ray records obtained on the *R. M. S. Aorangi* during fifteen additional voyages over the same route from July 28, 1937, to September 23, 1938, with the same meter. From January 29, 1937, to July 13, 1937, the meter was on the *S. S. Talune*, traveling between Newcastle (New South Wales) and Hobart (Tasmania). The method of collection and reduction of the data has already been explained.[1]

ANALYSIS OF THE DATA

In analyzing the data, the procedure of Compton and Turner was followed. The barometer effect was determined by correlating the daily mean values of the ionization I_0 with the daily mean values of barometer B in inches of Hg. For 1936–37 a barometer effect of -10.9 millivolts per hour per atmosphere of argon per inch of mercury was determined, which value was used throughout. This corresponds to -1.74 percent per cm of mercury. Compton and Turner used the value -10 millivolts per hour per atmosphere of argon per inch of mercury, or -1.6 percent per cm of mercury for the barometer effect. The

[1] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937).

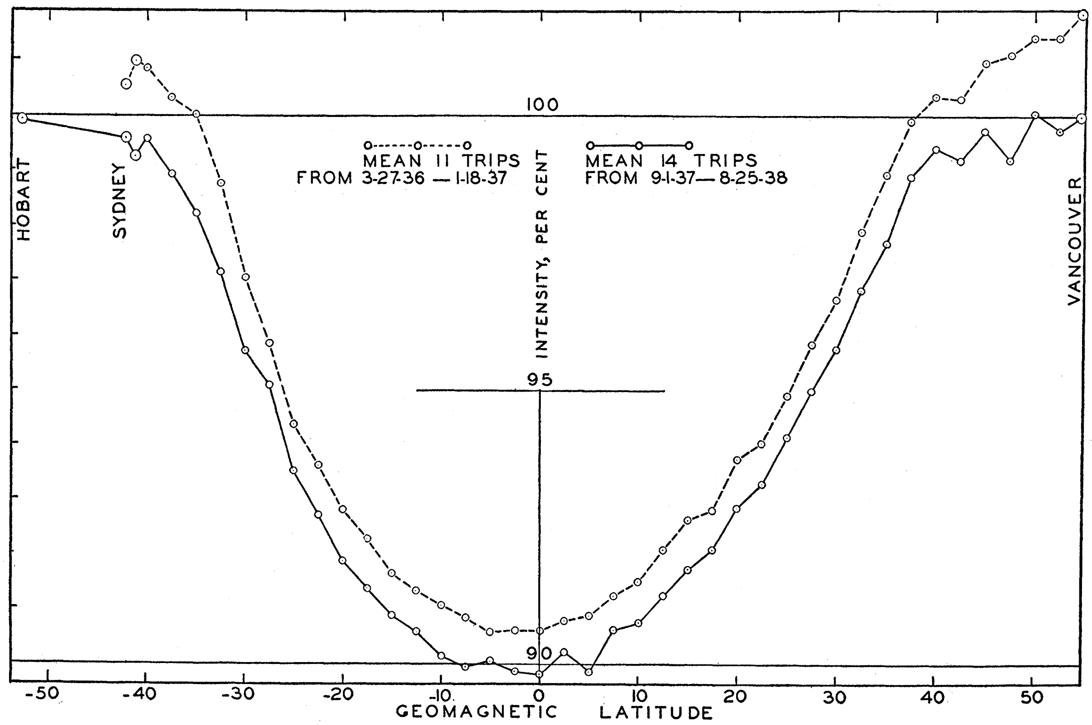

FIG. 1. Cosmic rays on the Pacific Ocean.

daily mean values of the barometric pressure for 1936–37 were obtained from a barograph calibration not significantly different from that found for the new series of data used in this paper. The absolute ionization at the latitude of Chicago is given by Compton and Turner as 249 millivolts per hour per atmosphere of argon, which corresponds to 84 ions per cm^3 per sec. in 50 atmospheres of argon, or 1.22 ions per cm^3 per sec. in standard air. The final observed intensities, after applying the barometric correction, are expressed in percentages of this normal ionization.

It has not been considered necessary to give all fifteen curves, each representing one trip, while the ship was at sea. All the data have been grouped, however, into two seasons, colder months (November 6–May 7) and warmer months (May 8–November 5), in order to discuss the dependence of cosmic-ray intensity on seasonal temperature. It has been previously shown by Compton and Turner[1] and Forbush[2] that the temperature coefficient of the meter is insignificant.

[2] S. E. Forbush, Terr. Mag. **42**, 1 (1937); Phys. Rev. **54**, 975 (1938).

ANNUAL MEAN AND SEASONAL DIFFERENCES

The solid curve in Fig. 1 shows the 12-month mean of all the observations taken between Auckland and Vancouver, while the broken curve shows the corresponding data (Fig. 6) of Compton and Turner. Each point represents the arithmetic average of the values observed at the corresponding 2.5° interval. The total change between Vancouver and the equator is 10.3 percent, which is the average of seasonal means that vary from 9.8 percent in the warmer months to 10.9 percent in the colder months.

This value of 10.3 percent is identical with that reported by Compton and Turner. Previous measurements over the same route include the value of 13 percent given by Compton,[3] as based on measurements with a shield equivalent to 6.5 cm of lead, and the value of 11 percent given by Millikan and Neher,[4] who used a shield equivalent to 12 cm of lead, the same as that for measurements here reported.

Minor differences between the present and the

[3] A. H. Compton, Rev. Sci. Inst. **7**, 71 (1936), Fig. 1.
[4] R. A. Millikan and H. V. Neher, Phys. Rev. **50**, 15 (1936), Fig. 14.

earlier data of Compton and Turner are that the knee in the Southern Hemisphere comes at a higher latitude than in their curve, and that at latitudes higher than the knee the increase in intensity with latitude is smaller than theirs in both hemispheres. The intensity at Sydney is 0.4 percent higher than the intensity at Auckland, while Fig. 6 of Compton and Turner shows 0.2 percent higher intensity at Auckland than at Sydney.

The latitude curve of Fig. 1 is extended farther south from Sydney (42.2°S)* to Hobart (Tasmania) (51.6°S) by adding the data collected on *S. S. Talune*. Because the meter on *S. S. Talune* was placed under deck, the mean value of I_0 at Sydney was 3.88 percent lower than the mean value of I_0 at the same place while the meter was on *R. M. S. Aorangi*. Since no essential changes in the meter were made when it was transferred from *R. M. S. Aorangi* to *S. S. Talune*, it was assumed that the daily mean values of I_0 at Sydney were unchanged. As the ship traveling between Newcastle (NSW) and Hobart (Tasmania) was seldom in port at Sydney over five hours, the mean I_0 at the port was obtained from daily means of I_0 for the days when the ship was between Newcastle (41.2°S) and 43.5°S.

Figure 1 now shows the knees more distinctly.

* Geomagnetic latitudes are used throughout.

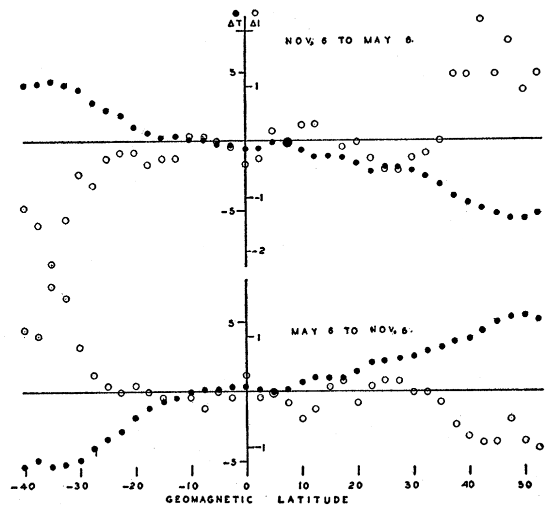

FIG. 3. Departures for colder and for warmer months from annual mean of ionization (ΔI) and shade temperature of the outside air (ΔT), plotted for the various latitudes.

They lie at about 40° in the Northern Hemisphere and at about 38° in the Southern Hemisphere. The increase in ionization beyond the knees is, within experimental error, the same in both hemispheres.

The fluctuations of I_0 from 40°N to 52.5°N and from 10°N to 7.5°S are not ascribable to experimental error, but are due to diurnal changes in cosmic-ray intensity. For most of the trips the ship crossed at about noon the latitudes

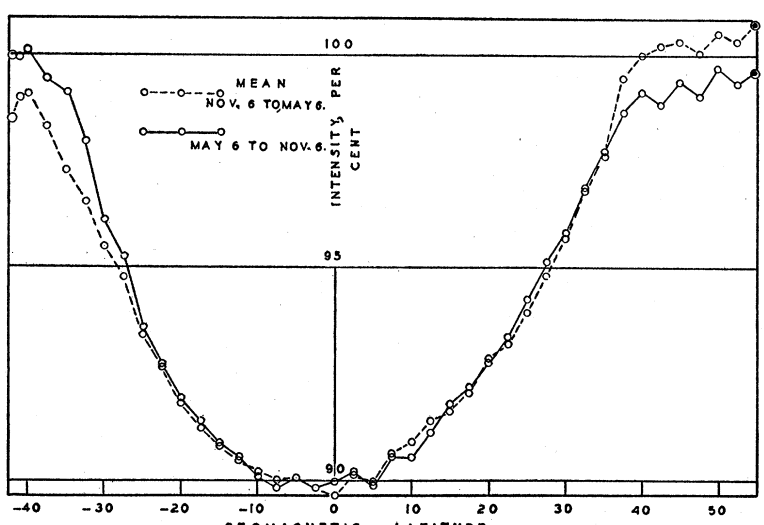

FIG. 2. Latitude effect curves for colder months (Nov. 6 to May 6) and for warmer months (May 7 to Nov. 5) for 1937–38 data.

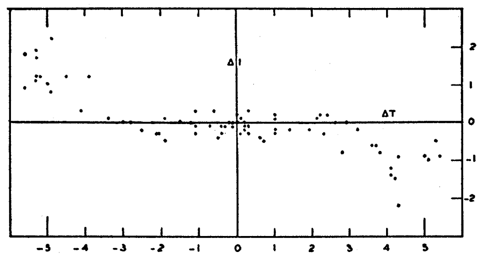

FIG. 4. Scatter diagram showing nonlinear correlation of ΔI *vs.* ΔT.

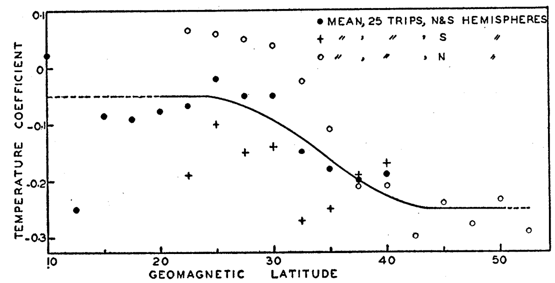

FIG. 5. Atmospheric temperature coefficient as a function of geomagnetic latitude.

where the intensity is slightly higher and at night where the intensity is lower.

EFFECT OF ATMOSPHERIC TEMPERATURE ON IONIZATION

Figure 2 shows that, in both the Northern and Southern Hemispheres, the intensity is greater during the cold months, as was likewise evident from Fig. 7 of Compton and Turner. They ascribed this variation to atmospheric rather than astronomical changes, a conclusion which was confirmed by the writer[5] from data obtained at four widely separated stations, which showed no significant correlation with various astronomical variables.

For each of the two curves of Fig. 2, the departure of the ionization from the annual mean was noted for each 2.5° interval of latitude. These departures in the ionization were compared (Fig. 3) with the departure in the outside shade temperature from its annual mean at the same latitude. This analysis shows a definite correlation of opposite sign between the external shade temperature and the observed ionization only in regions outside an equatorial belt extending approximately 10° either side of the magnetic equator. In Fig. 3 are shown at each latitude the departures from the annual mean values of the external temperatures for cold and hot months of the year. Outside of the equatorial belt, the opposing trends of this temperature and ionization are evident in both curves. The opposing trends of temperature and ionization in the equatorial belt for summer and winter are not evident in Fig. 8 of Compton and Turner,[1] but do appear in their curves for spring and autumn. From the data in the scatter-diagrams of the atmospheric temperature *vs.* ionization, temperature coefficients of the ionization for two different latitude zones were computed. Table I gives the values of these coefficients together with those obtained last year by Compton and Turner[1] (Table I). Values of the atmospheric temperature coefficient calculated in a similar manner for various land stations have recently been reported by the writer.[5]

A scatter diagram of ΔI *vs.* ΔT for all the data shown in Fig. 3 indicates (Fig. 4) that ΔI is not a linear function of ΔT. It will be noted, however, that the smaller values of ΔT are obtained at lower latitudes than are the higher values. The fact that the slope of ΔI *vs.* ΔT is steeper at the larger values of ΔT thus means that at the higher latitudes the atmospheric temperature coefficient is greater.

TABLE I. *Atmospheric temperature coefficient of cosmic-ray ionization (reduced to standard barometer).*

AUTHORITY	YEAR	LOCATION	COEFFICIENT PERCENT	PROBABLE ERROR PERCENT	CORRELATION FACTOR
Compton and Turner	Mar. 17, 1936, to Jan. 18, 1937	Vancouver (54.8)	−0.22	±0.02	−0.85±0.04
		Auckland (41.1)	−0.16	±0.04	−0.47±0.15
		Sydney (42.2)	−0.10	±0.02	−0.67±0.10
		At Sea	−0.18	±0.01	−0.68±0.03
This Paper	July 28, 1937, to Sept. 23, 1938	Vancouver (54.8)	−0.13	±0.02	−0.62±0.07
		Auckland (41.1)	−0.12	±0.04	−0.50±0.12
		Sydney (42.2)	−0.085	±0.03	−0.36±0.12
		At Sea between:			
		$\lambda = 15$ S & 15 N	−0.05	±0.04	−0.17±0.13
		$\lambda = 17\frac{1}{2}$ & 40 N & S	−0.31 −0.29	±0.03 ±0.04	−0.87±0.04 −0.72±0.07

[5] P. S. Gill, Phys. Rev. **55**, 429 (1939).

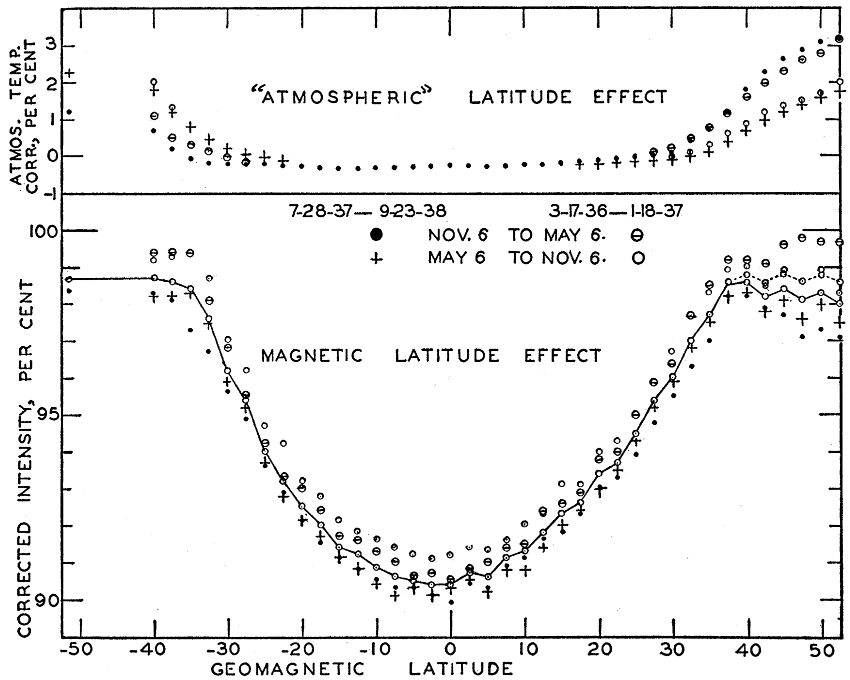

FIG. 6. Magnetic and atmospheric latitude effect for twenty-five trips.

The values of α, the atmospheric temperature coefficient of the ionization, at intervals of 2.5° geomagnetic latitude can be found as follows: By definition $\alpha=(1/I_a)(\Delta I/\Delta T)$, where I_a is the absolute ionization due to cosmic rays and ΔI and ΔT are the mean ranges between summer and winter deviations from the annual mean at the latitude for which α is evaluated. The value of α was calculated separately from the data for 10 trips reported by Compton and Turner and for the 15 trips analyzed in the present paper, and the mean was weighted accordingly. The results for latitudes greater than 10°N and S are shown in Fig. 5. At lower latitudes, because of the smallness of ΔT, the values of α become experimentally indeterminate.

The open circles represent the coefficients thus calculated for the Northern Hemisphere, the crosses for the Southern Hemisphere, and the solid circles the mean between the two values. One of the most important sources of error is the occurrence of world wide changes in cosmic-ray intensity.[2] When such a change persists for a prolonged period, it increases the apparent temperature coefficient in one hemisphere and decreases it in the other. For this reason the value of the mean between the two hemispheres is much more reliable than either individual value. Thus the atmospheric temperature coefficients beyond 40°, being based on measurements in the Northern Hemisphere alone, cannot be relied upon with the confidence that we have in the data between 30° and 40°. It is evident, however, that beyond 42.5° α appears to stay constant, and has its greatest numerical value. On the other hand, α decreases rapidly from 42.5° to 25° where it again appears to approach a constant minimum numerical value. This is in accord with Blackett's[6] view, in which he points out that the temperature coefficient at the equator should be lower than at bordering latitude zones.

It will be noted in Table I that the value of the temperature coefficient at Vancouver for this paper is 60 percent of that given by Compton and Turner, while those at Auckland and Sydney are the same within the probable error. The difference at Vancouver may be caused by sudden changes in ionization due to magnetic storms or other causes independent of the temperature of the atmosphere.

[6] P. M. S. Blackett, Phys. Rev. 54, 973 (1938).

Atmospheric and Magnetic Latitude Effects

The upper part of Fig. 6 shows the corrections to be applied to the two curves of Fig. 2, and also to the two similar curves obtained from the data used by Compton and Turner, to correct for the changes in the atmospheric temperature. These corrections are made by reducing the data to the mean value of 21°C, supposing that the atmospheric temperature coefficient is the function of geomagnetic latitude shown in the curve of Fig. 5. These correction curves thus represent a latitude effect of atmospheric origin, differing with colder and warmer months, which must be subtracted from the observed latitude effect curves to obtain the effect caused by the earth's magnetic field. The solid curve of Fig. 6 is the mean (weighted, ratio 10 : 15) of 10 trips reported by Compton and Turner and 15 trips analyzed here. This curve thus represents the part of the latitude effect which is of magnetic origin.

The lower (solid) curve beyond 35°N is obtained by applying the temperature coefficient as given in Fig. 5. This curve shows a slight decrease for latitudes higher than the knee (40°N). Since from theoretical reasons it is very improbable that the corrected cosmic-ray intensity should thus diminish with increasing latitude, the decrease shown by the solid curve presumably indicates that an over-correction has been made for the atmospheric temperature coefficient. By the method of trial and error, it is found that if for these latitudes the value of α is taken as -0.19 percent per degree C, instead of -0.25 as given in Fig. 5, the magnetic latitude

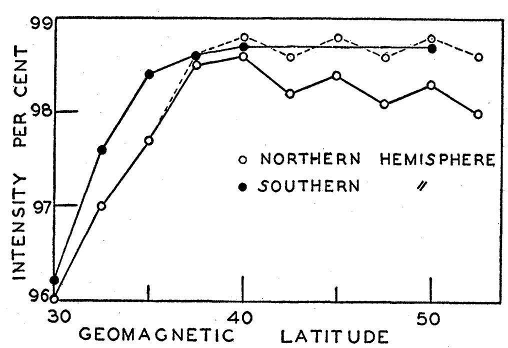

FIG. 7. Comparison of corrected latitude effect for Northern and Southern Hemispheres.

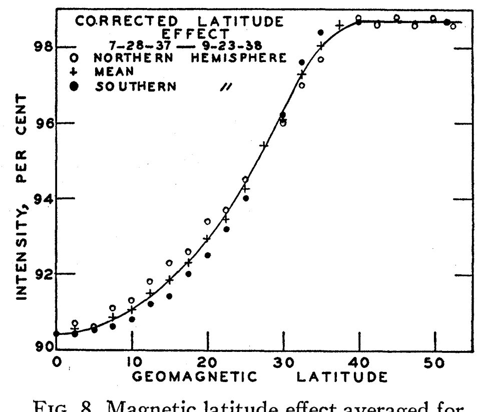

FIG. 8. Magnetic latitude effect averaged for both hemispheres.

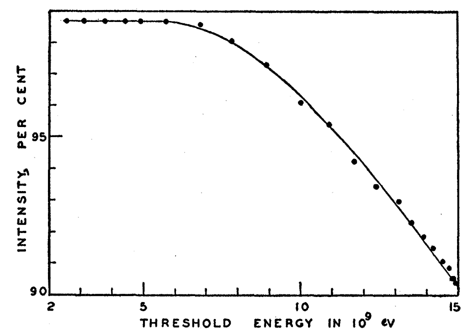

FIG. 9. Cosmic-ray ionization as a function of geomagnetic energy threshold.

effect curve becomes horizontal. It is thus that the broken curve of Fig. 6 is calculated. The assumption of a flat geomagnetic latitude effect curve beyond the knee thus affords an independent method of determining the atmospheric temperature coefficient. Since the result does not differ too greatly from that obtained directly,* we may conclude that the assumption of flatness is consistent with the experimental data. That is, there is no evidence of a geomagnetic latitude effect beyond the knee.

Comparison of Intensity in the Northern and Southern Hemispheres

Compton and Getting[7] predicted an excess of cosmic-ray intensity of about 0.5 percent in the

* It may be noted that the temperature correction applied in Fig. 6 should be correct only if, for a sea-level temperature of 21°C, the temperature at every altitude is the same at all latitudes. It is clear that this is not in general true. The method of correction can thus be expected to remove differences of only the first order.

[7] A. H. Compton and I. A. Getting, Phys. Rev. **47**, 817 (1935).

north, due to the motion of the earth with the rotation of the galaxy. The comparison of intensity in the Northern and Southern Hemispheres should be significant only for latitudes where the influence of the earth's magnetic field becomes negligible, that is, beyond the latitude knees (40°N and 38°S). This portion is shown in Fig. 7, where the corrected intensity curves for latitudes higher than 30°N and S are given. The question arises, which of the two curves in the north (broken or solid, as explained in the last section) is to be taken as the more reliable. Supposing that the curve which shows a flat plateau is the better measure, we find an exact equality of intensity in the two hemispheres.

A rough estimate of the probable error of this equality gives ± 0.1 percent, in which estimate the largest factor is that introduced by the uncertainty in the temperature correction.

This result indicates that a difference of 0.5 percent between the Northern and Southern Hemispheres are predicted by Compton and Getting is very improbable. It should be noted, however, that if the sun's motion with the rotation of the galaxy is, as indicated by the recent study by Camm,[8] only 200 instead of 300 km per sec., as assumed in the earlier calculations, the precision of the present measurements is inadequate definitely to rule out the possibility of the predicted effect.

Discussion of Latitude Curve

In Fig. 8 is shown the mean cosmic-ray intensity I for 25 trips, corrected for external temperature, as a function of λ. This curve, based upon the broken curve of Fig. 6, shows no increase in intensity for latitudes higher than 40°. That is, at sea level, beyond Compton's latitude knee, no detectable latitude effect of geomagnetic origin exists. Lemaitre and Vallarta[9] have given the threshold energy E_0 as a function of λ for vertically incident electrically charged primaries (electrons). Thus at a certain latitude only those electrons can enter the earth's atmosphere which have energies greater than E_0. From this relation between E_0 and λ, the curve of Fig. 9 shows the cosmic-ray intensity *vs.* threshold energy E_0. As this curve is obtained at sea level with a lead shield around the ionization chamber of 12 cm, the curve represents the latitude sensitive part of the penetrating radiation, presumably mesotrons, as a function of the threshold energy E_0 of the primary electrons.

One can compare the mesotron intensity at different latitudes corresponding to certain threshold energies E_0 as given in Fig. 9 with the energy distribution curve of mesotrons obtained by the Wilson chamber method[10] and as calculated by Euler and Heisenberg.[11] In order to calculate the energy spectrum at sea level Euler and Heisenberg assumed that all of the mesotrons are produced as secondaries by the soft component at the same altitude (about 16.6 km) in the atmosphere. For the spectrum of the primary electrons they consider a distribution function of the following kind: $F(E) = I_0 \times E^{-\gamma}$ where $F(E)$ represents the number of the vertically incident electrons having energies greater than E, I_0 and

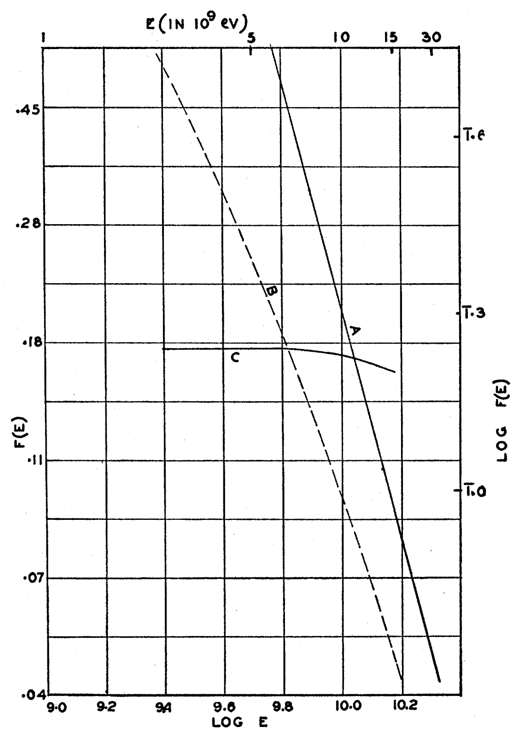

Fig. 10. Energy distribution curves: (A) for electrons at the top of the atmosphere; (B) mesotrons at sea level; (C) latitude *vs.* threshold energy.

[8] G. L. Camm, Roy. Astr. Soc. **99**, 71 (1938).

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

[10] P. M. S. Blackett, Proc. Roy. Soc. **A159**, 1 (1937).

[11] H. Euler and W. Heisenberg, Ergeb. Exakt. Naturwiss. **17**, 1–70 (1938).

γ are empirical constants. On the further assumption that the created mesotrons have the same energy distribution as the primaries, Euler and Heisenberg calculate the variation of the energy spectrum as the mesotrons travel through the earth's atmosphere losing energy by ionization[12] and by spontaneous decay.[13] Thus at sea level they obtain an energy distribution of mesotrons given by the broken line B of Fig. 10. This curve is represented in a double logarithmic diagram where $\log F(E)$ (number of vertically incident mesotrons per minute per cm^2) is ordinate and $\log E$ is abscissa. The curvature in the energy spectrum of the mesotrons at sea level compared with the straight line distribution at the top of the atmosphere is caused by the spontaneous decay of mesotrons in air which increases with decreasing energy of the particles. The straight line A in Fig. 10 represents the corresponding energy distribution of electrons at the top of the atmosphere when γ is given the value 1.8.[14] The broken curve is in good agreement with the energy distribution curve obtained from Wilson cloud-chamber measurements in the same range of energies by Blackett.[10]

Curve C represents the observed ionization, produced at sea level by mesotrons, as a function of the threshold energy of the primary electrical particles. The following characteristics are evident: (1) For energies smaller than 6×10^9 ev (knee) the ionization produced by the mesotrons is independent of the energy of the primaries, and does not follow the energy spectrum determined by (A) and (B). (2) For energies greater than 6×10^9 ev (knee) the ionization produced by the mesotrons varies with the threshold energy of the primaries, but much less rapidly than does the number of the primary electrons (A).

These differences between curves C and A give clear evidence that the mesotrons which produce the ionization in our lead-shielded chamber at sea level are not the primary particles which are affected directly by the earth's magnetic field. Rather it appears that the mesotrons are created as a secondary radiation in the atmosphere, and hence reflect only that dependence on the earth's magnetic field to which the much higher energy primaries that excite them are subject. This evidence for the secondary nature of the mesotrons from a consideration of the latitude effect has been discussed by Euler and Heisenberg.[11]

Professor Compton has suggested that the knee of the latitude curve should occur for that minimum energy of the secondary mesotrons which enables them to penetrate the barrier of the earth's atmosphere. This hypothesis is based on the now evident fact that neither electrons nor photons of any reasonable energy are able to penetrate the atmosphere, and that the predominant ionization at sea level seems to be caused by mesotrons and their secondaries. If we make the reasonable assumption that some of these mesotrons traverse the atmosphere with no energy loss other than that caused by ionization, various calculations[15] give for the minimum required energy about 2.5×10^9 ev. It may be noted that the mean decay constant for mesotrons is taken as $t_0=2\times 10^{-6}$ sec., and their effective height of production as 25 km, considering merely the decay, there should remain at sea level about 30 percent of the initial mesotrons of this threshold energy. Thus the sharply limiting factor is not the decay rate, but the ionization.

The minimum energy of the primary particle required to excite such secondary mesotrons will depend upon the nature of the exciting process. Perhaps as probable a mechanism as any is that the primary cosmic ray is an electron, positive or negative, which on collision with an atomic nucleus in the atmosphere produces a photon (x-ray) whose energy will be of the order of, but less than, that of the primary electron. As in electron pair production, we may suppose that if the resulting photon generates a mesotron, a pair of positive and negative mesotrons is produced, between which the energy is approximately equally divided. Thus if E_e is the energy of the primary electron, E_p that of the photon, and E_m that of each of the mesotrons,

$$E_e \geqslant E_p = 2E_m.$$

From $E_m=2.5\times 10^9$ ev, we thus find for the

[12] H. A. Bethe and W. Heitler, Proc. Roy. Soc. **A146**, 83 (1934).

[13] Yukawa and M. Taketani, Proc. Phys. Math. Soc. Jap. **20**, 720 (1938).

[14] L. W. Nordheim, Phys. Rev. **53**, 694 (1938); W. Heitler, Proc. Roy. Soc. **A161**, 261 (1937).

[15] H. J. Bhabha, Proc. Roy. Soc. **A164**, 257 (1938).

threshold energy of the primary electrons,

$$E_e \geqslant 5 \times 10^9 \text{ ev}.$$

This is in satisfactory agreement with the threshold energy of the latitude effect, which according to Fig. 9 occurs at about 6×10^9 ev.

Primary particles with energies less than 5×10^9 ev should thus not produce any ionization at sea level, which would account for the absence of any latitude effect beyond 40 degrees. At higher altitudes, since the minimum energy required to penetrate the atmosphere is less, one should expect a shift of the knee to higher latitudes. This is in qualitative agreement with the recent experimental results.

On the other hand, mesotrons of energies less than 2×10^9 ev, which constitute the more abundant part of those observed at sea level, have too little energy to penetrate the atmosphere. These must therefore have been produced far below the height (about 25 km) at which the first production occurs, and hence must be the result of several stages of energy transfer. That such production of mesotrons at relatively low altitudes does indeed occur is demonstrated by the recent airplane experiments of Schein and Wilson.[16] It follows that the energies of the primaries producing them must have been manyfold greater than the mesotron energies. It is thus not to be expected that they would be influenced by the earth's magnetic field. In this manner we can account for the small magnitude of the observed latitude effect, and the difference between curves B and C of Fig. 10.

For threshold energies higher than 6×10^9 ev (knee) a certain number of the primary electrons, producing those mesotrons which are capable of penetrating the barrier of the earth's atmosphere, is cut off at certain latitudes by the earth's magnetic field. Therefore a definite latitude effect of the penetrating radiation at sea level is present for energies between $E = 6 \times 10^9$ ev and $E = 15 \times 10^9$ ev, beyond which energy the earth's field, even at the equator, ceases to act as a barrier.

The author wishes to express his sincere appreciation to Professor A. H. Compton for assigning the problem and for his inspiring guidance throughout the investigation. It is a pleasure to thank Mr. R. N. Turner for his careful and remarkable work in taking care of the meter. Thanks are due likewise to the Canadian Australasian Steamship Company for permission to build the cosmic-ray observatory on the *R. M. S. Aorangi*, to the Union Carbide and Carbon Corporation for supplying the batteries required for operating the meter, and to the Carnegie Institution of Washington for the use of the cosmic-ray meter. The author also wishes to thank Mrs. Ardis T. Monk for help in calculations, and Dr. M. Schein for valuable discussions. Professor P. W. Burbidge of Auckland University College and Mr. F. L. Code of Vancouver have given valued help in the adjustments of the meter.

[16] M. Schein and V. C. Wilson, Phys. Rev. **54**, 304 (1938).