Cosmic Rays on the Pacific Ocean

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Records of cosmic-ray intensity obtained on the R. M. S. Aorangi during 12 voyages between Vancouver, Canada and Sydney, Australia, from March 17, 1936, to January 18, 1937, using a Carnegie model C cosmic-ray meter, are described and discussed. Typical records exhibiting the latitude effect are shown. A summary of the data taken at sea is given in the form of graphs, in which each datum point represents the average of 6 hours readings with a probable statistical error of ± 0.13 percent. Any variations due to a possible temperature coefficient of the instrument are negligible. The observed minimum of cosmic-ray intensity near the equator averages 10.3 percent less than the intensity at Vancouver, in satisfactory agreement, considering the difference in experimental conditions, with earlier measurements. The critical latitudes above which changes in intensity are less rapid, are found to be somewhat lower, 38.4°N and 34.2°S, than previously reported, and beyond these latitudes the intensity is found to continue to increase with latitude. At the higher latitudes is observed a variation, which appears to be seasonal, with the maximum in the cold months in both hemispheres. This variation is closely correlated with the atmospheric temperature. It is hence ascribed to changes in some atmospheric barrier of unknown nature, such as perhaps an atmospheric potential gradient, of whose strength the temperature of the atmosphere is an approximate but not exact index. Changes in this atmospheric barrier have been approximately allowed for by determining the external temperature coefficient and correcting the observations accordingly (this external temperature coefficient is comparable with that reported by Hess and his collaborators). The latitude effect curves as thus corrected should show the effect of the earth's magnetic field alone. They are now nearly flat beyond the critical latitudes and show a magnetic latitude effect of about 7.2 percent. This implies that a latitude effect of about 3.1 percent owes its origin to the atmospheric barrier. Seasonal variations in the corrected latitude effect curve are almost eliminated. Geomagnetic analysis of the energy distribution of the rays indicates a prominent component with a sharp energy threshold of about 7.5×10^9 ev, and a component so weak as to be questionable, whose energy threshold is not greater than 2.5×10^9 ev. It is not found possible to explain the 7.5×10^9 ev threshold in terms of atmospheric absorption as has previously been supposed. Two alternative interpretations are suggested. The difference in cosmic-ray intensity between the northern and southern hemispheres under comparable conditions, as calculated from these data in various ways, appears to be no larger than the probable error of about ± 0.1 percent. This result is in conflict with the prediction by Compton and Getting of an excess in the north of about 0.5 percent, due to the motion of the earth with the rotation of the galaxy, but is not inconsistent with the small diurnal variation that has been found to follow sidereal time, if it is supposed that the cosmic rays acquire a part of the galactic motion.

THROUGH the courtesy of the Canadian Australasian Steamship Company, we have been able to carry through a year of almost continuous cosmic-ray measurements on their motor ship Aorangi (17,500 tons), as it has plied the Pacific Ocean between Vancouver, British Columbia, and Sydney, New South Wales. This route, shown in the map of Fig. 1, covers the greatest range of geomagnetic latitudes of any of the regular passenger lines. The two main objectives were to obtain a precise comparison of the cosmic rays in the northern and southern hemispheres, and to learn more accurately their intensity at different latitudes at different seasons.

COLLECTING THE DATA

The measurements were made with one of the Carnegie model C cosmic-ray meters. This consists of a $19.3l$ ionization chamber, shielded with lead shot equivalent to 12 cm of solid lead, and has been described in detail elsewhere.[1] The only modifications required were mounting the meter on a strong conical steel base to hold it firmly during the rolling of the ship, and the use of a special Lindemann electrometer. This electrometer had a suspension so stiff as to operate at about twice the usual voltage on the quadrants. The

[1] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. 5, 415 (1934).

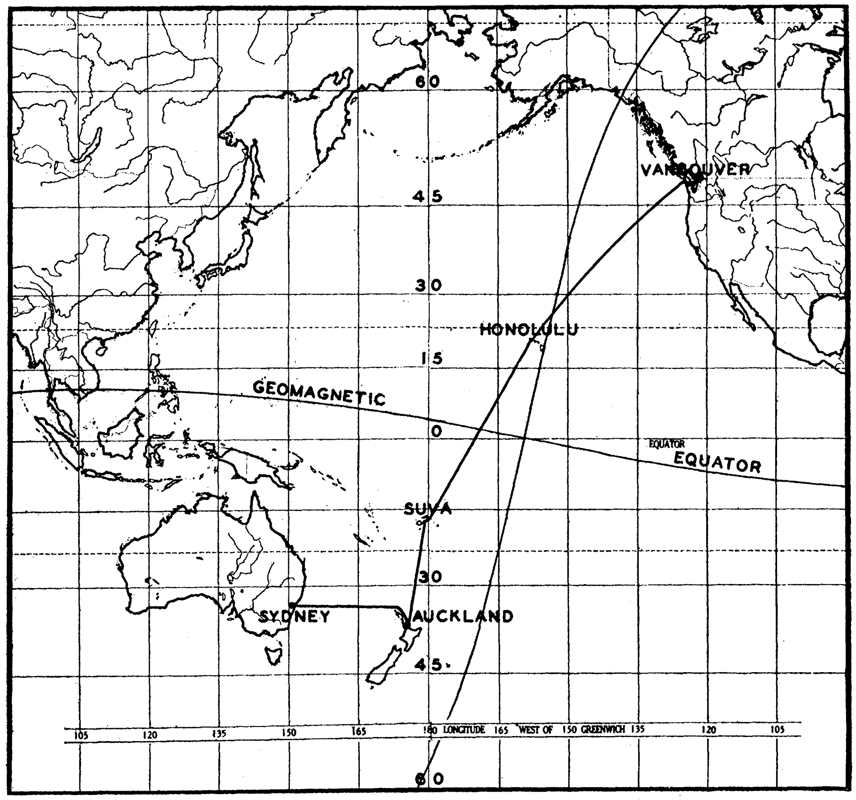

FIG. 1. Route of R. M. S. Aorangi.

effect of this is to increase the relative importance of the electrical forces on the needle as compared with the mechanical forces introduced by the rolling and pitching of the ship. During rough weather the ship's motion blurred the record appreciably, but did not prevent it from remaining accurately legible.

The meter was placed in a small wooden house built for the purpose on the aft deck of the ship (Fig. 2). While no attempt was made to keep the meter at constant temperature, the observatory has a double roof with a ventilated air space between the two layers to avoid excessive heating by the sun, and is supplied with an electric heater used to prevent the temperature from falling below about 12°C.

In Fig. 3 is shown a typical portion of the record, taken between 39° and 8° south geomagnetic latitude. The white line shows the drift of the electrometer needle, which is grounded at the end of each hour. The position of the uranium rod is so adjusted that the cosmic-ray ionization is approximately balanced by the beta-ray ionization in the balance chamber. At higher latitudes it will be seen that the electrometer needle moves upward, indicating an excess of cosmic rays; whereas the downward motion near the equator means a reduced intensity of the cosmic rays. The dark line is the photobarograph trace. Greenwich dates and hours are used.

In Fig. 4 the cosmic-ray minimum near the equator is made more evident by tracing the electrometer record for every eighth hour on a run from Auckland (41°S) to Vancouver (55°N). The high readings near 44°N are attributable to a low barometer. The record taken nearest the local noon hour is indicated in each case by the letter M. In the equatorial regions, daily variations can be noticed with their maxima near noon.

Daily readings were made of the ship's mercury barometer in order to standardize the photobarograph readings, and the ship's barograph record was used as an additional check. The daily log included also the ship's position, the outside and meter-house temperatures, and the weather conditions. For standardizing the data, the daily values of the argon pressure (about 750 lbs. per in.^{2}), the sensitivity voltage (about 1.5 volts) applied once every four hours to the electrometer needle, and the ionization chamber voltage (about 250 volts) were also recorded.

Analysis of the Data

In analyzing the data, the hourly deflections were tabulated and averaged in groups of 6 hours to reduce the labor of calculation. When a burst of ions causing a sudden deflection of more than 1 division was recorded, as, for example, at 17:20 GT on April 28 (cf. Fig. 3), the burst deflection was subtracted to obtain the net deflection for the hour. From the observed sensitivity of the electrometer over this interval, this average deflection was reduced to millivolts per standard atmosphere of argon. The barometer effect was determined by correlating these values with the barograph readings averaged over the same intervals. From the first few months a barometer effect of -10 millivolts per atmosphere of argon per inch of mercury was determined, which value was used throughout. This corresponds to -1.6 percent per cm of mercury, which is close to the mean value found by Doan[2] for a group of similar meters. Following the usual procedure,[1] the absolute ionization at the latitude of Chicago, as reduced to standard barometer and corrected for residual ionization as determined in a deep mine near Chicago, was found to be 249 millivolts per hour per atmosphere of argon. This corresponds to 82 ions per cm^3 per sec. in 50 atmospheres of argon, or 1.22 ions per cm^3 per sec. in standard air. Our final observed intensities, after applying the barometer correction, are expressed in percentages of this normal ionization.

All of the data obtained while the ship was at sea between Auckland and Vancouver during the interval from March 17, 1936 to January 18, 1937 are shown in Fig. 5. To avoid too much overlapping, the curves are grouped into seasons, with a different base-line for each season. Here each point represents the average of 6 hours' record, calculated as described above. Judging from the variations from hour to hour, the probable statistical variation of each hour's reading is 0.3 percent, whence that for a 6-hour reading is 0.13 percent. As we shall see below, the temperature coefficient of the meter is insignificant, and we have been unable to find any source of appreciable systematic error. When there is an abnormally high or low barometer, a possible error in the assumed value of the barometer coefficient may introduce a small error into the reduced data. This cannot, however, account for the observed changes at low latitudes, where the barometer changes are small. Thus, for example, the fluctuations of the order of 0.6 percent in cycles of four 6-hour intervals are to be considered as diurnal variations of significant magnitude.

Annual Mean and Seasonal Differences

Figure 6 shows the mean of all the observations taken between Auckland and Vancouver. Each point represents the arithmetic average of the values observed within the corresponding 2.5°

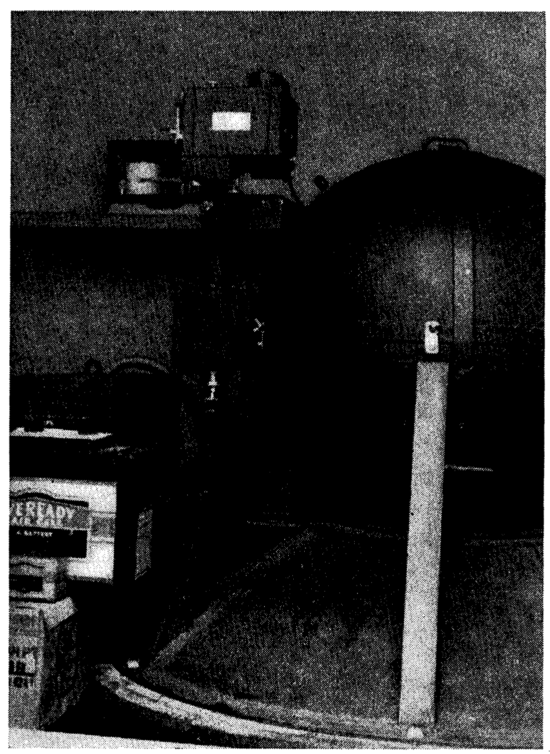

FIG. 2. Cosmic-ray meter in observatory on deck of Aorangi.

[2] R. L. Doan, Phys. Rev. 49, 107 (1936).

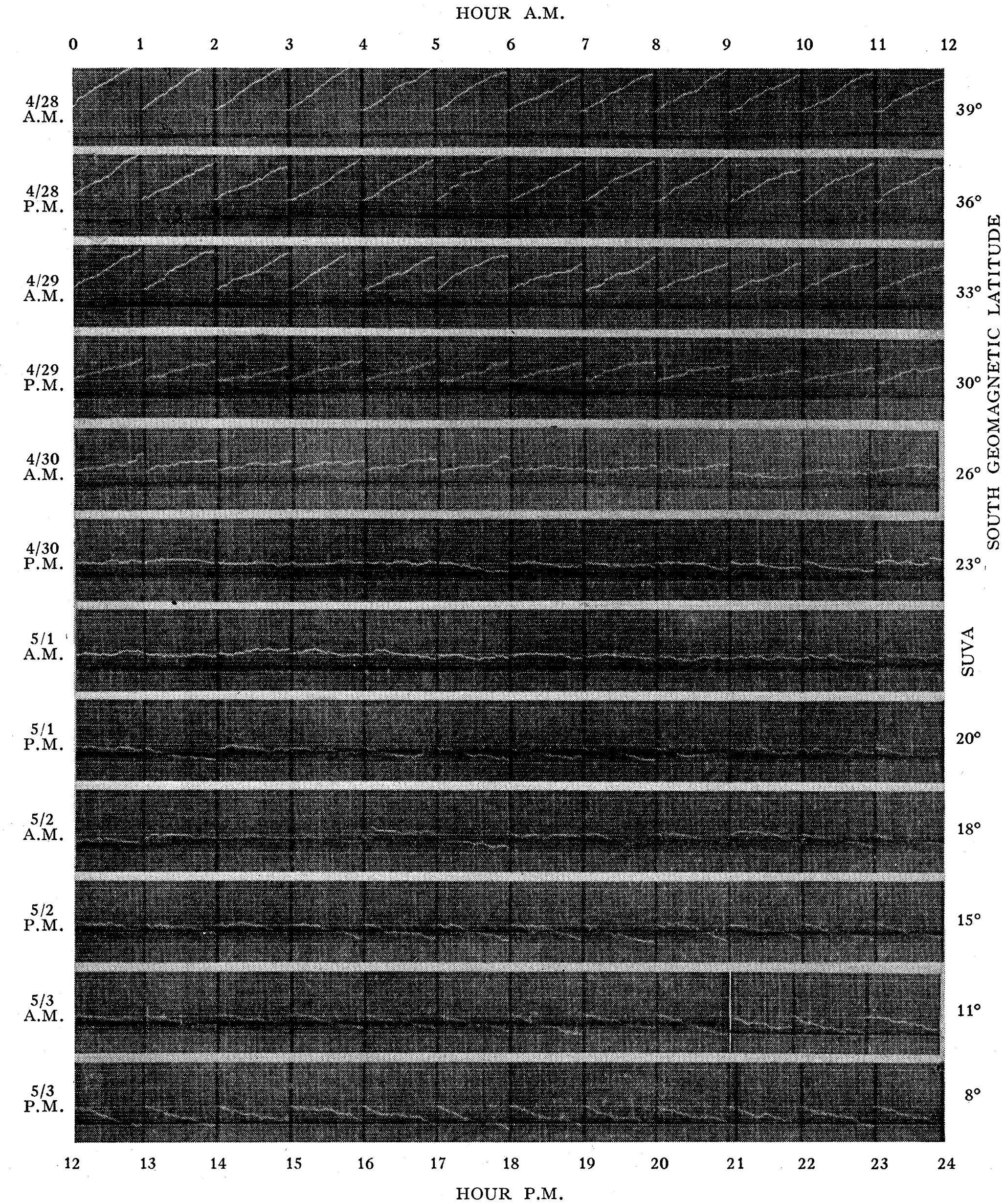

FIG. 3. Typical record showing latitude effect.

interval. The slight fluctuations near 20°N are not ascribable to experimental error, but rather to the fact that the ship was always at Honolulu (21.2°N) at noon, when the cosmic rays are most intense. The total change between Vancouver and the equator is 10.3 percent, which is the average of seasonal means that vary from 8.7 percent in the autumn to 12.4 percent in the winter months.

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

[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.

that for the measurements here reported. Because of the greater consistency of the data and the larger number of trips from which the results are averaged, the variation of cosmic rays with latitude shown in Fig. 6 is of a higher order of reliability than are the isolated exploratory data given in these earlier reports.

A striking difference between the annual mean latitude effect curve here obtained and those previously reported[5] is the absence of any really flat "plateau" for the high latitudes. The well-known "knee" is confirmed, though it is found at a somewhat lower latitude (34.2°S and 38.4°N) than previously observed (e.g., 40–45° by Compton,[6] 41° by Millikan and Neher[4] on the Pacific, and 55° by Hoerlin[7] in Europe. At latitudes higher than the knee, however, the intensity continues to increase with latitude, though at a slower rate. This phenomenon is more clearly apparent in Fig. 7, which compares the latitude effect as observed during the various seasons, and shows marked differences in the high latitude portions of the curves at different times of year. Most noticeable is the fact that in the winter the curve remains steep as far north as Vancouver, whereas in the autumn the change north of 40° is very small.

Closely associated with this difference in shape is the fact, evident from Fig. 7, that in both the northern and southern hemispheres the intensity is greater during the cold months. Since after about a year the latitude effect curve has returned to approximately its original form, it would appear that the change follows an annual cycle. On the basis of the present evidence, these maxima and minima of cosmic-ray intensity seem to occur approximately during the cold and hot months respectively, rather than at the winter and summer solstices. This indicates that the origin of the change is atmospheric rather than astronomical.

Correlation of Ionization with Atmospheric Temperature

The design and previous tests[1] had seemed to preclude the possibility of a temperature coefficient of the meter itself. We have, however, obtained a further test with the meter as it is used, in the following manner: For each of the four seasonal curves 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. 8) with the departure in the temperature of the meter from

[5] E.g., references 3 and 4. It is noteworthy that the recent counter measurements of T. H. Johnson and D. N. Read (Phys. Rev. **51**, 557, 1937) between New York and Valparaiso show a sloping plateau and season variations which, though provisionally ascribed to a temperature coefficient of the meter, appear to be of the same kind as those noted here.

[6] A. H. Compton, Phys. Rev. **43**, 387 (1933).

[7] H. Hoerlin, Nature **132**, 61 (1933); Naturwiss. **21**, 822 (1933).

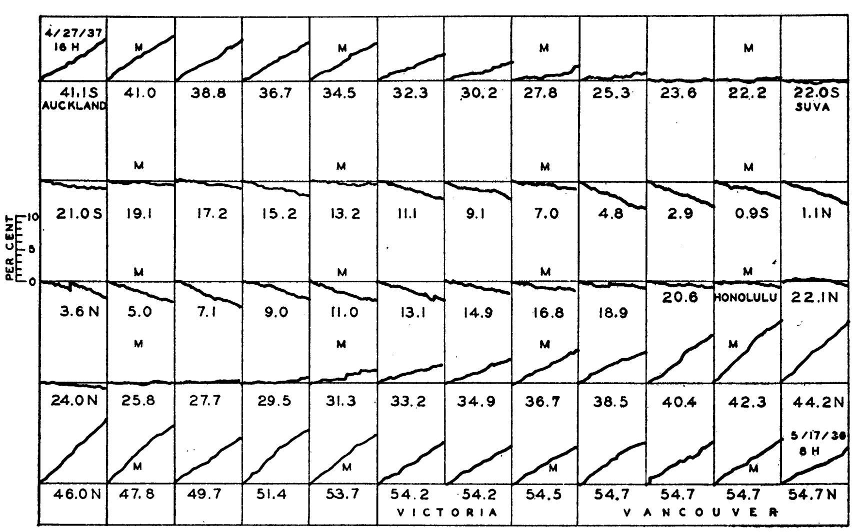

Fig. 4. Record of every eighth hour from Auckland to Vancouver.

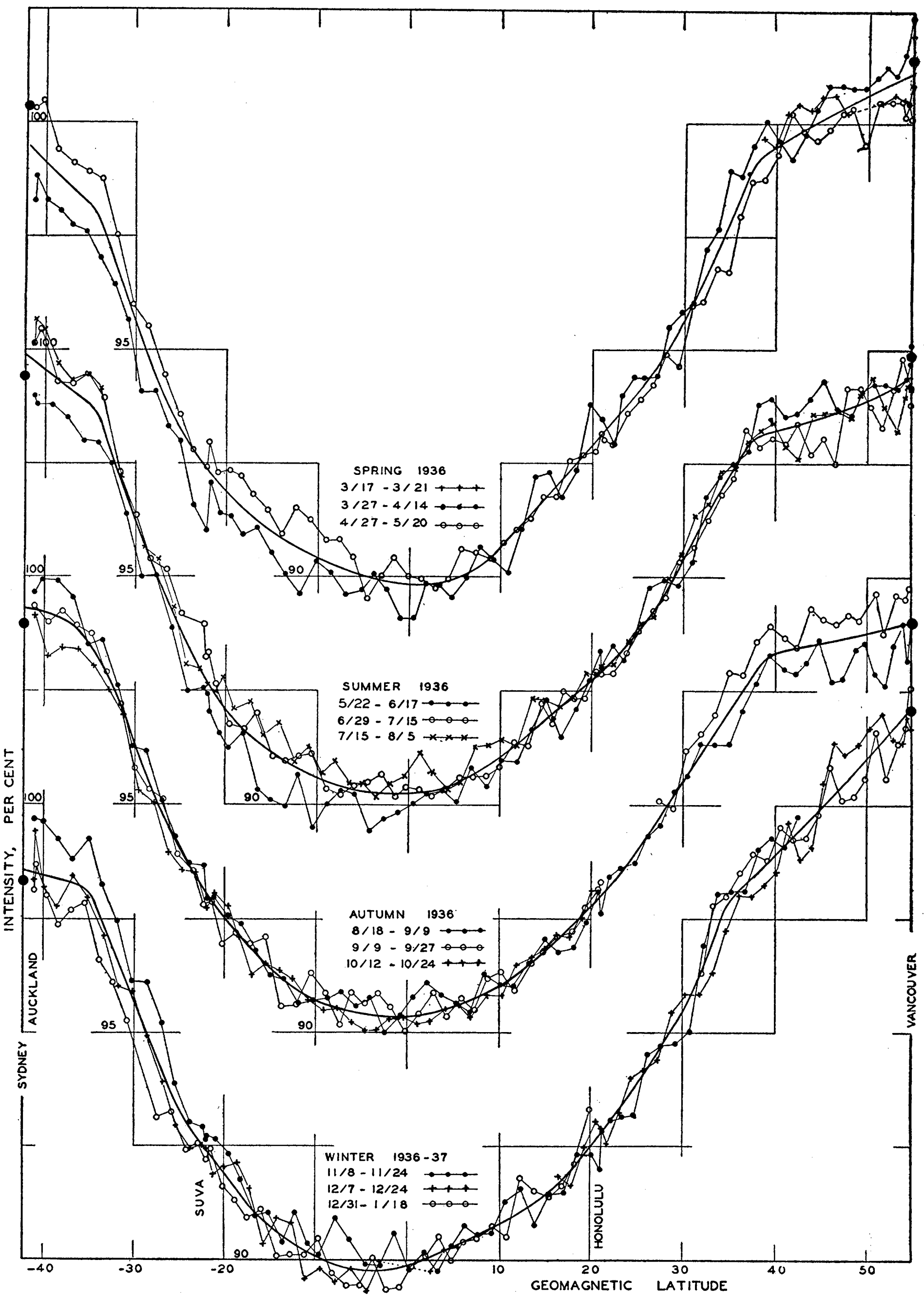

FIG. 5. Individual latitude effect curves for each trip, grouped into seasons.

its annual mean at the same latitude. The temperature of the meter was measured by the argon pressure, which thus served as a gas thermometer. Fig. 9 shows the scatter diagram of the points thus obtained. The erratic character of the pattern is of itself evidence that temperature changes of the meter cannot account for the main part of the fluctuations. The apparent temperature coefficient of the meter, in terms of the argon pressure changes, as calculated from these

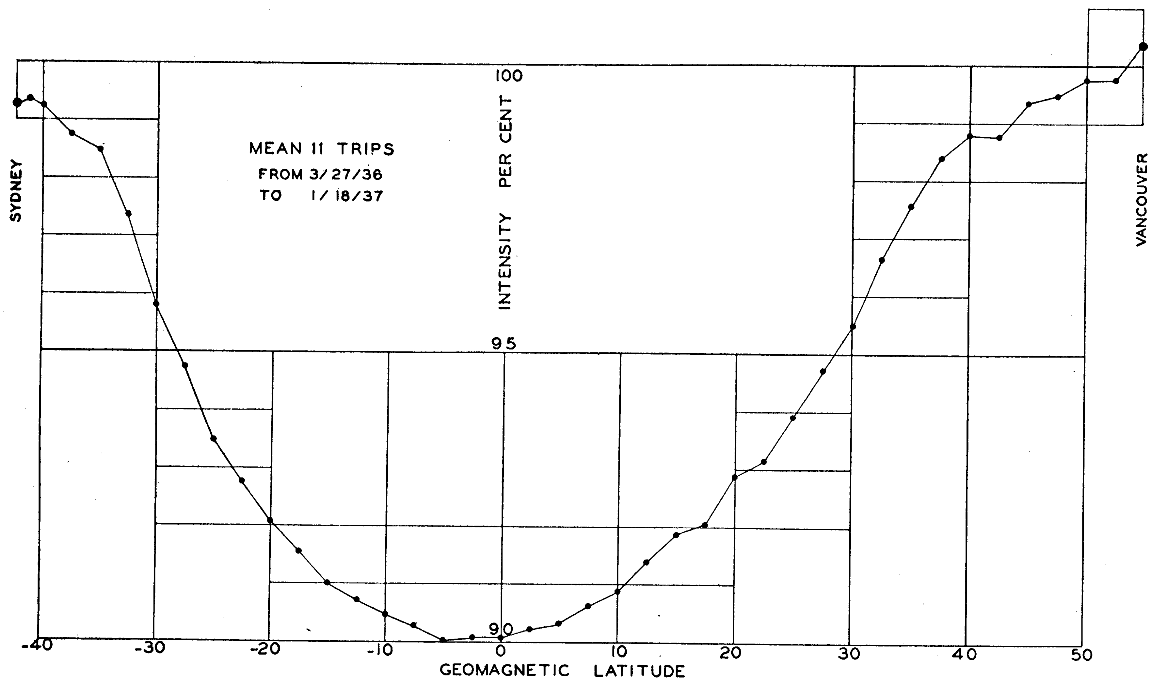

FIG. 6. Year's average of all data between Auckland and Vancouver.

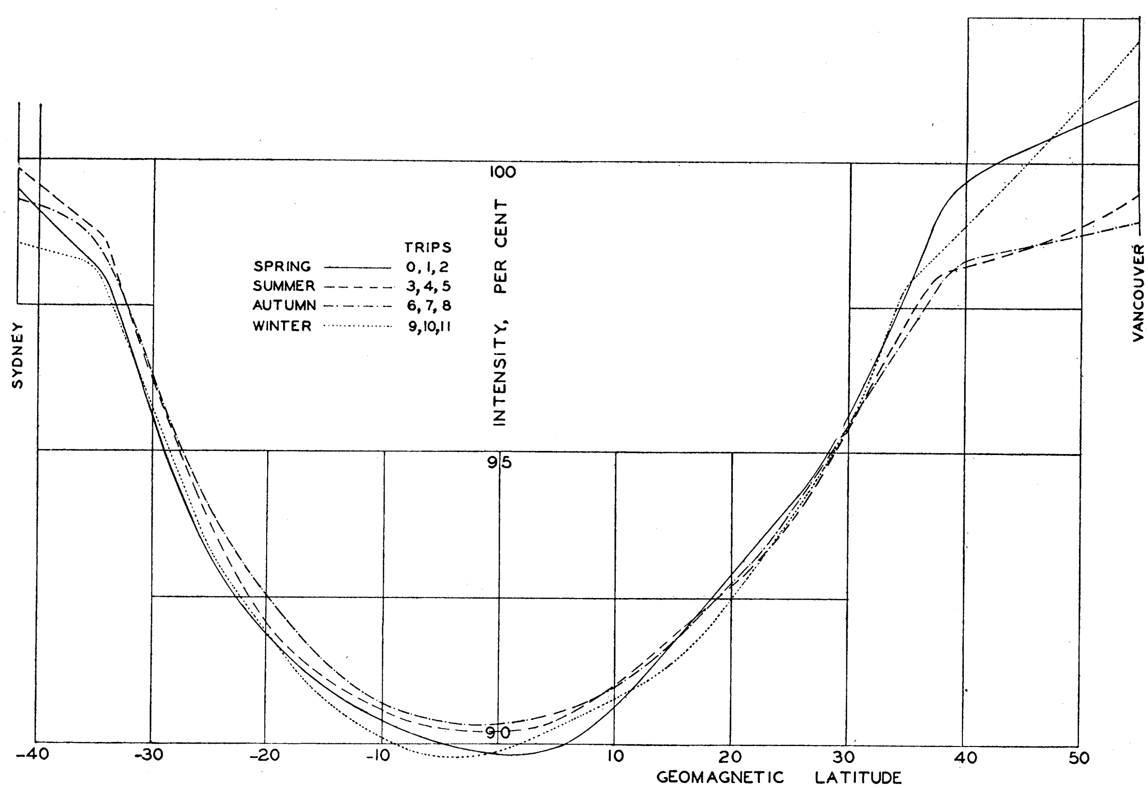

FIG. 7. Latitude effect curves for the various seasons.

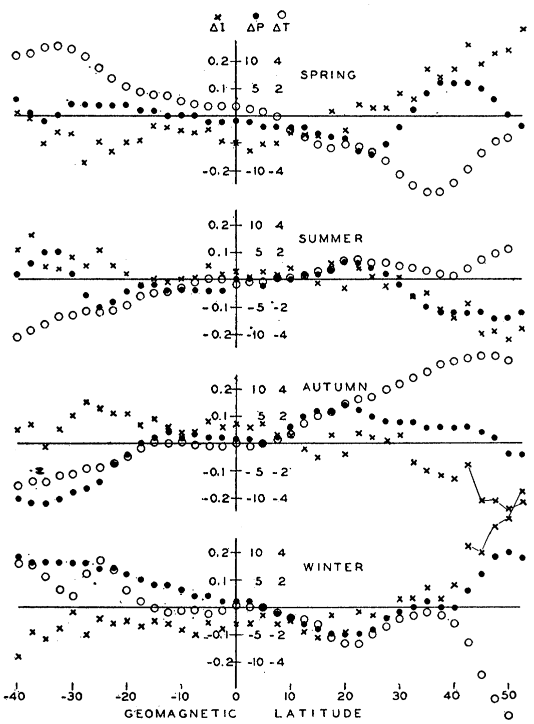

FIG. 8. Seasonal departures from annual mean of ionization (ΔI), argon pressure (ΔP, which measures the meter temperature), and shade temperature of the outside air (ΔT), plotted for the various latitudes.

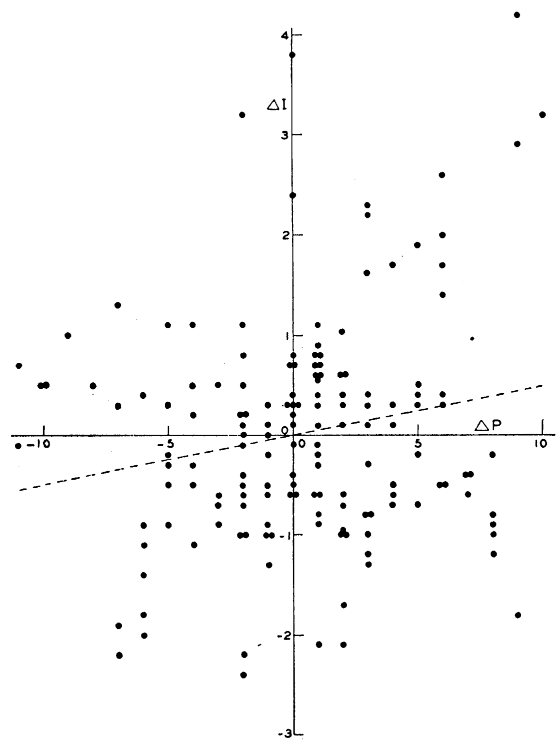

FIG. 9. Scatter diagram of ΔI *vs.* ΔP, showing low correlation and negligible temperature coefficient of the meter.

data, is 0.048 ± 0.014 percent per °C, with a correlation factor of only 0.18 ± 0.05. A slight positive correlation must occur between the argon pressure and the observed ionization because during the cold months when the ionization is high the meter house was so heated that the argon pressure averaged slightly higher than during the warm months. The small observed correlation does not therefore imply any true temperature coefficient of the meter. When a correction of the calculated magnitude is applied in accord with the temperature of the meter, no appreciable change in the slope of the curves is effected, nor is the difference between the winter and the summer curves appreciably reduced. This means that any possible temperature coefficient of the meter is insignificant.

On the other hand, a similar analysis shows a definite correlation of opposite sign between the external shade temperature and the observed ionization. In Fig. 8 are shown the departures from the annual mean values at each latitude of the external temperature for each season of the year. The opposing trend of this temperature and the ionization is evident in every curve. From a scatter diagram of δT *vs.* δI similar to Fig. 9, it is found that the correlation factor is -0.68 ± 0.03 and the external temperature coefficient of the ionization is -0.18 ± 0.011 percent per °C. This is 16 times the probable error, and hence real. In a similar manner, the values of the external atmospheric temperature coefficient have been obtained from the records made in port. These are given in Table I.

It will be noted that at Vancouver and Auckland the observed coefficient is in acceptable agreement with that found at sea. At Sydney, however, the coefficient observed differs from that at sea by much more than the experimental error. This difference seems to reflect the fact that at Sydney the air from over the land is subject to much wider temperature fluctuations than is the sea air which is prevalent at the other ports. This indicates in turn that the effect on the cosmic rays is not due directly to temperature changes in the lower atmosphere in the immediate neighborhood of the meter, but rather to some other changes in atmospheric condition for which the temperature serves as an approximate index. Such atmospheric conditions might for example include the electric potential gradient, or the height of the Heaviside layer.

Atmospheric and Magnetic Latitude Effects

In Fig. 10, in the broken lines, are shown the corrections to be applied to the seasonal curves of Fig. 7 to correct for the changes in this atmospheric barrier, supposing that its strength is represented by an external temperature coefficient of −0.18 percent per °C, and reducing the data to the mean value of 21°C. These broken curves thus represent a latitude effect of atmospheric origin, differing with the seasons, which must be subtracted from the observed latitude effect curves to obtain the effect caused by the earth's magnetic field. The solid curves of Fig. 10, as thus calculated, should accordingly represent the part of the latitude effect which is of magnetic origin. It will be noted that the atmospheric latitude effect is roughly half as great as the magnetic latitude effect (average of 3 percent and 7 percent respectively). Moreover, the resulting magnetic latitude effect curves now show much smaller, almost insignificant, seasonal changes, smaller north-south asymmetry, and the plateaus beyond 35°S and 39°N have become nearly flat.

Correlation of cosmic-ray ionization with temperature and with time of year similar to that here discussed has been noted by others. Thus, Hoffmann,[8] Messerschmidt,[9] Hess and Steinmaurer,[10] and Steinke,[11] among others, have considered the possible effect of temperature changes on the diurnal variations in ionization. Hess, Graziadei and Steinmaurer[12] have found in the data collected on the Hafelekar during 1932–34 evidence similar to that here presented for greater intensity in the cold months than for the warm months of the year, showing a close correlation with the external temperature. The difference which they observe between the months November to April and the months May to October is 1.2 percent as compared with our differences of 2.4 percent at Vancouver and −1.0 percent at Auckland and Sydney. The mean annual external temperature coefficient which they observe is −0.09 percent, not greatly different from that which we find for Sydney. From the more detailed study of these data by Priebsch and Baldauf,[13] however, it appears that the temperature coefficient varies from month to month. This supports the view expressed above that we are not concerned here with an effect due directly to changes in the temperature of the atmosphere, but rather with an effect of some other origin, presumably atmospheric, to which the temperature is only an approximate index.

Some earlier reports dealing with seasonal changes in cosmic rays by Clay,[14] Steinke,[15] and Priebsch and Steinmaurer,[16] indicated several percent change with a maximum in summer. This is opposite in sign to the effect present in our records and those of Hess, Graziadei and Steinmaurer.[12]

Variations at the Equator—Absence of Solar Rays

At the equator the curves of both Figs. 7 and 10 show a small change which appears to follow an annual cycle. Since seasonal differences do not occur at the equator, it seems reasonable to associate the 0.4 percent greater intensity observed during the half-year May to October with the greater distance of the earth from the sun during this interval. It will be recalled that the eccentricity of the earth's orbit is 1.68 percent,

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

Location	Coefficient Percent	Prob. Error Percent	Correlation Factor
Vancouver	−0.22	±0.02	−0.85±0.04
Auckland	−0.16	±0.04	−0.47±0.15
Sydney	−0.10	±0.02	−0.67±0.10
At sea	−0.18	±0.01	−0.68±0.03

[8] G. Hoffmann, Zeits. f. Physik **69**, 259 (1931).
[9] W. Messerschmidt, Zeits. f. Physik **78**, 668 (1932).
[10] V. F. Hess and R. Steinmaurer, Berlin Ber. **22**, 672 (1933).
[11] E. G. Steinke, *Handbuch der Physik*, Geiger u. Scheel, **23** II, 521 (1933).
[12] V. F. Hess, H. Th. Graziadei and R. Steinmaurer, Ber. Wien Ak. IIa, **143**, 313 (1934).
[13] J. A. Priebsch and W. Baldauf, Ber. Wien Ak. IIa, **145**, 583 (1936).
[14] J. Clay, Proc. Roy. Acad. Amsterdam **23**, 711 (1930).
[15] E. G. Steinke, Zeits. f. Physik **64**, 48 (1930).
[16] J. A. Priebsch and R. Steinmaurer, Gerl. Beitr. z. Geophys. **37**, 296 (1932).

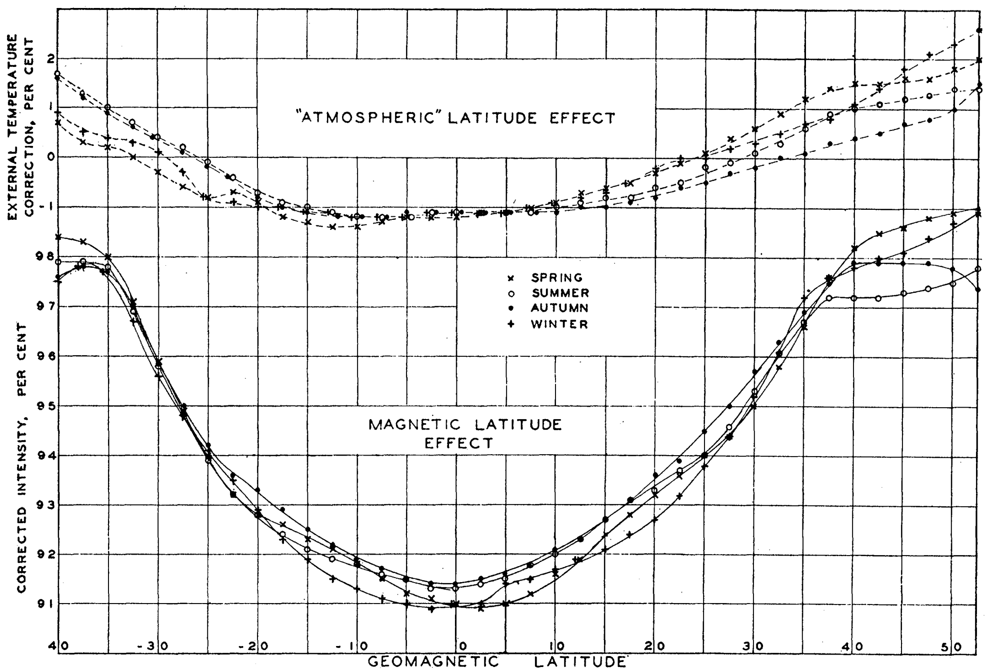

FIG. 10. Magnetic (solid lines) and atmospheric (broken lines) latitude effect for the four seasons. Sum of these two effects gives observed total effect of Fig. 7.

with the perihelion on January first. Assuming the inverse square law to apply, the intensity of the solar component should thus be 6.7 percent greater in January than in July. The observed excess of cosmic rays during the middle of the year is thus opposite in sign to any variation that would be caused by rays emitted from the sun itself, and confirms the conclusion previously drawn from other evidence that any contribution to the cosmic rays by the sun must be relatively small. Vallarta's hypothesis[17] of a shielding effect caused by the sun's magnetic field would, however, lead to an annual change of the observed sign and very possibly of the observed order of magnitude. One would anticipate on this hypothesis a minimum on January first, which is not in perfect phase agreement with our data. The difference is, however, within the probable error of a single year's measurements.

In a recent note,[18] Julian Thompson has called attention to the diurnal variation that is evident in the data of Fig. 5. He finds that the average daily variation of 0.6 percent at the equator is almost identical with that at latitude 50°, and has its maximum near noon, as has been found by others working at the higher latitudes. It is hoped that a further analysis of these diurnal changes may be published in the near future.

[17] M. S. Vallarta, Nature **139**, 839 (1937).
[18] J. Thompson, Phys. Rev. **52**, 140 (1937).

COMPARISON OF THE NORTHERN AND SOUTHERN HEMISPHERES

The interpretation of our data with regard to the relative intensity in the northern and southern hemispheres depends upon our treatment of the seasonal variations. When uncorrected for external temperature, though no flat intensity maxima occur, it is nevertheless possible to locate corresponding cosmic-ray latitudes in the two hemispheres by locating the "knees" between the steeply-sloping and the gradually-sloping parts of the curves. Fig. 11 shows the location of these knees, obtained from the individual curves of Fig. 5 by drawing approximately straight lines through the datum points. The average positions of the knees is thus found to be, at geomagnetic latitude 38.4±0.4°N, critical intensity $I_n = 98.87 \pm 0.16$ percent; at 34.2±0.1°S, critical intensity $I_s = 98.41 \pm 0.16$ percent. Thus the intensity of the cosmic rays as directly observed at the northern knee is greater than that at the southern knee by

$$I_n - I_s = 0.46 \pm 0.22 \text{ percent.}$$

In a preliminary report based upon a part of these data,[19] this difference was given as 0.6 percent.

This determination, however, leaves out of account the significant factor which causes the increase in cosmic-ray intensity above the critical latitude of the knee. The fact that this increase varies with the seasons shows that it is not determined by either the earth's magnetic field or the absorption in the atmosphere. Its close correlation with the atmospheric temperature indicates that we are, however, concerned with some kind of atmospheric barrier. If we assume that the temperature gives a reliable measure of the strength of this barrier, a correction for the difference in external temperature at the two knees will account for the corresponding difference in this barrier. Thus the average shade temperature at the northern knee was 2.1°C lower than at the southern knee. If the external temperature coefficient is taken as 0.18 deg.$^{-1}$ C, as determined above, a correction of 0.38 percent should be applied, leaving the critical intensity greater in the north by

$$I_n - I_s = 0.08 \pm 0.15 \text{ percent,}$$

which is an insignificant difference. (The probable error is reduced because the differences in the individual corrected values of I_n and I_s are less than in the uncorrected values.)

An alternative method of applying the correction for the atmospheric barrier is to compare the mean values of the corrected seasonal intensities as shown in Fig. 10 on the northern and southern plateaus. For the 7.5° zone south of the southern knee, the average intensity is 97.87 percent, while for an equal range north of the northern knee the intensity is 97.88 percent. This difference is,

$$I_n - I_s = 0.01 \pm 0.11 \text{ percent,}$$

which is likewise insignificant.

Another though less precise procedure is to compare the uncorrected intensities at the same north and south geographic latitudes, in both cases taken well above the critical latitude so that the earth's magnetic field no longer has a determining influence on the intensity. Our data do not extend to sufficiently high latitudes to ensure freedom from all magnetic effects. By way of illustration, however, at geographic latitudes 36° north and south, which correspond to geomagnetic latitudes 38.4°N and 40.2°S, the mean ionizations uncorrected for external temperature are $I_{36n} = 98.87 \pm 0.16$ percent and $I_{36s} = 99.30 \pm 0.18$ percent. The difference is now opposite in sign,

$$I_{36n} - I_{36s} = -0.43 \pm 0.24 \text{ percent,}$$

which considering the magnitude of the probable error is of doubtful significance.

It would thus appear that under comparable conditions, at latitudes of about 40°, the intensities in the northern and southern hemispheres probably do not differ by more than the experimental error, which is of the order of 0.1 or 0.2 percent. This result seems to be in definite conflict with the prediction by Compton and Getting[20] of an excess in the north of about 0.5

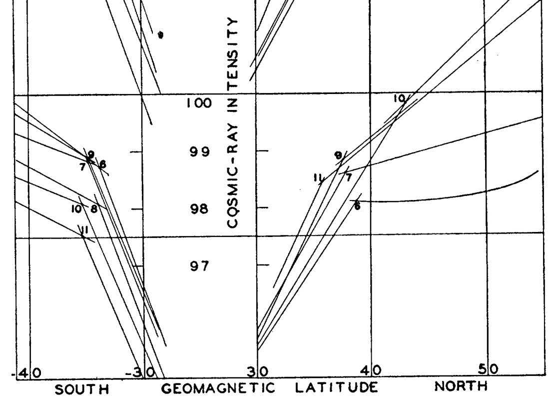

FIG. 11. Location of the critical latitude "knees" of the latitude effect curves of Fig. 5.

[19] A. H. Compton, Phys. Rev. **50**, 1119 (1936).

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

percent, due to the motion of the earth with the rotation of the galaxy.

Studies by Illing[21] of the data obtained by Hess in Austria, and by Schonland, Delatizky and Gaskell[22] in South Africa have strongly confirmed the existence of a diurnal variation following sidereal time, whose phase accords with that predicted from the galactic rotation theory, but whose magnitude is somewhat smaller than anticipated.[19] If the cosmic rays come directly from outside the Milky Way, the only means of reconciling these measurements with the theory of Compton and Getting would seem to be on the assumption that the sun's motion with the rotation of the galaxy is only a small fraction of the 300 km per second estimated by the astronomers. A more probable solution would seem to be that the cosmic rays are for the most part trapped within the galaxy and to a large extent share its motion. It will be noted that the present experiments would be consistent with an excess in the north at least 30 percent as great as predicted by the theory, and are hence not inconsistent with such a modified interpretation of the sidereal time variation observations. It may be added that if the cosmic rays are for the most part trapped within the galaxies, they should presumably be free from the "red-shift" loss of energy which affects starlight, and the problem of accounting for the stupendous energy of the rays becomes somewhat less difficult.[23]

Energy Distribution of Primary Cosmic Rays

Following the procedure of Zanstra,[24] we may use these latitude data as a basis for an approximate determination of the energy distribution of the primary cosmic rays. If E_0 is the threshold energy of the electrical particles which are able to transverse the magnetic field of the earth at a given magnetic latitude λ, the cosmic-ray ionization I may be plotted as a function of E_0. Thus in Fig. 12 is shown the mean cosmic-ray intensity I for the year, corrected for the atmospheric barrier as in Fig. 10, as a function of λ. E_0 as a function of λ is given by Lemaitre and Vallarta[25] for various angles of incidence. We have used their curve for vertical incidence as a sufficiently close approximation to the average for all angles, and the units used are those appropriate to electron primaries. Thus the solid curve of Fig. 13, giving I as a function of E_0, is obtained. The values of I represented by the datum points on this curve are the arithmetical means of the corrected observed values within the corresponding ranges, and are identical with those of Fig. 12. The energy distribution, in terms of the fraction of the ionization per unit energy range of the primary particles, is then

$$\phi(E) = -dI/dE_0. \quad (1)$$

This function, as obtained graphically from the solid line of Fig. 13, is shown in the broken line of the same figure. It will be seen that within experimental error the distribution consists of two sharply-separated portions, one of 1.35 percent per 10^{10} ev for energies less than 7.5×10^9 ev, and the other of 8.5 percent per 10^{10} ev for energies greater than 7.5×10^9 ev.

Again the question arises whether this analysis should be applied to the uncorrected curve (Fig. 6) or the curve (Fig. 12) that has been corrected for the external atmospheric temperature coefficient. The answer seems clear. The analysis depends solely upon the action on the cosmic rays by the earth's magnetic field, which is independent of both the temperature and the seasons. The variations in intensity which are found to be so closely correlated with the atmospheric temperature should accordingly be eliminated. While application of the temperature correction may not completely take account of the effect of variations in the unknown atmospheric barrier, the high correlation between the intensity changes and the temperature indicates that most of the effect of this barrier should thus be removed.

In a preliminary presentation of these results,[19] a similar analysis was made using, however, the uncorrected data, and Störmer's instead of Lemaitre-Vallarta's relation between λ and E_0. The results differ from those of Fig. 13 chiefly in

[21] W. Illing, Terr. Mag. and Elec. **41**, 185 (1936).
[22] B. F. G. Schonland, B. Delatizky and J. P. Gaskell, Nature **138**, 325 (1936).
[23] Cf. A. H. Compton and P. Y. Chou, Phys. Rev. **51**, 1104 (1937).
[24] H. Zanstra, Naturwiss. **22**, 171 (1934).
[25] G. Lemaitre and M. S. Vallarta, Phys. Rev. **50**, 493 (1936), Fig. 10.

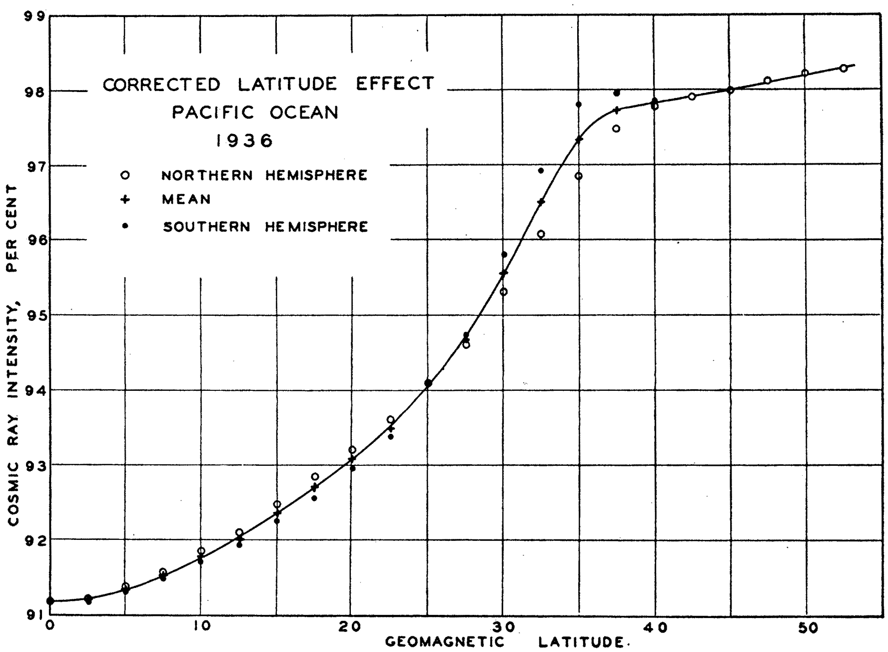

FIG. 12. Magnetic latitude effect averaged for complete year's data for both hemispheres.

assigning a value to the lower energy part of the energy distribution spectrum which is about twice that shown in Fig. 13. This reflects the fact that the uncorrected latitude curve is steeper than the corrected one for latitudes higher than the knee.

Millikan and Neher[4] have emphasized the conclusion that the slope of the latitude effect curve is zero above 40°. Their measurements, however, are inadequate to detect a slope of the small magnitude under consideration here. There can be but little doubt that the consistency of the present data is sufficient to justify a value of $\phi(E)$ greater than zero in the region of E_0 less than 7.5, as shown in Fig. 13. It is, however, not impossible that some error in our correction procedure may have resulted in a false indication of a low energy component.

Assuming the validity of the energy spectrum here obtained, its interpretation in terms of the action of the earth's magnetic field is clear: Two primary components of cosmic rays produce effects at sea level, the more prominent of which has energies only greater than a sharp limit of 7.5×10^9 ev, whereas the weaker component occurs with all energies greater than 2.5×10^9 ev. Strong support for the view that the primary cosmic rays are complex, and that the magnetic latitude effect continues well beyond 40°, comes from the observations of Alvarez,[26] Johnson,[27] Rossi,[28] Clay,[29] and others that in equatorial regions the direction of approach of the primary cosmic rays is predominantly from the west, and that the westward predominance continues in America[27b, c] to at least geomagnetic latitude 50°. According to Lemaitre and Vallarta's theory,[30] this observation means that a magnetic latitude effect, due predominantly to positive particles, must be present up to 50°. This result is in accord with our corrected latitude effect curves. Since, as far as is known, positrons are always paired with negatrons, it seems probable that the excess of positive particles consists of protons. We would thus suggest that the low energy component required to account for the observed

[26] L. Alvarez and A. H. Compton, Phys. Rev. **43**, 835 (1933).
[27] T. H. Johnson, (a) and J. C. Street, Phys. Rev. **43**, 381 (1933); (b) Phys. Rev. **43**, 834 (1933); (c) and E. C. Stephenson, Phys. Rev. **44**, 125 (1933); (d) Phys. Rev. **47**, 318 (1935).
[28] B. Rossi, (a) Ricerca Scient. **4**, 365 (1933); (b) and S. de Benedetti, Ricerca Scient. **5**, 594 (1934).
[29] J. Clay (a) and P. M. Alphen, C. G. 't Hooft, Physica **I**, 829 (1934); (b) and H. Zanstra, Physica **I**, 839 (1934).
[30] G. Lemaitre and M. S. Vallarta, Phys. Rev. **43**, 87 (1933).

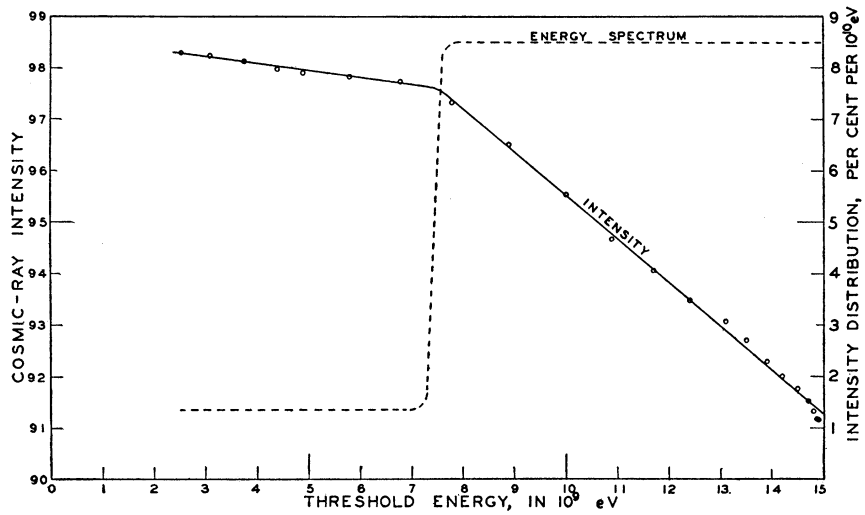

FIG. 13. Solid line, cosmic-ray ionization as function of geomagnetic energy threshold. Broken line, energy distribution of primary cosmic rays, according to geomagnetic analysis.

magnetic latitude effect persisting to the highest latitudes here studied may be due to protons.

It would be very desirable to continue similar observations to still higher latitudes, where any true magnetic effect should certainly disappear, because of the energy threshold imposed by the absorption of the atmosphere. As yet practical difficulties have prevented our carrying through such a program. Perhaps the best data now available at such high latitudes are those recently obtained by Clay, 't Hooft and Clay,[31] who carried a shielded and an unshielded meter from Amsterdam (54° geomagnetic) to North Cape (67°) and return. They found no difference within an experimental error of ±0.6 percent. Since their measurements were made only in the summer, there is no basis for distinguishing between a magnetic and an atmospheric latitude effect. Their results suggest, however, that north of 54° the magnetic latitude effect may be zero, which it should be if the tentative identification of the small effect here found between 38° and 54° as due to protons is valid.

It is not possible from these experiments to place an upper limit on the fraction of the cosmic rays that is electrically charged. Between 52.5° and the equator the difference shown by the corrected curve of Fig. 12 is only 7.2 percent. Yet from the approximately linear relation between I and E_0 shown in Fig. 13, it is evident that this fraction does not represent all of the electrically-charged primaries, but is limited rather by the finite strength of the earth's field. The trend of the I *vs.* E_0 curve suggests no limit to the magnitude of the latitude effect if a sufficiently large value of the threshold energy is assigned. The data thus give no suggestion of primaries of a nonelectrical type.

Origin of Sharp Knee in Latitude Effect Curves

A formidable difficulty is presented by the sharpness of the 36° knee of the latitude effect curve. Clay,[32] Compton,[6] Millikan,[4, 33] and others have confidently ascribed this knee to the fact that penetration of the atmosphere sets a threshold value upon the energy of the particles capable of reaching the meter, and that where this atmospheric threshold is greater than the geomagnetic threshold, no further increase in ionization with increasing latitude is to be expected.[34] This theory assumes that the primary particles shall have a sharply defined range in air. Recent theoretical and experimental studies

[31] J. Clay, C. G. 't Hooft and P. H. Clay, Physica **2**, 1033 (1935).

[32] G. Clay, Proc. Roy. Akad. Amsterdam **35**, 1282 (1932).

[33] I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **46**, 641 (1934).

[34] A detailed exposition of this theory is given by A. H. Compton, Proc. Phys. Soc. London **47**, 762 (1935).

have, however, shown rather definitely that, both for particles known to be electrons and for the cosmic rays which show the latitude effect, the absorption is not primarily of the range type but is more nearly exponential in character.[35] The only sharply defined range for high energy electrical particles that is anticipated according to current theories is that due to the gradual loss of energy spent in electron collisions. For electrons of energy greater than 10^8 ev, this is on the average of much less importance than the energy loss by photon (i.e., x-ray) production. There is, however, always a chance, though a small one, that a higher energy electron may come to the end of the range determined by electron collisions before it has suffered a photon producing collision. In this case, its range should be that due to the electron collisions alone. The energy thus spent by an electron passing vertically through the atmosphere would be about 2.4×10^9 ev. The energy loss by a proton through electron collisions would be of nearly the same amount; though here also is the possibility of nuclear collisions whose frequency and importance is unknown. The result is, however, that we now have no reason to anticipate any threshold of energy as determined by atmospheric absorption other than that of about 2.4×10^9 ev, due to electron collisions. This statement applies to any singly-charged electrical primary whose rest mass is not greater than that of a proton.

In the present experiments, the 12 cm lead shield is adequate to eliminate the "shower producing" primaries and to leave only the penetrating component of the cosmic rays. This component would at present appear to consist of particles more massive than electrons, but with a single electronic charge. Such auxiliary evidence as that from the ratio of the ionization produced to the number of incident penetrating particles supports the theoretical calculation of the loss of 2.4×10^9 ev by these rays on traversing the atmosphere.

The critical geomagnetic latitude corresponding to an energy threshold of 2.4×10^9 ev is, according to Lemaitre and Vallarta's theory, 50°. The experiments of Hoerlin[7] and of Clay,[29, 31, 36] and his collaborators indicate that in Europe the geomagnetic latitude of the prominent knee is much higher than we find in the Pacific Ocean. In fact a value of 54° for the critical latitude would be consistent with their data.[37] On the other hand, Millikan and Neher[4] find the critical latitude on the west coast of Europe to be 41° geomagnetic, just as they found on the Pacific Ocean. It is not unlikely that the differences between these observers are partly of the seasonal type, like those between the winter and summer curves of Fig. 7. It is noteworthy that all of the European cosmic-ray observations north of 54° were made in the warm months, when we find the curve to be flat for the higher latitudes. This may account for the apparently sharp knee which occurs at about the latitude of Amsterdam and Hamburg. Thus a reliable comparison of the European and the Pacific Ocean data is not now possible. Nevertheless, what comparisons are possible suggest a considerably higher critical latitude in Europe than in Western America.

In the part of the Pacific Ocean where the present measurements were made there are no marked magnetic anomalies, and the longitude is nearly midway between that of the maximum and that of the minimum horizontal magnetic fields at the equator. We should thus expect the energies calculated from the geomagnetic latitudes to be relatively reliable over this route. The difference between the observed critical latitudes of 38.4°N and 34.2°S and the calculated critical latitude of 50° accordingly appears to be too great to admit the validity of the explanation of the knees as due to sharply-defined ranges of the cosmic-ray particles in the atmosphere.

The immediate significance of this 36° knee,

[35] An account of this work, including latitude effect experiments at different altitudes by A. H. Compton, measurements of the stopping of cosmic-ray electrons by C. D. Anderson, and theoretical studies of the energy dissipation by electrical particles by Bethe and Heitler, Oppenheimer, and Swann, is given in reference 19, pp. 1128–29. Cf. also, I. S. Bowen, R. A. Millikan and H. V. Neher, Phys. Rev. **52**, 80 (1937).

[36] J. Clay, E. M. Bruins, and J. T. Wiersma, Physica **3**, 746 (1936).

[37] Cf. reference 34, Fig. 12. Between latitudes 41° and 54° geomagnetic, Hoerlin, reference 7, finds an increase of 3.8 percent, Clay, references 29 and 31, of 4.2 percent in the East Atlantic and, reference 36, of 2.4 percent in the middle Atlantic.

as indicated by the discussion of Fig. 13, is that the cosmic-ray ionization is due to electrical primaries approaching the earth with a threshold energy of about 7.5×10^9 ev. If atmospheric absorption is inadequate to account for this sharply defined threshold, what may be its origin? Vallarta's recent suggestion[17] of a limit imposed by the magnetic field of the sun may supply the answer. Or is there perhaps some sharply defined atmospheric barrier, analogous to a potential barrier, whose seasonal fluctuations may cause the seasonal fluctuations of the cosmic-ray ionization? To these questions, our observations have not supplied the answer.

ACKNOWLEDGMENTS

We wish to thank the Canadian Australasian Steamship Company for permitting us to build the cosmic-ray observatory on the R. M. S. Aorangi, and to use it for the year, the Union Carbide and Carbon Corporation for supplying the batteries required for operating the meter, and the Carnegie Institution of Washington for the use of the cosmic-ray meter. Mrs. Ardis Monk and Mr. Piara Gill have carried through most of the laborious calculations. 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.

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The Emission Spectrum of Diatomic Arsenic. II

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The emission spectrum of diatomic arsenic, previously studied in the interval 2100A to 3700A, has been extended to 7000A. The two prominent systems have been greatly extended so that the ground state of the molecule has been followed to $v=70$, in energy to nearly 0.8 of the heat of dissociation, $D(X)$. $D(X)$ is 3.9 volts by extrapolation and the same value is obtained from analysis of predissociation occurring in the two most prominent systems. Two new systems have been found, one having the same lower state as those previously reported and the other forming a double array. The latter has been tentatively assumed to be due to As_2^+.

INTRODUCTION

A VIBRATIONAL analysis of the emission spectrum of As_2 found between 2100A and 3700A has been given by Almy and Kinzer in a previous report.[1] The spectrum, complex in appearance, consists of three overlapping systems having a common lower state. By careful control of the source consisting of a quartz discharge tube filled with arsenic vapor and heated in an oven or by a flame, it has been possible to extend the spectrum to 7000A (see Fig. 1). A more complete analysis of the reported systems has been made and two additional systems found. A brief abstract of the new results has been included in a recent paper comparing the spectra of elements of the fifth periodic group.[2]

VIBRATIONAL ANALYSIS

The three systems originally reported[1] as lying between 2100A and 3700A have been extended to about 5600A. These are designated as $A\rightarrow X$, $B\rightarrow X$, and $C\rightarrow X$. Another system $D\rightarrow X$ was also found between 3700A and 4500A. The wave numbers of the new band edges with an estimate of the intensities and sharpness of edges of bands in these four systems are given in Table I. The v', v'' arrays for the $A\rightarrow X$, $B\rightarrow X$, and $D\rightarrow X$ systems are shown in Fig. 2 and Fig. 3. System $C\rightarrow X$ consists of a single ($v'=0$) progression. Averaged values of $\Delta G''(v+\frac{1}{2})$ are the same in these four systems, showing that they have a common lower state, X. In a study of the absorption spectrum of As_2, Gibson and MacFarlane[3] found the $A\rightarrow X$ system well developed in v' progressions, showing that the X state is

[1] G. M. Almy and G. D. Kinzer, Phys. Rev. **47**, 721 (1935).
[2] G. M. Almy, J. Phys. Chem. **41**, 47 (1937). The designation of states in the present paper corresponds to that in reference 1.
[3] G. E. Gibson and A. MacFarlane, Phys. Rev. **46**, 1059 (1934).

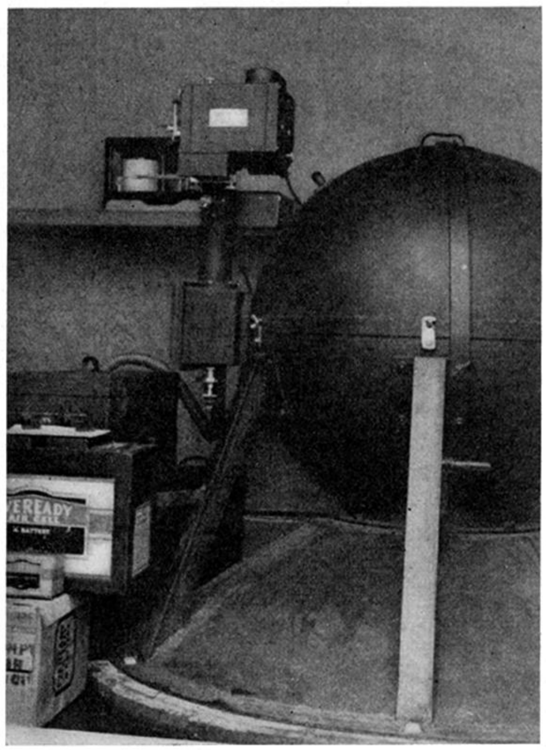

Fig. 2. Cosmic-ray meter in observatory on deck of Aorangi.

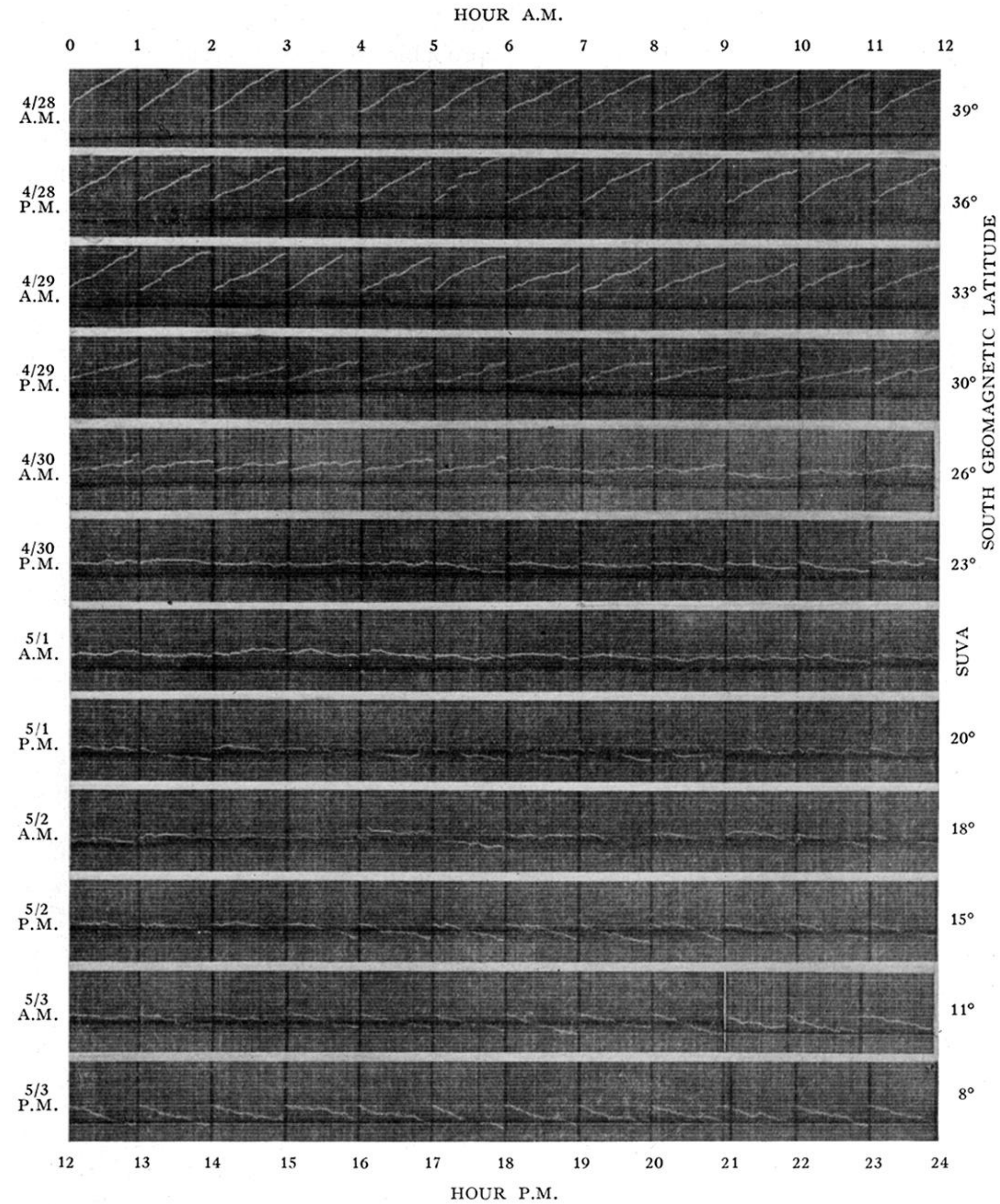

FIG. 3. Typical record showing latitude effect.