THE PHYSICAL REVIEW

A Journal of Experimental and Theoretical Physics Established by E. L. Nichols in 1893

VOL. 54, NO. 12 DECEMBER 15, 1938 SECOND SERIES

On World-Wide Changes in Cosmic-Ray Intensity

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(Received October 11, 1938)

Continuous cosmic-ray records for periods of 17 months or more obtained by Compton-Bennett meters at Cheltenham (United States), Teoloyucan (Mexico), Christchurch (New Zealand), and Huancayo (Peru) are reduced to a constant barometric pressure at each station. After deducting a 12-month wave from the data at each of these stations except at Huancayo, where none is found, a high correlation ($r \doteq 0.90$) is obtained between the means of cosmic-ray intensity for each one-third month for any two of the four stations. This high correlation, based on all available data for each pair of stations, is definite evidence that, except for the 12-month waves, the major changes in cosmic-ray intensity are world-wide. With published data from a Steinke instrument on the Hafelekar, near Innsbruck, the world-wide changes, when expressed in percent of the absolute intensity at each station, are found to increase rapidly with altitude for stations at the same latitude. A large increase in the world-wide effect for stations at high altitudes occurs between the equator and geomagnetic latitude 30° north, while no further very large increase occurs up to latitude 47° north. Results for Christchurch and Cheltenham indicate that the magnitude of the world-wide effect is symmetrical about the equator, and its connection with effects observed during certain magnetic storms is discussed. The amplitude of the 12-month wave, which in the Northern Hemisphere has its maximum near mid-January, increases from zero at the equator to about 1.0 percent at Teoloyucan, 1.6 percent at Cheltenham, and 1.9 percent on the Hafelekar. At Christchurch, its maximum occurs near the end of July, its amplitude being about 0.8 percent of the total intensity. Accordingly, it seems that the 12-month wave may not be ascribed to a solar-magnetic moment.

INTRODUCTION

THE decrease of several percent in cosmic-ray intensity which occurred[1–4] simultaneously at Cheltenham (United States), Huancayo (Peru), on the Hafelekar (Germany), Christchurch (New Zealand), and Teoloyucan (Mexico) during the magnetic storms which began April 24, 1937, and January 16, 1938, provided definite evidence that these changes were world-wide. The fact that the decrease in cosmic-ray intensity began within an hour or two after the sudden commencements of these magnetic storms led us to hypothesize[1, 4] that the change in cosmic-ray intensity resulted from the magnetic field of the current-system responsible for magnetic storms. The nature of the field-changes which occur over the earth's surface during magnetic storms is such that the world-wide characteristics of the storm field can be ascribed either to a system of westward currents forming a spherical current-sheet, concentric with the earth, in the upper atmosphere or to a westward current-system approximated by a ring concentric with the earth and in the plane of the earth's geomagnetic equator.[5]

[1] S. E. Forbush, Phys. Rev. **51**, 1108–1109 (1937).
[2] V. F. Hess and A. Demmelmair, Nature **140**, 316–317 (1937).
[3] V. F. Hess, R. Steinmaurer and A. Demmelmair, Nature **141**, 686–687 (1938).
[4] S. E. Forbush, Terr. Mag. **43**, 203–218 (1938).
[5] S. Chapman, Terr. Mag. **40**, 349–370 (1935).

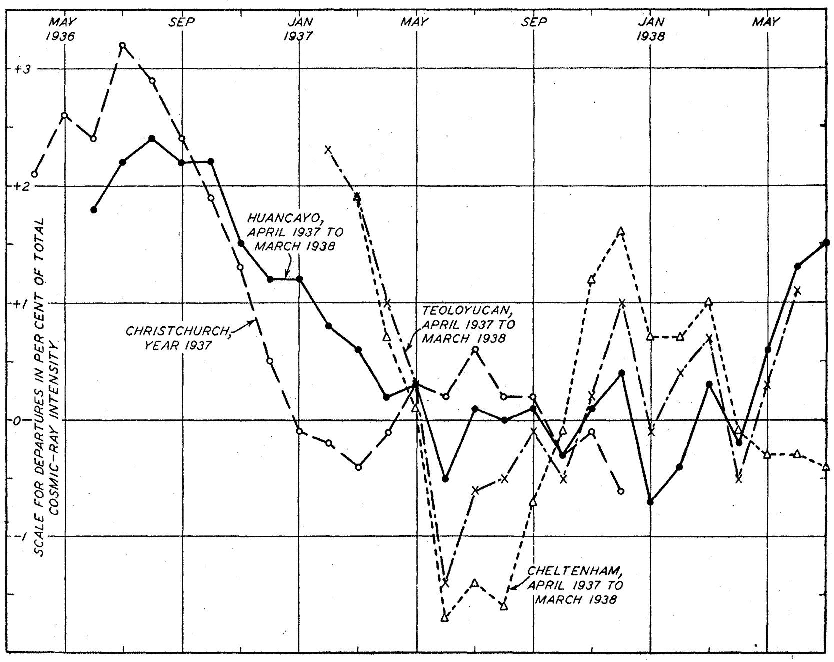

FIG. 1. Departures monthly means cosmic-ray intensity from mean for year indicated.

Further investigation[4] showed, however, two magnetic storms of equal intensity at the earth's surface, during one of which a world-wide decrease of about six percent in cosmic-ray intensity was observed, while no detectable change occurred in the other. Assuming the world-wide part of the storm field to arise from the above-mentioned ring-current system, we attempted[4] to calculate, using magnetic data from several observatories, the radius of the assumed ring for the two storms. Although this analysis provided no convincing evidence that the radius of the ring was significantly different for the two storms, it did indicate that a necessary condition for the existence of such a ring-current was satisfied by the magnetic data. We concluded that the radius for neither storm could be much less than about twice that of the earth, although the possibility of an indefinitely larger radius for either of the storms was not excluded.

We also found that, while there was close correlation between changes in daily means of cosmic-ray intensity and of the horizontal magnetic component at the equator during individual magnetic storms, the ratio between the two was significantly different even for storms accompanied by world-wide changes in cosmic-ray intensity. We therefore concluded that, if the major current-system for magnetic storms were approximated by an equatorial ring, its radius must be different even for the different storms accompanied by changes in cosmic-ray intensity.

Evidence is presented in the present investigation that the world-wide character of changes in

TABLE I. *Location and elevation of cosmic-ray stations and magnitude of world-wide effect, relative to Huancayo, for each.*

Station	Geographic Latitude	Geographic Longitude	Geomagnetic latitude	Elevation above sea level	World-wide effect relative to Huancayo
Cheltenham, United States	38.7N	76.8W	50.1N	72	1.11
Teoloyucan, Mexico	19.2N	99.2W	29.7N	2285	1.58
Huancayo, Peru	12.0S	75.3W	0.6S	3350	1.00
Christchurch, New Zealand	43.5S	172.6E	48.0S	8	1.05
Hafelekar, Germany	47.3N	11.3E	48.4N	2300	1.59

cosmic-ray intensity is found throughout the data available to us, and hence is not restricted to periods of intense magnetic storms.

Table I indicates the location and elevation of the several cosmic-ray meters. Those at the first four locations are Compton-Bennett[6] precision recording instruments operated under the auspices of the Committee on Coordination of Cosmic-Ray Investigations of the Carnegie Institution of Washington. Data from these were obtained with a total shielding equivalent to 12 cm of lead. Data for the last station of Table I were obtained from publications by V. F. Hess[2, 3, 7] and his co-workers who used a Steinke apparatus at constant temperature, shielded on all sides with ten cm of lead and seven cm of iron. Observed values of ionization were corrected for bursts and for changes in barometric pressure, by applying to all data at each station a constant barometric coefficient.[8] The percentage changes in cosmic-ray intensity for each station were determined on the basis of the total ionization, corrected for residual, given by the meter at that station.

[6] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415–422 (1934).
[7] A. Demmelmair, Ber. Akad. Wiss. Wien, **146**, IIa, 643–659 (1937).
[8] S. E. Forbush, Terr. Mag. **42**, 1–16 (1937).

Analysis of Data

In Fig. 1 are plotted, for four stations, the departures of observed monthly means of cosmic-ray intensity from the indicated annual means. It is evident that, in general, no particularly close correspondence exists between the departures for the different stations. From the 13 monthly mean departures for Cheltenham, beginning with April, 1937, we obtained by harmonic analysis[9] the 12-month wave which best fits the departures in this interval corrected for noncyclic change, which was assumed linear and was taken as the departure for April, 1938 minus that for April, 1937. The smooth function plotted in Fig. 2 is the sum of this wave and the linear change. This function, indicated in Fig. 2 by a dashed line where extrapolated, departs considerably from the observed departures.

The dashed curve in Fig. 2 indicates the ordinates of the 12-month wave deducted from the observed departures for Cheltenham. This curve resembles closely that for the observed departures for Huancayo. The correlation between the two ($r=0.90$) is shown in Fig. 10. This indicates that the variations in cosmic-ray intensity which occur at Huancayo also occur with about the same amplitude at Cheltenham, where they are superposed upon a 12-month wave.

[9] J. Bartels, Beitr. Geophysik **28**, 1–10 (1930).

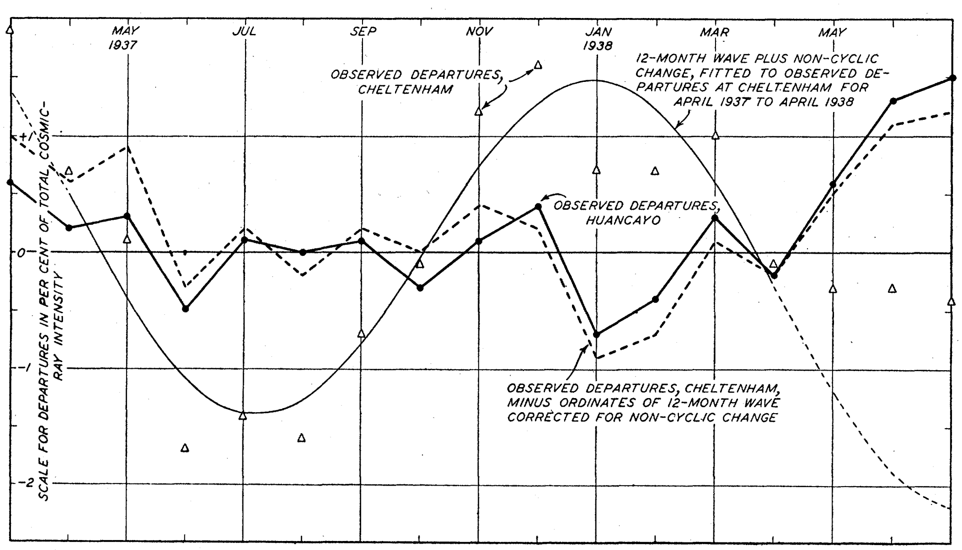

FIG. 2. Departures cosmic-ray intensity from Fig. 1, for Huancayo, and for Cheltenham before and after deducting 12-month wave.

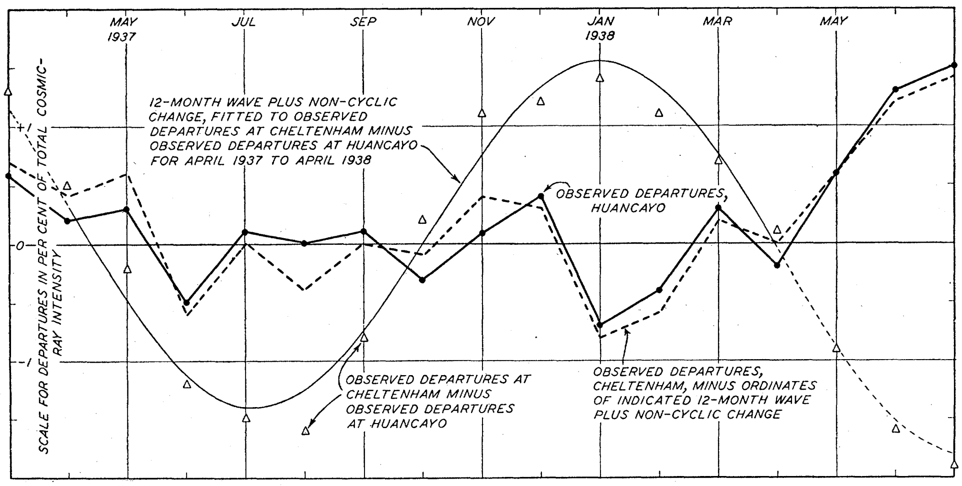

FIG. 3. Departures cosmic-ray intensity from Fig. 1, for Huancayo, and for Cheltenham after deducting departures for Huancayo.

When the departures at Huancayo for the interval April 1937 to April 1938 are corrected for noncyclic change and subjected to harmonic analysis, the amplitude of the resulting 12-month wave is practically zero. Thus, although the changes in cosmic-ray intensity at Huancayo are also found at Cheltenham superposed on a 12-month wave, our determination of the 12-month wave for Cheltenham is not materially affected by their presence. If, obscured by the changes which also occur at Cheltenham, a 12-month wave in cosmic-ray intensity existed at Huancayo, then the differences, taken month by month, between the two irregular curves of departures in Fig. 2 should determine the 12-month wave for Huancayo. In this way no significant amplitude for this wave is found.

If the indication is correct that changes in cosmic-ray intensity occur simultaneously at Huancayo and at Cheltenham superposed on a 12-month wave, then a 12-month wave should fit quite closely the differences obtained by subtracting the monthly mean departures of cosmic-ray intensity for Huancayo from those at Cheltenham. The result is shown in Fig. 3 in which the better approximation to the 12-month wave is evident.

To obtain a better indication of the relation

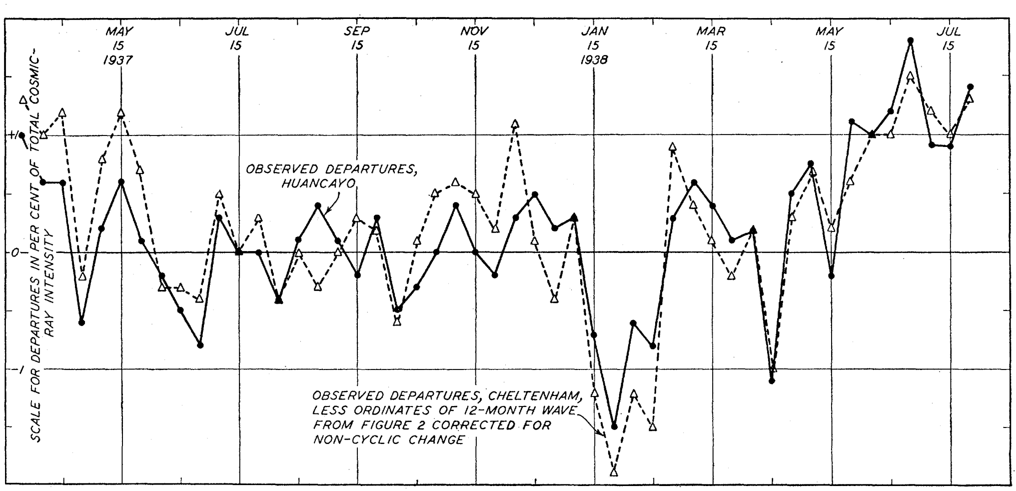

FIG. 4. Departures cosmic-ray intensity for each one-third month from mean April, 1937 to March, 1938 for Cheltenham after deducting 12-month wave, and for Huancayo.

between the world-wide changes at Huancayo and Cheltenham, the departures from the annual mean of those of cosmic-ray intensity for each one-third month were computed. From these means for Cheltenham were subtracted the ordinates of the 12-month wave of Fig. 2 and the result is shown in Fig. 4. The correlation between the two curves is 0.86 (see Fig. 12-*A*).

Figure 5 shows the close approximation of a 12-month wave to the result obtained by subtracting the monthly mean departures of cosmic-ray intensity at Huancayo from those at Christchurch. The dashed curve, which is remarkably similar to that for the observed departures at Huancayo, results from deducting the ordinates of this 12-month wave from the observed de-

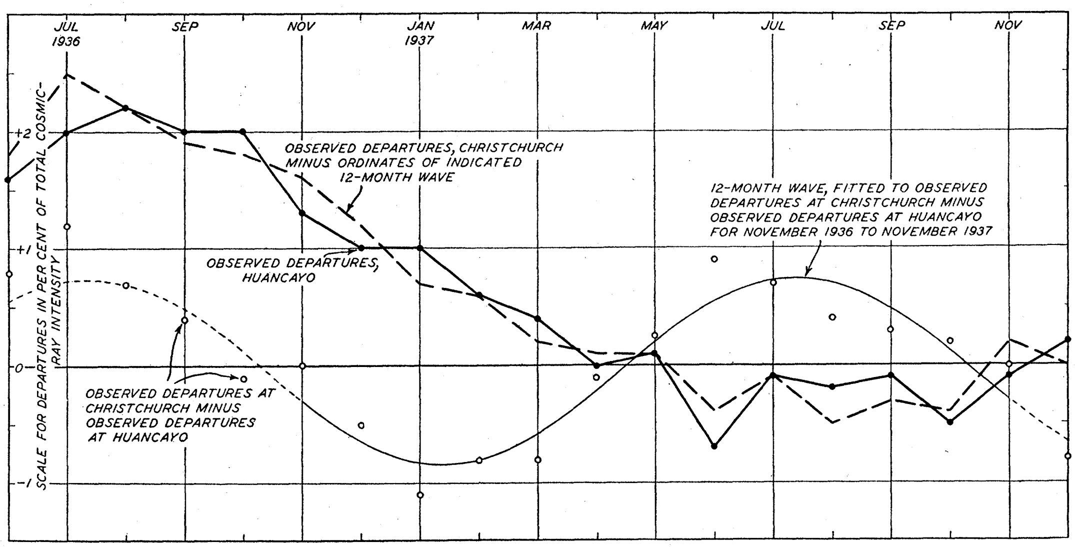

FIG. 5. Departures monthly means cosmic-ray intensity from mean for 1937 for Huancayo and for Christchurch after deducting departures for Huancayo.

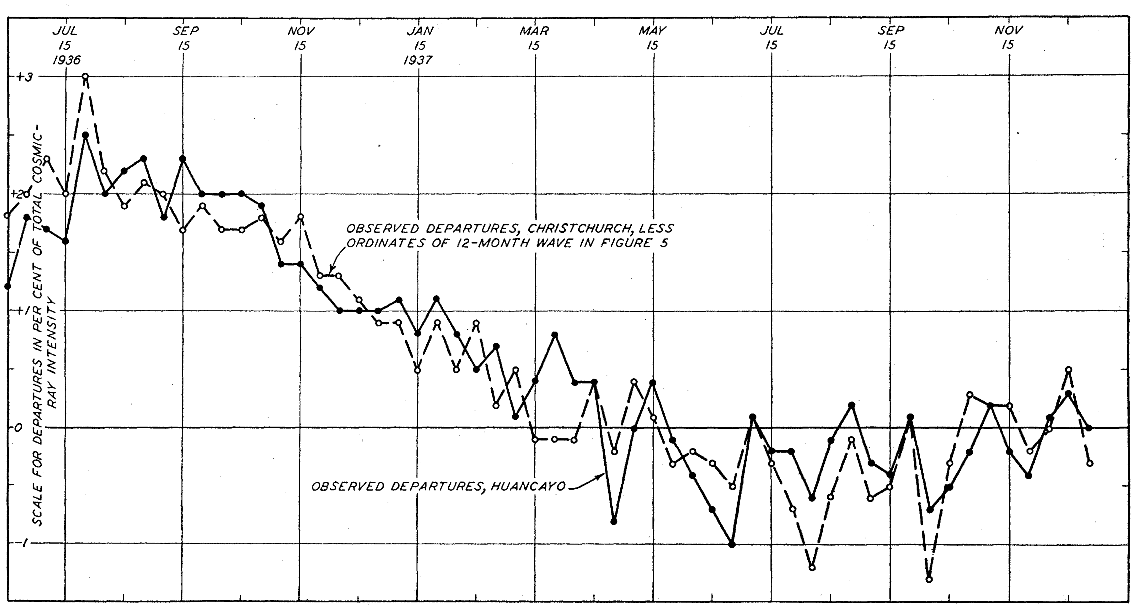

FIG. 6. Departures cosmic-ray intensity for each one-third month from mean for 1937, for Christchurch with 12-month wave deducted, and for Huancayo.

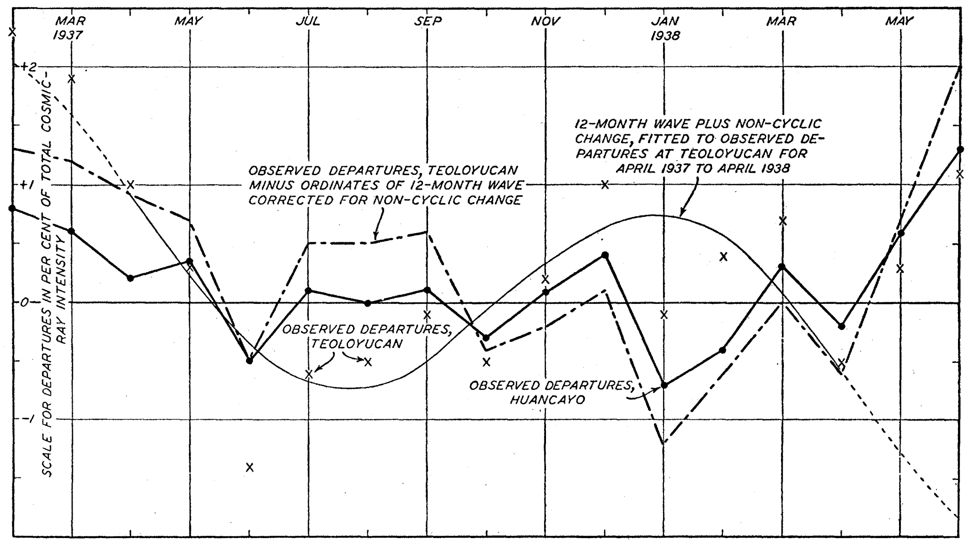

FIG. 7. Departures cosmic-ray intensity from Fig. 1, for Teoloyucan after deducting 12-month wave, and for Huancayo.

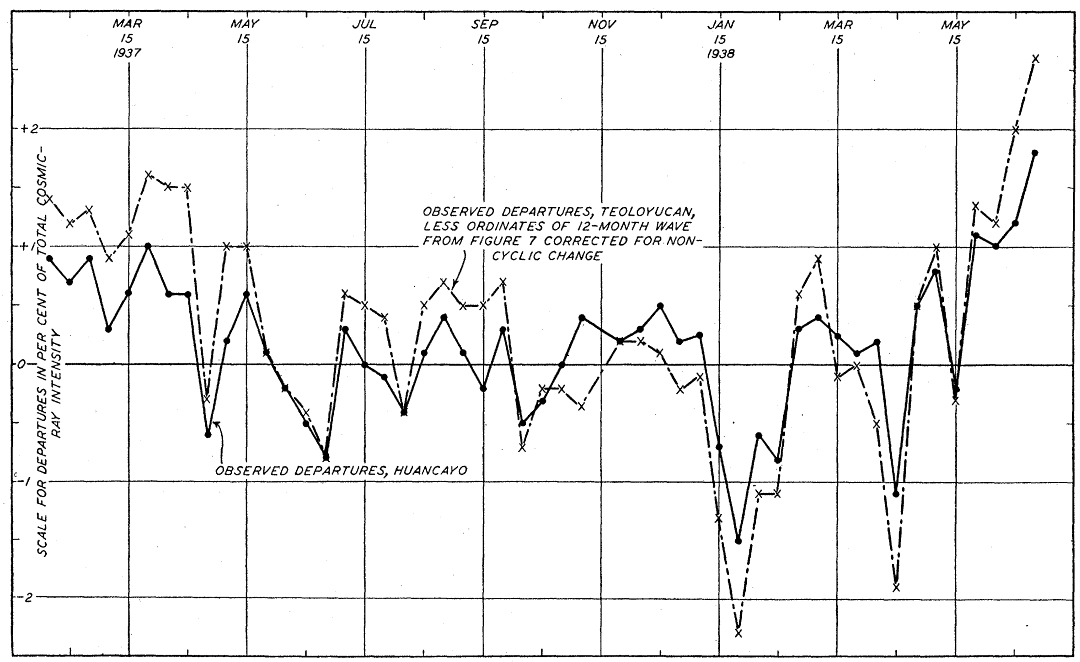

FIG. 8. Departures cosmic-ray intensity for each one-third month from mean for year beginning April 1937, for Teoloyucan after deducting 12-month wave, and for Huancayo.

partures (see Fig. 1) at Christchurch. The high correlation ($r=0.97$, see Fig. 10) between these curves results from the similarity in their trends rather than from correspondence of individual changes. However, a parallelism between changes in the means of cosmic-ray intensity for each one-third month at Christchurch, after deducting the 12-month wave, and those at Huancayo is evident in Fig. 6.

The similarity between the observed departures of monthly means of cosmic-ray intensity at Huancayo and those obtained by deducting

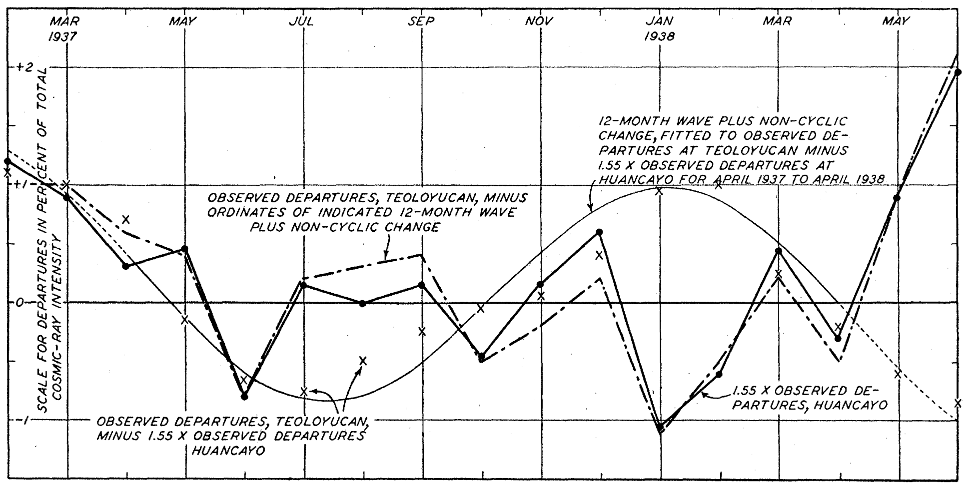

FIG. 9. Departures cosmic-ray intensity from Fig. 1, times 1.55 for Huancayo, and for Teoloyucan after deducting 1.55 times departures for Huancayo.

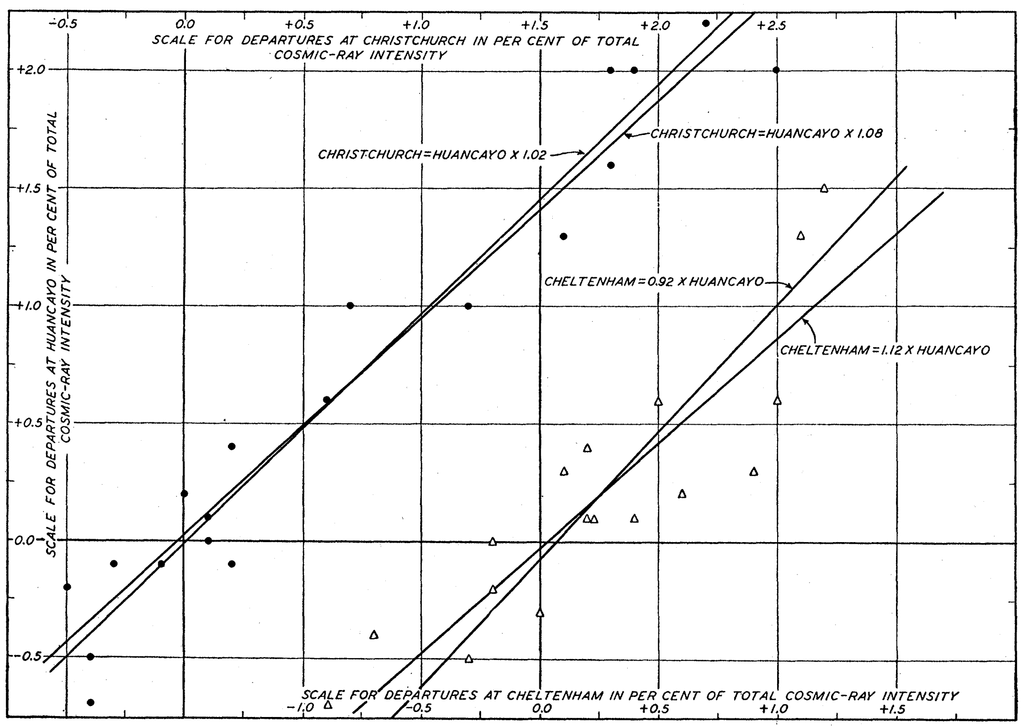

FIG. 10. Correlation between departures cosmic-ray intensity from Fig. 1, after deducting 12-month waves for Christchurch and Cheltenham.

the 12-month wave at Teoloyucan is shown in Fig. 7. The correlation between the two ($r=0.92$) is shown in Fig. 11-*A*, which indicates that the world-wide changes at Teoloyucan are between 50 and 80 percent greater than at Huancayo. This is also evident from the curves in Fig. 8, the correlation between which is 0.92 (see Fig. 12-*B*). It will later be shown that the world-wide changes in cosmic-ray intensity at Teoloyucan are about 55 percent greater than at Huancayo.

The close approximation of a 12-month wave, plus a linear change, to the result obtained by

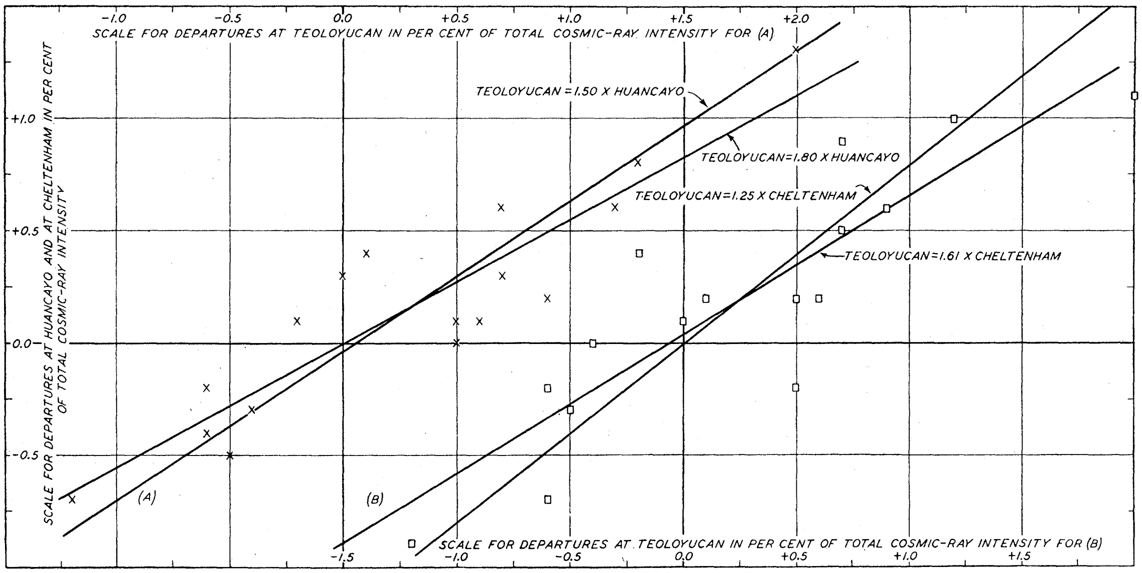

FIG. 11. Correlation between departures cosmic-ray intensity from Fig. 1, after deducting 12-month waves for Teoloyucan and Cheltenham.

subtracting 1.55 times the departures at Huancayo from those at Teoloyucan is shown in Fig. 9. The dashed curve, which so closely parallels the curve for 1.55 times the observed departures at Huancayo, results from deducting the ordinates of the indicated wave from the observed departures at Teoloyucan.

Relative Magnitude of World-Wide Changes in Cosmic-Ray Intensity at Different Latitudes and Elevations

In Fig. 11-*B* is shown the correlation between monthly means of cosmic-ray intensity at Teoloyucan and Cheltenham after deducting the respective 12-month waves. If one arbitrarily assumes the best relation between the world-wide changes at any two stations to be the average of the two factors indicated for the regression lines in Figs. 10 and 11, it is found that (1) the world-wide changes at Cheltenham and at Christchurch are each a few percent greater than those at Huancayo, and (2) the world-wide changes at Teoloyucan are about 65 percent greater than at Huancayo and about 43 percent greater than at Cheltenham. However, these factors for the three relations, of which only two are independent, between Cheltenham, Teoloyucan, and Huancayo are mutually only roughly consistent. This is to be expected since the factors were selected somewhat arbitrarily.

To obtain more reliable values for these relations, assumed linear, between world-wide changes at different stations, use is made of the data in Fig. 12. *C* of Fig. 12 indicates the correlation between world-wide changes in the means for each one-third month at Teoloyucan and Cheltenham. For Figs. 12, 4, 6 and 8, only those days were used in each one-third month for which simultaneous data were available from both stations; there are, however, but few cases in which all days were not available for all stations.

The slopes of the lines indicated in Fig. 12 represent the most probable values, in the sense of least squares, consistent with the assignment of weights[10, 11] 1, 2 and 3, respectively, to the departures at Cheltenham, Teoloyucan, and Huancayo. Since these weights were assigned in an objective manner, there is nothing arbitrary, except the use of least squares, in the method used to obtain the slopes indicated.

The correlation coefficients for *A*, *B*, and *C* of Fig. 12 are 0.86, 0.92, and 0.86, respectively.

[10] W. E. Deming, Phil. Mag. **11**, 146–158 (1931); **17**, 804–829 (1934).

[11] H. S. Uhler, J. Opt. Soc. Am. **7**, 1043–1066 (1923).

The slopes of the regression lines, which result if infinite weight is given to one or the other of the two coordinates, are 1.01 and 1.36 for A, 1.42 and 1.68 for B, and 1.11 and 1.50 for C. Any slope between these limits may be obtained by least squares depending upon the relative weights assigned to the two coordinates. Suppose a slope midway between that for the two regression lines is arbitrarily adopted for A and B. With these slopes, values for the departures for Huancayo can be calculated separately from those at Cheltenham and at Teoloyucan. The variance (square of standard deviation) for single differences in each of the two sets of differences between the observed and calculated departures for Huancayo is computed. With the same arbitrary slopes, the variance is now determined for single differences between the two series of calculated departures for Huancayo. Since each of these three computed values of variance is the sum of two separate variances because of independent statistical variations at the two stations involved, one obtains three equations from which the variance, because of statistical fluctuations, at each of the stations is readily obtained. The variance thus obtained of statistical variations at each station is measured in terms of the original unit for Huancayo, and thus in terms of units, which are larger (on account of the arbitrary factors used for calculating departures for Huancayo) for Cheltenham and Teoloyucan than the original units for those two stations. Correcting for this change of units, one obtains the variance for statistical variations at each station in terms of the original units used for that station. The weights are then assigned to each station in inverse proportion to the variance of statistical fluctuations at that station. The slopes indicated for the lines in Fig. 12 were obtained with these weights. These slopes were then used to obtain a closer approximation to the weights; these second approximations differed so little from the previous ones that the slopes calculated from them were not significantly different from those in Fig. 12.

The three slopes given in Fig. 12 are mutually quite consistent. Also the weights, thus objectively assigned, are not surprising since variations in daily means of barometric pressure are in general largest at Cheltenham and practically absent at Huancayo.

To determine the magnitude of the world-wide

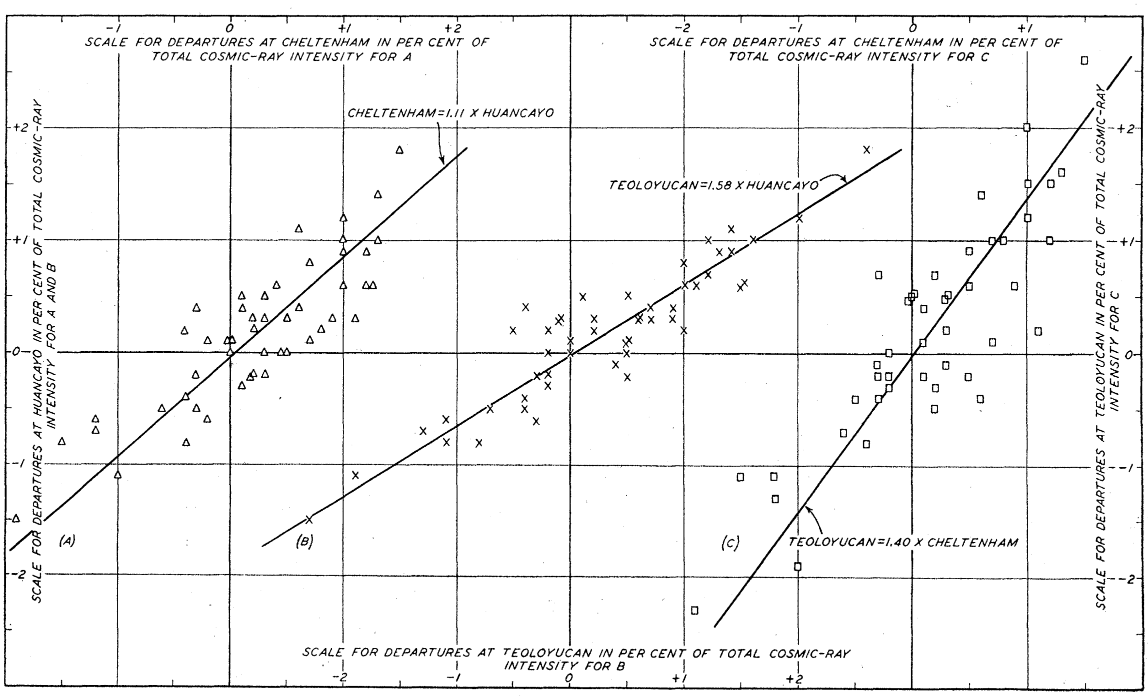

FIG. 12. Relation between departures cosmic-ray intensity from Figs. 4 and 8.

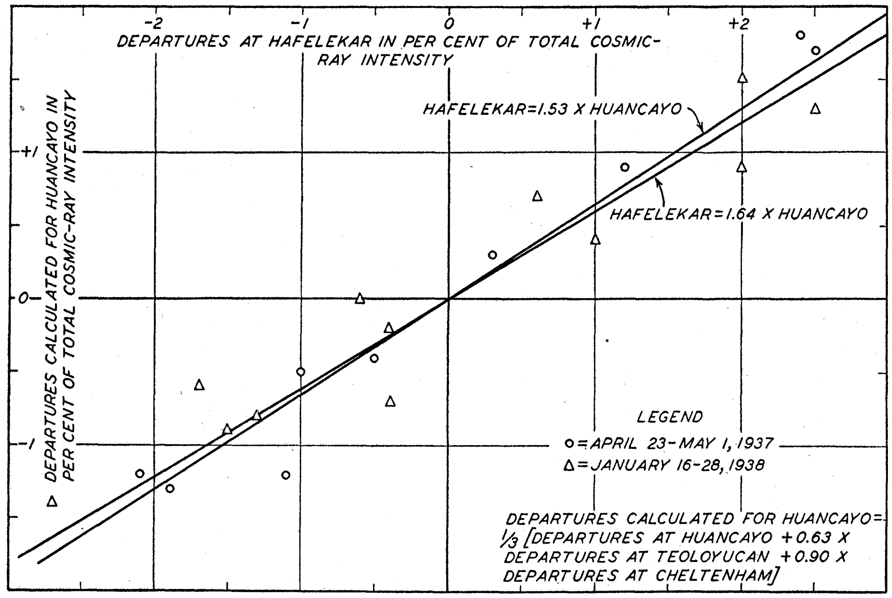

FIG. 13. Correlation between observed departures daily means cosmic-ray intensity from average during two magnetic storms for Hafelekar and calculated departures for Huancayo.

effect in cosmic-ray intensity for a station at great elevation and high latitude, data published by V. F. Hess[2, 3] and his co-workers for the Hafelekar during two intense magnetic storms were used. Departures of the scaled daily cosmic-ray intensity (75° west meridian day) from the means for each of the storms are plotted in Fig. 13. Daily (75° west meridian) means of cosmic-ray intensity were then computed separately for Huancayo, Teoloyucan, and Cheltenham. Their departures from the means for the respective storms were used in the equation of Fig. 13 to compute calculated departures for Huancayo; the high correlation of $r=0.96$ between the two departures is evident. The indicated regression lines fit the separate data for the two periods of magnetic storms about equally well. The correlation in Fig. 13 is considerably higher than that found when the *observed* departures at Huancayo were used as ordinate. Since the factors used in the equation for calculated departures at Huancayo are those indicated in Fig. 12, we assumed that the ratio between the world-wide effects at different stations during individual magnetic storms is the same as that for means for each one-third month. However, this point was carefully tested for each station in the same manner as for the Hafelekar in Fig. 13. While the correlation in most cases is not so high as for Fig. 13, no evidence was found indicating that the relations in Fig. 12 do not also apply to changes in cosmic-ray intensity at the other stations during the same magnetic storms. Thus for the magnitude of the world-wide effect at different stations relative to that for Huancayo, the values of Table I are adopted. In the case of the station on the Hafelekar the average of the two slopes in Fig. 13 was taken since any reasonable weighting will not appreciably alter the result.

Summary and Discussion of Twelve-Month Waves in Cosmic-Ray Intensity at Different Stations

In Fig. 14 are summarized the results for the 12-month waves in cosmic-ray intensity at different stations after deducting the world-wide effects. Each vector in the harmonic dial[12] of Fig. 14 points to the date of the wave maximum and its length represents the amplitude. The world-wide effects were determined, as previously described, from the data for Huancayo, where

[12] J. Bartels, Terr. Mag. **40**, 1–60 (1935).

the 12-month wave is absent. The world-wide effects at each of the other stations, except Hafelekar as noted below, were computed from those at Huancayo with the factors given in Table I.

The 12-month wave at the Hafelekar was based on monthly means, corrected only for barometric pressure, for April 1936 to March 1937 obtained from Table III of A. Demmelmair's paper.[7] Since no data for Huancayo prior to June 1936 were available, the world-wide changes for April and May 1936 were determined from the data at Christchurch (see Fig. 15). Fig. 14 also indicates the 12-month waves in temperature of outside air based, except for Teoloyucan, on data for the same intervals used to obtain the 12-month waves in cosmic-ray intensity. For Teoloyucan the temperature-wave is the average for the five years,[13] 1917–1921.

The phase of the 12-month wave in temperature at each station differs, except for Teoloyucan, by about 180° from that of the 12-month wave in cosmic-ray intensity. The ratio of the amplitude of the 12-month wave in cosmic-ray intensity to that in temperature is about the same for Cheltenham and Christchurch, which have similar elevations and geomagnetic latitudes. However, this ratio is quite different for the other stations, excluding the possibility that the variation in cosmic-ray intensity is, in general, closely connected with temperature. Whether or not the 12-month wave in cosmic-ray intensity is the result of the 12-month wave in temperature, the fact that the two are about opposite in phase would necessarily lead to a correlation between the two, which has been reported by Hess[14] and others. Possibly the cause for the apparent seasonal wave in cosmic-ray intensity may be associated with the seasonal variation[15] in the distribution of air-density with height in the earth's atmosphere, as was implied by Schonland.[16]

If we arbitrarily assume a seasonal wave in cosmic-ray intensity having the same amplitude but opposite phase at Cheltenham and Christchurch, the observed 12-month waves in cosmic-ray intensity at these two stations could then be attributed to an annual wave, with the same phase and amplitude at both stations, superposed upon the seasonal waves. It is readily seen from Fig. 14 that this annual wave would have its maximum in January. This is just opposite in phase to that of the annual wave which, according to the calculations of Vallarta,[17] would arise if the sun had a magnetic moment. Thus it seems impossible to ascribe the 12-month wave in cosmic-ray intensity to a solar magnetic moment,

[13] Bol. Obs. Astr., Tacubaya, No. 10, Table 11 (1928).

[14] V. F. Hess, Terr. Mag. **41**, 345–350 (1936).

[15] W. J. Humphreys, *Physics of the Air*, second edition (1929).

[16] B. F. J. Schonland, B. Delatizky and J. Gaskell, Terr. Mag. **42**, 137–152 (1937).

[17] M. S. Vallarta, Nature **139**, 839 (1937).

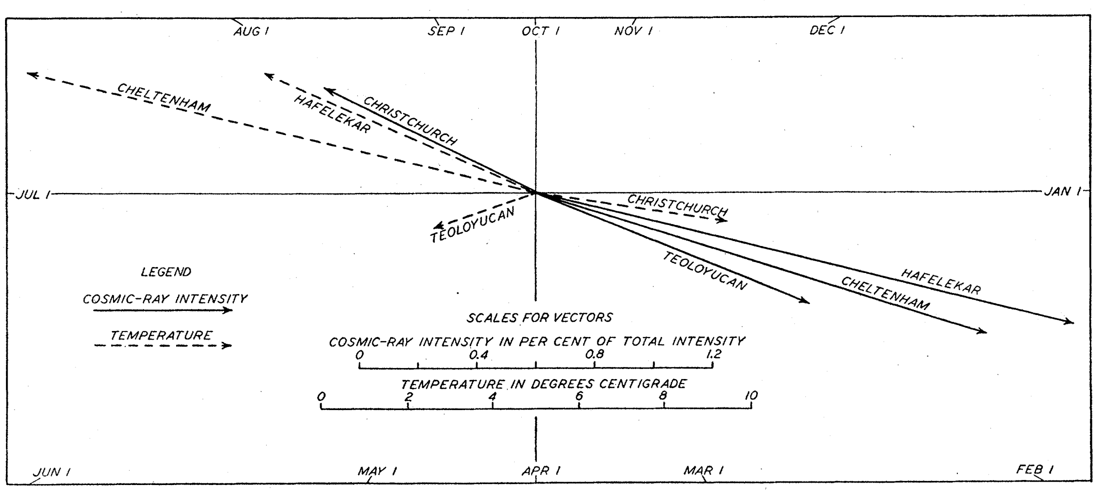

FIG. 14. Harmonic dial for 12-month waves in cosmic-ray intensity after deducting world-wide changes and in temperature showing dates and amplitudes of wave-maximum.

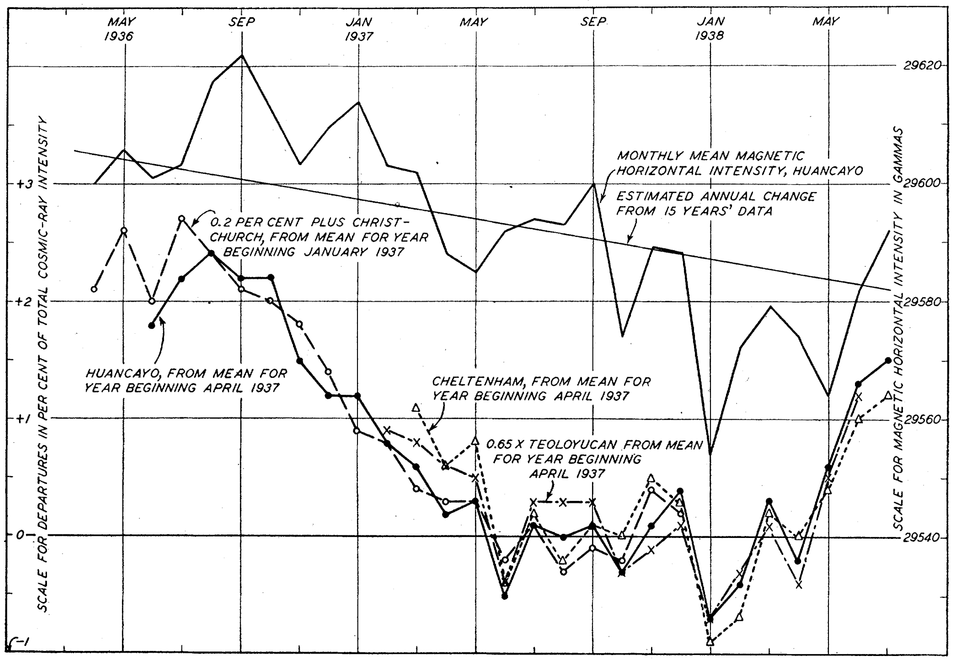

FIG. 15. Departures cosmic-ray intensity from Fig. 1 after deducting 12-month waves.

unless perhaps the annual variation in the angle between the earth's magnetic axis and the ecliptic introduces an unsuspected variation. This latter, however, would seem to be excluded on the basis that the diurnal variation of about 12° in the angle between the earth's magnetic axis and the ecliptic should then be expected to result in a diurnal variation in cosmic-ray intensity with amplitude many times that actually observed.[8]

Since the relative amplitudes of the 12-month waves are quite different from those of the world-wide changes at the different stations, the two effects must be ascribed to different causes. It would seem impossible to obtain the excellent agreement indicated in Figs. 4, 6, 8 and 12 unless the fundamental mechanism for the 12-month wave at each station varied almost perfectly sinusoidally.

It should be added that by varying the temperature of the Compton-Bennett meter at Cheltenham over a range of 15°C and comparing results over a period of many weeks with those from two Millikan-Neher electroscopes at constant temperature, the Compton-Bennett meter is found to be unaffected by temperature.

Discussion of the World-Wide Effect in Cosmic-Ray Intensity

The high correlation which exists between changes in cosmic-ray intensity at any two stations definitely establishes the fact that the major changes in cosmic-ray intensity, after eliminating the 12-month wave, are world-wide. The relative amplitude of the world-wide changes at different stations derived from data extending over periods of more than a year is not significantly different from that derived from two short periods of intense magnetic storms. This suggests that the mechanism responsible for changes occurring over longer periods of time is similar to that which causes the decrease of intensity during certain individual magnetic storms.

The world-wide character of changes in monthly means of cosmic-ray intensity, after removing the 12-month wave, is summarized in Fig. 15. If the hypothesis that the decrease in intensity during certain magnetic storms is due to alteration of trajectories of cosmic-ray particles resulting from the magnetic field of an equatorial ring-current, or its equivalent, is correct, then the more or less continued world-wide changes in intensity evident in Fig. 15 would imply the continued existence of such a current-system with changing strength or radius. Störmer[18] concluded that such a current-system was necessary to account for the large diameter of the auroral zones.

For comparison, the monthly means of magnetic horizontal intensity are indicated in Fig. 15. The average rate of decrease, derived from fifteen years of data, of the horizontal magnetic intensity at this station is indicated by the slope of the straight line. Any correspondence between the trend in this line and that in cosmic-ray intensity must therefore be regarded as accidental. However, the correspondence between departures of monthly means in horizontal intensity from this line and those in cosmic-ray intensity is doubtless significant. That the correspondence in some instances is more marked than in others is not surprising in view of the fact[4] that some magnetic storms are not accompanied by significant changes in cosmic-ray intensity.

Since the period of minimum values for the departures in cosmic-ray intensity in Fig. 15 agrees roughly with that of maximum magnetic activity, and since we have also indicated[4] the existence of a 27-day wave, probably quasi-persistent,[12] in cosmic-ray intensity, it would not be unexpected to find, when adequate data are available, the 11-year cycle of sunspot-activity reflected in cosmic-ray intensity.

From values for the relative magnitudes of the world-wide effect in cosmic-ray intensity given in Table I, the effect at the Hafelekar, where the instrument had somewhat greater shielding than at the other stations, is about 40 percent greater than at Cheltenham. This indicates that the intensity of the cosmic-ray component which is affected by the mechanism causing the world-wide changes increases much faster with altitude than does the total intensity. This is consistent with the fact that Clay and Bruins[19] found, in an instrument shielded by 110 cm of iron, no measurable change in cosmic-ray intensity during the magnetic storm which began April 24, 1937. They were thus enabled to set an upper limit to the energy of particles affected by the field of the magnetic storm.

Table I also indicates for high altitude stations a rapid increase in the magnitude of the world-wide effect between the equator and geomagnetic latitude 30° north. While the value for the Hafelekar indicates no further increase up to latitude 47° north, the additional shielding may have somewhat reduced the ratio in Table I for that station. Since no data are available for a sea-level station at the equator, it is not possible to determine the latitude variation in the world-wide effect at sea level. However, the agreement between Cheltenham and Christchurch indicates that the variation with latitude is probably symmetrical about the equator. Whether the world-wide changes in cosmic-ray intensity are due to the magnetic field of an equatorial ring-current system, or its equivalent, can only be answered when the difficult problem of finding the trajectories of cosmic-ray particles in such a field superposed on that of the earth's doublet has been solved.

The world-wide effects indicated in Fig. 15 imply that special precautions are necessary to obtain accurate determinations of the longitude effect. Also, if the magnitude of the world-wide effect increases as rapidly with altitude and latitude as the results in Table I suggest, then the results for latitude variations at extreme altitudes may also be materially affected if the mechanism responsible for the world-wide effect operates somewhat continuously but with varying intensity. Although this suggests a possible explanation for the exclusion of low energy cosmic-ray particles from the top of the earth's atmosphere at high latitudes, it is open to the serious objection that it would also be expected to exclude the auroral particles.

Finally, it should be emphasized that the results of this investigation could not have been secured without remarkable stability in the several cosmic-ray meters by which the data were obtained. Thus the estimated probable error for each entry in the last column of Table I is roughly ± 0.03. Although an examination of barometric coefficients at the separate stations does not indicate the existence of appreciable instrumental differences, it may be desirable to obtain further

[18] C. Störmer, Terr. Mag. **35**, 193–208 (1930).

[19] J. Clay and E. M. Bruins, Physica **5**, 111–114 (1938).

confirmation of this through an intercomparison of instruments at some of the stations.

Acknowledgments

We are indebted to the Committee on Coordination of Cosmic-Ray Investigations of the Carnegie Institution of Washington for providing the assistance of W. R. Maltby, without whose aid the reduction of the data here used would have been long delayed.

We are also under obligation to G. Hartnell and the staff of the Cheltenham Magnetic Observatory of the United States Coast and Geodetic Survey for operation of a cosmic-ray meter at that station, to J. W. Beagley of the Christchurch Magnetic Observatory for operation of a meter and reduction of records, to Professor J. Gallo, Director of the National Astronomical Observatory at Tacubaya, Mexico, for supervising the operation of the meter at Teoloyucan, and to the staff of the Huancayo Magnetic Observatory of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for operating the meter at that station. We are also especially indebted to Professor A. H. Compton and his assistants for making available to us the reduced data from Teoloyucan, and to the National Carbide Company, Incorporated, for providing all batteries for operating the Compton-Bennett meters.

Finally, it is a pleasure to acknowledge the encouragement received from Dr. J. A. Fleming, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

DECEMBER 15, 1938 PHYSICAL REVIEW VOLUME 54

Anomalous Dispersion of X-Rays in Calcite

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(Received October 11, 1938)

The index of refraction of calcite ($CaCO_3$) for x-rays has been investigated in the wave-length range from 2880 to 3550 x.u., which includes the K absorption edge of calcium. The method is such that all of the incident beam enters the crystal through an artificial face, ground so that after reflection from the (100) planes a part of the beam emerges through this face at a sufficiently small angle to be refracted appreciably. At the same time another part of the beam emerges from a cleavage face at a large angle and is refracted only a little. The separation between the two is a measure of the index. The continuous spectrum is used rather than emission lines, thus enabling measurements to be made as closely spaced in wave-length and as near the absorption edge as is desired. The absolute accuracy of the method in its present form is probably not great, but the relative accuracy is sufficient to show a distinct dip in δ/λ^2 in the vicinity of the absorption edge. A comparison is made with Hönl's theoretical curve.

Introduction

Because the index of refraction of all substances for x-rays is very nearly unity, the refractive bending of an x-ray beam has a measurable magnitude only when the angle between the beam and the interface is very small. Bergen Davis first suggested grinding an artificial face on a crystal in order that an x-ray undergoing Bragg reflection might make a small angle with the surface. The experiments of Davis and Hatley[1, 2] gave the first quantitative determinations of the index of refraction. Variations of this method have been used by Lindsay and his collaborators[3, 4] to measure the index of cerussite ($PbCO_3$). Retaining the idea of a small angle at the interface, but not using Bragg

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[1] C. C. Hatley and Bergen Davis, Phys. Rev. **23**, 290 (1924).
[2] C. C. Hatley, Phys. Rev. **24**, 486 (1924).
[3] H. C. Hoyt and G. A. Lindsay, Phys. Rev. **49**, 498 (1936).
[4] J. E. Field and G. A. Lindsay, Phys. Rev. **51**, 165 (1937).