

WORLD-WIDE COSMIC-RAY VARIATIONS, 1937-1952

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ABSTRACT

Annual means from continuous registration of cosmic-ray ionization at four stations from 1937 to 1952 show a variation of nearly four per cent, which is similar at all stations and which is negatively correlated with sunspot numbers. This variation in cosmic-ray intensity is quite similar for the annual means of all days, international magnetic quiet days, and international magnetic disturbed days, which indicates that it is not due to transient decreases accompanying some magnetic storms. Although the cosmic-ray intensity at some stations is affected by meteorological conditions, it is shown that on the average the cosmic-ray changes observed at Huancayo agree well with those at other stations. From an analysis of the variability of daily means at Huancayo and a sample comparison with Simpson's neutron data, it is concluded that the cosmic-ray ionization at Huancayo is very little affected by meteorological effects. Through a comparison with Neher's balloon observations, evidence is provided to indicate the reliability of cosmic-ray results at Huancayo over long periods of time. The relation between cosmic-ray decreases and some measures of geomagnetic activity is indicated, and it is shown that the major transient decreases in cosmic-ray intensity occur during magnetic disturbance. Graphs are included which depict the daily means of cosmic-ray intensity at Huancayo for all available data, 1937-1953.

Introduction

The uninterrupted cooperation of several organizations with the Department of Terrestrial Magnetism, Carnegie Institution of Washington, has resulted in continuous operation of Compton-Bennett cosmic-ray meters for the four stations listed in Table 1 from the dates indicated therein. The cooperating organizations are as follows: *Godhavn*—The Danish Meteorological Institute and the staff of its Godhavn Magnetic Observatory; *Cheltenham*—The United States Coast and Geodetic Survey and the staff of its Cheltenham Magnetic Observatory; *Huancayo*—The Government of Peru and the staff of its Instituto Geofísico de Huancayo; and *Christchurch*—The Department of Scientific and Industrial Research of New Zealand and the staff of its Christchurch Magnetic Observatory.

Additional details of the installations and of corrections for bursts and baro-

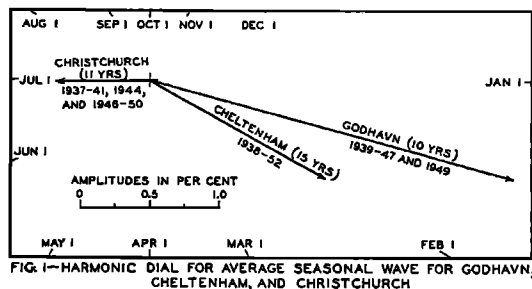
TABLE 1—Location of Compton-Bennett meters

Station	Lat.	Long.	Geomag. lat.	Elev.	Bar. coeff.	Continuous registration began
	°	°	°	meters	% (cm Hg) ⁻¹	
Godhavn, Greenland	69.2 N	53.5 W	79.9 N	9	−0.18	Oct. 1938
Cheltenham, Maryland	38.7 N	76.8 W	50.1 N	72	−0.18	March 1937
Huancayo, Peru	12.0 S	75.3 W	0.6 S	3350	−0.30	June 1936
Christchurch, N.Z.	43.5 S	172.6 E	48.6 S	8	−0.18	April 1936

metric pressure are given in the publication [see 1 of "References" at end of paper]: "Cosmic-ray results from Huancayo Observatory, Peru, June 1936–December 1946, including summaries from observatories at Cheltenham, Christchurch, and Godhavn, through 1946." Tabulations for a similar publication extending through 1952 are now completed.

Seasonal wave

Early investigations [2] showed that, except for a seasonal wave, the major variations in cosmic-ray ionization were world-wide. Subsequently, four large [3, 4] increases of cosmic-ray intensity, associated with solar flares, were found at all stations except those at or near the equator. From the present long sequence of data, the average seasonal waves shown in Figure 1 were derived. No statistically

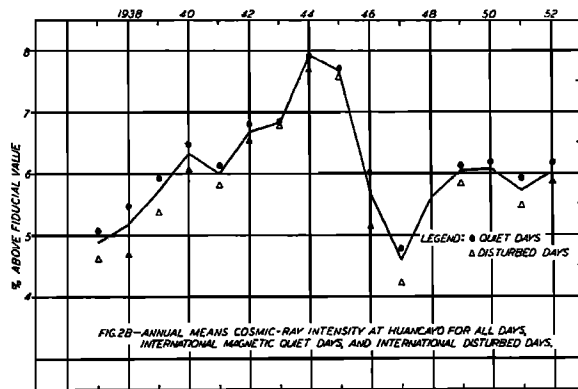
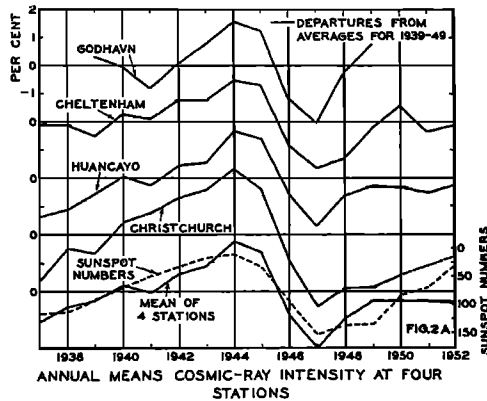


significant seasonal wave was found for Huancayo. The seasonal waves are undoubtedly the consequence of seasonal variations in the vertical air-mass distribution, resulting in variations in the fraction of μ -mesons decaying before reaching the meters. These seasonal waves (corrected for non-cyclic change) have been deducted from all data used in this paper. This removes only the systematic seasonal variations. It does not remove variations arising from non-systematic, unpredictable, changes of vertical air-mass distribution, the magnitude of which for the different stations will be discussed later.

Sunspot-cycle variation in cosmic-ray intensity

When all available annual means of cosmic-ray ionization, corrected for bursts and barometric pressure, were examined, a large secular decrease was obvious in

the results for Christchurch. Since there was no evidence in the results for Cheltenham of any significant secular change, other than the sunspot variation as shown in Figure 2A, no correction for drift was applied to the data for Cheltenham. By



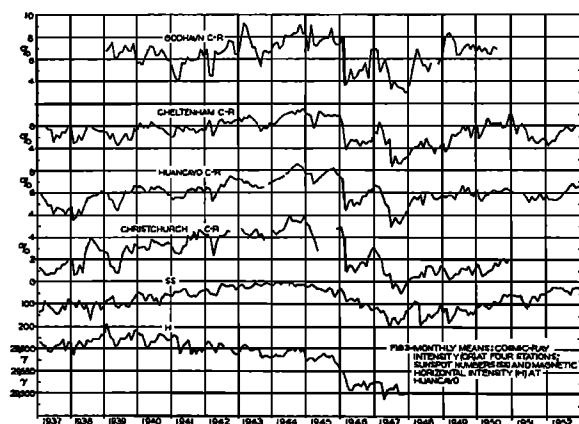
comparing results for the other stations with those for Cheltenham, the following linear changes were found: Christchurch, $-1.40\% \text{ yr}^{-1}$; Godhavn, $-0.25\% \text{ yr}^{-1}$; and Huancayo, $+0.40\% \text{ yr}^{-1}$. The annual means of Figure 2 have been corrected for the above linear changes, which are assumed to be instrumental and probably arise from decay of radioactive contamination in the main chamber or in the balance chamber of the meters. The agreement between the annual means of cosmic-ray intensity for the four stations, or their average, and that for annual mean sunspot numbers is evidence that the mechanism responsible for these changes in cosmic-ray intensity involves some phenomenon associated with solar activity.

It is known that some magnetic storms are accompanied by large decreases in cosmic-ray intensity, and it is shown later that most of the major decreases which occur during intervals of a few days are associated with magnetic storms or periods of magnetic disturbance. Thus, there arises the question of whether these decreases are mainly responsible for the variation of cosmic-ray intensity with sunspot numbers shown in Figure 2A. To answer this question, the variation

of annual means of cosmic-ray intensity at Huancayo for all days (as used in Fig. 2A) is compared in Figure 2B with that for international magnetic quiet days and with that for international magnetic disturbed days. It is evident from Figure 2B that the variation of annual means for all days, which in Figure 2A was shown to follow the curve of sunspot numbers, is very little different from that for quiet days and not greatly different from that for disturbed days. Thus, the main features of the variation of cosmic-ray intensity with sunspot numbers persist for long periods (six months or more) and are not ascribable to transient decreases accompanying some magnetic storms.

Further evidence of effects that persist for long periods of time is indicated in Figure 16D, in which the curve (*h*) for daily means of cosmic-ray intensity at Huancayo shows a gradual increase of about 1.5% from January 1944 to September 1944 during a period in which there was no very large transient decrease in cosmic-ray intensity and no great magnetic storm. It thus appears that the transient decreases in cosmic-ray intensity which occur during some magnetic storms and magnetically disturbed periods are superimposed upon a variation with sunspot cycle.

Figure 3 shows the variation of the monthly means of cosmic-ray intensity



for four stations after removing the seasonal wave and linear trend. Also shown is the monthly mean horizontal magnetic component at Huancayo corrected for a linear estimate of secular change. It is evident that the horizontal intensity and cosmic-ray intensity were both markedly lower throughout 1946 and 1947 than in 1944. This fact suggests the possibility that the same mechanism may be responsible for both effects. In this connection, it should be mentioned that Vestine [5], from a long series of magnetic data from many observatories, found evidence for an 11-year variation in the horizontal component of the earth's field. In deriving the latitude distribution for the three geomagnetic components of the storm-time field, D_{st} (disturbed minus quiet days) he found [5] that the eastward geomagnetic component of D_{st} was zero, on the average. However, he points out that the yearly average of the east component for all days is not only not zero but varies during the sunspot cycle, indicating that the cause of this variation (and probably also

that for horizontal intensity on all days) may be distinct from that for D_{90} . Thus, this unexplained variation in the earth's field is possibly connected with the sunspot variation in cosmic-ray intensity.

The variation of monthly means is further compared in Figure 4. To effect this comparison, the monthly means for Huancayo were categorized in six intervals of one per cent (3% to 9%). Monthly means for each of the other stations were averaged for each of these six categories. These group means are reasonably well fitted by the straight lines shown in Figure 4. These lines thus approximate the

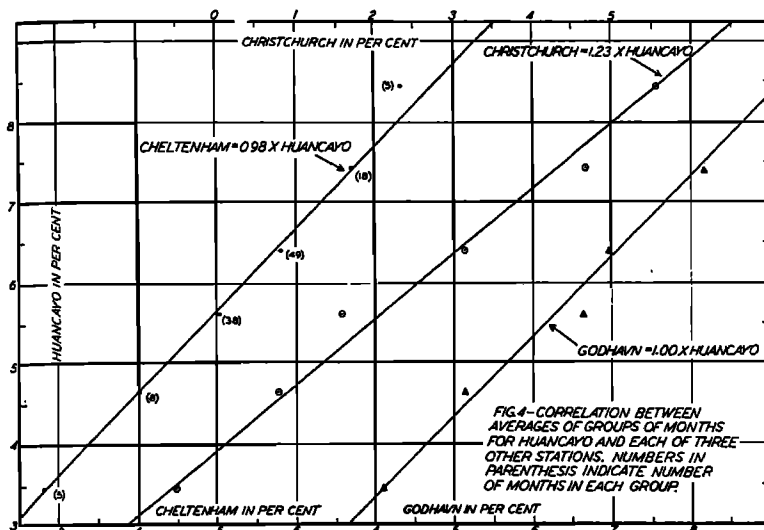


FIG. 4—CORRELATION BETWEEN AVERAGES OF GROUPS OF MONTHS FOR HUANCAYO AND EACH OF THREE OTHER STATIONS. NUMBERS IN PARENTHESIS INDICATE NUMBER OF MONTHS IN EACH GROUP.

regression lines obtained by assuming the monthly means at Huancayo are free of statistical errors, which are presumed present only in the means for the other stations. The factor of 1.23 for the ratio of changes at Christchurch to those at Huancayo is roughly 20% greater than that found earlier from a shorter series of data [2]. This factor is also greater than that derived in the following section. For Cheltenham and Godhavn, the factors shown on Figure 4 are more nearly consistent with those derived earlier [2] and with those derived in the following section.

Variation of daily means

Comparison of variations for average of ten selected 20-day intervals—From a plot of daily means for Huancayo (see Fig. 16), ten intervals of 20 days were selected with each interval exhibiting a variation similar to that shown for Huancayo in Figure 5. Figure 5 indicates the variation averaged for the same ten intervals for each of the other three stations. Figure 6 indicates the correlation between the averaged variation for Huancayo and that for each of the other three stations. The correlation coefficients and slopes of the regression lines are also indicated. The smaller of the two slopes results from the assumption of no statistical error in the means for Huancayo. Except for Christchurch, the factors are in fair agreement with those shown in Figure 4 and with those derived earlier [2, 6].

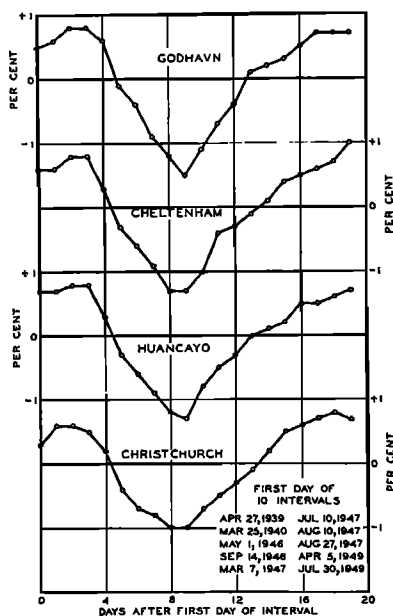


FIG. 5—COSMIC-RAY INTENSITY VARIATIONS AVERAGED FOR TEN INTERVALS OF 20 DAYS, EACH WITH COMPARABLE VARIATION AT HUANCAYO

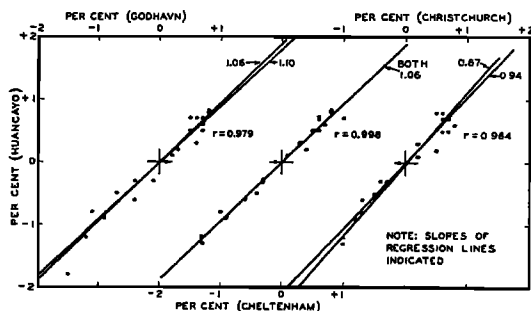
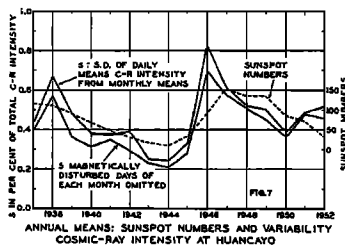


FIG. 6—CORRELATION (r) BETWEEN VARIATIONS AT HUANCAYO AND THOSE AT GODHAVN, CHELTENHAM, AND CHRISTCHURCH FROM DATA IN FIGURE 5

Variability of daily means at Huancayo—Figure 7 indicates the standard deviation of daily means from monthly means at Huancayo for each year, 1937-1952. The curves show that standard deviations of departures from the monthly means are roughly four times smaller near sunspot minimum than near sunspot maximum. They are only slightly less when the five magnetically disturbed days of each month are excluded.



For 1944, the standard deviation of daily means from monthly means is about 0.21% (excluding the five magnetically disturbed days). Since this figure includes the variability of the world-wide component, it is an upper limit for the combined effects of statistical fluctuations in the records and those from variations of μ -meson decay due to changes in vertical distribution of air-mass. It is thus evident that the latter effects are quite small at Huancayo, and that the daily means (relative to the mean of the month) at Huancayo are reliable to within at most 0.2% (that is, their s.d. $\leq 0.2\%$). From a previous investigation [2], it was found that the world-wide changes at Teoloyucan, Mexico, were about 1/0.63 times those at Huancayo. For 1937, daily means, with seasonal wave removed, were available from Teoloyucan for all months except January and November. These daily means for Teoloyucan were multiplied by 0.63 to reduce them to Huancayo. The difference between the daily mean at Huancayo and the reduced daily mean at Teoloyucan was found for each day of the ten months. The standard deviation of single differences about their average for the month was found to be 0.24% from pooling the ten samples of one month each. Assuming equal variance for statistical fluctuations at both stations, the standard deviation for the statistical fluctuations in single daily means is only 0.17%, which is slightly less than the figure of 0.2 derived from the fluctuations of daily means from the monthly means for Huancayo in 1944. The standard deviation of the ten monthly mean differences about their average is about three times greater than would be expected from the fluctuations in the differences in daily means. This may indicate some small systematic change which would arise if the seasonal variations at Teoloyucan deviated from a pure 12-month wave. It will be shown later that variations arising from non-world-wide changes are much greater at the other stations than at Huancayo and Teoloyucan and that the data from Huancayo and Teoloyucan provide more reliable measures of the world-wide component than do those from the other stations. The absence of any significant seasonal variation at Huancayo is further indication that the vertical distribution of air-mass there must vary little with season.

Comparison with neutron results—Figure 8 is a comparison of the variation of daily means for June 1951 from the Compton-Bennett meter at Huancayo and those published [7] by Simpson from neutron counters at Sacramento Peak, New Mexico. The standard deviation (s.d.) of the differences between daily means from the Compton-Bennett meter at Huancayo and those from the neutron counters (multiplied by 0.389) at Sacramento Peak is about 0.25%. The series is too short to determine whether there are systematic changes in background in either instrument involved. The occurrence of any such changes results in increasing the s.d. If the value of 0.17% is accepted for the s.d. of single daily means from the monthly average at Huancayo, then from the value of 0.25% for the s.d. of differences between the Huancayo daily means and those for neutrons in June 1951, the s.d. of daily means for the latter is found to be about 0.19%, in the reduced neutron units. Or, the s.d. of the neutron daily means would be $0.19/0.389 = 0.49\%$. Since this figure is many times greater than would be expected in view of Simpson's high neutron counting rate, it is evident that during the period of this comparison one of the two instruments was subject to variations, either real or instrumental, which did not affect the other. Since the Instituto Nacional de la Investigacion

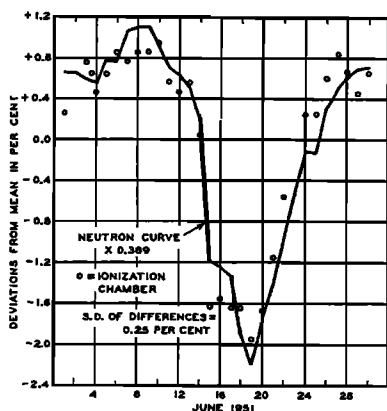


FIG. 8—COMPARISON NEUTRON DAILY MEANS (NEW MEXICO) WITH THOSE FROM IONIZATION CHAMBER AT HUANCAYO

Cientifica and the University of Mexico, Mexico, D.F., are now collaborating (since September 1, 1954) with the Department of Terrestrial Magnetism in the operation of a Compton-Bennett meter at the University of Mexico, Mexico, D.F., it will be possible in future comparison with neutron results to determine definitely whether there are variations in neutron values at New Mexico which do not occur at Huancayo or Mexico.

Comparison with results from balloon-borne ionization chambers—Figure 9

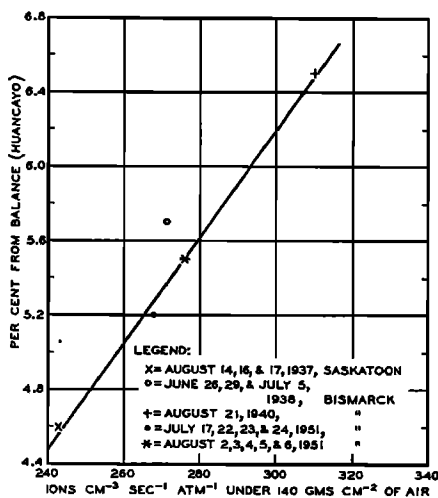
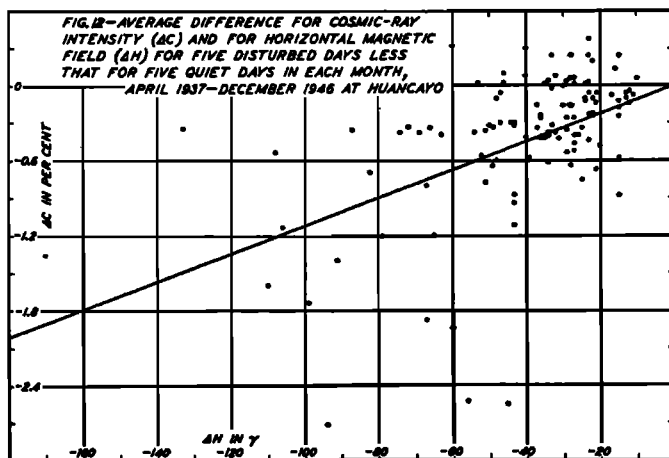
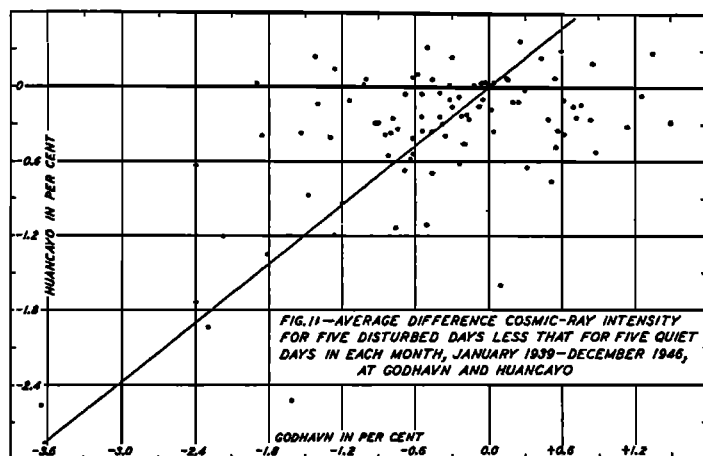
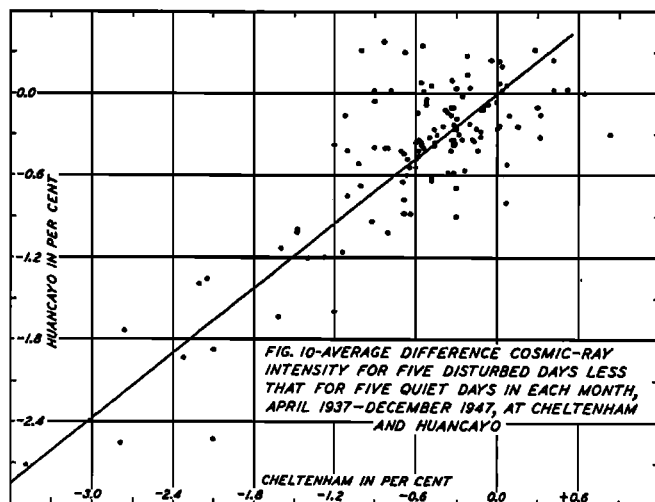


FIG. 9—COSMIC-RAY INTENSITY AT HUANCAYO AS FUNCTION OF INTENSITY FROM BALLOON-BORNE IONIZATION CHAMBERS

indicates a comparison between the changes in ionization at Huancayo and those obtained by Neher, *et al.* [8, 9], from balloon-borne ionization chambers under 140 gms cm⁻² of air. The values for Huancayo are averages for those days in each of five different years on which the balloon flights were made. Comparing Neher's curve of ionization, as a function of the amount of the air overhead, for June-July

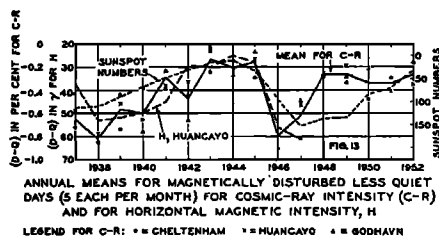


1938 with that for August 1951 (Fig. 3 of reference 8), it is seen that the two agree for an amount of air overhead greater than about 140 gms cm^{-2} , but for less than 140 gms cm^{-2} the curves start to diverge considerably. For this reason, the ionization at 140 gms cm^{-2} was used in the comparisons with the Huancayo data. It would be of interest to obtain ionization-data from balloon flights which would involve a greater range in intensity at Huancayo than that of Figure 9. For example, with flights near sunspot minimum and maximum, a range of five per cent (if Fig. 3 is typical) could readily be realized. A further extension of range could be effected by flights during a period of large decrease which occurs during some magnetic storms. It would also be valuable to know whether decreases in intensity are observed from balloon flights during magnetic storms when no decrease is observed at Huancayo.

Cosmic-ray effects and geomagnetic activity

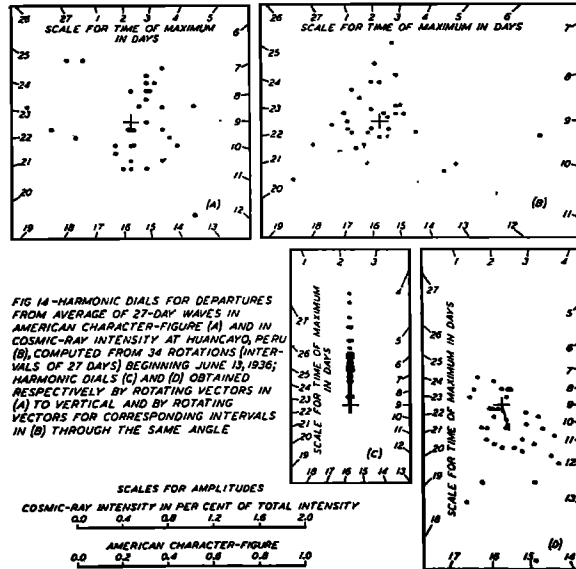
Cosmic-ray intensity for magnetically quiet and disturbed days—Figures 10 and 11 indicate, respectively, for Huancayo and Cheltenham, and Huancayo and Godhavn, the correlation between the average difference of cosmic-ray intensity for the five magnetically disturbed days of each month less than that for the five quiet days. It is evident from Figure 10 that the frequency of positive values of the differences for Huancayo is only about one-fifth that for negative values, which indicates definitely that the cosmic-ray intensity tends to be less for the five magnetically disturbed days than for the five quiet days. It is evident from Figures 10 and 11 that the correlation between the differences for Huancayo and Godhavn is less than for Huancayo and Cheltenham. This, as will be shown later, is probably due to greater variations in vertical air-mass distribution at Godhavn as compared with those at Cheltenham.

Cosmic-ray intensity and magnetic horizontal intensity for disturbed minus quiet days—Figure 12 indicates the relation between the differences, disturbed minus quiet days, for cosmic-ray intensity and magnetic horizontal intensity at Huancayo. The differences are always negative for the horizontal intensity and preponderantly negative for cosmic-ray intensity at Huancayo. The correlation coefficient for data of Figure 12 would obviously be low. This is expected from the fact that the ratio between changes in cosmic-ray intensity to those in horizontal intensity is



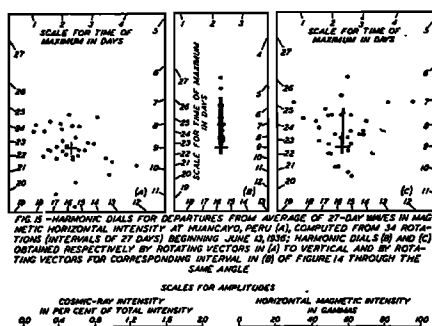
known to vary from one storm to another [6]. Figure 13 indicates the variation in the annual means, for disturbed minus quiet days, in cosmic-ray intensity at three stations and in horizontal intensity, H , at Huancayo. Values for H were unavailable after 1947.

Twenty-seven day waves in cosmic-ray intensity, magnetic activity, and horizontal intensity—For completeness, Figures 14 and 15, published previously, are included here [10]. Figures 14 (A) and (B) are harmonic dials, indicating the departures from the average 27-day wave for American character-figure and for cosmic-ray



intensity at Huancayo, respectively. Figures 14 (B) and (C) were obtained, respectively, by rotating the vectors in (A) to vertical and by rotating vectors for corresponding intervals (of 27 days) through the same angle. Statistical tests show that the probability, P , of obtaining an average vector as large or larger than that in Figure 14 (D) in a sample of 34 vectors from a population in which the components of the vectors are independent and random, with standard deviations estimated from the 34 vectors in (D), is only about 2×10^{-6} . This indicates that the vectors in (A) and (B) definitely tend to have similar phases. Furthermore, the phases in (C) and (D) of Figure 14 indicate that the maxima of the 27-day waves in cosmic-ray intensity tend to occur near the minima of the 27-day waves in magnetic activity, as measured by the American character-figure. Figure 15 indicates the results of a similar comparison between magnetic horizontal intensity and cosmic-ray intensity at Huancayo. For (C) of Figure 15, the probability, P , is 7×10^{-5} , indicating correlation between the phases of the vectors in (A) and (B) of Figure 15. Here it will be noted that the maxima of the waves in cosmic-ray intensity and those in horizontal intensity tend to be in phase, which is consistent with the results in Figure 14, since low values of horizontal intensity occur at times of high magnetic activity.

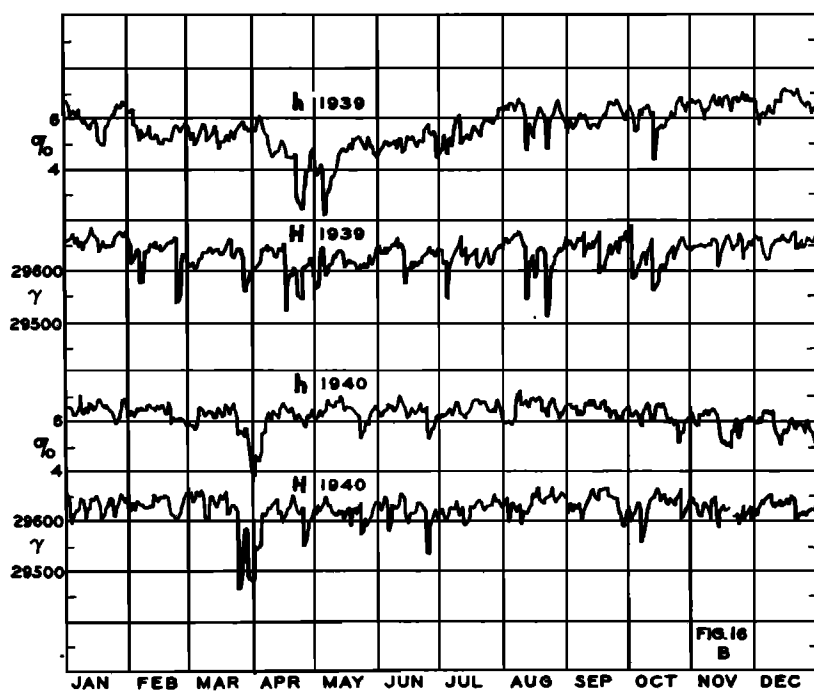
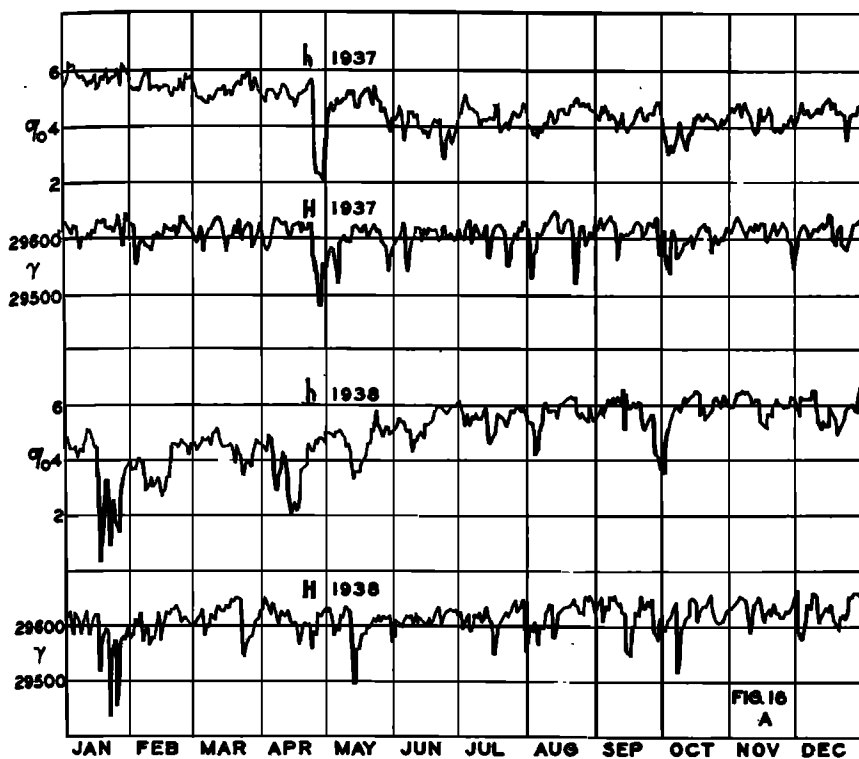
Variations in daily mean cosmic-ray intensity at Huancayo, 1937-1953, compared with variations in the earth's magnetic field and with cosmic-ray variations at other stations for selected years—Inspection of the graphs of cosmic-ray intensity for Huancayo in Figure 16 indicates a marked difference in the variability of daily

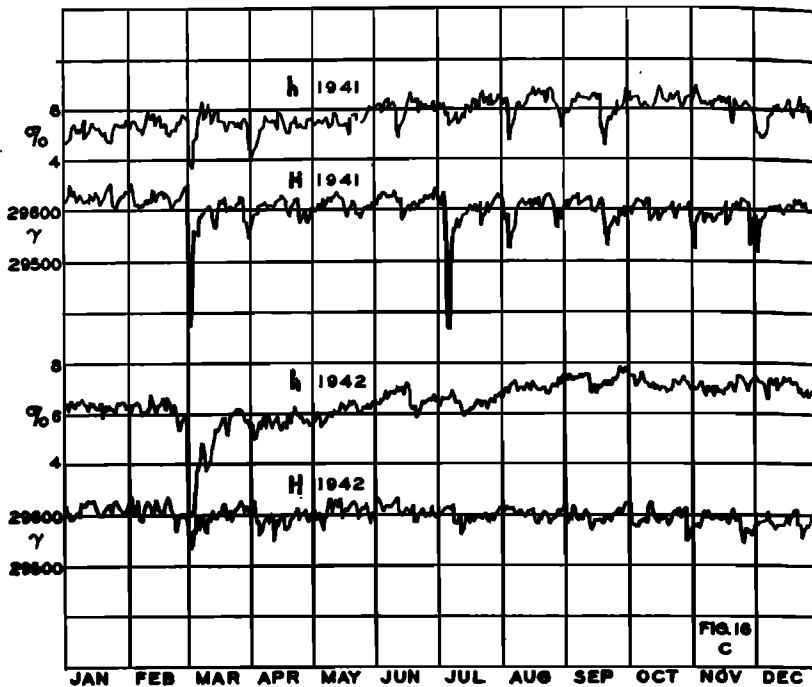


means in different years, which is particularly evident if the curves for 1944 are compared with those for 1946 and 1947; this variability was shown quantitatively in Figure 7. During 1946 and 1947, there were large variations at Huancayo, which in general follow those at Cheltenham, Godhavn (1946 only), and Christchurch (1946 only). There is, of course, the large increase at Godhavn, and Cheltenham on July 25, 1946, which occurred during a large solar flare on that date, and which is absent at Huancayo, and at Christchurch where the meter was out of operation for eight days starting July 23. On the other hand, a comparison of the graphs for the four stations for 1944 shows that the variability of the daily means is decidedly less at Huancayo than at the other three stations, and that the variability is greatest at Godhavn. Moreover, the major variations at Godhavn, Cheltenham, and Christchurch during 1944 were seen (by overlaying the original curves) to be essentially uncorrelated. At Cheltenham, and to some extent at Godhavn, the larger variations in 1944 (which were absent at Huancayo) occurred more often in winter than in summer. At Godhavn and at Cheltenham, it was found that the large variations in 1944 generally occurred during periods when the barometer was changing rapidly. These large variations are thus probably due to changes of the vertical air-mass distribution accompanying the movement of a front over the station and the consequent effects arising from meson decay. Although smaller variations occurring at Huancayo are often obscured at the other stations by this meteorological effect, it has already been shown in Figures 5 and 6 that the averages of a sample of such variations are very nearly the same at all four stations.

Figure 16 also shows the daily mean values of the horizontal magnetic component (H) at Huancayo, 1937-47, from which it can be seen whether decreases in (H), which occur during magnetic storms, are accompanied by decreases in cosmic-ray intensity. From these graphs, a tabulation showed 48 cases (1937-47) when from one day to the next a decrease, in H , of 75 gammas or more occurred. In 36 of these cases, the change in cosmic-ray intensity at Huancayo was negative, although in only 22 cases was the decrease in cosmic-ray intensity greater than

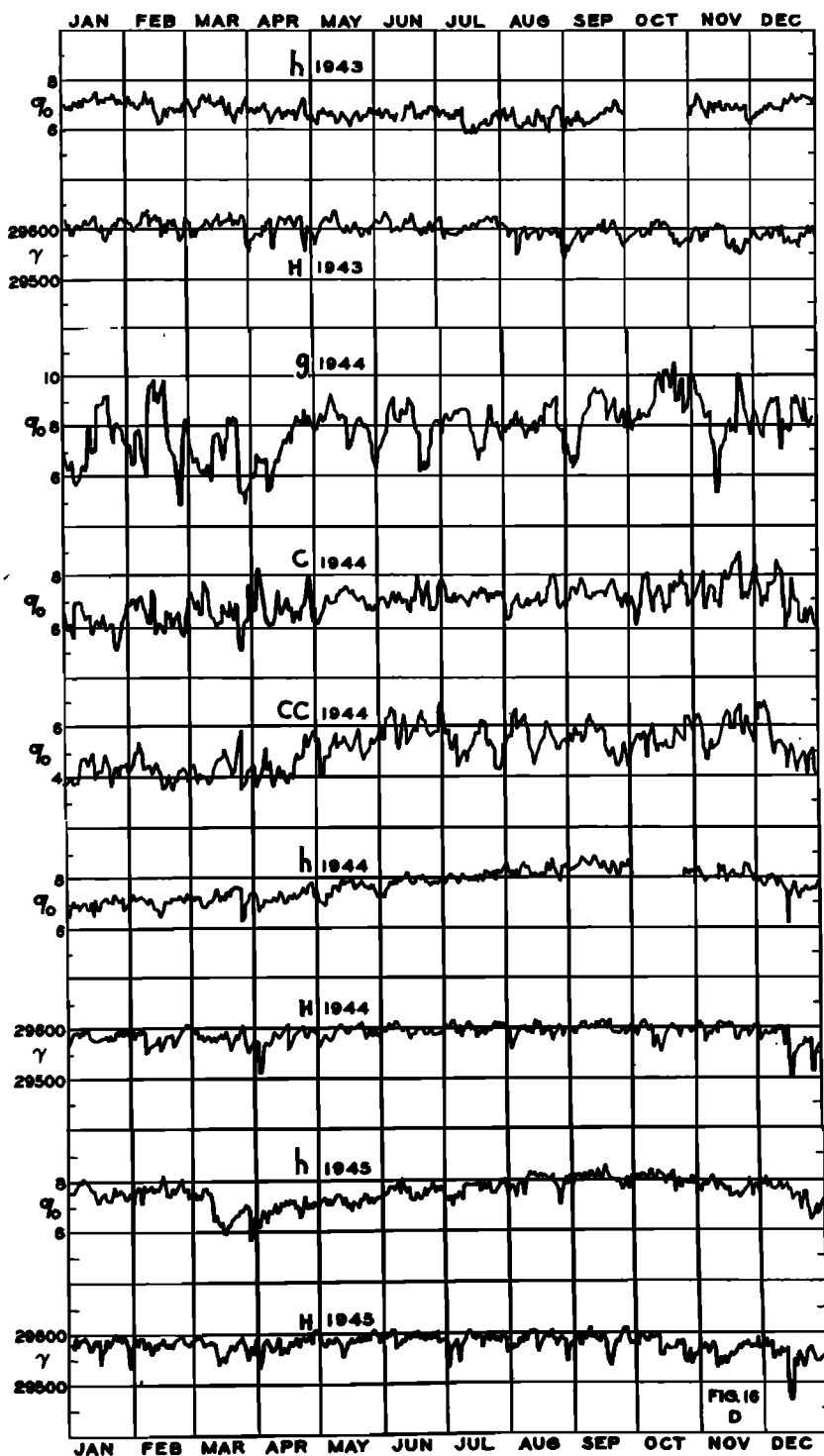
FIG. 16 (A to F)—Daily means cosmic-ray intensity: for Huancayo 1937-1953 (h), for Cheltenham 1944, 1946, and 1947 (c), for Godhavn 1944 and 1946 (g), and for Christchurch 1944 and 1946 (cc); and daily mean horizontal magnetic component at Huancayo 1937-1947 (H). (Note: h , c , H on 75° WMT, g on 45° WMT, and cc on 172.5° EMT; h , c , g , and cc in per cent above fiducial values.)

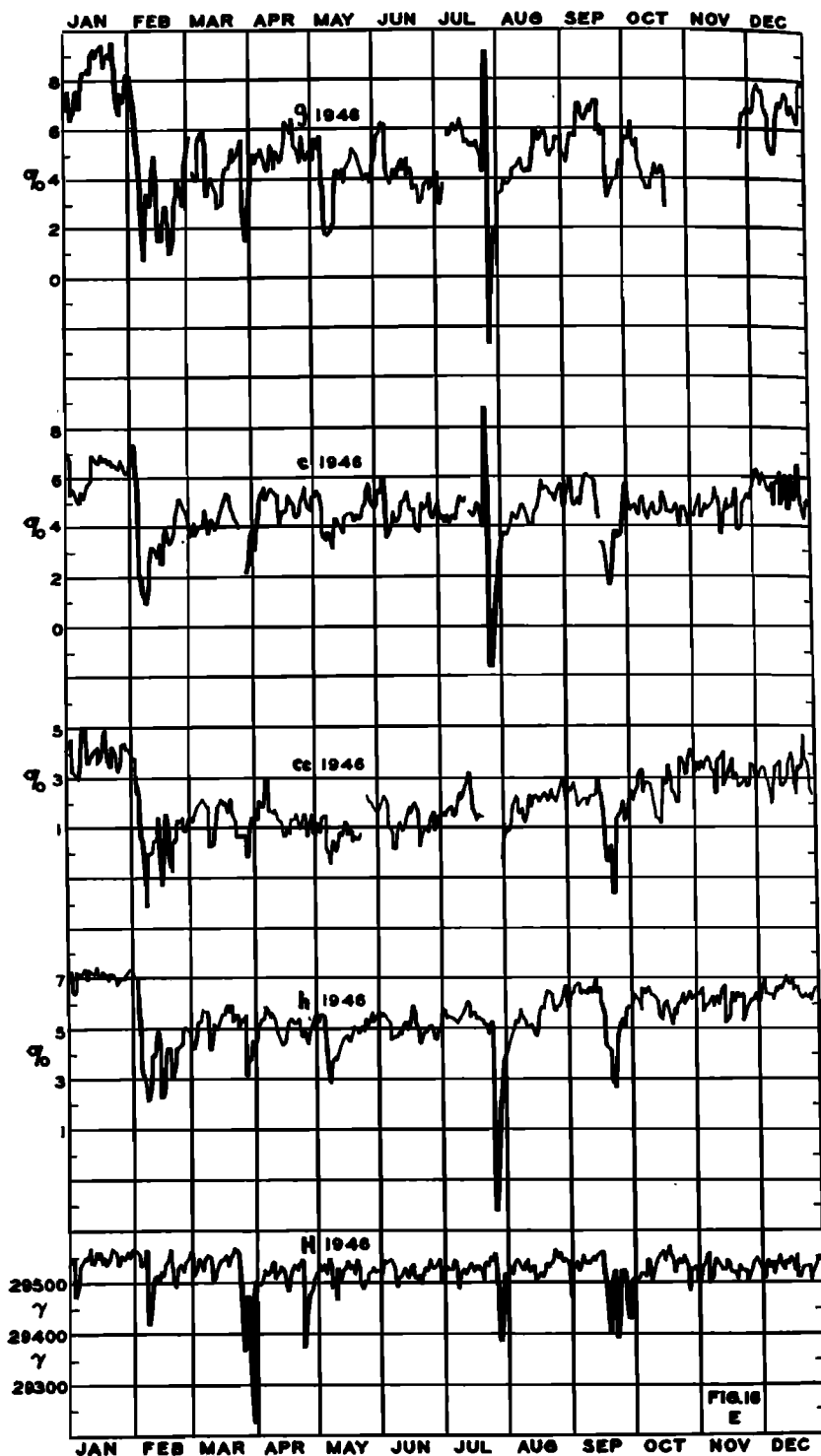


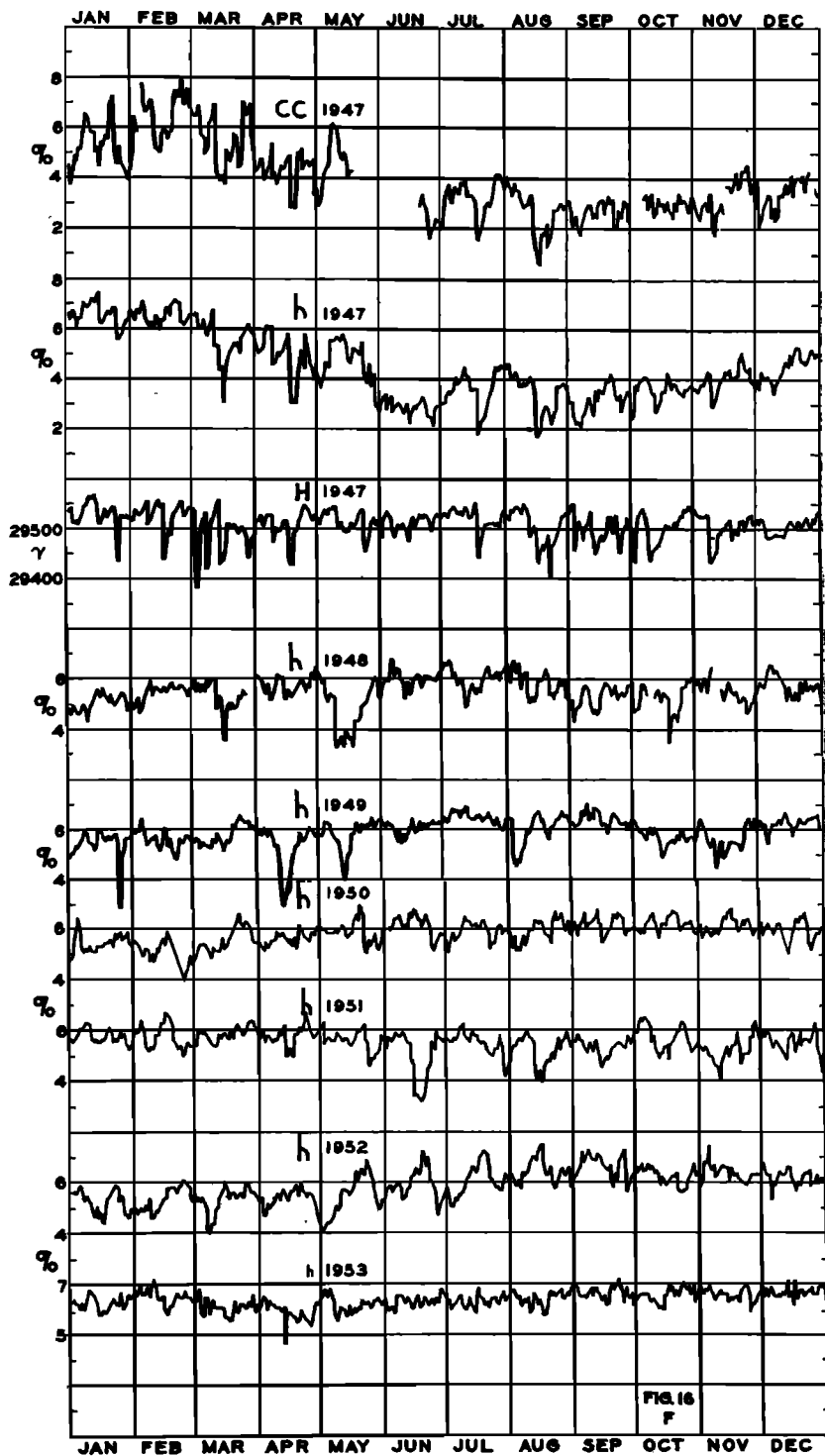


0.4%. The graphs were also used to tabulate the dates between which the daily means of cosmic-ray intensity at Huancayo decreased continuously (successive days with no change were included) for a total decrease of 1.0% or more. There were 92 such intervals from 1937 to 1947. The change, ΔH , in daily mean horizontal magnetic intensity at Huancayo from the first to the last day of each of the above-selected intervals was also tabulated; in 71 (out of 92) of the intervals, ΔH was negative. Examination of magnetograms for Huancayo (Peru) and Watheroo (Australia) indicated magnetic disturbance in most of the 21 cases for which ΔH was either zero or positive. It thus seems evident that during most of the periods when the cosmic-ray intensity at Huancayo is decreasing there is evidence for magnetic disturbance, which suggests that the cause of the cosmic-ray decreases is quite probably connected with the mechanism giving rise to magnetic disturbance.

Finally, in this connection, attention should be called to the graphs of daily means for cosmic-ray intensity and magnetic horizontal intensity, H , for February 1946 in Figure 16. Between February 3 and 6, 1946, the five per cent decrease in cosmic-ray intensity at Huancayo was accompanied by only a small decrease in H , while the large decrease in H after February 6 was accompanied by only a small further decrease in cosmic-ray intensity. There was at Huancayo and Watheroo a marked magnetic sudden commencement at 08^h42^m 75° WMT a few hours before the start of the decrease in cosmic-ray intensity. Attention should also be called to the fact (see also Fig. 3) that after February 6, 1946, both the cosmic-ray intensity and H at Huancayo remained low during the rest of the year. While it seems clear that most of the decreases in cosmic-ray intensity occur during







periods of magnetic disturbance, no measurable characteristic of magnetic disturbance has yet been found which is quantitatively well correlated with changes in cosmic-ray intensity.

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