Cosmic Radiation Intensity-Time Variations and Their Origin. V. The Daily Variation of Intensity*

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Properties of the 24-hour intensity variations which were established by ion chamber and counter telescope measurements at high primary-particle energies have now been extended to the low-energy portion of the primary spectrum by measurements with high-altitude neutron piles at geomagnetic latitudes 0° and 48°. The observations demonstrate that the peak-to-peak amplitude of the 24-hour variation increases with latitude and, hence, is dependent on primary-particle rigidity. The latitude ratio for the peak-to-peak variation is $\sim 1.4 \pm 0.2$ and the amplitude at 48° is of the order 1 percent. These facts preclude primary neutrons or a general solar dipole field as the origin of this intensity variation.

It is shown that although the amplitude of the variation changes from day to day, the amplitudes of the intensity variations of particles at low and at high energy are related. It is further shown that the amplitude on one day persists for only the next 1 or 2 days and that there is not a strong 27-day recurrence tendency.

The general features of the changes in peak-to-peak amplitudes of the monthly average 24-hour variations appear in both neutron detectors and in the Freiburg ionization chamber. Arguments based on the experimental observations are presented to exclude meteorological factors, the terrestrial magnetic field variations, and simple geoelectric field accelerations as the origin of the variation. Since it is shown that the particles which produce the 24-hour variation are charged and have their highest intensity near or after noon local time, it does not appear probable that they come from the direction of the sun. Although it is doubtful that this variation is of terrestrial origin, no proof has yet been given that the variation is of extra terrestrial origin.

I. INTRODUCTION

THE following experimental facts concerning cosmic-ray intensity variations within 24-hour periods, as measured by detectors deep in the atmosphere, are now well established.

a. Existence.[1–7] On the average the intensity near noon is greater than the intensity near midnight. The amplitude of the variation has an average value of ≈ 0.2 percent for shielded ion chambers, ≈ 0.4 percent for counter telescopes, and ≈ 1.0 percent for local production neutron detectors. The variation is present after the data are carefully corrected for atmospheric effects.

b. Variability with time.[4–9] The amplitude of the daily variation is not constant, and the changes which occur in the amplitude are world-wide in extent, both for the day to day changes and for the long time changes in the average values.

Some facts which are less well established than these two are the following:

c. Association with the geomagnetic field.[4,5,8,9] The amplitude and perhaps the time of maximum of the daily variation are related to the occurrence of geomagnetic field disturbances. The amplitude tends to be larger during times of disturbances than during quiet periods.

d. Energy dependence.[6,7,9] Both the amplitude of the daily variation and the changes which occur in this amplitude are energy dependent, being larger when measured by a low-energy detector (neutron monitor) than when measured with a high-energy detector (charged particle detector). The variation exists at Huancayo, near the magnetic equator, and the changes in the monthly averages of amplitude also appear there. Hence the variation and its changes extend to high energy—greater than 13 Bev if produced by primary protons.

The preceding summary represents mostly observations obtained with ion chambers or counter telescopes deep within the atmosphere, and, therefore, the effects of intermediate- and high-energy particles in the primary-particle spectrum. We have shown that the measurements of intensity variations may be extended to much lower mean primary energies by measuring the local neutron production from the nucleonic component.[10] Intensity variations of primary particles down to ~2-Bv rigidity may be observed at large atmospheric depths, and we have already reported the existence of the 24-hour intensity variation in the neutron component.[6,7] In this paper we shall present a preliminary report on the properties of this variation as a function of primary particle rigidity and show

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[1] F. Lindholm, Gerlands Beitr. Geophys. **20**, 12 (1928).
[2] S. E. Forbush, Terrestrial Magnetism and Atm. Elec. **42**, 1 (1937).
[3] A. R. Hogg, Mem. Commonwealth Obs. **2**, No. 5 (1949).
[4] H. Elliot and D. W. N. Dolbear, J. Atm. and Terrest. Phys. **1**, 205 (1951).
[5] A. Ehmert and A. Sittkus, Z. Naturforsch. **6a**, 618 (1951).
[6] Fonger, Firor, and Simpson, Phys. Rev. **89**, 891 (1953).
[7] W. H. Fonger, Phys. Rev. **91**, 351 (1953). Hereafter we refer to this paper as reference II.
[8] Sekido, Yoshida, and Kamiya, Report Ionos. Res. Japan **6**, 195 (1952).
[9] V. Sarabhai and R. P. Kane, Phys. Rev. **90**, 204 (1953).
[10] Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953). Hereafter we refer to this paper as reference I.

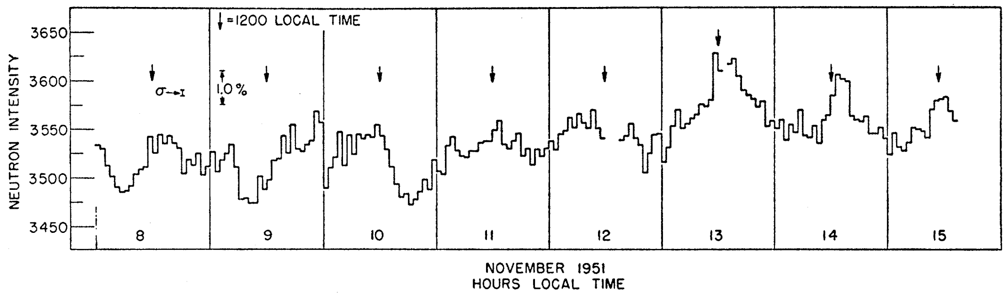

FIG. 1. Hourly values of local neutron production in pile D-3 for the period November 8–15, 1951. The standard deviation and the magnitude of a 1 percent change of intensity are shown. The local time is 106°W. meridian time. The arrows indicate 1200 hour.

that these results restrict the possible hypotheses for the origin of this variation.

Two additional properties of neutron intensity measurements are important for studying the 24-hour variation. First, the counting rate is high and second, there is no observed temperature coefficient. This latter property is especially useful in view of the difficulties encountered by charged particle detectors in removing effects of meteorological origin.

The results in this paper are based on data from the neutron pile monitors located at Huancayo, Peru (Station H-1, $\lambda \approx -0.5°$ and mean atmospheric depth $\bar{x} = 694$ g-cm^{-2}) and Climax, Colorado (Stations D-1 and D-3, $\lambda = 48°$N and $\bar{x} = 672$ g-cm^{-2}.) For further details on the instrumentation and the method of measurement the reader is referred to reference I. All data are corrected for barometric pressure variations; even though the pressure coefficients are well established by experiments the peak to peak amplitudes of the corrected curves of intensity variations are insensitive to changes in the pressure coefficient as large as 20 percent.

For observations at mean primary particle rigidities higher than obtained with a neutron pile at $\lambda = 0°$ we shall use the data published by Sittkus for a shielded ionization chamber.[11] The instrument and its temperature and pressure coefficients have been described elsewhere.[12]

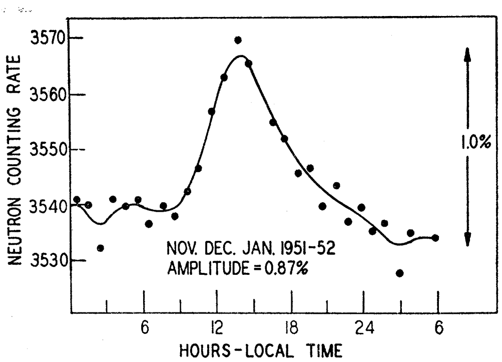

FIG. 2. The average 24-hour variations of neutron intensity for the months November-December, 1951, and January, 1952, for pile D-3.

In the following sections we shall first consider the behavior of the 24-hour variation, averaged over extended intervals of time, and then report on the individual day characteristics.

II. THE AVERAGE 24-HOUR VARIATION

A typical interval of several days is sufficient to indicate the variable character of the 24-hour cosmic-ray intensity variation. For example, the hourly values of the D-3 neutron pile counting rate for 7 consecutive days is shown in Fig. 1. Clearly the character of the 24-hour variation is changing day by day and the average 24-hour variation over these days will not represent any of the individual days. In Fig. 2 the average intensity curve for the months November, December, 1951, and January, 1952, displays the outstanding feature of the averaged 24-hour variation; namely, there is an intensity maximum somewhat after local noon.

Although there are difficulties in interpreting the "average" behavior of this variation over extended intervals of time we have examined the changes of the peak-to-peak amplitude of monthly average 24-hour variations to search for changes of amplitude at different times of the terrestrial year. The average peak-to-peak amplitude of the variation for each month between May, 1951, and March, 1953, was prepared for piles D-1 and D-3, from all the data available on pile H-1, and from the Freiburg ionization chamber for the same 2 year period. The results are shown in Fig. 3. We note that (1) there are continuous changes in the monthly averages of the peak-to-peak amplitude, and (2) these changes are observed in all detectors. Hence, we conclude that this month by month change in the average amplitude of the variation is observed over a wide range of primary particle energy. Since seasonal meteorological effects are negligible for the neutron pile H-1 ($\sim$12°S. geographic latitude), and since the temperature coefficient for a local neutron production detector can at most be only a small fraction of the

[11] Ionization intensity records published quarterly by A. Sittkus in the "Sonnen-Zirkular" of the Fraunhofer Institute, Freiburg-in-Baden, Germany, 1951–1952.

[12] A. Sittkus, Z. Naturforsch. 1, 204 (1946).

charged particle coefficient, we do not ascribe this variation of the monthly peak-to-peak amplitude to meteorological factors.

III. BEHAVIOR ON INDIVIDUAL DAYS

To study the amplitude of the intensity variation which occurs on a single day, Fonger[7] adopted a procedure which gives a measure of the amplitude of variations in phase with the *mean* 24-hour cycle. This measure, called D, is the difference in intensity of a period near noon and the average of two periods, one from the preceding night and one from the succeeding night. The time limits chosen for these periods are so adjusted that, for the mean daily cycle the ratio of D to the statistical error in D is a maximum. Figure 4 gives an example of a mean daily cycle for a 3 month period and the times used to compute D values for the individual days in the period.

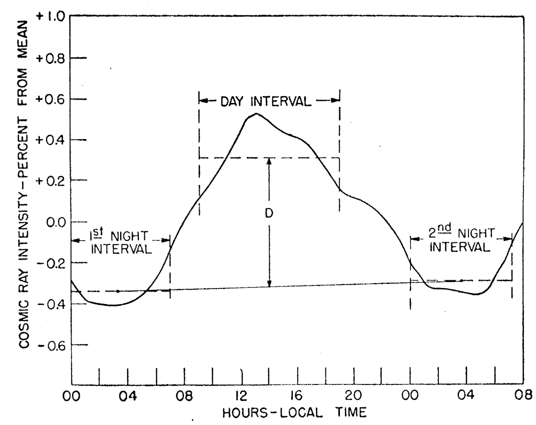

FIG. 4. The mean daily cycle for the period July-October, 1951, using pile D-1. The procedure for computing the difference, D, between the daytime and nightime intensity is shown.

a. The Persistence of the 24-Hour Variation

It is clear from Fig. 1, and similar figures given by Ehmert and Sittkus[5] and Sekido *et al.*,[8] that the amplitude of the 24-hour variation changes from day to day. One question of interest in this connection is: is the amplitude of the variation on one day related to the amplitude the next day, or τ days later? To investigate this question the autocorrelations of the D values for two periods (July–October, 1951, and January–April, 1952) have been obtained and are shown in Fig. 5. Clearly the changes from the mean amplitude which are in phase with the mean cycle persist for only a day or two, and do not have a strong 27-day recurrence tendency as do the daily averages of intensity.[7]

It is obvious from this lack of persistence that two identical detectors separated by many hours in local time will not observe identical 24-hour variations in local time. Thus the 24-hour intensity variation is a continuously changing local time effect.

b. Energy Dependence of the Daily Variation

To investigate the dependence of the daily variation on mean primary-particle energy, we have selected the neutron piles located at $\lambda=0°$ and $\lambda=48°$. These detectors are separated by only 2 hours in local time. The measurements with pile H-1 at 0° are limited at present by the precision of the barometric pressure corrections. Hence, rather than compare single-day amplitudes at $\lambda=48°$ with single-day amplitudes at $\lambda=0°$ we select small groups of days in order to study with greater precision the change in amplitude with geomagnetic latitude. Using an interval of 76 days at $\lambda=48°$, the individual days were listed in descending order of D values. Five groups of days were formed beginning with group a as the 17 days of largest D value, group b as the next largest 10 days, and so forth. Within each group the average intensity for each hour of the 24-hour period was obtained for the D-3 pile. These same days were then used to obtain corresponding average 24-hour curves for the H-1 pile. The curves for groups a through e at both latitudes are shown in Figs. 6, 7, 8, 9, and 10. These results along with the already reported correlation of the daily intensity variation at Climax with the ion chamber at Freiburg, demonstrate that the amplitude variation of the daily variation appears over a wide range of the primary

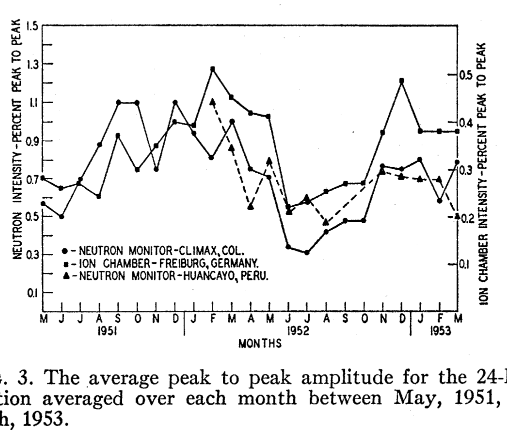

FIG. 3. The average peak to peak amplitude for the 24-hour variation averaged over each month between May, 1951, and March, 1953.

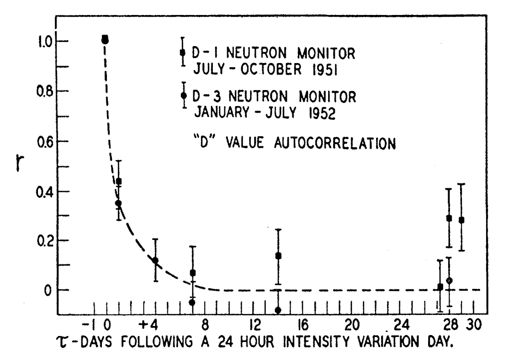

FIG. 5. The persistence of the amplitude of the 24-hour variation is shown for two independent periods; one for pile D-1, the other for pile D-3. There does not appear to be a strong 27-day recurrence tendency.

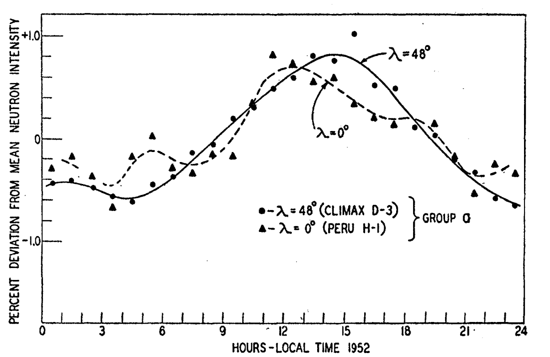

FIG. 6. The 24-hour variation for the 17 days of largest peak-to-peak amplitudes as determined by pile D-3. See also Table I.

spectrum. Since only a small number of days were selected for each group, this conclusion may be safely extrapolated to describe the most probable individual-day behavior at these latitudes.

In view of the response of neutron piles to primary radiation at low energy discussed in references I and II, we can state that the primary radiation spectrum with mean energy at least as low as $\sim$5 Bev undergoes this daily variation. The dependence of daily variation amplitude upon latitude and, hence, upon primary particle rigidity can only be estimated at this time. From the data in Figs. 6 and 7 the ratio of peak to peak amplitude variation at 48° and 0° is 1.4 ± 0.2. This shows that the amplitude of the 24-hour variation is dependent upon primary particle energy. We assume primary particles of $z\geq 1$ participate in the intensity variation.

IV. ON THE ORIGIN OF THE DAILY VARIATION

Although we are not prepared to describe a theory which will account for the daily variations, we now have sufficient evidence from the combined results of the neutron intensity and charged particle intensity observations to discard some hypotheses which have been proposed to explain the origin. We shall consider some of them here.

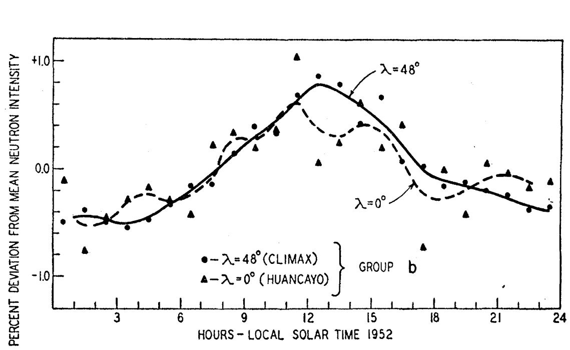

FIG. 7. The 24-hour variation for the 10 days comprising the second largest peak-to-peak amplitudes as determined by pile D-3. See also Table I.

a. A 24-Hour Atmospheric Temperature Cycle

The neutron detector with its negligible temperature coefficient displays larger 24-hour intensity variations at $\lambda=0°$ and $\lambda=48°$ than the shielded ion chamber which has a temperature coefficient. As shown in reference I the largest fraction of temperature sensitive links in the nucleonic component occur at high energy, and if sufficient in number would lead to a measureable negative coefficient. Thus the largest effect, if it existed, would occur at $\lambda=0°$. The mean daily atmospheric temperature cycle is known in tropical regions to have a maximum near noon at all altitudes.[13] Thus, if the neutron detector H-1 were only influenced by these temperature links in the nucleonic component a series of small noon day intensity *minima* would have been observed. This does not agree with the experimental observations.

Also, the similar behavior of the detectors at 0° and 48° over extended periods of time precludes meteorological factors as the origin of the variation.

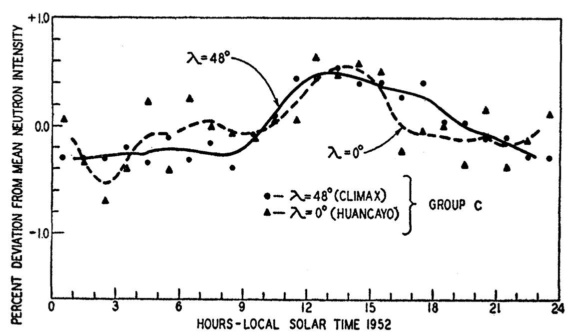

FIG. 8. The 24-hour variation for the 12 days comprising the third largest peak-to-peak amplitudes as determined by pile D-3. See also Table I.

b. A General Solar Dipole Magnetic Field

Recent evidence indicates that the general solar dipole moment is probably less than $\sim 6\times 10^{32}$ gauss-cm^3. If we assume, however, that it is a factor of ten larger there may be an appreciable effect due to the solar cone from Stoermer theory which limits the permitted particle trajectories reaching the earth. There will be a 24-hour variation of the combined solar and terrestrial cone effect which could produce a small 24-hour diurnal variation. However, this effect is strongly dependent on particle energy, and it has been shown by Vallarta[14] that there is no effect for protons of energy greater than 6 Bev. Consequently this effect would not be observed by a neutron detector at $\lambda=0°$ for protons or particles of $Z\geq 2$. Clearly the 24-hour variation which we report in this paper for particles of energy ≥ 13 Bev is the same order of magnitude as

[13] H. Riehl, Bull. Am. Meteorol. Soc. 28, 311 (1947).
[14] M. S. Vallarta and O. Godart, Revs. Modern Phys. 11, 180 (1939) and references therein.

for primary particles of much lower energy as shown in IIIb.

c. Primary Neutron Emission from the Sun

If we assume that a stream of particles of cosmic-ray energy approaches the earth from the direction of the sun, then it might also be assumed that high-energy neutrons are part of the cosmic radiation. Since neutrons are not deflected by the geomagnetic field, the most probable impact point on the earth is local noon irrespective of latitude. We shall assume the case where the equatorial plane lies in the plane of the solar system.

It is well established (reference I) that the latitude factor of increase for the nucleonic component is 2.4 between $\lambda=0°$ and $\lambda=48°$ for $x\approx600$–700 g-cm^{-2}. Consequently a 1 percent noon peak at $\lambda=0°$ due to a plane source of neutrons from the direction of the sun would appear as a 1 percent/2.4=0.42 percent effect at $\lambda=48°$ neglecting the oblique absorption of the primary neutrons at this latitude. However, since the observations are made deep within the atmosphere the intensity observed at high-latitude stations must be corrected for absorption at oblique incidence. This

TABLE I. Neutron pile *D*-3. $\lambda=48°$.

Group	Peak-to-peak amplitude	K_p day average
a	1.4%	33.8
b	1.2%	27.0
c	0.7%	27.8
d	0.5%	23.8
e	0.3%	22.7

further reduces the effect at $\lambda=48°$ ($\sim$39° geographic) to $0.42(0.2)\approx0.08$ percent. Thus the ratio of the amplitudes at Climax to the amplitude at Huancayo would be 8×10^{-2}, whereas the neutron measurements given in part IIb show that this ratio is approximately 1.4. We conclude that primary neutrons in the cosmic radiation do not account for the main features of the daily variation. For a mixed beam of neutrons and protons a peak in the region of the 0400-hour local-time impact zone[15] could be expected at $\lambda=48°$.

d. Modulation by Geomagnetic Field Disturbances

It has been pointed out that the amplitude of the daily variation is enhanced during periods of geomagnetic field disturbances.[4,5,8,9] We may further illustrate this effect by using the 5 groups of days studied in IIb. For the groups of days at $\lambda=48°$ the average values of K_p (a measure of the degree of magnetic disturbance)[16] have been determined with the results shown in Table I. Clearly there is a significant decline of geomagnetic activity with decreasing amplitude of the daily variation.

[15] J. W. Firor, Phys. Rev. 94, 1017 (1954).
[16] J. A. Simpson, Phys. Rev. 94, 426 (1954).

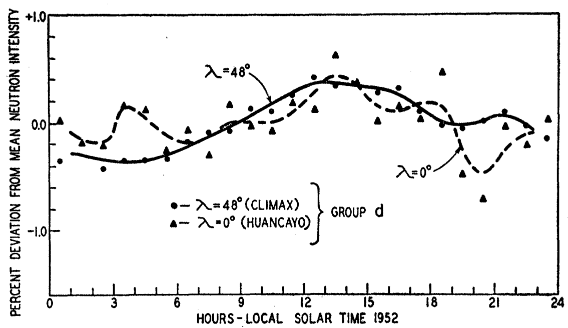

FIG. 9. The 24-hour variation for the 16 days comprising the fourth largest peak-to-peak amplitudes as determined by pile *D*-3. See also Table I.

We cannot conclude, however, that geomagnetic phenomena *produce* the variation. This physical problem may be somewhat analogous to the problem of identifying the origin of the 27-day variation,[16] i.e., the phenomena may be associated by means of a common mechanism located either near the earth or in the vicinity of the sun. In fact, there are some serious difficulties with the assumption that the geomagnetic field produces the daily variation. We may consider this problem first for the periods of undisturbed geomagnetic field variations.

1. The observed variations of the horizonaal magnetic field intensity component are believed to be the combined effect of fields produced by a westward current flow outside the ionosphere (e.g., the Chapman-Ferraro ring current) and circulating currents within the ionosphere. There is no evidence to indicate that the ring current could produce 24-hour oscillations with respect to the axis of the permanent geomagnetic field even though this axis does not coincide with the rotation axis. At present there is increasing and good evidence that the 24-hour variation of the geomagnetic field intensity arises entirely from circulating currents within the terrestrial ionosphere,[17] along with corresponding currents in the surface of the earth.

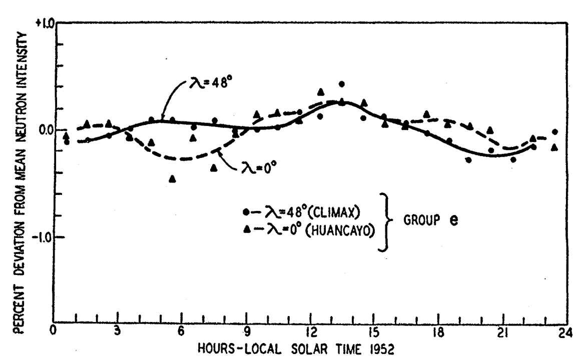

FIG. 10. The 24-hour variation for the 21 days comprising the smallest peak-to-peak amplitudes as determined by pile *D*-3. See also Table I.

[17] S. Chapman and J. Bartles, *Geomagnetism* (Clarendon Press, Oxford, 1940).

These currents are of such a character that they contribute mostly to quadrupole and higher-order terms in the geomagnetic field and are only effective over a short range compared with the dipole contributions from other mechanisms.

To estimate the effect which this 24-hour variable quadrupole field would have on cosmic-ray intensity we first compare the magnitude of this term relative to the magnitude of the equivalent quadrupole term of the permanent geomagnetic field. We calculate this latter field by considering that, for cosmic radiation, the eccentric dipole field is equivalent to a centered dipole with the addition of quadrupole and higher-order terms. We find that this quadrupole term is 5×10^2 to 10^3 larger than the equivalent quadrupole term of the 24-hour variation magnetic field.

Now the cosmic ray intensity longitude effect which is produced by the permanent quadrupole term is considered to be the order of a few percent,[18] but for the following argument we shall assume it may be as large as 20 percent for the nucleonic component since we lack precise measurements of this effect.

Then, the contribution to the cosmic ray intensity variation of the quadrupole term in the geomagnetic field daily variation is certainly less than 0.5×10^{-3} of the total intensity during undisturbed days. It is well established that for disturbed days the amplitude of the 24-hour variation of the horizontal field component increases, but not by more than a factor of 2. Consequently, we can state that the *maximum* 24-hour variation in the cosmic radiation intensity would be <0.2 percent for the neutron component. Clearly, the geomagnetic field variations cannot account for the observed 1–2 percent peak-to-peak amplitude of the daily variation.

Thompson,[19] by a different argument, reaches the same conclusion.

We have shown in IIa that the monthly average of the daily variation amplitude changes with time. These changes are, however, in disagreement with the amplitude variations of the daily magnetic field variations which are maximum in summer months and minimum in winter months.[17]

There are additional arguments which might be invoked against accepting the magnetic field as the cause of the intensity variation, but we believe that the above discussion is sufficient to indicate the nature of the difficulties.

It has already been pointed out that geoelectric fields cannot be invoked to explain the intensity variations occurring in local time due to the high conductivity of the ionosphere.[7]

V. CONCLUSIONS

We have shown that the properties of the 24-hour intensity variations, which were established by ion chamber and counter telescope measurements for the intermediate to high-energy range of the primary spectrum, are also found in the low-energy part of the spectrum. The peak-to-peak amplitude of the 24-hour variation displays a latitude dependence between the geomagnetic cut-offs at 0° and 48° which precludes primary neutrons or a general solar dipole field as the origin of the variation. From the energy dependence and other properties of the neutron observations, we present arguments to exclude meteorological factors, the terrestrial magnetic field variations, and simple geoelectric field accelerations as the origin of the variation. Although doubt is cast on the terrestrial origin of this variation, we have no proof that the variation is of extra terrestrial origin. Since we have shown that the particles which produce the energy dependence of this variation are charged, and since these particles pass through the geomagnetic field arriving at the earth near or somewhat after local noon, then, assuming that the particles carry positive charge, they would approach the earth from the direction of the eastern sky. Consequently, there would be serious difficulties in assuming that these particles have come from the direction of the sun.

The possibility exists that more than one mechanism is producing the observed 24-hour intensity variations. For example, it is possible that one mechanism produces a true 24-hour variation cycle while another mechanism modulates the amplitude of this variation.

At present we do not know whether the charged particles which undergo this variation are protons, heavy nuclei, or a mixture of both. Evidence from the high-altitude observation of heavy nuclei in photographic emulsions indicates that there is probably an effect.[20] Since observations indicating both the presence and absence[21] of the effect have been made, perhaps the effect has the properties of changing amplitude as shown in Fig. 5 for the total radiation.

We wish to thank both the staff at the High Altitude Observatory, Climax, Colorado and A. Giesecke, Jr., and H. Goller at the Instituto Geofisico de Huancayo for their excellent cooperation in maintaining the experimental apparatus.

[18] R. A. Millikan and H. V. Neher, Phys. Rev. **47**, 204 (1935); **50**, 15 (1936).

[19] J. L. Thompson, Phys. Rev. **50**, 869 (1936).

[20] V. Yngve and M. Schein, Phys. Rev. **91**, 432 (1953).

[21] Anderson, Freier, and Naugle, Phys. Rev. **91**, 431 (1953).