Cosmic Radiation Intensity-Time Variations and Their Origin. II. Energy Dependence of 27-Day Variations*

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(Received April 2, 1953)

Cosmic-ray intensity-time variations recorded in the lower atmosphere by one neutron detector (D-1, Climax, Colorado) and three ionization detectors (Freiburg, Germany; Cheltenham, Maryland; and Huancayo, Peru) are compared. Irregular intensity variations characterized by time parameters of 27 days and 24 hours are shown to occur in coincidence in the records of both types of detectors. It seems reasonable to ascribe correlated neutron and ionization intensity variations to a common origin.

It has been shown that 27-day neutron intensity variations are produced by primary intensity variations. The magnitude of these variations must be greater for low energy primaries as 27-day neutron intensity variations at Climax are ≈5 times larger than corresponding ionization intensity variations at Freiburg, Cheltenham, and Huancayo. These variations must extend, however, to high energy primaries, as their effects are observed at the geomagnetic equator. From the ≈5:1 relative response (Climax neutron to northern sea level ionization detector) one parameter describing the energy dependence of 27-day primary intensity variations can be empirically evaluated. Assuming a power law similar to that describing the energy dependence of the time average primary intensity spectrum, it is found that the amplitude of 27-day primary intensity variations is required to decrease with increasing primary energy approximately one power of energy more rapidly than the time average primary spectrum itself. The electric field acceleration process hypothesis predicts primary intensity variations with approximately this energy dependence.

Twenty-four-hour neutron (Climax) and ionization (Freiburg) intensity variations are correlated in local time. It is not certain that these variations are produced by primary intensity variations. Even if this were the case, the relative response (Climax to Freiburg) to such primary intensity variations cannot be accurately determined from the data studied here.

I. INTRODUCTION

A. Slow Irregular Neutron Intensity Variations

In this paper two types of cosmic-ray intensity-time variations are considered in detail. We first summarize features of these variations already established in the literature.

Studying the intensity of disintegration product neutrons from stars in a lead producer, Simpson *et al.*[1] found a slow irregular neutron intensity variation that appeared coincidently at three widely separated stations in the lower atmosphere. Their intensity records from Climax, Colorado, are reproduced in Fig. 1. This is a typical record from a lower atmosphere neutron station. The intensity *vs* time curve is not a constant with superimposed, occasional, marked increases and decreases but is rather a slowly and irregularly varying function with, principally, a few broad maxima and minima per month. This irregular intensity variation includes, however, a quasi-regular variation with time constant approximately equal to the rotation period of the sun. For example, Fig. 1 shows three obvious neutron intensity maxima centered about 8 August, 2 September, and 4 October, 1951—that is, about 28

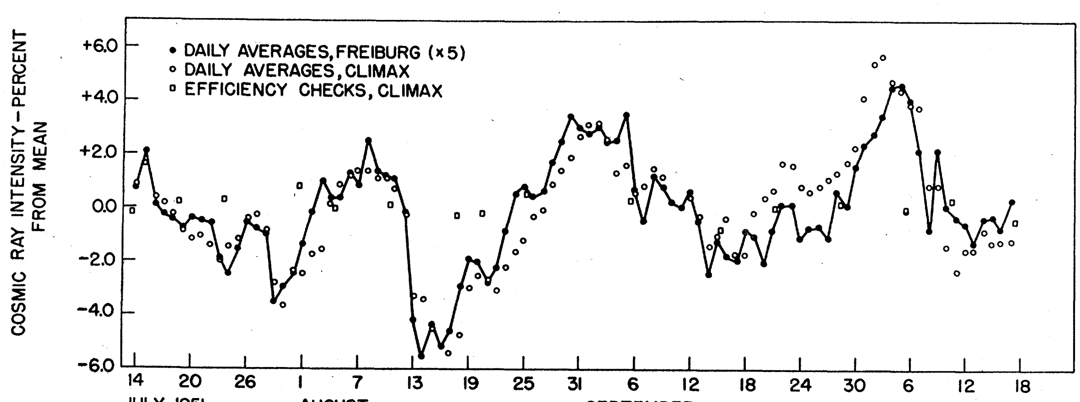

FIG. 1. Daily average cosmic-ray intensities measured by the Climax D-1 neutron detector and Freiburg ionization detector (with intensity variations multiplied by the factor 5.0) during the period 14 July through 17 October, 1951. The standard deviation of the daily intensity averages at both stations resulting from random errors is ≈0.2 percent (graph scale). The standard deviation of the efficiency checks at Climax is ≈0.6 percent, and none of these checks differs significantly from the mean.

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.
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‡ Based on a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Department of Physics, University of Chicago.
[1] Simpson, Fonger, and Wilcox, Phys. Rev. 85, 366 (1952).

days apart. Simpson *et al.*[1] related these neutron intensity maxima over six solar rotation periods with central meridian passages of active solar regions and associated the quasi-regular nature of the neutron intensity curve with changes in the locations of active regions of the solar corona. On occasion the ≈ 27-day period is very marked, and there can be no doubt that the sun somehow accounts for the principal features of the slow irregular world-wide neutron intensity variation.

In Part I[2] of this series of publications the vertical neutron intensity R_v, yield function S_Z, and primary spectrum j_Z were related by

$$R_v(\lambda, x, t)=\sum_Z \int_{N_v(\lambda,t)}^{\infty} S_Z(N, x) j_Z(N, t) dN. \quad (1)$$

At atmospheric depths where neutron intensity is decreasing exponentially, Treiman[3] showed that R_v and measured intensity R are accurately related by the Gross transformation,

$$2\pi R_v = R[1+x/L]. \quad (2)$$

In Part I the effects of atmospheric temperature variations on lower atmosphere neutron intensity were estimated and found negligible compared to the amplitude of the slow irregular world-wide variation. In Eq. (1), this corresponds to the yield function S being independent of atmospheric temperature.

Simpson[4] argued that geomagnetic field variations cannot produce large neutron intensity-time variations above the knee of the intensity *vs* latitude curve. For, if one assumes that the integral limit N_v is determined by the geomagnetic field, then a weak dependence of R_v on λ (above, say, 55°) implies that the integrand $S_Z(N, x) j_Z(N, t)$ vanishes for $N < N_v(55°, t)$ and hence that variations in the integral limit $N_v(\lambda, t)$ cannot alter the value of the integral.

Observing with neutron detectors in aircraft, Simpson *et al.*[1] found at high latitudes large intensity-time variations (in phase with the slow irregular variation observed in the lower atmosphere) above the knee of the intensity *vs* latitude curve and thus concluded the slow irregular world-wide neutron intensity variation cannot be produced by geomagnetic field variations.

Because it is not due to the atmosphere or magnetic field of the earth, these authors attributed[1] the slow irregular world-wide neutron intensity variation to a primary[2] intensity variation.

The slow irregular neutron intensity variation was subsequently observed at Mexico City ($\lambda = 29°$). Primary particles of sufficient momentum to appear at this latitude could not be influenced by the heliomagnetic field, so no temporal variation of any kind in $N_v(\lambda, t)$ could explain the slow irregular world-wide neutron intensity variation. Simpson *et al.*[5] therefore attributed it to a variation in the primary spectrum $j_Z(N, t)$ for (at least) N values greater than $N_v(29°, t)$. Hereafter, we write $N_v(\lambda, t)$ as $N_v(\lambda)$, as its temporal dependence is not pertinent for the intensity variations considered here.

B. Effective Primary Spectra

Before discussing intensity-time variations observed with charged particle detectors, we consider the responses of neutron and charged particle detectors in the lower atmosphere to primary particles of various energies.

The absorption mean free path L for neutron intensity at ≈ 680 g/cm² atmospheric depth (Climax) is independent of latitude.[2,6] At this depth the latitude curve $R_v(\lambda, 680, t)$ therefore differs from the measured latitude curve $R(\lambda, 680, t)$ only by a *constant factor.* The absolute magnitude of R_v is of no consequence in this paper so R_v in Eq. (1) will be replaced by R.

We replace the momentum-to-charge ratio N by the energy per nucleon variable E. Neglecting the small binding energy between nucleons in a nucleus and considering neutrons and protons identical, we assume S_Z can be separated into the product:

$$S_Z(E, 680) = A_Z S(E, 680), \quad (3)$$

where A_Z is the atomic weight of a nucleus of charge Z. Thus, Eq. (1) becomes[6]

$$R(\lambda, 680, t)=\sum_Z A_Z \int_{E_Z(\lambda)}^{\infty} S(E, 680) j_Z(E, t) dE. \quad (4)$$

If R and j_Z are measured simultaneously, $S(E, 680)$ may be derived[2,3] for $E < E_{Z=1}(0°)$ and may then be projected to higher energies by reasonable extrapolations.

Although R and j_Z have not been measured simultaneously the yield function relation is valid for time average values $\bar{R}$, $\bar{j}_Z$, and we calculate S under the assumption that the values reported in the literature are time average values.

The primary differential energy spectrum $j_Z(E, t)$ will be written

$$j_Z(E, t) = \bar{j}_Z(E)[1+f_Z(E, t)], \quad (5)$$

where $f_Z(E, t)$, the fractional time variation of the primary spectrum, has time average value zero. For $\bar{j}_Z(E)$ we adopt the primary energy spectrum given by Kaplon *et al.*[7] These authors present formulas equivalent to

$$\begin{aligned} \bar{j}_{Z=1}(E) &= 0.43/(1+E)^{2.07}, \\ \bar{j}_{Z=2}(E) &= 0.054/(1+E)^{2.35}, \\ \bar{j}_{Z\approx 7}(E) &= 0.0027/(1+E)^{2.35}, \\ \bar{j}_{Z\approx 12}(E) &= 0.0011/(1+E)^{2.35}, \end{aligned} \quad (6)$$

[2] Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953). Hereafter we refer to this paper as Part I.
[3] S. B. Treiman, Phys. Rev. **86**, 917 (1952).
[4] J. A. Simpson, Phys. Rev. **81**, 639 (1951).
[5] Simpson, Fonger, and Wilcox, Phys. Rev. **87**, 240 (1952).
[6] J. A. Simpson and W. C. Fagot, Phys. Rev. **91**, 1068 (1953).
[7] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

where the fluxes are measured in particles/cm² sec sterad and the kinetic energies per nucleon are measured in Bev. We consider only latitudes below 48° in this paper, so inaccuracies in these formulas at very low energies E would not affect our results. Since $E_Z(\lambda)$ and the analytic form of $\bar{j}_Z(E)$ are the same for all nuclei with $Z>1$, we may perform a summation inside the integral sign,

$$\sum_{Z>1} A_Z \bar{j}_Z(E) = \frac{0.28}{(1+E)^{2.35}}, \quad (7)$$

and reduce $\bar{R}$ to a sum of two integrals:

$$\bar{R}(\lambda, 680) = 0.43 \int_{E_{Z=1}(\lambda)}^{\infty} S(E, 680) \frac{dE}{(1+E)^{2.07}} + 0.28 \int_{E_{Z>1}(\lambda)}^{\infty} S(E, 680) \frac{dE}{(1+E)^{2.35}}. \quad (8)$$

The vertical cut-off values of momentum-to-charge ratio $N_v(\lambda)$ have been given as a function of latitude for longitude 80°W by Neher.[8] We adopt corresponding values of $E_{Z=1}(\lambda)$ and $E_{Z>1}(\lambda)$ computed by Treiman.[9]

It has been determined that the empirical slowly varying yield function

$$S(E, 680) = \begin{cases} 0, & E<E_0, \\ 9.6 \ln[(1+E)/(1+E_0)], & E>E_0, \end{cases} \quad (9)$$

with $E_0 = 0.83$ Bev/nucleon generates, in Eq. (8), the experimental neutron intensity (normalized to unity at the geomagnetic equator) *vs* latitude data $\bar{R}(\lambda, 680)$ given in reference 6.

We define the effective primary spectrum for a neutron detector at depth 680 g/cm² and latitude λ to be the yield function, primary spectrum product

$$A_Z S(E, 680) \bar{j}_Z(E) \quad (10)$$

for $E>E_Z(\lambda)$; we assume the effective spectrum has value zero for $E<E_Z(\lambda)$. The mean energy $\bar{E}_Z$ of the effective spectrum is defined (arbitrarily) by

$$\frac{1}{1+\bar{E}_Z} \int_{E_Z(\lambda)}^{\infty} S(E, 680) \bar{j}_Z(E) dE = \int_{E_Z(\lambda)}^{\infty} S(E, 680) \frac{\bar{j}_Z(E)}{1+E} dE. \quad (11)$$

By a similar method the intensity recorded by a sea-level ionization chamber may be related to the primary intensity. In Eq. (8), we replace the 680 g/cm² neutron yield function S by a 1030 g/cm² ionization yield function S' and the 680 g/cm² neutron intensity data $\bar{R}$ by 1030 g/cm² ionization intensity data $\bar{R}'$. The empirical yield function

$$S'(E, 1030) = \begin{cases} 0, & E<E_0, \\ 0.041[(1+E)^2 - (1+E_0)^2], & E_0<E<12.7 \text{ Bev/nucleon}, \\ 0.72(1+E)^{+0.86}, & E>12.7 \text{ Bev/nucleon}, \end{cases} \quad (12)$$

with $E_0 = 3.7$ Bev/nucleon generates,[10] in Eq. (8), the experimental ionization intensity (normalized to unity at the geomagnetic equator) *vs* latitude data $\bar{R}'(\lambda, 1030)$ reported by Berry and Hess.[11]

The time average differential energy spectrum for primary protons ($Z=1$) arriving from the vertical at geomagnetic latutude $\lambda=48°$ (Curve A) and the effective primary proton spectra for shielded ionization chambers (Curve B) at 1030 g/cm² and neutron detectors (Curve C) at 680 g/cm² at the same latitude are plotted in Fig. 2—arbitrarily normalized to unit amplitude at proton kinetic energy $E=10$ Bev. It is clear that the energy distributions of effective spectra B and C are very different ($\bar{E}_{Z=1}=7.3$ Bev for the neutron detector, 46 Bev for the ionization detector). Thus, since neutron detectors respond to *low* energy primaries and ionization detectors to *high* energy primaries, it is not *a priori* obvious that intensity-time

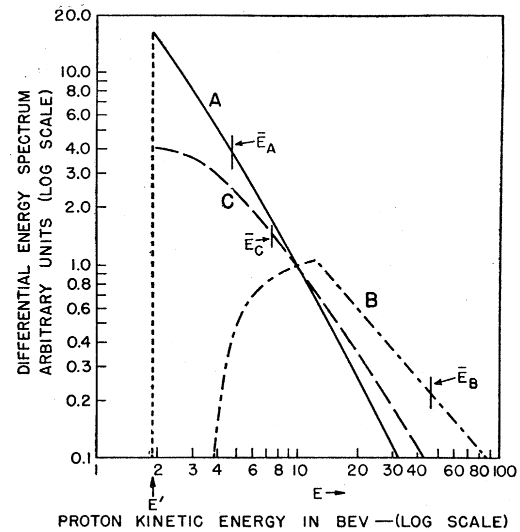

FIG. 2. Time average differential energy spectrum of primary protons arriving from the vertical at geomagnetic latitude $\lambda=48°$ (Curve A) and the effective primary proton spectra for ionization chambers (Curve B) and neutron detectors (Curve C) at the same latitude in the lower atmosphere. All three spectra are normalized to unit amplitude at proton kinetic energy $E=10$ Bev. The sharp change in differential intensity at $E=E'$ for spectra A and C is due to a cutoff imposed by the geomagetic field. The sharp change in slope at $E=12.7$ Bev for the spectrum B is due to approximations used in its derivation. The mean energies of spectra A, B, and C are $\bar{E}_A$, $\bar{E}_B$, and $\bar{E}_C$, respectively.

[8] H. V. Neher, Phys. Rev. **78**, 674 (1950).
[9] S. B. Treiman, unpublished Ph.D. dissertation, Dept. of Physics, University of Chicago, 1951.
[10] The extrapolation of S' to energies above 12.7 Bev/nucleon is subject to doubt. We have assumed that in this range the effective primary spectrum $A_Z S'(E, 1030)\bar{j}_Z(E)$ for a shielded ionization chamber follows a power law in the quantity $(1+E)$.
[11] E. B. Berry and V. F. Hess, Terrestrial Magnetism Atm. Elec. **47**, 251 (1942).

variations measured with both types of detectors will be identical.

C. Slow Irregular Charged Particle Intensity Variations

We consider now studies of cosmic-ray intensity variations observed with charged particle detectors in the lower atmosphere.

Forbush[12,13] observed a slow irregular ionization intensity variation that appeared coincidently at the several widely separated Carnegie Institution stations. Forbush used 10- and 30-day intensity averages which obscured any 27-day quasi-periodicity, and he tended to associate this irregular variation with geomagnetic field variations. Monk and Compton[14] demonstrated an ≈ 27-day recurrence tendency in ionization intensity records from Teoloyucan but did not stress a connection between this effect and Forbush's irregular world-wide variation. Other workers[15,16] attempted to account for irregular intensity variations measured with charged particle detectors by upper air temperature effects. But, even after elaborate temperature corrections, there remains a slow irregular variation in lower atmosphere charged particle intensity.[17] It is the purpose of this paper to compare this variation with the slow irregular world-wide neutron intensity variation reviewed above.

D. Intensity Variations within 24-Hour Intervals

Fonger *et al.*[18] reported neutron intensity *vs* time curves measured at Climax to have different characteristics on different days. These authors also reported 24-hour cycles obtained by averaging neutron intensities over many solar days to exhibit daytime maxima ~ 1 percent above nighttime minima at both Climax, Colorado, and Huancayo, Peru.

Ehmert and Sittkus[19] reported charged particle intensity *vs* time curves measured in Germany to have different characteristics on different days. Sekido and Yoshida[20] reported analogous results from Japan. Twenty-four-hour cycles obtained by averaging charged particle intensities over many solar days have long been known to exhibit daytime maxima ~ 0.3 percent above nighttime minima.[21,22]

[12] S. E. Forbush, Phys. Rev. **54**, 975 (1938).
[13] S. E. Forbush, Revs. Modern Phys. **11**, 168 (1939).
[14] A. T. Monk and A. H. Compton, Revs. Modern Phys. **11**, 175 (1939).
[15] A. Duperier, Proc. Phys. Soc. (London) **A62**, 684 (1949).
[16] D. W. N. Dolbear and H. Elliot, J. Atm. Terrest. Phys. **1**, 215 (1951).
[17] For example, see ionization intensity records published quarterly by A. Sittkus in the "Sonnen-zirkular" of the Fraunhofer Institute, Freiburg-in-Baden.
[18] Fonger, Firor, and Simpson, Phys. Rev. **89**, 891 (1953).
[19] A. Ehmert and A. Sittkus, Z. Naturforsch. **6a**, 618 (1951).
[20] Y. Sekido and S. Yoshida, Repts. Ionos. Research Japan **4**, 37 (1950).
[21] V. F. Hess and R. Steinmaurer, Sitzber. preuss. Akad. Wiss., 521 (1933).
[22] H. Elliot, *Progress in Cosmic Ray Physics* (North Holland Publishing Company, Amsterdam, 1952), Chap. VIII.

In this paper we compare briefly such 24-hour effects measured with neutron and charged particle detectors.

II. COMPARISON OF SLOW IRREGULAR WORLD-WIDE INTENSITY VARIATIONS MEASURED WITH NEUTRON AND IONIZATION DETECTORS

A. The Detectors

In comparing intensity variations measured with neutron and ionization detectors we use neutron intensity records from Climax, Colorado ($\lambda = 48°$, $x = 680$ g/cm^2), and ionization intensity records from Freiburg, Germany ($\lambda = 49°$, $x = 1000$ g/cm^2), Cheltenham, Maryland ($\lambda = 50°$, $x = 1030$ g/cm^2), and Huancayo, Peru ($\lambda = 1°$, $x = 700$ g/cm^2), during the period 14 July through 17 October, 1951.

The D-1 neutron detector at Climax has been described in detail in Part I. Neutron intensities from Climax used in this paper have been corrected to 680 g/cm^2 depth with a pressure coefficient corresponding to an absorption mean free path $L = 145$ g/cm^2. The Climax detector responds to effective primary proton spectrum C of Fig. 2.

Ionization intensity records from Freiburg have been scaled from graphs published quarterly by Dr. A. Sittkus in the "Sonnen-zirkular" of the Fraunhofer Institute, Freiburg-in-Baden, Germany. His detector has been described.[23] It is shielded on all sides with 10-cm iron, as compared with 10.7-cm lead for the Carnegie Institution Model C chambers. The ionization resulting from bursts is eliminated from the data, and reported intensity is believed to be proportional to the flux of single charged particles at the detector.

Sittkus has eliminated atmospheric effects by applying the following corrections to his data:

1. Barometric: -0.091 percent/millibar.
2. μ meson decay: -3.8 percent/km (96-millibar layer).
3. π meson decay: $+1.8$ percent/km (96-millibar layer relative to 225-millibar layer).

The barometric coefficient corresponds to -0.121 percent/mm Hg, or $\sim\frac{1}{8}$ that associated with the Climax neutron detector. The π-meson decay coefficient corresponds to $+0.046$ percent/°C where the temperature is averaged over the air layer between the 96- and 225-millibar levels.

Ionization intensity records from Cheltenham and Huancayo have been kindly supplied by Dr. S. E. Forbush of the Carnegie Institution. The Carnegie Institution Model C chambers have been described in detail.[24] Forbush has corrected his data for bursts and for atmospheric pressure effects (barometric coefficient $= -0.18$ percent/mm Hg at Cheltenham, -0.30 percent/mm Hg at Huancayo); no temperature corrections have been applied.

[23] A. Sittkus, Z. Naturforsch. **1**, 204 (1946).
[24] Compton, Wollan, and Bennett, Rev. Sci. Instr. **5**, 415 (1934).

In Sec. IB we derived a yield function for sea-level shielded ionization chambers from intensity *vs* latitude data obtained by Berry and Hess[11] with a Compton-Bennett chamber identical to that at Cheltenham. We assume that intensity *vs* latitude data obtained with the Freiburg chamber would be identical, hence, that the Freiburg and Cheltenham chambers respond to the effective primary proton spectrum B of Fig. 2. The yield function for a shielded ionization chamber at 700 g/cm^2 depth (Huancayo) is unknown.

B. Slow Irregular Primary Intensity Variations

Daily averages of cosmic-ray intensity measured by the Climax and Freiburg detectors during the 96-day period from 14 July through 17 October, 1951 are plotted in Fig. 1. Local time, midnight-to-midnight averages were used in each case. The Climax daily averages are plotted in percent from a mean count rate of 632 counts/min; the Freiburg daily averages in percent *times 5* from a mean ionization rate of $+0.57$ percent on Sittkus' "Sonnen-zirkular" scale. These mean rates were realized during the period under study. The standard deviations of the daily intensity averages caused by random fluctuations are 0.14 percent at Climax and 0.20 percent at Freiburg (after multiplying by 5). These are observable widths in Fig. 1 but are not plotted, as they do not explain actual discrepancies between intensities measured by the two detectors.

A general agreement between the records of these quite different detectors separated by 5500 miles is evident. The slow irregular world-wide intensity variations observed with ionization chambers and with neutron detectors are clearly related and probably have a common origin. Neher and Forbush[25] have independently noticed the good agreement between the slow irregular neutron intensity variation reported by Simpson *et al.*[1] and the slow irregular intensity variation recorded by lower atmosphere charged particle detectors. Neher and Forbush agree that both variations have a common origin but stress correlations of such intensity variations with geomagnetic field variations. In the Introduction we have summarized evidence in the literature that led to the conclusion that the slow irregular *neutron* intensity variation is produced by temporal variations in the primary spectrum $j_Z(E,t)$. We extend this conclusion to the highly correlated slow irregular *ionization* intensity variation. Both neutron and ionization variations will hereafter be ascribed to a slow irregular *primary* intensity variation.

The Climax neutron detector responds to intensity-time variations integrated over the effective primary spectrum

$$S(E,680)A_Zj_Z(E,t) \quad (13)$$

from the lower integration limits $E=E_Z(48°)$ to the upper limits $E=\infty$. Shielded ionization chambers at ≈ 1030 g/cm^2 depth and $\approx 48°$ geomagnetic latitude (Freiburg, Cheltenham) respond to intensity-time variations integrated over the effective primary spectrum

$$S'(E,1030)A_Zj_Z(E,t) \quad (14)$$

within the same integration limits. Since the effective primary spectrum of the Climax neutron detector is peaked at low primary energies and that of the Freiburg, Cheltenham ionization detectors is peaked at high primary energies, the fact that the slow irregular *primary* intensity variation is recorded in the amplitude ratio $\approx 5:1$ (Climax neutron detector relative to Freiburg, Cheltenham ionization detectors) proves that $j_Z(E,t)$ varies most at low primary energies.

The Huancayo ionization chamber responds to intensity-time variations integrated over an effective primary spectrum that is unknown, but whose lower integration limits are $E=E_Z(1°)$. Thus, appearance of the slow irregular primary intensity variation at Huancayo proves the slow irregular variation in $j_Z(E,t)$ extends at least to energies greater than $E_Z(1°)$.

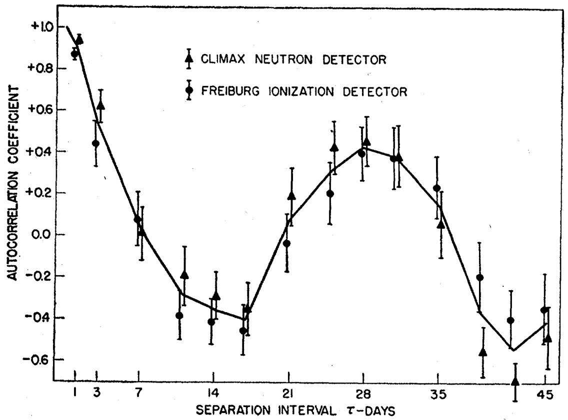

FIG. 3. Autocorrelations of daily average cosmic-ray intensities measured by the Climax D-1 neutron and Freiburg ionization detectors during the period 14 July through 17 October, 1951.

C. The 27-Day Recurrence Tendency

In this section we demonstrate a close connection between the slow irregular intensity variation and the 27-day quasi-periodicity. Since slow irregular intensity variations measured with neutron and ionization detectors have a common origin, it therefore will follow that 27-day recurrence tendencies previously reported in neutron[1] and ionization[14] intensity records have a common origin.

Figure 3 shows the autocorrelation functions $r_C(\tau)$, $r_F(\tau)$ computed from daily intensity averages measured with the Climax neutron and Freiburg ionization detec-

[25] H. V. Neher and S. E. Forbush, Phys. Rev. **87**, 889 (1952). See Fig. 2 of this reference for a graph showing ionization intensity variations at Cheltenham and Huancayo agreeing very well with the slow irregular neutron intensity variation at Climax.

tors during the period 14 July through 17 October, 1951. The autocorrelation $r_C(\tau)$ is the correlation of daily neutron intensity averages at Climax with daily averages at the same station τ days later, and similarly at Freiburg. The general smoothness of the functions is a consequence of the high autocorrelations for $\tau=1$ day. The peaks of negative autocorrelation at $\tau \approx 14$, 42 days ($\frac{1}{2}$, $\frac{3}{2}$ solar rotation periods) and that of positive autocorrelation at $\tau \approx 28$ days (1 solar rotation period) are clear at both stations. Indeed, the basic features of autocorrelation at both stations are identical.

From Fig. 1 we see that intensity variations measured at Climax and Freiburg do not agree perfectly. The agreements that do exist must produce the essentially identical Climax, Freiburg autocorrelation cycles shown in Fig. 3. Fine details of the intensity *vs* time curves (which are somewhat different at Climax and Freiburg) evidently do not contribute importantly to the values of autocorrelation coefficients.

The obvious, gross features of measured cosmic-ray intensity variations are world-wide effects observable in both neutron and ionization records, are produced by slow irregular primary intensity variations extending across a wide region of the primary energy spectrum, and produce the ≈ 27-day recurrence tendency exhibited by an autocorrelation (or equivalent[14]) method.

D. The Relative Responses of Neutron and Ionization Detectors to Slow Irregular Primary Intensity Variations

The degree of agreement between intensity *vs* time curves measured at two cosmic-ray stations C, F will now be considered in detail. Let $\delta C(t)$, $\delta F(t)$ be departures from means of two (supposedly related) physical quantities measured at C, F at time t. Let σ_C, σ_F, and r_{CF} be the standard deviations and correlation

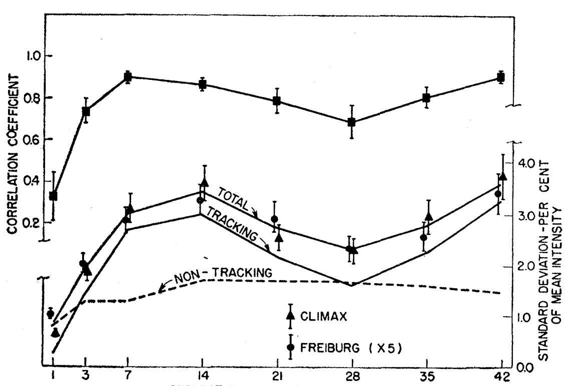

FIG. 4. Correlation coefficients and standard deviations of the changes (over time intervals of τ-days) in daily average cosmic-ray intensity measured by the Climax D-1 neutron and Freiburg ionization detectors. The mean standard deviation has been separated into standard deviations produced by tracking and nontracking components. Data are from the period 14 July through 17 October, 1951.

coefficient of the δC, δF pairs during the period under consideration.

We divide the variation δC into tracking and nontracking components:

$$\delta C = \delta C_T + \delta C_{NT}, \tag{15}$$

where the tracking component, defined by

$$\delta C_T = r_{CF}(\sigma_C/\sigma_F)\delta F, \tag{16a}$$

has *unit* correlation with the variation δF and the nontracking component, defined by

$$\delta C_{NT} = \delta C - \delta C_T, \tag{16b}$$

has *zero* correlation with the variation δF. A similar division can be made with the symbols C, F interchanged. The standard deviations of the tracking and nontracking components are:

$$\sigma_{CT} = |r_{CF}|\sigma_C, \quad \sigma_{CNT} = (1-r_{CF}^2)^{\frac{1}{2}}\sigma_C. \tag{17}$$

Physical nontracking variations include errors of all kinds and could obviously be larger at one observing station than at another. Our statistical definitions do not provide for such differences, and tracking and nontracking components (as measured by their standard deviations) appear in the same proportion $[|r_{CF}|/(1-r_{CF}^2)^{\frac{1}{2}}]$ at both stations. Thus our *defined* components do not necessarily correspond to actual physical components.

In so far as the slow irregular primary intensity variation has uniform phase across the entire primary energy spectrum, it would produce proportional intensity variations at all stations. We therefore identify such variations with the tracking components defined above.

For the study of the energy dependence of primary intensity variations, we need the amplitude ratio of perfectly correlated intensity variations at C, F:

$$\sigma_{CT}/\sigma_{FT} = \sigma_C/\sigma_F. \tag{18}$$

We are assured that this ratio accurately describes the physical situation only if nontracking contributions are negligible, that is, if

$$(1-r_{CF}^2)^{\frac{1}{2}} \ll r_{CF}. \tag{19}$$

Instead of taking δC, δF to be departures from means of daily intensity averages, we adopt a special analysis that stresses the 27-day quasi-periodicity in the slow irregular primary intensity variation. Let δC, δF be increments in daily intensity averages measured at stations C, F on pairs of days separated by a fixed interval τ:

$$\delta C(t) = C(t+\tau) - C(t), \quad \delta F(t) = F(t+\tau) - F(t). \tag{20}$$

These sets of increments have standard deviations $\sigma_C(\tau)$, $\sigma_F(\tau)$, and a correlation coefficient $r_{CF}(\tau)$. These three quantities are plotted in Fig. 4 as a function of the separation interval τ from Climax, Freiburg data during the period 14 July through 17 October, 1951. (The standard deviations of Freiburg increments have been expanded by the factor 5.)

The standard deviations of the increments increase with τ, pass through a maximum ($\approx$3.4 percent, Climax scale) at $\tau\approx 14$ days, decrease to a minimum ($\approx$2.3 percent, Climax scale) at $\tau\approx 28$ days, and then increase again, at least up till $\tau\approx 42$ days. This behavior is a consequence of the 27-day recurrence tendency. Cosmic-ray intensity variations over $\approx$14-day intervals tend to be maximal; intensity variations over $\approx$28-day intervals tend to be minimal.

The correlation coefficients of the increments follow the same pattern. The relatively large cosmic-ray intensity variations over $\approx$14, 42-day intervals are highly correlated at Climax and Freiburg. The relatively small cosmic-ray intensity variations over $\approx$1, 28-day intervals are less highly correlated.

In Fig. 4 we have drawn a curve through the mean of the Climax, Freiburg standard deviations and have then divided this mean total deviation into deviations caused by tracking and nontracking components from the corresponding correlation coefficients. The nontracking component has standard deviations relatively independent of τ($\approx$1.5 percent, Climax scale; only decrease slightly as $\tau\rightarrow 1$ day). The tracking component has standard deviations which increase with τ, pass through a maximum ($\approx$3.0 percent, Climax scale) at $\tau\approx 14$ days, decrease to a minimum ($\approx$1.5 percent, Climax scale) at $\tau\approx 28$ days, and then increase again, at least up till $\tau\approx 42$ days. It is only at $\tau\approx 14$, 42 days that the tracking component is substantially larger than the nontracking component and that the standard deviations of intensity increments can therefore be taken as measures of the responses of these detectors to the slow irregular primary intensity variation.

Figure 5, similar to Fig. 4, shows the standard deviations and correlation coefficients of intensity increments measured by the Cheltenham and Huancayo ionization chambers between pairs of days separated by an interval τ during the period 14 July through 17 October, 1951.[26] The same features are evident as in Fig. 4 for Climax and Freiburg—maxima of both total deviation and correlation at $\tau\approx 14$, 42 days. The total deviation is again composed of a nontracking deviation relatively independent of τ and a tracking deviation with a marked minimum at $\tau\approx 28$ days. Again the tracking component is substantially larger than the nontracking component only at $\tau\approx 14$, 42 days.

Figures 4 and 5 show the comparison of the station pairs Climax neutron-Freiburg ion and Cheltenham ion-Huancayo ion. While not plotted, the corresponding figures for other combinations of these stations (Climax neutron-Cheltenham ion, Climax neutron-Huancayo ion, Freiburg ion-Cheltenham ion, and Freiburg ion-Huancayo ion) are similar.

[26] Ionization intensity records from Cheltenham and Huancayo were kindly supplied by Dr. S. E. Forbush of the Carnegie Institution. Direct daily intensity averages during most of this period may be found in reference 25. The standard deviations in Fig. 5 are expressed in percent units based on the total cosmic-ray ionizations at Cheltenham and Huancayo, respectively.

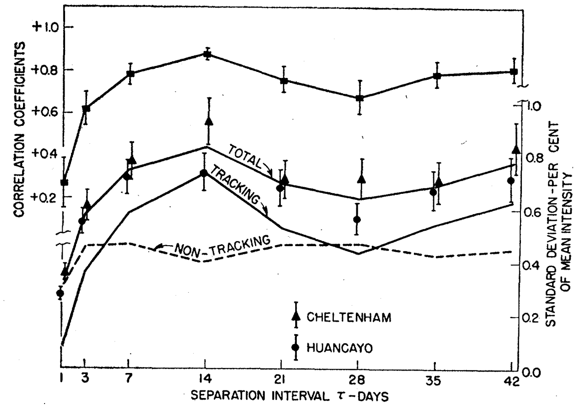

FIG. 5. Correlation coefficients and standard deviations of the changes (over time intervals of τ-days) in daily average cosmic-ray intensity measured by the Cheltenham and Huancayo ionization chambers. The mean standard deviation has been separated into standard deviations due to tracking and nontracking components Data are from the period 14 July through 17 October, 1951.

To estimate the relative responses of these detectors to the slow irregular primary intensity variation, we have plotted in Figs. 6 and 7 the ratios $\sigma_i(\tau)/\sigma_j(\tau)$ as a function of the ratios $r_{ij}(\tau)/[1-r_{ij}^2(\tau)]^{\frac{1}{2}}$, i.e., ratios of standard deviations of intensity increments against ratios of tracking and nontracking components, for all station pairs i, j. For each pair of stations the three plotted points with largest abscissas orginate from sets of intensity increments with τ-parameter 7, 14, and 42 days. For sets of intensity increments with τ-parameter $\approx$1, 28 days, the tracking components are consistently less outstanding, and, generally speaking, the ratios $\sigma_i(\tau)/\sigma_j(\tau)$ change. Thus, tracking and nontracking changes do not enter proportionately at different stations, and the relative responses of these detectors to $\approx$27-day primary intensity variations should be taken as the limiting values of the ordinates for large abscissas. These limiting values are recorded in Figs. 6 and 7; they are of course self-consistent.

The ratio Cheltenham ion/Huancayo ion is consistent with the ratio 1.11±0.04 derived by a somewhat different procedure by Forbush[12] for cosmic-ray intensity change trends over ~1 year. This author also pointed out that the same ratio results from comparing the magnitudes of the occasional large intensity decreases sometimes associated with magnetic storms. It follows that intensity change trends over ~1 year, $\approx$27-day intensity oscillations, and occasional large intensity decreases may perhaps all be produced by primary intensity variations with approximately the same energy dependence.

The ratio Cheltenham ion/Freiburg ion is inconsistent with the expected ratio unity. Both detectors are similarly shielded and similarly located (geomagnetic latitude and atmospheric depth) and should respond equally to primary intensity variations. We believe this discrepancy is due to systematic inaccuracies in converting collected charge to percent units based on the mean cosmic-ray ionization. The problem of relating, year after year, collected charge to mean cosmic-ray ionization is quite difficult, and the departure of the ratio Cheltenham ion/Freiburg ion from unity is probably an indication of the magnitude of the errors involved.[27] Thus the limiting ratios given in Figs. 6 and 7 are probably determined more accurately than the percentage change units on which they are based.

We conclude that the responses of shielded ionization chambers at Freiburg, Cheltenham, and Huancayo to the slow irregular primary intensity variation are approximately *equal* and approximately *one-fifth* that of a neutron detector at Climax.

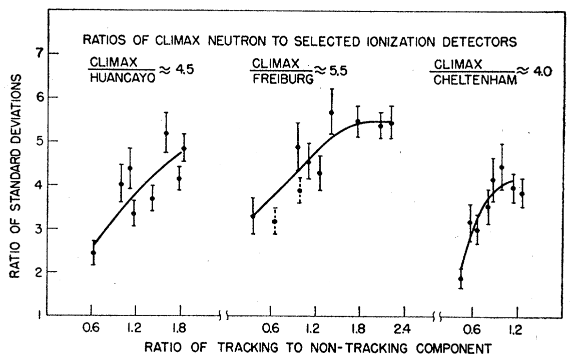

FIG. 6. Ratios of standard deviations of the changes (over time intervals of τ-days) in daily average cosmic-ray intensity measured by the Climax neutron and selected lower atmosphere ionization detectors as a function of the ratios of tracking to nontracking components. Two dotted points originate from an analysis of intensity variations within 24-hour intervals at Climax and Freiburg. Data are from the period 14 July through 17 October, 1951.

The correlations of intensity increments over time intervals τ measured with any pair of the three detectors Climax neutron, Freiburg ion, and Huancayo ion are about equal for any $\tau > 1$. Thus, nontracking components cannot be principally due to nonproportional variations in different parts of the primary particle energy spectrum, and uncompensated atmospheric effects and instrumental errors appear to be their most probable origins.

E. Energy Dependence of Slow Irregular Primary Intensity Variations

Substituting in Eq. (4) from Eq. (5), we obtain the intensity variation $\Delta R^i(\lambda, x, t)$ that would be produced at detector i (at latitude λ and depth x) by a fractional primary intensity variation $f_Z(E, t)$:

$$\Delta R^i(\lambda, x, t) = \sum_Z A_Z \int_{EZ(\lambda)}^{\infty} S^i(E, x)\bar{j}_Z(E) f_Z(E, t) dE. \quad (21)$$

Suppose some mechanism perturbs the primary cosmic-ray spectrum with a prescribed energy dependence but with a magnitude varying in time. This corresponds mathematically to supposing that $f_Z(E, t)$, for this particular variation, is a product of two functions, one depending on Z and E alone, the other on t alone:

$$f_Z(E, t) = g_Z(E) h(t). \quad (22)$$

The fractional variation in intensity produced at detector i is then

$$\frac{\Delta R^i(\lambda, x, t)}{\bar{R}^i(\lambda, x)} = \frac{G^i(\lambda, x)}{\bar{R}^i(\lambda, x)} h(t), \quad (23)$$

where $G^i(\lambda, x)$ has the time-independent value

$$G^i(\lambda, x) = \sum_Z A_Z \int_{EZ(\lambda)}^{\infty} S^i(E, x)\bar{j}_Z(E) g_Z(E) dE. \quad (24)$$

Such a separated argument dependence guarantees proportional variations in the intensities measured by *all* cosmic-ray detectors independent of the nature of the temporal dependence $h(t)$.

Assume the separated argument dependence holds for the slow irregular primary intensity variation. [In this case, $h(t)$ must vary slowly and irregularly but with a 27-day quasi-periodicity.] To prove the validity of this assumption one would have to demonstrate (in the future) proportional intensity variations with many detectors responding to new and different effective primary spectra. For the present, this hypothesis will at least explain the agreement of the obvious, gross features of the slow irregular intensity variation measured at Climax and Freiburg (Fig. 1).

The energy dependences $g_Z(E)$ may be arbitrarily complex, and we cannot proceed straightforwardly to deduce them from the meager experimental data. We possess one quantitative result—the $\approx 5:1$ relative response (Climax neutron to Freiburg, Cheltenham ion) to the slow irregular primary intensity variation—and one qualitative result—the existence of the slow irregular intensity variation at primary energies greater than the equatorial cut-off energies. We now hypothesize a few qualitatively correct energy dependences $g_Z(E)$ containing one parameter and adjust this parameter to fit the one quantitative result.

Assume the slow irregular primary intensity variation is confined exclusively to the proton component, and assume the energy dependence $g_{Z=1}(E)$ is a power law in the quantity $(1+E)$, the exponent $\gamma_{Z=1}$ being the adjustable parameter:

$$g_{Z=1}(E) = (1+E)^{-\gamma_{Z=1}}. \quad (25)$$

[27] In reference 12 Forbush found the relative response (Teoloyucan ion to Huancayo ion) to intensity change trends over ~ 1 year to be 1.58 ± 0.04. This seems large compared to his other response ratios and may also be due to calibration differences.

This choice is in analogy with the fitting of time average primary energy spectrum data to power laws.[28] While increasing $\gamma_{Z=1}$ displaces intensity variations to primary particles with progressively lower energies, with this choice there remains a "tail" to the variations at high primary energies.

Substituting in Eqs. (23), (24) for $S(E, 680)$, $S'(E, 1030)$, $j_Z(E)$, and $g_{Z=1}(E)$ from Eqs. (9), (12), (6), and (25), respectively, we find that the $\approx 5:1$ relative response (Climax neutron to Freiburg, Cheltenham ion) to the slow irregular primary intensity variation would be realized for $\gamma_{Z=1} \approx 1.0$.

Now assume the slow irregular primary intensity variation is confined exclusively to one heavier nuclei component, say $Z = Z' > 1$, and assume the energy dependence $g_Z'(E)$ is a power law in the quantity $(1+E)$.

By an analogous calculation we find that the $\approx 5:1$ relative response (Climax neutron to Freiburg, Cheltenham ion) to the slow irregular primary intensity variation would be realized for $\gamma_{Z'} \approx 0.6$, independent of the value of Z'. The difference between $\gamma_{Z=1}$ and $\gamma_{Z'}$ is partly due to the larger exponent of the time average heavier nuclei spectrum relative to that of the proton spectrum[7] and partly due to the greater proton (relative to heavier nuclei) cut-off energy per nucleon at Climax.

If we attempt to generalize our initial extreme hypotheses and consider simultaneous intensity variations in both proton and heavier nuclei primary components, then any convenient expression for the energy dependences $g_Z(E)$ involving only one adjustable parameter becomes highly artificial. There exists, fortunately, an electric field acceleration process hypothesis of primary intensity variations that involves all primary components and no arbitrary parameters. Thus the $\approx 5:1$ relative response (Climax neutron to Freiburg, Cheltenham ion) to the slow irregular primary intensity variation provides a real test of this hypothesis.

Starting from an isotropic distribution of primaries $j_Z(E)$ constant in time at a great distance from the earth, the electric field acceleration process hypothesis assumes an electric potential difference $V(t)$ between the earth and this great distance which varies in time and thereby produces variations in measured cosmic ray intensity. Nagashima[29] has discussed such an hypothesis in order to explain the large cosmic-ray decreases sometimes associated with magnetic storms. His calculation of the effect of electric field acceleration of cosmic-ray particles on measured intensity is similar to the type of calculation used here and is independent of the origin of the potential difference. We disregard Nagashima's model for the production of electric fields and consider merely the cosmic-ray effects that would follow from a time variable difference in potential $V(t)$ between the earth and great distances.

[28] Some advantage to this choice will appear later, when we consider the electric field acceleration process hypothesis of primary intensity variations.

[29] K. Nagashima, J. Geomagn. Geoelect. **3**, 100 (1951).

The flux $j_Z(W)$ of cosmic-ray particles of atomic number Z per unit solid angle and per unit total energy W (*not* per nucleon) is related to Liouville's constant D by[30]

$$j_Z(W) = P^2 D = (W^2 - W_0^2)D/c^2, \tag{26}$$

where P, the momentum of the particles, changes when they move in an electric field while D remains constant. Following the particles, the change in observed intensity $j_Z(W)$ as a result their gaining an energy ΔW in an electric field is (neglecting higher order terms in ΔW):

$$\delta j_Z(W) = \frac{2W\Delta W}{c^2} D = j_Z(W) \frac{2\Delta W}{W} \frac{1}{1-(W_0/W)^2}. \tag{27}$$

The simultaneous change in $j_Z(W)$ at fixed total energy W resulting from the energy dependence of the differen-

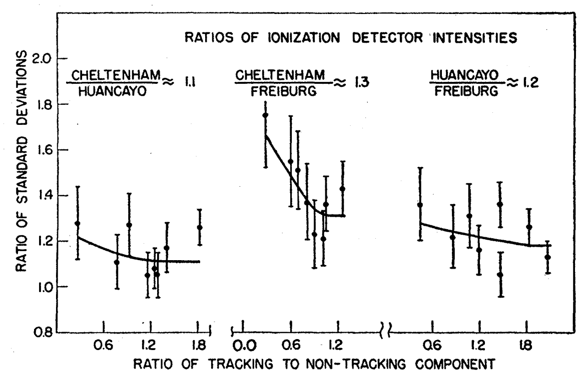

FIG. 7. Ratios of the standard deviations of the changes (over time intervals of τ-days) in daily average cosmic-ray intensity measured by selected lower atmosphere ionization detectors as a function of the ratios of tracking to nontracking components. Data are from the period 14 July through 17 October, 1951.

tial intensity spectrum is

$$\delta j_Z'(W) = -(dj_Z/dW)\Delta W. \tag{28}$$

To the approximation that the rest energy of a nucleon is 1 Bev, the primary spectrum given by Kaplon *et al.*[7] [Eq. (6)] states that $j_Z(W)$ is a power law in W:

$$j_Z(W) = \text{constant } (W)^{-\alpha_Z}. \tag{29}$$

Thus,

$$\delta j_Z'(W) = -(dj_Z/dW)\Delta W = +\alpha_Z j_Z(W)\Delta W/W. \tag{30}$$

The total change in $j_Z(W)$ is the sum $\Delta j_Z(W) = \delta j_Z(W) + \delta j_Z'(W)$. The total energy W and the kinetic energy per nucleon E are related by $W \approx A_Z(1+E)$; the energy gain ΔW and the electric potential $V(t)$ are related by $\Delta W = ZeV(t)$. Since the flux per unit total energy W is only a constant multiple of the flux per unit energy

[30] L. Janossy, *Cosmic Rays* (Clarendon Press, Oxford, 1948), p. 289. Nagashima used Janossy's intensity per unit momentum for intensity per unit energy and stated this relation incorrectly.

per nucleon E, we have

$$\Delta j_Z(E)=j_Z(E)\frac{Z}{A_Z}\frac{1}{1+E}\left[\frac{2}{1-1/(1+E)^2}+\alpha_Z\right]eV(t). \quad (31)$$

Identifying $j_Z(E)$ with the time average differential energy spectrum $\bar{j}_Z(E)$ given by Kaplon *et al.*[7] [Eq. (6)] and comparing Eq. (31) with the earlier phenomenological expression $\bar{j}_Z(E)g_Z(E)h(t)$ that assumed proportional temporal variations in $j_Z(E,t)$ extending over a wide variation of the energy argument E, we find that equating $h(t)$ with $eV(t)$ yields the following energy dependences $g_Z(E)$ for the electric field acceleration process hypothesis:

$$g_Z(E)=\frac{Z}{A_Z}\frac{1}{1+E}\times\left[\frac{2}{1-1/(1+E)^2}+\alpha_Z\right], \quad \alpha_{Z=1}=2.07, \quad \alpha_{Z=Z'>1}=2.35. \quad (32)$$

Substituting in Eq. (24), we find (using $Z/A_Z=\frac{1}{2}$ for nuclei heavier than the proton) that a 5.3:1 relative response (Climax neutron to Freiburg, Cheltenham ion) to primary intensity variations of electric field acceleration process origin is predicted. This agrees with their $\approx$5:1 experimental relative response to the slow irregular primary intensity variation.

The magnitude of the electric portential may be related to the magnitude of the cosmic-ray intensity variation by Eq. (23). We find the correspondence:[31]

1 percent variation in neutron intensity
$\leftrightarrow 2.1\times10^7$ volts variation in $V(t)$.

Since intensity variations measured by the Climax neutron detector over periods $\approx$14, 42 days have standard deviation $\sim$3 percent, an electric potential explaining the slow irregular primary intensity variation would be required to have variations characterized by a standard deviation $\sim 6\times10^7$ volts over periods $\approx$14, 42 days. A potential $V(t)$ of the earth with respect to great distances would need not have time average value zero. In contrast with Nagashima's specific storm model, an electric potential explaining the slow irregular primary intensity variation would be always present, and its variations—correlated with the rotation period of the sun—would produce the observed cosmic-ray intensity variations. In the case that $\bar{V}$ were not zero, the time average spectrum $\bar{j}_Z(E)$ observed at the earth would not be identical with the cosmic-ray spectrum at great distances from the earth.

[31] We find that a potential variation of 10^8 volts would produce a 0.9 percent variation in the intensity measured by a sea-level ionization chamber at high latitudes. Nagashima (reference 29) predicted 1.3 percent with a power law intensity per unit energy primary spectrum with exponent 2.75. His yield function was also different from the ionization chamber yield function derived and used here, and, as pointed out above (reference 30), his computation of the intensity changes following the particles contained an error.

We have calculated cosmic-ray intensity variations predicted by the electric field acceleration process hypothesis as if the cut-off energy $E_Z(\lambda, t)$ did not change in time. This would be the case, so far as electric fields are concerned, if cosmic-ray particles crossed the accelerating potential *before* entering the geomagnetic field. The ionosphere is essentially an equipotential surface with respect to voltages of the order of 10^7 volts.[32] We have presumed that this equipotential state extends well out into the geomagnetic field.

Any hypothesis explaining the slow irregular primary intensity variation must explain the approximately equal variations recorded by the Cheltenham and Huancayo ionization detectors. Through the yield function $S'(E, 1030)$, we can calculate, for given energy dependences $g_Z(E)$, the relative responses of sea-level ionization chambers at different latitudes. For a chamber at the geomagnetic equator the electric field acceleration process hypothesis predicts intensity variations only $\frac{3}{8}$ smaller than those predicted for high latitude chambers (Freiburg, Cheltenham). Intensity variations predicted for the Huancayo chamber ($x=700$ g/cm^2) would, therefore, be more than $\frac{5}{8}$ times those predicted for the Freiburg, Cheltenham chambers. Thus, the electric field acceleration process hypothesis leads to a sufficiently strong "tail" in $g_Z(E)$ at high primary energies to account qualitatively for the appearance of the slow irregular ionization intensity variation at Huancayo.

Using the expansion

$$\frac{1}{1-1/(1+E)^2}=1+\frac{1}{(1+E)^2}+\frac{1}{(1+E)^4}+\cdots, \quad (33)$$

we see that the electric field acceleration process hypothesis $g_Z(E)$ is a linear combination of power laws $g\sim(1+E)^{-\gamma}$ with $\gamma=1, 3, 5, \cdots$. The first term, however, contributes over 97 percent to any such intensity variation that might be produced at the Climax neutron station.

The electric field acceleration process hypothesis, as an explanation of the slow irregular primary intensity variation correlated with the rotation period of the sun, passes the test of the *two* experimental results (one quantitative, one qualitative) discussed here. It remains, however, to be further tested by additional observations with detectors responding to effective primary spectra with different energy distributions. On the basis of the measurements studied here, the amplitude of the slow irregular primary intensity variation seems, at any rate, to fall off approximately one power of energy more rapidly than the time average primary spectrum itself.

[32] S. Chapman and J. Bartels, *Geomagnetism* (Clarendon Press, Oxford, 1940), Chap. XV.

III. COMPARISON OF INTENSITY VARIATIONS WITHIN 24-HOUR INTERVALS MEASURED WITH NEUTRON AND IONIZATION DETECTORS

There exist agreements between intensity variations measured within 24-hour intervals by neutron and ionization detectors.

In Fig. 8 we have plotted 24-hour cycles obtained by averaging neutron and ionization intensities at Climax and Freiburg, respectively, over 74 solar days during the period 14 July through 17 October, 1951. The abscissa is local time. Freiburg variations have been expanded by the factor 5. For convenience both cycles have been extended at one end beyond midnight. The duplicated intervals from 0000 to 0700 have somewhat different average cosmic-ray behaviors, as some data are not common to both intervals.

The standard deviation ratio and correlation coefficient of the hourly intensity averages of these cycles are:

$$\sigma_C/\sigma_F \approx 3.9, \quad r_{CF} \approx +0.71. \tag{34}$$

We have defined a scaler D_C that provides a measure of neutron intensity variations during individual days at Climax in phase with the mean Climax cycle of Fig. 8. Defining an analogous scaler D_F at Freiburg, we find that the standard deviation ratio and correlation coefficient of 74 D_C, D_F pairs are:

$$\sigma_{DC}/\sigma_{DF} \approx 3.2, \quad r_{DCDF} \approx +0.56, \tag{35}$$

when D_F is defined to measure ionization intensity variations with the same local time phasing as D_C. The positive correlation r_{DCDF} shows that days with large daytime neutron intensity maxima at Climax are, on the average, days with large daytime ionization intensity maxima at Freiburg, etc.

The concept of tracking and nontracking variations may be introduced again here, and we may study the ratios of standard deviations of intensity variations measured at Climax and Freiburg as a function of the ratios of tracking and nontracking components. Points computed from Eqs. (34) and (35) have been entered (dotted) in the Climax neutron, Freiburg ionization detector study in Fig. 6. We see that the ratios of standard deviations of intensity variations measured during 24-hour intervals at Climax and Freiburg are approximately the same as corresponding ratios computed from slow irregular intensity variations when the comparison is made with comparable tracking and nontracking mixtures in both types of variations.

It is not certain that intensity variations measured within 24-hour intervals are due to primary intensity variations extending, with constant phase, across a wide range of primary energies E. However, if one would assume this then such variations would correlate perfectly at Climax and Freiburg, and the limiting value of standard deviation ratios (σ_C/σ_F) for large tracking to nontracking ratios $[r_{CF}/(1-r_{CF}^2)^{\frac{1}{2}}]$ would measure the relative response of these detectors to such primary intensity variations. Because nontracking variations are large in the two measurements reported here this limiting ratio cannot be accurately determined, but (Fig. 6) could perhaps be equal to the $\approx 5.5:1$ relative response (Climax neutron to Freiburg ion) to the slow irregular primary intensity variation. If this were true, it would be a point against an electric field acceleration process hypothesis explanation of slow intensity variations. Tracking 24-hour and 27-day intensity variations detected with the same relative response at Climax and Freiburg would be expected to be explained by a single mechanism. It has already been mentioned that the high conductivity of the ionosphere does not permit an electric field explanation of intensity variations occurring in local time.

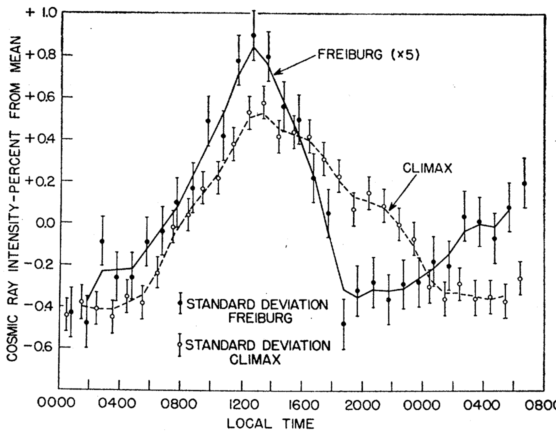

FIG. 8. Average 24-hour cycles of cosmic-ray intensity measured by the Climax D-1 neutron and Freiburg ionization detectors during the period 14 July through 17 October, 1951.

This investigation of intensity variations within 24-hour intervals is being extended, and a more detailed account will be submitted for publication shortly.

The writer wishes to thank Professor J. A. Simpson, in whose cosmic-ray laboratory and under whose guidance this investigation was performed, for his generous advices and aids of all kinds. We are indebted to Dr. S. B. Treiman and Mr. J. W. Firor, former and present members, respectively, of this laboratory, for a good deal of cooperative experimental endeavor and for valuable discussions covering their own closely related researches. The many student assistants and computers of this laboratory contributed heavily to the reduction of data, as did Mr. A. Hoteko to the construction of the experimental equipment. The Electronics Laboratory under Mr. P. Shevick and the Counter Laboratory under Mrs. N. Wood were very helpful.

Our neutron monitors were serviced principally by Mr. R. Allen (Climax, Colorado) of the High Altitude Observatory, Mr. G. Schnable (Sacramento Peak, New Mexico) of the Solar Observatory, Dr. M. Coronado (Mexico City) of the University of Mexico, and Mr. H. Goller (Huancayo, Peru) of the Geophysical Institute.

The writer is personally indebted to Mr. Albert A. Giesecke, Jr., Technical Director, and to the Directive Committee under the chairmanship of Dr. J. A. Broggi for very excellent and pleasant accommodations during his stay at the Geophysical Institute at Huancayo.