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Cosmic-Radiation Intensity-Time Variations and Their Origin. III. The Origin of 27-Day Variations*

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It is shown that (a) the 27-day recurring cosmic-radiation intensity variations are not produced by geomagnetic field disturbances, and (b) this 27-day variation is a primary intensity variation produced by a charged particle accelerating mechanism.

These results were obtained without invoking special models for the magnetic field disturbances or requiring detailed time correspondence between cosmic-radiation intensity and magnetic field intensity variations. The conclusions were based upon experimental observations covering a 19-month period in 1951 and 1952. The results are derived from neutron-intensity variations measured as a function of time in aircraft and neutron monitor piles. The data reveal that an indirect association exists between the 27-day intensity variation and geomagnetic disturbances: i.e., geomagnetic disturbances are most likely to occur approximately 2 days after the 27-day maxima of cosmic-ray intensity. It is also shown that intensity changes of $\sim$3–6 percent are sometimes not followed by any geomagnetic disturbance.

An example is given of a nonrecurring sharp intensity decrease of >6 percent, and it is shown that even this event is not produced by geomagnetic field variations.

The results suggest that there is a common mechanism which produces both the accelerating process for cosmic-radiation particles and, indirectly, the geomagnetic disturbances. A search was made for the probable location of such a mechanism. Varying electrical fields of terrestrial origin were considered whereby the incoming primary radiation would undergo an acceleration or deceleration either (1) before entering the geomagnetic field, (2) within the magnetic field region, or (3) after passing through the magnetic field. None of these three possibilities, nor a combined geomagnetic and geoelectric field storm, accounts for all the established experimental facts. In view of these results it is concluded that the accelerating mechanism probably is not of terrestrial origin. The 27-day recurrence corresponds in time to the proper rotation of the solar equatorial latitudes and, since it has been shown that active solar regions at these latitudes are associated with the 27-day cosmic-radiation intensity variations, the required accelerating mechanism is probably controlled by solar processes and may be located near the sun.

From the dependence of the 27-day intensity variation upon particle rigidity, the experimental results show that primary protons undergo the variation, but it is still not proved whether or not particles of $Z\geq 2$ also display this variation.

The experimental data also exclude the production of this variation by the influence of a solar dipole magnetic field.

I. INTRODUCTION

WORLD-WIDE and occasionally large intensity variations of cosmic radiation have been observed over a period of approximately 20 years by using ion chambers and counter telescopes.[1–5] Although these variations usually could be shown to be independent of atmospheric phenomena, it has been widely assumed that these variations were produced directly or indirectly by geomagnetic storms or other geomagnetic field perturbations and, hence, were of terrestrial origin.[2,3,6] In recent years some doubt has been cast upon this assumption since observers have been unable to explain the various aspects of the cosmic-radiation intensity variations on the basis of observed geomagnetic field variations.[5,7–10] It is the purpose of this paper to present experiments which may decide whether or not this assumption is true.

By studying variations of cosmic-ray neutron intensity we have recently shown that it is possible to extend the measurement of intensity-time variations to the low-energy end of the primary-particle spectrum, and in this region we have found intensity variations much larger than heretofore reported for charged particle observations.[11] Since we have shown that meteorological effects do not produce the variations,[12] it is clear either that (a) the prevailing assumption is true and the variations are produced by geomagnetic or geoelectric field perturbations, or that (b) these variations are of primary or extraterrestrial origin, i.e., the intensity variations would be observed even if the earth were removed from the region of the detector, or that (c) some kinds of intensity variations are produced by geomagnetic field variations and other kinds are not.

In earlier preliminary reports we showed that individual examples of intensity variations the order of 5–30 percent in amplitude could not be produced by the geomagnetic field perturbations.[9] In this paper we report the results of a more extensive series of experiments which we believe confirms the earlier results. The study is based upon the largest recurring intensity variations which are to be found throughout the primary-particle momentum spectrum. These are the approximately 27-day recurring variations observed in

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[1] V. F. Hess, Terrestrial Magnetism and Atm. Elec. **41**, 345 (1936).
[2] S. E. Forbush, Phys. Rev. **51**, 1108 (1937); **54**, 975 (1938); S. E. Forbush and I. Lange, Phys. Rev. **76**, 164 (1949).
[3] A. R. Hogg, J. Atm. Terrest. Phys. **1**, 56 (1950).
[4] H. Gheri and R. Steinmaurer, Terrestrial Magnetism and Atm. Elec. **52**, 343 (1947); H. Gheri, Z. Naturforsch. **6a**, 775 (1951).
[5] H. Elliot, *Progress in Cosmic Ray Physics* (Interscience Publishers, New York, 1952), Chapter VIII.
[6] S. Chapman, Nature **140**, 423 (1937).
[7] K. Nagashima, J. Geomag. and Geoelect. **3**, 100 (1951).
[8] D. H. Loughridge and P. F. Gast, Phys. Rev. **57**, 938 (1940).
[9] J. A. Simpson, Phys. Rev. **83**, 1175 (1951).
[10] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).
[11] Simpson, Fonger, and Wilcox, Phys. Rev. **85**, 366 (1952); Phys. Rev. **87**, 240 (1952).
[12] Simpson, Fonger, and Treiman, Phys. Rev. **90**, 934 (1953); hereafter we refer to this paper as reference I.

the neutron intensity.[11,13] Since it is now established that these variations extend to particle momenta sufficiently high to permit detection with small amplitude by charged particle monitors,[11,13,14] we are confident that the reported ∼0.3 percent 27-day variations observed in charged particle detectors from time to time in the past are real and are the same type of recurring variation we have been reporting. The recently found energy dependence of this variation is such that the amplitude of the variation is largest at the low-energy end of the particle differential spectrum.[13] This fact, along with the high counting rates obtained with neutron pile detectors, makes it possible for the first time to study the energy dependence of a single 27-day "cycle" with considerable precision. We find that this kind of variation is composed of moderately well-defined maxima and minima. The neutron observations also show simultaneous series of 27-day recurring variations which appear to be related to active solar regions distributed around the low solar latitudes.[11]

In addition to these recurring intensity variations there are occasional large, sharp decreases of cosmic radiation intensity discovered by Forbush.[2] This is also a world-wide phenomenon. From observations with neutron monitors we find that this type of event usually interferes with the 27-day observations.[4,15] Forbush has associated these occasional large decreases with great geomagnetic storms which do *not* have a 27-day recurrence tendency.

Although no large geoelectric fields have been discovered outside the ionosphere layers, we shall, to consider the origin of these intensity variations more completely, investigate whether or not the 27-day variation could be produced by varying geoelectric fields.

Specifically, we wish to answer the following questions:

(1) Are the cosmic-radiation 27-day recurring intensity variations produced by geomagnetic field perturbations?

(2) Are the intensity variations produced by varying geoelectric fields?

(3) Is the mechanism which produces the 27-day recurrence located at the earth, or is it independent of the earth system but associated with the sun?

II. 27-DAY RECURRING COSMIC-RAY INTENSITY VARIATIONS AND GEOMAGNETIC-FIELD PERTURBATIONS

In order to decide the fundamental question of whether or not geomagnetic-field perturbations produce the 27-day recurring intensity variations, we wish to consider relationships between cosmic-ray and geomagnetic-field variations which are subject to experimental test. These relations may be considered in three general groups. The first group of relationships is independent of special assumptions regarding the mechanisms producing geomagnetic storms and does not require that the geomagnetic storm be a world-wide phenomenon. The second and third groups of relations, as we shall see, depend to some extent upon the assumed magnetic storm mechanism or the assumption that variations of geomagnetic field observed at the surface of the earth also represent variations of the field which interacts with incoming charged particles. Clearly the first group of relations will be of most general interest for comparison with experimental observations.

A. Cosmic-Ray Geomagnetic Field Relations Independent of Special Assumptions

Irrespective of special theories, we know that the geomagnetic field produces the observed "latitude effect" for incoming cosmic radiation. The trajectories of charged particles in a magnetic field are determined uniquely by their directions of arrival and by their ratio, p/Z, of momentum p to charge Z. For a specified rigidity, pc/Ze, certain directions of arrival at the earth may be forbidden. However, at high latitudes we may prescribe, approximately, a unique value for $[p/Z]_\lambda$ at latitude λ above which all rigidities are allowed and below which all rigidities are forbidden. This problem has been discussed in reference I. This is a satisfactory approximation in the latitude range $\lambda > 40°$ for the observations to be reported in this paper.

Since, for continuous observations, we are required to measure the secondary radiations generated by the primaries, we have chosen to observe local neutron production rate as a measure of integrated primary intensity at the top of the atmosphere. In reference I we obtained the relationship between the counting rate R of a neutron detector located at atmospheric depth x, geomagnetic latitude λ, and the vertical, differential primary flux $j_Z(p/Z,t)$ of particles of momentum p and charge Z. We defined the specific yield of neutrons as a function $S_Z(p/Z,x)$ which is experimentally determined from the time-averaged parameters j_z and R to yield the neutron counting rate at depth x arising from a unit flux of vertically incident primary particles of charge Z and rigidity $\propto (p/Z)$. Thus, we found [reference I, Eq. (2)]

$$R_v(\lambda,x,t)=\sum_Z \int_{[p/Z]_\lambda}^{\infty} S_Z\left(\frac{p}{Z},x\right) j_Z\left(\frac{p}{Z},t\right) d\left(\frac{p}{Z}\right), \quad (1)$$

where $[p/Z]_\lambda$ is the cutoff for vertical arrival at λ and $R_v(\lambda,x,t)$ is the counting rate due only to those primaries which arrive from the vertical direction per unit solid angle at time t. R_v and the observed rate R are related in good approximation by the Gross transformation.[16]

[13] W. H. Fonger, Phys. Rev. **91**, 351 (1953); we refer to this paper as reference II.
[14] H. V. Neher and S. E. Forbush, Phys. Rev. **87**, 889 (1952).
[15] A. T. Monk and A. H. Compton, Revs. Modern Phys. **11**, 175 (1939).
[16] S. B. Treiman, thesis, University of Chicago, 1952 (unpublished).

Clearly a variation of R_v may be produced by either a variation of the lower limit of the integral which is determined by parameters of the geomagnetic field, or by a variation of j_z in the integrand, namely, a variation of j_z with time. We shall now consider these two cases in detail.

1. Variations of the Geomagnetic Cutoff

It has been reasonably well established that the primary differential number spectrum for protons at low energies rapidly vanishes near 1 Bev energy (λ approximately 56–58°N).[10,17] For the special case within the atmosphere where the function $S_Z(p/Z,x)$ vanishes for finite values of $j(p/Z,t)$ the observed cutoff of the latitude curve is determined by S rather than j and the observed "knee" of the latitude curve will appear at lower latitudes. Sea level ion chambers and counter telescopes are examples of detectors for which $S(p/Z,x)$ vanishes at moderately small values of (p/Z) with the cutoff appearing in the region of $\lambda\approx 45°$.

However, extensive measurements with disintegration product neutron detectors in 1951 and 1952 demonstrate conclusively that $dR/d\lambda\to 0$ near 55° at $x\approx 300$ g-cm^{-2} as we shall later show. Since the cutoff in the primary spectrum is in the range 56°–58°N, we cannot decide at present whether or not $S_Z(p/Z,x)\to 0$ for $x>0$ at the spectrum cutoff. In any case it appears that the cutoff latitudes for the primary spectrum and the observed neutron production near 300 g-cm^{-2}, where the experiments to be reported here were made, are the same within approximately ±2° geomagnetic latitude.

The arguments which follow are not dependent upon the origin of these cutoffs.

The integral counting rate R_v is unchanged by variations of $[p/Z]_\lambda$ above the knee of the curve since either $j_z(p/Z,t)$ or $S_z(p/Z,x)$ go to zero above the knee (Changes in the shadow cone above the knee may result from variations of the geomagnetic field; however, this effect is an order of magnitude smaller than the effects reported here.) This effect may be illustrated by using a typical latitude curve and allowing the lower limit of the integral, Eq. (1), to undergo variations $\pm[\delta p/Z]_\lambda$. The typical curve is shown as Fig. 1, curve (*a*). For a variation $+[\delta p/Z]_\lambda$ the integrated intensity will appear approximately as shown in Fig. 1, curve (*b*). For a variation $-[\delta p/Z]_\lambda$ the curve will appear approximately as shown in Fig. 1, curve (*c*).

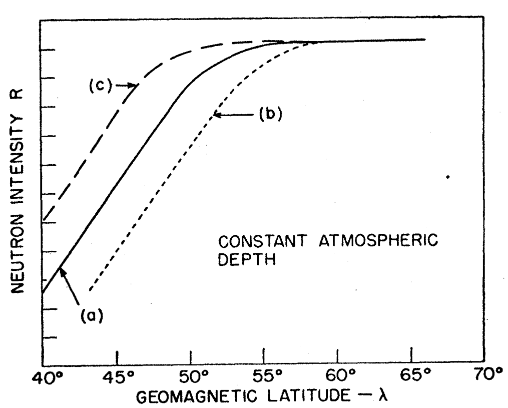

FIG. 1. The predicted behavior of neutron intensity as a function of latitude based upon the assumption that the primary cosmic-radiation intensity variation is produced by a geomagnetic-field variation.

Thus, perturbations of the geomagnetic field as represented by variations of $[p/Z]_\lambda$ reveal two unique characteristics for the integrated counting rate R_v *vs* λ. *First*, for observations well above the cutoff of the latitude curve, R_v is constant—independent of $[p/Z]_\lambda$ variations. Namely, at $[p/Z]_\lambda$

$$\frac{dR_v}{d\lambda}=-S_z j_z\frac{d[p/Z]_\lambda}{d\lambda}=0,\ \text{where}\ j_z=0\ \text{or}\ S_z=0. \quad (2)$$

Hence, the fractional change in counting rate is $\delta R_v/R_v=0$, where $j_z=0$ or $S_z=0$. *Second*, the fractional change of counting rate $\delta R_v/R_v$ for $\lambda\gtrsim 35°$ varies as follows:

$$\frac{[\delta R_v/R_v]_{\lambda_2}}{[\delta R_v/R_v]_{\lambda_1}}<1,\quad \text{for}\quad \lambda_2>\lambda_1. \quad (3)$$

2. Variations of Primary Cosmic-Radiation Intensity

We now consider the consequences of changes of the differential primary spectrum $j(p/Z,t)$ with time t. From Eq. (1), the maximum value for the integral at time t is obtained by setting the lower limit equal to the minimum particle rigidity $[p/Z]_{\min}$ observed in the primary spectrum. Hence, for all values of $[p/Z]_\lambda<[p/Z]_{\min}$ the integral is a constant. Now, if $j_z(p/Z,t)$ undergoes a variation, the observed counting rate will change for observations at latitudes corresponding to $[p/Z]_\lambda<[p/Z]_{\min}$ as well as for latitudes corresponding to $[p/Z]_\lambda\geqslant[p/Z]_{\min}$. Thus, an observer within the atmosphere would measure a change in secondary particle intensity above and below the cutoff of the latitude curve. For example, if the fast neutron latitude curve at time t is represented as curve (*a*), Fig. 2, then, if at time t^1 a variation occurs to produce a fractional change of intensity $-\delta R/R$, which variation for simplicity we shall make independent of latitude, then at t^1 the neutron latitude curve will appear as curve (*b*), Fig. 2.

For the special case where the function $S_z(p/Z,x)$ vanishes for finite values of $j(p/Z,t)$ the observed cutoff of the latitude curve will be determined by S rather than j, and again, if j undergoes a variation of intensity with time, the counting rate of the detector will change with time above and below the cutoff determined by S_z.

[17] J. Van Allen (private communication).

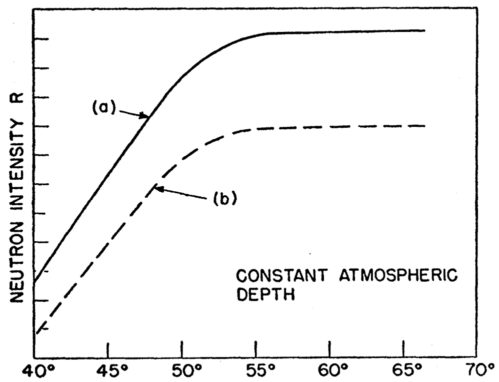

FIG. 2. The predicted behavior of neutron intensity as a function of latitude based upon the assumption that the cosmic-radiation intensity variation is produced by a change in the primary flux with time.

B. Test Experiments

It is clear from the previous discussion that, without invoking special assumptions regarding the origin of geomagnetic field perturbations, we may determine whether intensity variations observed with neutron detectors at high latitudes are produced by geomagnetic field variations or whether the variations are produced by changes in the *primary* intensity. The crucial test consists in determining the behavior of the neutron intensity in the latitude range of $\lambda \sim 40°$ to $\lambda \sim 65°$ during the period of an intensity variation. As noted earlier the largest recurring variations are the approximately 27-day variations in the nucleonic component; hence, we apply the criteria discussed above to the experimental observations of this variation. At constant atmospheric depth a family of latitude curves is to be obtained with each curve representing the different levels of observed cosmic radiation intensity at different times.

We have already reported several preliminary measurements using the detection of fast disintegration product neutrons to measure nucleonic component intensity with B-29 aircraft flying at atmospheric depth $x \approx 300$ g-cm^{-2} in 1948 and 1949. These results demonstrated that observed large variations of cosmic radiation intensity could not be due to geomagnetic field variations.[9] To investigate the behavior of the 27-day recurring variations, a more extensive series of measurements was undertaken in the period 1950–1952 using a type RF-80 jet aircraft. The measurements we report here were obtained in this latter period. The instrumentation was installed in the nose of the aircraft and either atmospheric or local neutron production could be measured with the apparatus. Experimental details regarding the apparatus and flight procedures for the jet aircraft are described elsewhere.[18] No longitude corrections are required for these observations since all data were recorded over a fixed route between $\lambda = 40°$ and 65° N. A single, enriched BF_3 proportional counter surrounded by paraffin with a cadmium shield was used for all the measurements reported in this paper.

The individual curves of neutron intensity *vs* latitude for different times are related by continuous recordings of neutron intensity using pile geometries at selected latitudes. Thus, the observed changes with time of the discrete intensity *vs* latitude curves at high altitudes can be related to long-time continuous intensity variations. Details regarding the continuous neutron monitor stations have been published in reference I.

Several flights are required to obtain data for a single latitude curve over the latitude range of 40° to 65°N with an aircraft of small range. Because of widely varying weather conditions the sequence of flights may extend over a period the order of 10 to 60 hours. Changes of intensity may occur within this time interval. Consequently, to avoid distortion of a latitude curve constructed from several flights, the data in the latitude interval 40° to 53° (large $dR/d\lambda$) are obtained within a few hours. All additional data required to construct the latitude curve, such as data from flights between $\lambda = 52°$ to 65°, are corrected for the intensity at the time of the lower latitude flights. The individual segments of the latitude curves were fitted by requiring that, for any two completed latitude curves, there must be no discontinuities in the observed change of intensity δR over the entire range of λ. A complete latitude curve constructed from data taken over a period of a few days is referred to a specific day and time, namely, the time for the data obtained in the interval $\lambda \approx 40°$ to 53°. In general, the intensity variations during the collection of data for constructing a single latitude curve were small.

All data reported here are for the atmospheric depth $x = 312$ g cm^{-2}.

1. Case 1

We first consider a case where two latitude curves were obtained at times when *no* magnetic storms were

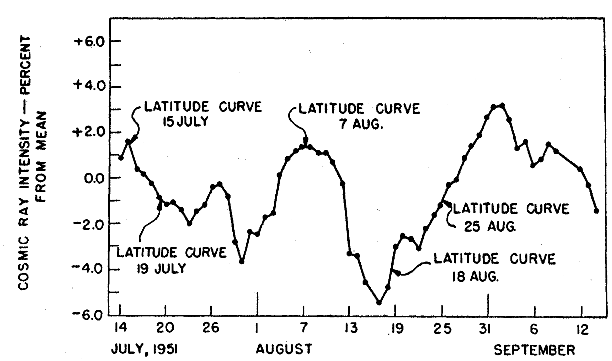

FIG. 3. The percent change of neutron-pile intensity from the mean intensity in pile D-1 using 24-hour average values of intensity.

[18] J. A. Simpson and W. C. Fagot, Phys. Rev. 90, 1068 (1953).

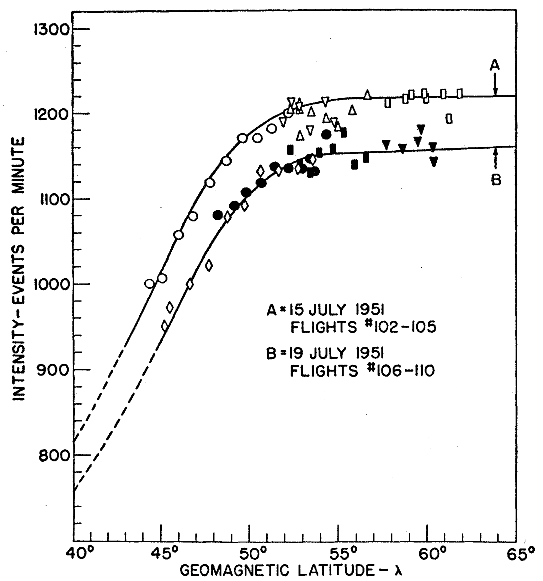

FIG. 4. The neutron-intensity data used to establish the latitude curves for 15 and 19 July, 1951 are shown. The smooth curves (with dashed lines for extrapolations) are used for analysis. The curves are based upon the following aircraft flights (standard deviations are given by the size of the flight identification symbols):

○ 15 July (flight No. 102) ◇ 19 July (flight No. 106)
△ 16 July (flight No. 103) ● 19 July (flight No. 107)
□ 16 July (flight No. 104) ■ 20 July (flight No. 108)
▽ 16 July (flight No. 105) ▼ 20 July (flight No. 109).

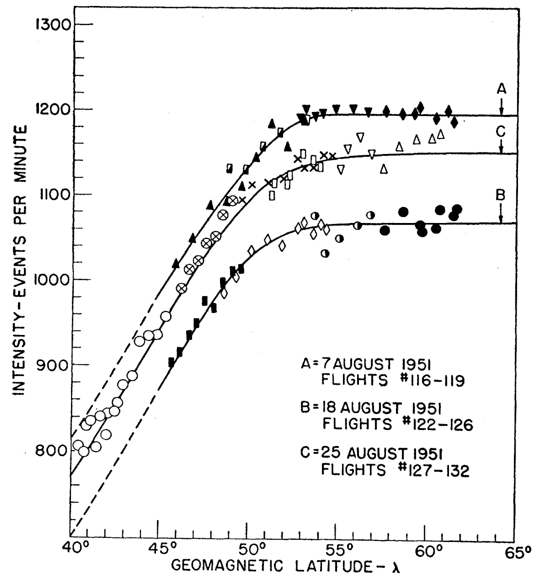

FIG. 5. The neutron-intensity data used to establish the latitude curves for 7, 18, and 25 August, 1951, are shown. The smooth curves (with dashed lines for extrapolations) are used for analysis. The curves are based upon the following aircraft flights (standard deviations are given by the size of the flight identification symbols):

▲ 7 August (flight No. 116) ◑ 17 August (flight No. 122)
◪ 7 August (flight No. 117) ● 17 August (flight No. 123)
▼ 9 August (flight No. 118) ■ 18 August (flight No. 125)
⧫ 9 August (flight No. 119) ◇ 18 August (flight No. 126)
▽ 24 August (flight No. 127)
△ 24 August (flight No. 128)
□ 24 August (flight No. 129)
○ 25 August (flight No. 130)
⊗ 25 August (flight No. 131)
× 25 August (flight No. 132).

reported during the measurements. The change of daily mean intensity within the interval July 14 through September 9, 1951, is shown in Fig. 3. The first high-altitude measurements were 15–16 July, and we refer these flights to the time of the July 15 flight (see Fig. 4). Similarly, the latitude curve for July 19 and 20 is called the latitude curve for July 19. From these data we have determined the smooth curves which best represent the data for July 15 and July 19. The fractional change of omnidirectional intensity $[\delta R/R]_\lambda$ *versus* λ has been computed in Table I.

2. *Case 2*

In the following example three latitude curves were studied during an especially well-defined series of variations in August, 1951; the continuous intensity variations are shown in Fig. 3. Figure 5 presents the experimental data and the corresponding smoothed curves. Minor geomagnetic storms were underway during the latter two measuring periods. See Table II, example 8.

TABLE I. Experimental values of $\delta R/R$.

Date / λ	18 June and 26 June	15 July and 19 July	7 August and 18 August	18 August and 25 August	29 March and 18 June
40°	0.08				
45°	0.08	0.08	0.13	0.08	0.20
48°	0.09	0.07	0.11	0.07	0.22
50°	0.10	0.06	0.11	0.07	0.23
52°	0.09	0.06	0.12	0.07	0.22
56°–65°	0.08	0.06	0.12	0.08	0.22

Again the evidence supports the conclusion that the observed cosmic-ray intensity variations are due to changes in the primary spectrum. The intensity variations in this period have approximately 27-day recurring variations.[11,13] This is the most complete set of measurements we have been able to obtain within a single 27-day "cycle."

3. *Case 3*

In the previous two cases we have considered sequences of measurements within single 27-day intervals. Since the same neutron detector with constant efficiency was used over periods the order of 6–8 months, latitude curves separated by long time intervals may be compared. For example, there is a large difference in observed cosmic-radiation intensity between 29 March, and 18 June, 1951, Fig. 6. The fractional change of intensity $[\delta R/R]_\lambda$ is given in Table I. The measurements for both the March 29 and June 18 curves were obtained during geomagnetic storms.

4. *Case 4*

A sharp decrease of cosmic-ray intensity was observed in June, 1951, which interfered with the ~27-day recurring variations.[11] The change of daily mean intensity with time in the interval June 4–27, 1951 is shown in Fig. 7. This event possesses two of the characteristics of a Forbush-type decrease,[2] namely, (1) the decrease is rapid and the recovery is slow, and (2) this type of event is infrequent and interferes with the 27-day recurring intensity variations. This decrease is unlike the Forbush-type in that the geomagnetic storm which occurred during the decrease was not unusually large as shown in Table II, examples 6 and 7. Two latitude curves were obtained which are related to this event. The data for June 18 and June 26 latitude curves are displayed in Fig. 8. Clearly, the sharp intensity

TABLE II. Neutron intensity changes and magnetic storms; Climax, $\lambda = 48°$.

Example 1: 21 May 1951 Decrease of *3 percent* starts ~1100 U.T. with no magnetic storm.

				K_w				K_w	
20 May	1.8	2.0	1.7	1.6	2.0	1.1	1.7	1.3=13.2	three of the five
→21	1.0	0.9	0.9	1.1	1.1	1.0	1.4	1.6= 9.0	most quiet days
22	2.4	1.3	0.6	1.1	2.3	2.3	1.3	1.0=12.3	in May

Example 2: 23 May 1951 Decrease of *5 percent* starts ~2000 U.T. with no magnetic storm.

				K_w				K_w
22 May	2.4	1.3	0.6	1.1	2.3	2.3	1.3	1.0=12.3
→23	2.3	2.1	2.2	3.8	3.6	2.9	5.0	4.1=26.0
24	3.8	2.5	2.0	2.4	2.7	3.4	2.3	2.6=21.7

Example 3: 10 June 1951 Decrease of *4 percent* starts ~2000–2100 U.T. with no magnetic storm.

				K_w				K_w	
9 June	3.5	2.6	1.7	2.3	3.1	3.4	0.4	0.8=17.8	
→10	1.0	0.7	0.8	2.4	3.1	2.5	2.1	1.4=14.0	← one of five most quiet days, June
11	2.1	2.5	1.7	2.3	2.2	3.1	3.0	2.8=19.7	

Example 4: 29 July 1951 Decrease of *3 percent* starts ~0200 U.T. with no magnetic storm.

				K_w				K_w
28 July	3.8	4.4	3.5	4.1	3.2	4.1	4.2	3.1=30.4
→29	2.9	3.4	2.8	3.1	2.7	2.6	2.4	2.2=22.1
30	2.2	2.0	1.8	2.9	2.8	2.7	3.3	3.4=21.1

Example 5: 2 September 1951 Decrease of *3 percent* starts ~1800 U.T. with no magnetic storm.

				K_w				K_w	
1 Sept.	2.1	1.6	1.3	1.2	1.9	1.4	0.9	2.6=13.0	four of the five
→ 2	2.2	1.4	1.1	1.1	1.2	1.4	1.0	1.6=11.0	most quiet days
3	2.2	1.6	1.9	2.4	2.5	1.2	1.2	2.8=15.8	in September
4	2.1	2.7	1.4	1.1	2.1	1.9	2.0	2.2=15.5	

Example 6: 14 June 1951 Decrease of *6 percent* starts ~1700 U.T. with magnetic storm s.c. 1750.

				K_w				K_w
13 June	2.5	1.6	3.0	2.8	3.4	1.7	1.8	2.2=19.0
→14	0.9	1.1	0.4	1.2	0.9	3.8	4.6	4.6=17.5
15	3.6	2.9	3.3	2.8	3.8	3.4	3.5	3.0=26.3

Example 7: 17 June 1951 Decrease of *3 percent* starts ~1000–1300 U.T. with magnetic storm s.c. 1701.

				K_w				K_w	
16 June	3.5	2.3	2.7	2.9	2.7	3.0	2.8	2.5=22.4	
→17	2.3	1.5	1.3	1.0	0.9	4.3	3.6	6.3=21.2	two of five most dis-
18	5.3	5.2	5.1	3.7	3.3	3.5	2.1	3.2=31.4	turbed days in June

Example 8: 11 August 1951 Decrease of *6 percent* starts ~1700 U.T. and continues for a few days—magnetic storm s.c. 0315 August 11.

					K_w				K_w
	10 Aug.	1.6	1.9	2.4	2.3	3.1	1.5	2.0	2.3=17.3[a]
	→11	2.2	2.3	2.5	2.9	3.6	2.9	2.9	3.3=22.6
Note: *4 percent* of total	12	3.3	2.8	3.1	3.1	3.3	2.8	3.2	3.5=25.1
decrease begins ~0200	→13	2.4	4.6	4.6	3.8	4.4	4.6	4.7	2.2=31.3[b]
August 13	14	1.4	1.2	1.1	2.8	2.4	2.5	2.6	3.1=17.1[a]
	15	3.2	2.2	3.0	1.6	2.5	2.9	4.4	3.3=23.1

[a] Two of the ten most quiet days in August.
[b] One of five most disturbed days in August.

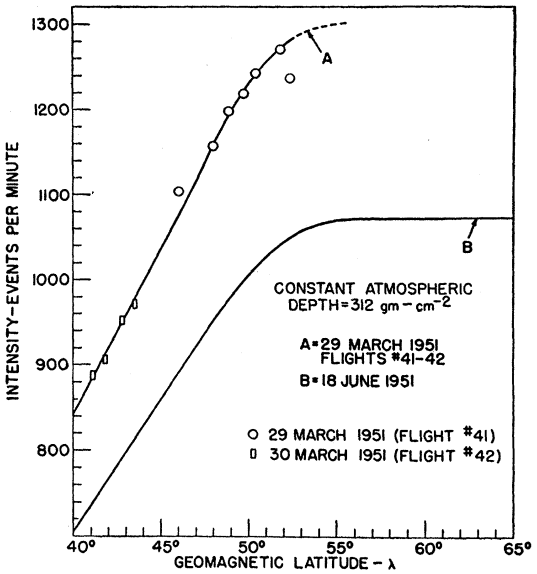

FIG. 6. The neutron-intensity data used to establish the latitude curves for 29 March and 18 June, 1951, are shown. The smooth curves (with dashed lines for extrapolations) are used for analysis. See Fig. 8 for 18 June, 1951, data.

decrease of Fig. 7 was not produced by geomagnetic-field variations.

5. *Further Evidence and Conclusions*

In addition to the above cases selected on the basis of a variety of magnetic storm conditions, we have recorded eight additional latitude curves in 1951–52. To these we add the results of the 1948–49 measurements representing five latitude curves. Without exception, the behavior of these latitude curves is the same as for cases 1–4.

In view of these experimental results we believe *it is now proved that cosmic-radiation 27-day recurring intensity variations are produced by changes of primary-particle flux rather than by variations of the geomagnetic-field intensity.*

C. Search for Association of 27-Day Intensity and Geomagnetic Field Variations

1. *Early Work with Ion Chambers or Counter Telescopes*

In view of the experimental results obtained in the previous section, how may we interpret the careful and extensive work of Forbush, Hess, and others who find evidence indicating much more than an accidental relationship between cosmic-ray intensity variations and changes of geomagnetic-field intensity? We shall now examine this question.

Early studies have often been predicated on the doubtful assumption that a recording magnetometer located at the surface of the earth measures variations of the external horizontal magnetic field component which are proportional to the magnetic field variations in the regions where the field interacts with charged cosmic-ray particles, and that the observed variations of magnetic-field and radiation intensity may be related. If this assumption is valid, there should exist a *detailed time correspondence* between horizontal component field intensity and measured cosmic-ray intensity variations at the surface of the earth. The observations using ion chamber and counter telescope detectors have provided contradictory evidence; however, from these early results there appears to be general experimental agreement that:

(a) large decreases of cosmic-ray intensity may occur with geomagnetic storms;
(b) not all large magnetic storms are accompanied by cosmic-radiation intensity changes;
(c) the magnitudes of the storms do not bear a unique relationship to the magnitudes of the cosmic-ray change;
(d) in some cases there appears to be remarkable time correspondence between the principal variations of the field and cosmic-ray intensity;
(e) those intensity decreases which are associated with geomagnetic storms appear most closely with the main phase of the storm. Subsequently the cosmic-ray intensity slowly returns to "normal" level;
(f) some large cosmic-ray decreases are world-wide phenomena as are the associated geomagnetic storms;[2]
(g) the intensity decreases are observed at high energies (>20 Bev) and down to the cutoff of ion chambers or counter telescopes;
(h) there is a small 27-day recurring cosmic-ray intensity variation. (Independently, it has been established that geomagnetic storms of moderate intensity also possess a 27-day recurrence tendency.)[19]

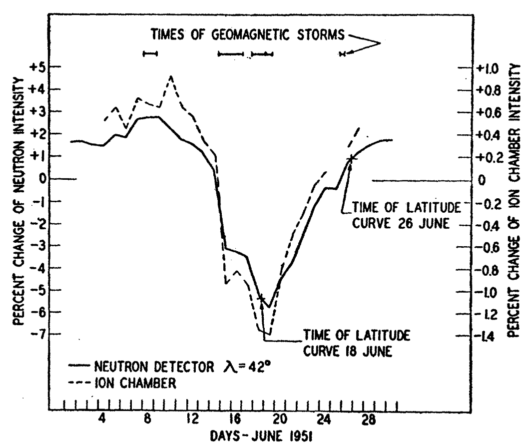

FIG. 7. The percent change of neutron pile intensity from the mean intensity in pile F-1 at $\lambda = 42°$ using 24-hour average values of intensity. The published data from the Sittkus ion chamber at Freiburg, Germany, are shown. The ion chamber percent changes are multiplied by a factor 5 for comparison with neutron intensity changes.

[19] J. Bartels, Terrestrial Magnetism and Atmos. Elec. **40**, 1 (1935). C. Chree, Phil. Mag. Trans. **A213**, 245 (1913).

To account for these observations and the fact that there does not appear to be a unique relationship between cosmic-ray and geomagnetic-field intensity variations, Forbush[2] has invoked a theory of magnetic storms proposed by Chapman.[6] In principle, a variable storm magnetic field produced by an ionic ring current circulating around the earth is added vector-wise to the permanent dipole magnetic field of the earth. The onset of the storm may be sudden (sudden commencement = s.c.) or gradual (no s.c.) followed shortly by the main phase of the storm usually consisting of a decrease of observed horizontal component of the order of $5\times10^2\gamma$ ($\gamma=10^{-5}$ gauss). This model appears to describe satisfactorily many features of the storm.

With a specific model of this type the expected phase relationship and relative magnitude of cosmic-ray intensity and magnetic-field variations have been computed by Forbush,[2] Johnson,[20] Hayakawa,[21] *et al.*, and more recently by Treiman[22] in this laboratory whose results we may briefly summarize as follows:

(1) the *algebraic sign* of the calculated variations $\delta H/H$ is wrong to account for observed variations $\delta R/R$, and
(2) the magnitudes of the cosmic-ray variations are one to two orders of magnitude larger than computed from this model of geomagnetic-field variations.

We conclude from the foregoing evidence that results based on the assumption of detailed time correspondence or on the determination of phase and intensity relationships from a specific model indicate that a relationship between the two phenomena exists but that the measurements are, in some cases, inconclusive or contradictory.

2. *Neutron-Intensity Results*

Owing to these difficulties and to the fact that the 27-day recurring cosmic-ray variation is not produced by geomagnetic-field variations, we approach the problem from a different point of view, using the variations of neutron intensity at high geomagnetic latitudes. This shifts the observations to a lower mean particle momentum range of the primary momentum spectrum. The most readily distinguished feature of the neutron-intensity variations is the time of maximum intensity which has been shown to display the 27-day recurrence phenomenon. We select for study an interval of time containing many of these maxima and determine the most probable time relation of these maxima to well-established features of geomagnetic disturbances, such as periods of greatest field variations, and so forth. Thus, instead of considering the possible

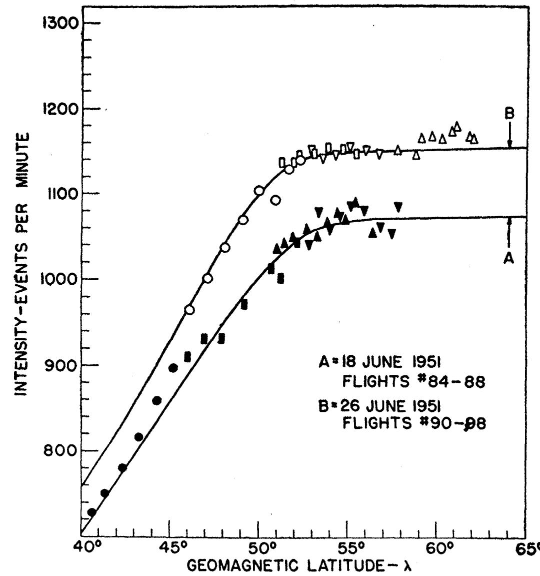

FIG. 8. The neutron-intensity data used to establish the latitude curves for 18 and 26 June, 1951, are shown. The smooth curves (with dashed lines for extrapolations) are used for analysis. The curves are based upon the following aircraft flights (standard deviations are given by the size of the flight identification symbols):

● 18 June (flight No. 84)	○ 26 June (flight No. 90)
■ 18 June (flight No. 85)	▽ 30 June (flight No. 96)
▲ 23 June (flight No. 87)	△ 30 June (flight No. 97)
▼ 23 June (flight No. 88)	□ 30 June (flight No. 98).

geomagnetic-field—cosmic-ray association of individual events, we study the distribution in time of a relatively large number of events to determine the most probable time association between the two parameters being studied.

In a 19-month period of neutron-intensity registration between May 1, 1951, and November 30, 1952, we obtain 41 neutron-intensity maxima that are sufficiently large to be readily identified, without detailed analysis, at two or more widely separated neutron monitoring stations above 40° geomagnetic latitude. Some of the maxima are shown in Fig. 3. In general, the times of these world-wide maxima are defined within approximately ±1 day.

We first investigate how the magnitudes of geomagnetic disturbances are distributed with respect to the times of cosmic-ray intensity maxima. Observers of geomagnetic-field variations have established an arbitrary but reliable measure of the deviations of magnetic-field intensity from average values on undisturbed days. These deviations or disturbances have been reduced to a scale or index of 0 (very "quite") to 9 (extremely disturbed), representing the average deviation of field intensity per 3-hour interval. This scale is called the 3-hour K index. Each magnetic observatory contributes its scaled values to a central group which prepares average K values on a world-wide basis. Thus, the K value for a day consists of an average of eight K values. K_p, the planetary index, is the mean standard-

[20] T. H. Johnson, Terrestrial Magnetism and Atmos. Elec. 43, 1 (1938).
[21] Hayakawa, Nishimura, Nagata, and Sugiura, J. Sci. Research Inst. (Tokyo) 44, 121 (1950).
[22] S. B. Treiman, Phys. Rev. 86, 917 (1952).

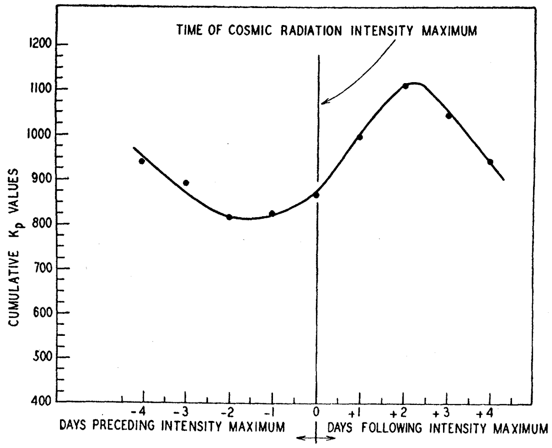

FIG. 9. The most probable distribution of daily K_p values (K_p is a measure of magnetic disturbances) (see reference 23) for the 4 days preceding and following the days of the 41 cosmic-radiation intensity maxima. The most probable time for smallest geomagnetic disturbances is ~1 day before the cosmic-radiation intensity maximum, and the most probable time for geomagnetic disturbances is ~2 days *after* the intensity maximum.

ized K index from 11 observatories located between geomagnetic latitudes 47 and 63 degrees throughout the world.[23]

Since K_p is a measure of the magnitude of magnetic disturbances, we may determine the most probable distribution of K_p values for the $\pm n$ days with respect to the times of cosmic-ray intensity maxima. Since we do not define the times of maximum closer than one day we shall use the daily sums of K_p indices. After summing for 41 neutron maxima we obtain the results shown in Fig. 9. The largest statistical errors are in the assignment of the times of neutron intensity maximum. However, it is clear that geomagnetic field perturbations increase steadily from $n=-1$ to a maximum at $n=+2$, showing that the times of greatest geomagnetic disturbance will most probably occur 2 days after the appearance of a low-energy cosmic-radiation intensity maximum.

We may check this result by noting that the 10 days each month which have the *smallest* geomagnetic-field disturbances are regularly reported by the same 11 geomagnetic observatories. The distribution of these "quiet" days may be determined with respect to the dates of the 41 neutron-intensity maxima. The results are shown in Fig. 10. A broad but significant maximum appears near $n=-1$. The 5 most disturbed days each month are also reported; an identical analysis shows that a peak lies near $n=+2$ as shown in Fig. 11. The limitation of the number of selected days gives this result a lower statistical weight than the previous results.

[23] For a complete description of K_p see: Geomagnetic Indices C and K, 1948, Association of Terrestrial Magnetism and Electricity, International Union of Geodesy and Geophysics, Washington, D. C., 1949. For monthly reports of the K_p index see, for example, Series F reports of Central Radio Propagation Laboratory, Natl. Bur. Standards, Washington, D. C.

We can show that the onset of cosmic-ray intensity *decreases*, which follow the intensity maxima described above, is not necessarily accompanied by *any* geomagnetic disturbance. Several cosmic-ray intensity changes of 3 percent or more were selected from a five-month interval of 27-day recurrences which includes the period of the aircraft observations in 1951. The data obtained from the Climax D-1 neutron pile monitor are given in Table II. Values of the K index, K_w, for 36 or more magnetic observatories distributed on a world-wide basis were used to determine the existence of geomagnetic disturbances. From this table we find 5 examples where there is no evidence for magnetic disturbances near the time when the neutron intensity begins to decrease. Several of the magnetic "quiet" days occurred during these periods.

We conclude that large intensity variations need not be accompanied by an observable geomagnetic storm; i.e., $(\delta R/R)/(\delta H/H)\rightarrow\infty$.

A 6 percent decrease is shown in example 6 with close time correspondence between start of the decrease and storm commencement; the K_w values show that only a minor geomagnetic storm occurred.

In view of the already reported relationship[11] between discrete regions of intense solar activity and neutron-intensity maxima these results are of particular interest in interpreting and understanding solar-terrestrial phenomena (for example, with respect to the possible existence of discrete streams of low-velocity ions originating at the sun). However, we shall consider this aspect of the problem in a later paper.

It should be pointed out that, although these relationships may aid in the prediction of geomagnetic storms, more data are required over a greater portion of the 11-year solar half-cycle before these relationships can be considered firmly established.

We now return to the question of the interpretation of ion chamber and counter telescope results. By noting that following a cosmic-radiation intensity maximum an intensity *decrease* certainly occurs, we

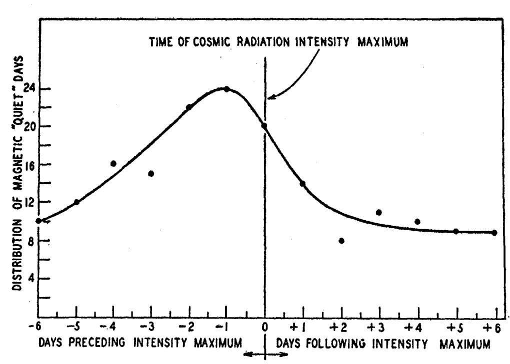

FIG. 10. The distribution of geomagnetic "quiet" days (10 are reported each month) with respect to the times of the 41 neutron-intensity maxima.

may restate our neutron intensity observations as follows:

(1) the most probable time for the commencement of a geomagnetic storm is near the beginning of a cosmic-radiation intensity *decrease*, and
(2) the most probable time for geomagnetic disturbances is during a decrease of cosmic-ray intensity.

Thus, the properties outlined in 1(a–h) of this section for ion chambers may be interpreted from the point of view of the neutron intensity observations. Whether or not the large and rare great magnetic storms and cosmic-ray intensity decreases—the Forbush-type decreases (see Sec. B, case 4)—also possess these properties is not known.

D. On The Location of the Phenomenon Associating Cosmic-Ray and Magnetic Field Variations

The nature of the indirect link or association between cosmic-ray variations and magnetic-field disturbances is obscure; however, there are two limiting possibilities:

(a) the link occurs in the region of the earth and is of terrestrial origin;
(b) the link is independent of the earth system and is of solar origin.

To distinguish between these alternatives we noted that the variation of counting rate R in Eq. (1) must arise from changes in $j_z(p/Z,t)$. Since this differential number spectrum is a function of p/Z, a change δj may occur either through a change in the number of particles in the primary spectrum, *or* through an acceleration (or deceleration) of particles which reach the earth. Consequently, the problem of identifying the location of the cosmic-ray—magnetic-field link reduces to the following alternatives; either

(1) the cosmic-radiation intensity variations are produced by *geoelectric* fields and are, therefore, of terrestrial origin, or
(2) the intensity variations are of extraterrestrial origin and are produced by injection, acceleration, or perturbation processes (see Fig. 1 of reference I).

If (1) is correct, the geoelectric fields are probably related to the geomagnetic field disturbances; if (2) is correct, the cosmic-radiation intensity variations are of primary origin and are indirectly associated with terrestrial magnetic field perturbations by means of a solar-controlled mechanism outside the earth system. Although at present geoelectric fields are not known to exist outside the ionosphere, we shall consider this question in the next section, using the results from measurements of nucleonic component intensity-time variations.

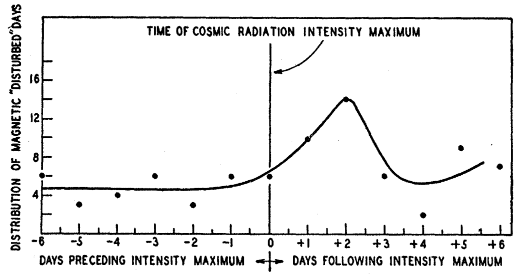

FIG. 11. The distribution of geomagnetic "disturbed" days (5 are reported each month) with respect to the times of the 41 neutron-intensity maxima.

III. THE ENERGY DEPENDENCE OF COSMIC-RAY INTENSITY VARIATIONS AND THE GEOELECTRIC FIELD VARIATION HYPOTHESIS

A. Introduction

In this section we shall consider observations related to the question: are the 27-day recurring cosmic-ray intensity variations produced by varying geoelectric fields? This is a difficult question to evaluate, particularly since there is no experimental evidence to show that geoelectric fields exist outside the quasi-equipotential "surface" of the terrestrial ionosphere. The question of the existence of distant varying electric fields is deferred for later discussion.

Without requiring special models for the production of varying electric fields in the region of the earth we may note that cosmic-ray intensity variations arise from three general factors whenever such an accelerating-field variation is operative:

(1) there is a contribution to the average intensity since the number spectrum is a function of energy; i.e., $dj(E,t)/dE\neq 0$;
(2) there is a change in the number of particles found in an energy interval dE which arises from the application of Liouville's theorem. This was first pointed out by Nagashima.[7]
(3) If the particle acceleration occurs within the geomagnetic field, a contribution to the change of intensity is produced by changes of the observed cutoff rigidity at the earth.

Thus, whenever a geoelectric field undergoes a variation, the accelerated charged particles will form an energy spectrum which differs from the mean differential energy spectrum, and it is this fact which offers the possibility of comparing the effects of an assumed varying electric field with experimental observations.

Three properties of cosmic-ray intensity variations are accessible for experimental observations if varying geoelectric fields produce the intensity variations. They are:

(1) The magnitudes of the intensity variations are dependent on particle energy. The detailed form of the energy dependence is determined by the

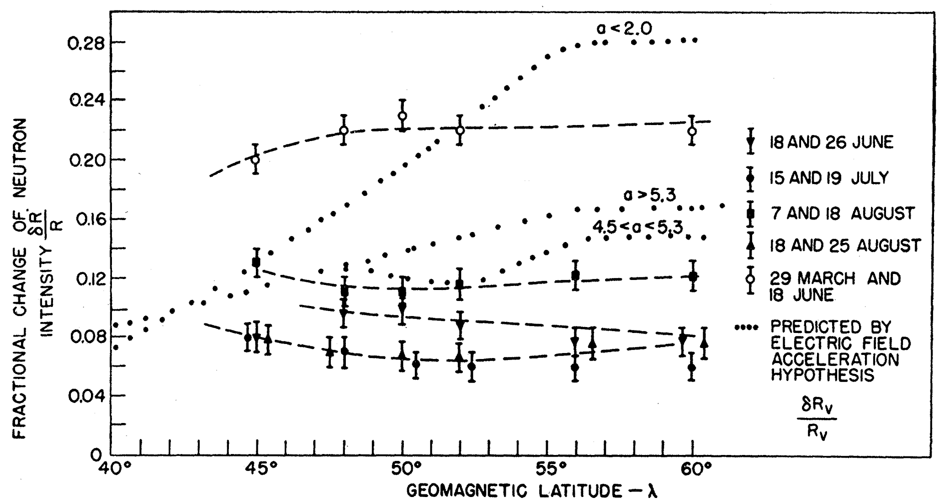

Fig. 12. The experimentally determined ratio $\delta R/R$ is shown with experimental errors for the latitude range 45°–60°. The calculated ratio $\delta R_v/R_v$ is shown for three cases where a geoelectric field is assumed to produce the required particle acceleration. Preacceleration corresponds to $a>5.3$. Mixed field acceleration corresponds to $4.5<a<5.3$. Postacceleration corresponds to $a<2.0$. These calculated curves are normalized to 0.10 at $\lambda=42°$ for comparison with the experimental results.

assumed properties of the geoelectric field model as we shall indicate later.

(2) From Eq. (1), Sec. II it is clear that intensity variations are predicted at geomagnetic latitudes, not only where $dj/dE\neq 0$, but also where $dj/dE=0$ (above the knee of the integral geomagnetic latitude curve). This is contrary to the results from perturbations due to geomagnetic field cutoff.

(3) All charged particles, $Z=1,2,\cdots$, experience the common accelerating mechanism.

Whereas (3) requires detailed measurements at the top of the atmosphere, (1) and (2) may be studied within the atmosphere. We demonstrated in reference I that the neutron intensity variation method is most suitable for the study of energy dependence of intensity variations Hence, the aforementioned properties (1) and (2) are measured using neutron detectors within the atmosphere at intermediate and high geomagnetic latitudes.

B. Experimental Observations

The neutron intensity measurements obtained with aircraft and neutron piles at fixed locations which were described in Sec. II will also be used here. It is most convenient to compare experiment with theory by comparing the observed fractional changes of counting rate $\delta R/R$ (as defined in Sec. II for the omnidirectional detector) with the ratio $\delta R/R$ calculated from specific models for geoelectric field variations. Since the calculations are carried out for vertically incident primary particles of charge Ze at the top of the atmosphere, it is the fractional change arising from these vertically incident particles which is calculated, namely $\delta R_v/R_v$. But since the absorption mean free path for the neutron-producing radiation L is a function of λ at small atmospheric depths, we have for the region below the air transition-curve maximum the relation (reference I):

$$\frac{\delta R_v}{R_v}=\frac{\delta R}{R}-\frac{\delta L}{L}\left[\frac{x/L}{1+x/L}\right].$$

For our present aircraft measurements of $\delta R/R$ at $x=312$ g cm^{-2}, we must determine the importance of the second term in δL in the latitude range 40°–65° before the experimental results can be compared with computed values of $\delta R_v/R_v$. As we shall observe subsequently from the hypothesis of varying electric fields, we only require the sign and order of magnitude of this term. Wherever $j_z(p/z,t)=0$ or $S_z(p/z,x)=0$, we know that $L(\lambda)=$ constant and

$$\delta R_v/R_v=\delta R/R.$$

Elsewhere, in the region $56°>\lambda>40°$ an increase $+\delta R$ produces a change in mean free path $-\delta L$. Hence, for an increase (or decrease) of intensity in general, we have

$$\delta R_v/R_v\geqslant\delta R/R.$$

For the measurements reported here, the range of L values is 155 to 180 g cm^{-2} and the contribution of the term δL is small.

The experimental values of $\delta R/R$ are given in Table I and are plotted as a function of latitude λ in Fig. 12. As a consequence of the above arguments on the effect of δL *vs* λ, these experimental curves represent the *lower limits* for the fractional changes of counting rate for $\lambda<56°$.

C. Assumed Geoelectric Fields

Without postulating at this time the mechanism whereby a geoelectric field is produced, we may determine its effect upon cosmic-ray intensity if the radial extension or spatial limits of the field are specified. There are three cases we wish to consider: (1) The electric field accelerates (or decelerates) the primary charged cosmic radiation prior to its being deflected in the geomagnetic field—we call this case *preacceleration*; (2) the cosmic rays are accelerated by an electric field within the geomagnetic field—called *mixed field acceleration*; (3) the cosmic rays are accelerated by electric fields after passing through the geomagnetic field—called *postacceleration.*

1. Preacceleration

The expected intensity variations for charged particles accelerated by a varying electric field prior to their deflection in the geomagnetic field may be calculated with the following assumptions:

(a) The particles arrive vertically incident at the atmosphere.
(b) Both protons and heavy nuclei are accelerated and the yield of disintegration product neutrons per primary particle nucleon is independent of the atomic weight of the primary particle (see reference I).
(c) The primary spectrum at "infinity" is known and is given by the time averaged spectrum at the top of the atmosphere.

With these assumptions the expected dependence of the variation $\delta j(p/z,t)$ upon magnetic rigidity may be determined from reference II. Using the neutron specific yield as a function of λ, the dependence of $\delta R_v/R_v$ upon geomagnetic latitude has been calculated for $x=312$ g cm^{-2} for the latitude range $\lambda>40°$ (see Table III and Fig. 12). It is clear that the calculated latitude effect for $\delta R_v/R_v$ between $\lambda=40°$ and $\lambda<56°$ is

TABLE III. Values of $\delta R_v/R_v$. $x=312$ g cm^{-2}.

λ	$a<2.0$	$3.6<a<4.5$	$4.5<a<5.3$	$5.3<a$
42°	1.00	1.00	1.00	1.00
48°	1.74	0.91	1.29	1.29
52°	2.24	1.18	1.18	1.49
56°	2.82	1.48	1.48	1.67

$$\frac{\delta R_v}{R_v}(56°)\bigg/\frac{\delta R_v}{R_v}(40°)=1.7,$$

whereas from the experimental points in Fig. 12 we note that this ratio must be <1, since, for $\lambda<56°$, $\delta R_v/R_v>\delta R/R$ as shown earlier.

2. Mixed Field Acceleration

For preacceleration the geomagnetic cutoff rigidity of charged particles is unchanged, i.e., the changes in observed intensity are due only to $\delta j_z(p/z,t)$. However, for cases of particle acceleration within the geomagnetic field there is an additional contribution, namely, the lower limit of Eq. (1), undergoes a change $[\delta p/Z]_\lambda$ at the earth. For the cases of mixed field acceleration and postacceleration this latter contribution has been computed by Treiman and Jory[24] in this laboratory. Without requiring a detailed model for the production of the electric field, their calculations are based upon the following additional assumptions:

(a) The geoelectric field is assumed to have axial symmetry about the magnetic axis of the earth.
(b) In the equatorial plane the radial extent of the electric field, Δr, is small compared with the distance of the field from the axis of the dipole geomagnetic field, i.e., $\Delta r \ll ar_e$, where r_e is the radius of the earth.

If ar_e is the distance between the geomagnetic dipole and the region Δr of strong electric field, then the fractional change in neutron counting rate can be determined as a function of λ for various values of a. For $a>5.3$ the cosmic-ray particles are in the outer allowed Stoermer region; hence, this case corresponds to preacceleration. Intermediate values of a ($2<a<5.3$) are in the region of mixed field acceleration. From Table III we note for $3.6<a<5.3$ that there are some latitude intervals for which $\delta R_v/R_v$ is an inverse function of λ. These are the short latitude intervals where the solutions for the preacceleration cases are joined to the solution for the mixed field cases. However, as shown in Fig. 12, even these results are in disagreement with the experimental observations.

3. Postacceleration

For $a\sim1$ we obtain the limiting case where the charged particles are accelerated in a varying electric field after their deflection in the geomagnetic field. These conditions can only be approximately satisfied near the surface of the earth.[25] For this case the calculated dependence of $\delta R_v/R_v$ on λ is also large and in disagreement with observations.

D. Other Evidence

In the preceding discussion we have shown the substantial disagreement at the low-rigidity end of the primary spectrum between experimental observations and the results predicted by assuming the existence of varying geoelectric fields. On the other hand, by using the experimental data at mountain and aircraft altitudes, given in Sec. II, we can show that the fractional variation of total intensity, $\delta R/R$, is a function of atmospheric depth x. Therefore, it cannot be independent of particle energy for all particle energies. For example, if we consider the dependence of $\delta R/R$ on x at $x=48°$, we find that the ratio of $\delta R/R$ ($x=312$ g cm^{-2}) to $\delta R/R$ ($x=680$ g cm^{-2}) is 1.7 ± 0.2 using the data from the D-1 monitor. In reference II it was shown that the 27-day variation is energy-dependent in the mean energy ranges of $\sim$7–40 Bev for protons and that this is consistent with the energy dependence required by a preacceleration-type electric field. We encounter the difficulty that none of the forms of energy dependence postulated thus far explain all the experimental data, and we cannot identify the location of the accelerating mechanism on the basis of energy dependence alone. Hence, we shall investigate the extent to which the other known properties of this variation may assist in resolving this problem.

There are several well-established properties of the 27-day intensity variation. They are summarized as follows:

(a) The variation is not produced by meteorological effects.
(b) The variations are recurring and not periodic. The variation may extend to as many as 9–11 cycles or to as few as 2 or 3 cycles.
(c) During the progress of a 27-day sequence of variations, a second sequence is sometimes present. Hence, at least two series of recurrences may occur simultaneously.

[24] S. B. Treiman and F. Jory (unpublished).

[25] The potential between the ionosphere and the surface of the earth is the order of 4×10^5 volts; hence, even for the primary particles of lowest observed rigidity an acceleration by this field is only $a\sim0.01$ percent amplitude effect and, therefore, negligible.

(d) The variation is a world-wide phenomenon.
(e) The variation is not produced by geomagnetic field variations.
(f) In a single 27-day "cycle" the maximum to minimum intensity variation can be as large as ~20 percent–30 percent by including the low-energy portion of the particle spectrum.
(g) The *average* maximum to minimum intensity variation for a single cycle has been decreasing in successive years from 1951 through 1952 and into 1953.
(h) Especially at low primary-particle energy, the variation is composed of a series of irregular maxima and minima. There is no evidence for a constant level of intensity interrupted by intensity decreases at 27-day intervals.
(i) The ratio of the intensity variation between a particle detector observing a proton spectrum of mean energy ~7 Bev and a detector observing a proton spectrum of mean energy ~40 Bev is 5:1. Thus, the 27-day variation displays an energy dependence, and particles of the order of 40-Bev energy are observed to undergo this variation.
(j) At very low primary-particle energies the variation has a negligible energy dependence.

To proceed with the discussion, taking into account the foregoing facts, we introduce the reasonable assumption that world-wide magnetic and electric field variations and storms are manifestations of a common electromagnetic system; i.e., geoelectric field storms coexist with geomagnetic field storms. We do not specify the nature of the moving charges or their distribution except to note that the current flow must be in a westward direction to account for the phase of well-established features of geomagnetic storms.

We now examine the foregoing (a) to (j) properties insofar as they relate to the identification of the accelerating mechanism which produces the 27-day variation. Property (a) was discussed extensively in reference I and will not be considered further here. Properties (b) and (c) are common to either a solar or a terrestrial phenomenon induced by solar processes; hence, they provide no unique identification of the origin of the variation. Properties (d) and (e) likewise are indecisive since, by invoking suitable assumptions, either alternative could be supported.

Since the intensity variation is world-wide, it is clear that property (f) implies that a large fraction of the total *number* of particles in the cosmic radiation incident on the earth undergoes this variation. Thus, from the point of view of the solid angle involved it would be most desirable to locate the mechanism close to and surrounding the earth. To fulfill this requirement the magnitude of the electric field variations would be $\sim 4\times 10^8$ volts or more to account for a 20 percent variation. (Variations of at least 30 percent were observed, but, although they are produced by an accelerating mechanism, we have not proved that these variations are part of a 27-day sequence.[9]) The geoelectric field hypothesis in its present form fails to satisfy this condition since the magnitude of electric fields generated by a wide range of storm current systems is at least an order of magnitude less than this value.[7]

A further difficulty with the assumption of large, varying geoelectric fields during geomagnetic storms arises from the evidence given in Table II wherein 3–6 percent changes of cosmic-radiation intensity are unaccompanied by any observable geomagnetic storm and, hence, by any large geoelectric field variation. On the other hand, it is known that large magnetic storms may produce no change of cosmic-radiation intensity. Thus, it is difficult to support any theory which involves electromagnetic field variations derived from circulation currents in the region of the earth.

Continuous recording of neutron intensity variations with 3 or more widely separated detectors began in 1951 and the recordings clearly show that in the subsequent period of time the average amplitude of the 27-day intensity variation has been decreasing (property (g)). However, we have no evidence to show that the magnitudes of the geomagnetic storms in the same period have decreased.

In an attempt to explain the large Forbush-type sharp decreases Nagashima has invoked the geoelectric field variations which accompany geomagnetic storms. The required westward current flow which occurs during magnetic storms restricts the production of geoelectric storm fields to decelerating fields. Hence, only intensity decreases are expected during magnetic storms. In view of property (h), however, it is clear that these arguments cannot be introduced at present as evidence for or against the production of the 27-day variation by geoelectric field storms.

We have already presented considerable evidence to show that properties (i) and (j) require a varying acceleration mechanism to explain the observed 27-day recurring variations. In view of the high-energy particles which undergo this variation an accelerating mechanism which could modulate an already existent primary particle distribution would be the simplest assumption to make tentatively at the present time.

E. Charged Earth Hypothesis

The cosmic radiations bring to the earth sufficient positive charge to produce 10^9 volts potential with respect to infinity in the order of 30 days if the earth is assumed to be a spherical, equipotential surface that can retain the accumulated charge. This time for charge buildup would be even less if charged particles in the auroral regions are included. However, Ferraro[26] has considered this problem. He finds that to maintain an ionosphere the upper limit for the accumulated charge would provide a decelerating potential of less than 10^2

[26] V. C. A. Ferraro (private communication).

volts for incoming charged particles. Thus, no Coulomb-type field accounts for the acceleration mechanism.

F. Conclusions Regarding a Geoelectric Field Hypothesis

There are serious difficulties in accounting for the 27-day variation by a geoelectric field. No proof has been given that such a field does not exist. Rather, the foregoing evidence indicates that even if a nearby electric field exists it does not by itself or in combination with a geomagnetic field satisfactorily account for the observed properties of the 27-day cosmic-radiation variations.

In view of these conclusions we are led to the assumptions that the cosmic-ray accelerating mechanism is of extraterrestrial origin, and that the association or link between processes on the sun and this accelerating mechanism is independent of the earth system.

IV. THE 27-DAY VARIATION AND THE GENERAL SOLAR MAGNETIC FIELD

Many investigators have searched for a periodic 27-day intensity variation which could be explained by a solar eccentric dipole field. Vallarta and Godart[27] have computed the effect of the solar plus Stoermer cones on the cosmic-radiation intensity as a function of time and predicted a small 27-day periodicity. It might be argued that the recurring variation discussed in this paper could, indeed, be periodic with occasional periods concealed by an unknown interfering intensity variation.

We can show that this argument cannot be accepted for the following reasons:

(1) The solar-terrestrial cone does not influence particles at the high rigidities which are observed to undergo the 27-day variation.
(2) At low primary-particle rigidity the magnitude of the observed variation is an order of magnitude greater than for a solar-cone induced variation.
(3) A single 27-day period is predicted, whereas simultaneously at least two 27-day sequences are sometimes observed.
(4) Since the observed 27-day period is the *synodic* rotation period, we may compute the proper solar rotation from this observation. Let us assume that the observations permitted a synodic period as long as 28 days; then the observed proper solar rotation becomes 26 days. Since the proper rotation of the sun changes from $\sim$25.2 days near the equator to over 30 days near the poles, it is obvious that the region of the sun related to the cosmic-ray variations, which we have reported in this paper, lies in the equatorial zone and not in the polar regions. Hence, the period predicted by a solar cone is in disagreement with observations unless the solar magnetic poles lie near the equator.

[27] M. S. Vallarta and O. Godart, Revs. Modern Phys. 11, 180 (1939).

It is clear from these arguments that the observed 27-day recurrence intensity variation described by neutron and ion chamber intensity variations is not the phenomenon predicted by Vallarta.

If a periodic variation exists, it must be small and appear at low primary-particle energies and would probably be covered up by the much larger 27-day recurrence variation. However, in view of the increasing evidence that (a) the general magnetic field of the sun is small and (b) that whatever field does exist may be of a higher order than a dipole, the existence of a measurable, true "27"-day periodicity is unlikely.

V. KINDS OF PARTICLES PRODUCING THE 27-DAY VARIATIONS

It was shown in reference I that the specific yield of neutrons for primary particles of $Z \geqslant 2$ decreases to zero for $\lambda \gtrsim 45°$. Since the 27-day intensity variation is observed at latitudes up to the cutoff near $\lambda = 55°$, it is clear that primary particles of charge $Z = 1$, i.e., protons, are undergoing the variation. Whether or not particles of $Z \geqslant 2$ also contribute is an open question which would provide a critical test for the identification of the accelerating mechanism.

CONCLUSIONS

We have shown that cosmic-radiation intensity variations possessing a 27-day recurrence are not produced by geomagnetic field variations. On the other hand, since we find an indirect association between the intensity maxima of these 27-day variations and geomagnetic field disturbances, we have investigated whether there is a mechanism common to both processes, and whether the association is of terrestrial origin. The experimental observations show that the variations are due to changes in the primary particle intensity and, therefore, must be produced by a charged particle accelerating mechanism. We have investigated the possibility of a nearby accelerating-decelerating electric field having a 27-day recurrence. Neither a geoelectric field alone nor combined with geomagnetic field variations fit the experimental facts, and we conclude, on the basis of our present experimental knowledge, that the acceleration mechanism may be of extraterrestrial origin.

Since we find that a 27-day recurrence observed in the earth coordinates is consistent with the proper motion of the solar equatorial band of latitudes, and since it is known that special solar regions located in this solar latitude range are associated with both geomagnetic storms and the cosmic-ray 27-day variation, we conclude that the mechanism which changes the energy distribution of the primary-particle spectrum is controlled by processes on the sun.

We have also shown that primary protons undergo the 27-day intensity variations, but the extent to which particles of $Z \geqslant 2$ participate remains unknown.

An example of a nonrecurring, sharp intensity decrease of >6 percent was found which may be the type discovered by Forbush. It is clear from the observations that this large intensity decrease was not produced by a geomagnetic storm.

It may develop that the solar-terrestrial associations indicated by these neutron intensity measurements will find application in interpreting and predicting the occurrence of solar related phenomena.

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The Origin of Cosmic Rays*

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The isotropy and composition of the primary cosmic radiation suggest that cosmic rays are trapped within the galaxy for an average time of the order of 10^6 years,—a long time compared with the time of escape along straight-line paths, but short compared with the mean life against nuclear collisions with interstellar matter. If one accepts this conclusion, it appears possible to account for the observed properties of cosmic rays under the assumption that cosmic rays acquire their large energies through a gradual acceleration in space, such as suggested by Fermi. In contrast to the original Fermi theory (which denied any possibility of escape from the galaxy), we now find that the energy spectra of protons and heavier nuclei are approximately the same, and that the required injection energies are very modest for all components. We are obliged, however, to assume a much faster rate of acceleration than the original theory required.

In this paper we develop in some detail the consequences of the above assumptions on the basis of a specific model, describing the motion of cosmic rays through the galaxy as a random motion between scattering centers represented by moving magnetized clouds. We briefly discuss the astrophysical implications of our assumptions and the plausibility of the model.

I. GENERAL CONSIDERATIONS

A. Introduction

FERMI[1] has proposed a theory of the origin of cosmic rays according to which the cosmic-ray particles diffuse randomly in interstellar space, gaining energy by collisions against moving magnetic fields, until eventually they loose their accumulated energy catastrophically, by collisions with hydrogen nuclei. This theory explains in a natural way the general isotropy and the observed energy spectrum of the cosmic-ray protons. It fails to account satisfactorily for the considerable flux of alpha particles, and for the heavier nuclei in the primary cosmic radiation. The difficulty is twofold. In the first place, according to Fermi's theory, the injection energy, i.e., the energy required for initiating the acceleration process (an energy at which the rate of energy gain overtakes the rate of loss of energy by ionization), is extremely high for the heavier components. In the second place, the energy spectrum computed for the heavier particles falls off much more steeply at high energy than that of the protons, because their mean free path against collisions with hydrogen nuclei is much shorter. Experimentally, however, the energy spectrum of the various components seem quite similar up to some 10^{13} ev per nucleon at least.[2]

Both difficulties can be overcome if one assumes that cosmic-ray particles diffuse around the galaxy for a time long compared with the average time for escape from the galaxy along straight-line paths, yet short compared with the mean life before collisions with interstellar hydrogen. Under this assumption (which, as originally pointed out by Bradt and Peters, has strong experimental support[3]) the mean life of a cosmic-ray particle in the galaxy is determined mainly by the escape probability, and is thus roughly independent of its mean free path for nuclear collisions. Then the

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[1] E. Fermi, Phys. Rev. 75, 1169 (1949).

[2] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. 85, 295 (1952).

[3] H. Bradt and B. Peters, Phys. Rev. 80, 993 (1950); see also B. Peters in *Progress of Cosmic Ray Physics*, edited by J. G. Wilson (North-Holland Publishing Company, Amsterdam, 1952).