plotted in Fig. 6. The polarizations for the higher-energy beams are plotted there, also, and in fact are plotted at an angle increased by the ratio of the De Broglie wavelengths for 310 and for 430 Mev, accordingly as the elastic diffraction pattern shrinks with increasing energy. For comparison with the predictions of the spin-orbit coupling hypothesis,[8] the polarization of beryllium calculated for the lower energy is plotted. Although it would be preferable to recalculate this curve for the higher energy, yet one expects that probably it will be very much the same in its major features.

One sees that large dips in the elastic polarization curve are not in evidence. Higher proton intensities and, correspondingly, measurements with better angular resolution are needed to prove or disprove the existence of small dips. The present data suggest that a nuclear potential with smooth features such as a Gaussian would give a somewhat better description of the elastic polarization in light nuclei.

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# Changes in Amplitude of the Cosmic-Ray 27-Day Intensity Variation with Solar Activity*

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Both cosmic-ray neutron and ionization-chamber intensity observations reveal that the amplitude of the 27-day recurring intensity variation has been changing over an interval of several years. A method for studying this phenomenon using ionization chamber data for the period 1936–1946 and neutron intensity data for 1951–1953 is described which not only selects preferentially the 27-day variations but also selects the variations which are world wide.

The amplitude of the 27-day intensity variation over these years displays minima and a maximum closely related in time to the minima and maxima of the approximately 11-year cycle in general solar activity. Thus, these results provide additional, and independent, evidence that solar active regions are responsible for producing the mechanism which controls the 27-day cosmic-ray primary intensity variations.

## I.

IN continuing the study of the 27-day recurring intensity variations[1,2] we have observed that the amplitude of this variation displays a remarkable decrease over the years 1951 to 1954. A network of widely distributed neutron intensity monitors was completed in 1951 to detect this world-wide variation in the low-energy portion of the primary cosmic radiation spectrum. It was clear from the measurements in 1951 that the amplitude of the variation was 4–5 times larger than the amplitude at high primary particle energy as measured by shielded ion chambers. In later years the relative amplitudes of the variations in the low and high energy parts of the primary spectrum have become increasingly difficult to measure because of the decline in the amplitude of the variations over these years.

Since individual solar regions have been associated with the 27-day recurring variations in 1951, and since the synodic rotation period for equatorial regions of the sun is ~27 days, we have searched for an association between the decline of amplitude in the intensity variations and the changing level of solar activity over the ~11-year solar "cycle." In this paper we propose to investigate this change of amplitude and demonstrate that a close association exists between this phenomenon and the general level of solar activity.

## II.

The decline in amplitude of the mean daily 27-day neutron intensity is most readily demonstrated by using a method devised by Chree[3] for the analysis of recurrences of geomagnetic character figures. The method requires adding together the intensity of all days that display a maximum (or minimum) intensity. These days are called day zero. The summation is carried over the preceding and following days out to day $n$, where $n$ extends beyond the period of the variation being investigated. This superposition of data will display any recurrence tendency among the maxima of mean daily intensities and give the average period of the recurrence. The Chree-type curves shown in Fig. 1 have been obtained for 10 neutron intensity maxima from eight months of data in 1951, 22 neutron maxima in

* Assisted by the Office of Scientific Research, Air Research and Development Command, U. S. Air Force.

[1] For example, A. T. Monk and A. H. Compton, Revs. Modern Phys. **11**, 173 (1939). A complete list of publications through 1951 is found in the review article by H. Elliot, *Progress in Cosmic Ray Physics* (North-Holland Publishing Company, Amsterdam, 1952), Chapt. VIII.

[2] J. A. Simpson, Phys. Rev. **94**, 426 (1954) and references therein.

[3] C. Chree, Trans. Roy. Soc. (London) **A212**, 75 (1913).

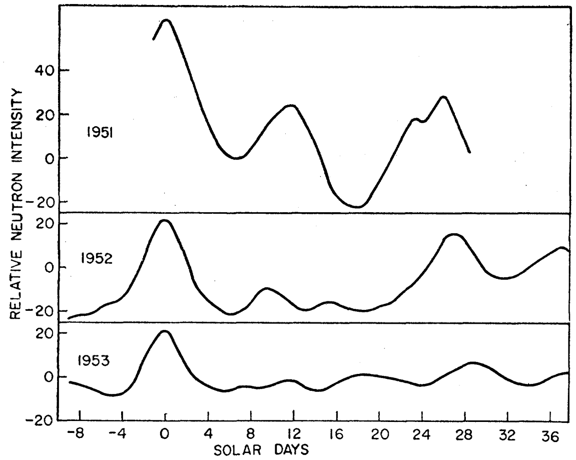


FIG. 1. Superposition of neutron intensity maxima for data obtained using a neutron monitor at Climax, Colorado. These curves represent the 3-day running average of the mean daily intensity and show the decline of amplitude for 27-day recurrence in successive years.

1952, and 28 maxima in 1953. The approximately 27-day recurrence is quite apparent in all of these curves. The amplitudes of the recurring maxima, however, are decreasing with each successive year.

In order to explore this phenomenon over an entire solar cycle prior to 1951 it is necessary to study the ionization chamber measurements which have been obtained and published by Lange and Forbush[4] over the years 1936 to 1946 at three independent stations. To these results we shall add the neutron data for the period 1951 through 1953. Since it has already been shown that 27-day intensity variations observed in ion chambers are closely related in time and relative amplitude to the same type of variations detected by low-energy neutron detectors, we shall use both kinds of detectors in our analysis.

We first explain the method adopted to measure the amplitude of the 27-day recurring variation in different years. There are two conditions which must be fulfilled:

(1) The method must select preferentially those variations of intensity which have a "quasi periodicity" of 27 days.

(2) Only world-wide intensity variations should be measured. Hence, we are to consider only the variations which appear simultaneously at widely separated observing positions.

In order to satisfy the first condition, we study the differences of increments in average daily intensity at Station $A$ for *pairs* of days separated by $\tau$ days from each other:

$$\delta_A=[I_A(t)-I_A(t+\tau)]/\langle I_A\rangle,$$

where $I_A(t)$ is the cosmic-ray intensity at day $t$ and $\langle I_A\rangle$ is the average intensity; hence, $\sigma_A=\langle\delta^2\rangle^{\frac{1}{2}}$ is the standard deviation of a set of $\delta$'s. Fonger[5] has shown for the neutron and ion chamber data of 1951 that $\sigma_A$ has a maximum value for $\tau=14$ days, which is a consequence of the existence of 27–28 day recurring intensity variations. We shall use our definition of $\sigma_A$ as a quantitative measure of the 27-day amplitude at station $A$. To preferentially select the 27-day variations we also choose $\tau=14$ days.

The second condition is fulfilled by applying the above procedure to a second station detector, called station $B$, widely separated from station $A$; thus, we determine $\sigma_B$. We then obtain the correlation coefficient between the $\delta$'s for the two stations $A$ and $B$; namely,

$$r_{AB}=\langle\delta_A\times\delta_B\rangle/(\sigma_A\times\sigma_B),$$

where $r_{AB}$ has an absolute value between zero and unity depending on how perfectly the increments $\delta$ from the two stations agree in time and relative amplitude, i.e., how well the station data track each other. Finally, the parameter which we define as the measure of the amplitude of the world-wide 27-day intensity variation is

$$\sigma_A(\text{tracking})=|r_{AB}|\times\sigma_A,$$

which is the standard deviation of that portion of the increments of intensity, $\delta$, which tracks perfectly. We call station $B$ the reference station.[5]

For variations of neutron intensity the data were analyzed for the period 1951 through 1953 by using the Climax neutron detector as station $A$ and the Chicago neutron detector as station $B$, or reference station. Half-year intervals were used with the numerical results given in Table I. The Forbush ion chamber data for the period 1936–1946 at Huancayo (Peru), Cheltenham, Maryland (U.S.A.), and Christchurch (New Zeland) were divided into 6-month intervals for computing $\sigma$(tracking). We arbitrarily selected Huancayo as station $A$ and used successively Cheltenham and Christchurch as two independent reference stations for computing the correlation coefficients with the numerical results shown in Table II. In Fig. 2, $\sigma$(tracking) is plotted as a function of time between 1936 and 1953. The ordinate

TABLE I. Analysis of neutron pile intensity data.

| Period | $\sigma$ Climax % | $\sigma$ Chicago % | $r$ correlation coefficient Climax-Chicago | $\sigma$(tracking) Climax correlated to Chicago % |
|---|---|---|---|---|
| 1951 July–Dec. | 3.3 | 3.9 | 0.60 | 2.0 |
| 1952 Jan.–June | 2.3 | 1.8 | 0.58 | 1.3 |
| 1952 July–Dec. | 1.2 | 0.9 | 0.54 | 0.7 |
| 1953 Jan.–June | 1.5 | 1.2 | 0.68 | 1.1 |
| 1953 July–Dec. | 0.9 | 0.8 | 0.05 | 0.0 |

[4] I. Lange and S. E. Forbush, "Cosmic ray results from Huancayo Observatory, Peru, June 1936–December 1946", Researches of the Department of Terrestrial Magnetism, Washington, D. C. (1948), Vol. 14, Pub. 175.

[5] W. H. Fonger, Phys. Rev. **91**, 351 (1953); see this reference for a more detailed description of the procedure for determining $\sigma$(tracking).

on the left refers to Huancayo values of $\sigma$(tracking) with respect to both Cheltenham and Christchurch. The scale on the right refers to the larger values of $\sigma$(tracking) for the Climax neutron detector with reference to the Chicago neutron detector. No continuous data were available for the period 1947 through 1950 for either ion chamber or neutron detectors.

There are two kinds of nonperiodic intensity changes which disturb the results of the analysis we have reported here. The first of these is the solar flare effect which is a sudden but temporary increase in cosmic-ray intensity; the second is the sharp decrease of cosmic-ray intensity followed by a slow recovery to normal intensity, discovered by Forbush. It is principally this latter type of intensity variation which leads to spurious and large values for $\sigma$(tracking) since these sudden decreases of intensity are world wide.[6–12] Accordingly, a list of these large and nonrecurring type variations was prepared and the cosmic-ray data for these periods were deleted from the study. These special events with their deleted periods are shown in Table III. There were, in addition, events of a similar character but of much smaller magnitude which we did not remove from the reported results since they do not shift the points in Fig. 3 by as much as the probable error of the individual points. The points in 1946 may be an exception. Even though the large changes of intensity reported in Table III were removed, there still remain some moderately large variations which may be nonperiodic in character; hence, these terminal points on the curve should be viewed with caution.

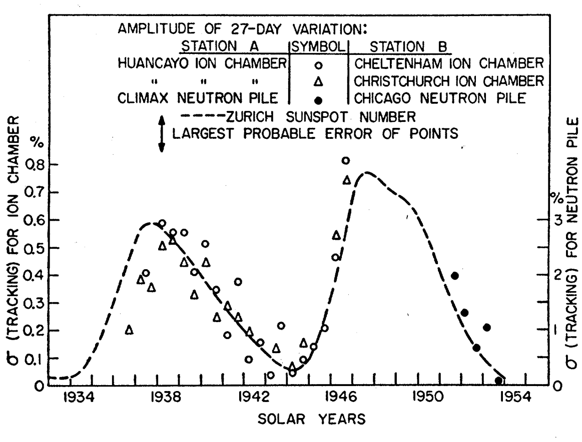


FIG. 2. Amplitude of the 27-day recurring intensity variations as a function of time. Data for the period 1947 through 1950 are not available. The left-hand scale refers to Carnegie Institution ion chamber data; the right-hand scale refers to neutron detector intensity.

[6] S. E. Forbush, Terrestrial Magnetism and Atm. Elec. **43**, 203 (1938).
[7] S. Chapman and J. Bartels, *Geomagnetism* (Clarendon Press, Oxford, 1951), Vol. 1, p. 328.
[8] Terrestrial Magnetism and Atm. Elec. **46**, 473 (1941).
[9] Terrestrial Magnetism and Atm. Elec. **47**, 85 (1942).
[10] S. E. Forbush and I. Lange, Terrestrial Magnetism and Atm. Elec. **47**, 331 (1942).
[11] Terrestrial Magnetism and Atm. Elec. **51**, 287 (1946).
[12] S. E. Forbush, Phys. Rev. **70**, 771 (1946).

TABLE II. Analysis of ionization chamber data.

| Period | $\sigma$ Huancayo % | $\sigma$ Cheltenham % | $r$ correlation coefficient Huancayo-Cheltenham | $\sigma$(tracking) Huancayo correlated to Cheltenham % |
|---|---|---|---|---|
| 1937 May–Oct. | 0.67 | 0.86 | 0.61 | 0.41 |
| 1938 Jan.–June | 0.82 | 1.16 | 0.72 | 0.59 |
| July–Dec. | 0.81 | 0.80 | 0.68 | 0.55 |
| 1939 Jan.–June | 0.78 | 1.08 | 0.71 | 0.55 |
| July–Dec. | 0.65 | 0.90 | 0.62 | 0.41 |
| 1940 Jan.–June | 0.75 | 1.09 | 0.69 | 0.51 |
| July–Dec. | 0.55 | 0.83 | 0.63 | 0.34 |
| 1941 Jan.–June | 0.63 | 0.91 | 0.29 | 0.18 |
| July–Dec. | 0.58 | 0.73 | 0.64 | 0.37 |
| 1942 Jan.–June | 0.43 | 0.83 | 0.25 | 0.11 |
| July–Dec. | 0.40 | 0.77 | 0.38 | 0.15 |
| 1943 Jan.–June | 0.37 | 0.85 | 0.10 | 0.04 |
| July–Dec. | 0.43 | 0.84 | 0.50 | 0.21 |
| 1944 Jan.–June | 0.36 | 0.75 | 0.13 | 0.05 |
| July–Dec. | 0.41 | 0.77 | 0.23 | 0.09 |
| 1945 Jan.–June | 0.43 | 0.72 | 0.32 | 0.14 |
| July–Dec. | 0.51 | 0.83 | 0.40 | 0.20 |
| 1946 Jan.–June | 0.88 | 0.98 | 0.53 | 0.46 |
| July–Dec. | 1.04 | 1.08 | 0.78 | 0.82 |

| Period | $\sigma$ Huancayo % | $\sigma$ Christchurch % | $r$ correlation coefficient Huancayo-Christchurch | $\sigma$(tracking) Huancayo correlated to Christchurch % |
|---|---|---|---|---|
| 1936 July–Dec. | 0.58 | 0.69 | 0.34 | 0.20 |
| 1937 Jan.–June | 0.73 | 0.81 | 0.52 | 0.38 |
| July–Dec. | 0.56 | 0.83 | 0.63 | 0.35 |
| 1938 Jan.–June | 0.82 | 0.87 | 0.61 | 0.50 |
| July–Dec. | 0.81 | 0.85 | 0.64 | 0.52 |
| 1939 Jan.–June | 0.80 | 0.80 | 0.55 | 0.44 |
| July–Dec. | 0.63 | 0.93 | 0.52 | 0.33 |
| 1940 Jan.–June | 0.76 | 1.01 | 0.58 | 0.44 |
| July–Dec. | 0.55 | 0.68 | 0.44 | 0.24 |
| 1941 Jan.–June | 0.57 | 0.87 | 0.50 | 0.29 |
| July–Dec. | 0.58 | 0.80 | 0.42 | 0.24 |
| 1942 Jan.–June | 0.41 | 0.83 | 0.48 | 0.20 |
| 1943 April–Sept. | 0.40 | 0.77 | 0.34 | 0.14 |
| 1944 Jan.–June | 0.37 | 0.73 | 0.14 | 0.05 |
| July–Dec. | 0.43 | 0.92 | 0.35 | 0.15 |
| 1946 Jan.–June | 0.86 | 0.93 | 0.62 | 0.54 |
| July–Dec. | 1.07 | 1.10 | 0.69 | 0.74 |

## III.

In 1951, when $\sigma$(tracking) for the neutron monitor stations was relatively large, we were able to associate special regions of solar activity with individual 27-day variations.[13] These solar regions were recognized by enhanced coronal emission (in the green and red spectral lines), radio noise, $H_\alpha$ flares, local magnetic fields, calcium plage areas, and, many times, by nearby sun spots. If we now wish to select a quantitative measure of the frequency of occurrence and magnitude of these solar active regions, as early as 1936 we encounter the problem that only sunspot measurements cover the entire period in question. Quantitative measurements of coronal activity, flare observations, and radio noise on a routine basis were developed much later. Consequently, we compare the changing ampli-

[13] Simpson, Fonger, and Wilcox, Phys. Rev. **85**, 366 (1952).

TABLE III. List of extraordinary events which are associated with very large cosmic-ray intensity changes. The periods in which these changes occurred were deleted from the correlation data.

| Date of special event | Type of event | Deleted period | Reference |
|---|---|---|---|
| 1938 Jan. 16 | cosmic-ray decrease associated with magnetic storm | Jan. 3–Jan. 23 | 6 |
| 1938 April 16 | cosmic-ray decrease associated with magnetic storm | March 29–April 20 | 7 |
| 1941 Sept. 18–21 | cosmic-ray decrease associated with magnetic storm | Sept. 5–Sept. 24 | 8 |
| 1941 Dec. 1–2 | cosmic-ray decrease associated with magnetic storm | Nov. 17–Dec. 6 | 9 |
| 1942 Feb. 28 and March 7 | cosmic-ray increase and decrease associated with solar flare and magnetic storm | Feb. 14–March 11 | 10 |
| 1946 Feb. 7-8 | cosmic-ray decrease associated with magnetic storm | Jan. 22–Feb. 14 | 11 |
| 1946 July 26 | cosmic-ray increase and decrease associated with solar flare and magnetic storm | July 11–July 31 | 12 |

tude of the 27-day intensity variations with sunspot number as shown by the dashed line in Fig. 2. Although we assume that sunspot numbers are closely related to the solar active regions, we do *not* wish to imply that the sunspots are the underlying cause of these cosmic-ray intensity changes. The minima in the solar cycle are quite clearly associated with $\sigma$(tracking) minima. The corresponding maxima and slopes of the two curves also appear to be in agreement.

It is now quite clear why attempts to measure a 27-day intensity variation with ion chambers and counter telescopes were more successful for some observers than for others. For example, Monk and Compton[1] detected the variation in 1937–1938 when $\sigma$(tracking) was near maximum.

One of the important consequences of using the nucleonic-component neutrons to measure intensity variations is the possibility of determining the amplitude of the variation as a function of primary-particle energy. Initial measurements were made in 1951,[2,5] but during 1952 and 1953 it became increasingly difficult to repeat the observations not only because $\sigma$(tracking) decreased sharply but also because the nontracking fluctuations among all stations remained large. Therefore, attempts to measure the ratio of the amplitude variations, (neutron intensity)/(ion chamber intensity) or the ratio (neutron intensity)/(counter telescope intensity) encounter serious difficulties near the minimum of solar activity, i.e., when the 27-day intensity variation is no longer the predominant variation and the number of active solar regions on the sun is considerably reduced.

Although an investigation of the origin of the nontracking intensity fluctuations detected by ion chambers and neutron piles has not been undertaken, we believe at the present time that these fluctuations may be caused by non-world-wide variations of primary intensity.

In view of the fact that $\sigma$(tracking) for both neutron detectors and ion chambers in Fig. 2 appear to fit a common curve provided the scale ratio $\sigma$(neutron tracking)/$\sigma$(ion chamber tracking) is approximately 5, we find no indication that this ratio has appreciably changed with time.

## IV.

Although there is strong evidence that the cosmic-ray 27-day intensity variation is extra terrestrial in origin, we do not yet know the nature of the mechanism producing the modulation or acceleration of the primary particles. We believe, however, that the association between the amplitude of the variation and the eleven-year cycle of solar activity, reported here, provides additional and independent evidence that solar active regions are responsible for generating this mechanism.

We wish to thank Mr. James Ayers, Dr. Ely Gelbard, and the computing group for their help in preparing the data and carrying out the numerical calculations. We also thank Dr. R. P. Kane for providing us with special neutron intensity tables.