in the first column are taken to be equal to the half-widths at half maximum of the incident proton spectra. The cross sections of the second column were obtained by interpolating existing data, as mentioned above. The next three columns give coefficients b_{2l} and their standard deviations, calculated from least-squares analysis of the data. The results of Fischer and Baldwin at 170 Mev, and of Dickson and Salter at 133 Mev, were included in the calculations. The quantity 100α, appearing in the sixth column, arises from application of the chi-square test to each of the least-squares fits, and represents the percentage probability that an independent measurement will deviate by at least as much from the function of best fit.

An inspection of these results indicates that a description of *p-p* scattering involving *S* and *P* waves alone would be statistically consistent with the data at 170 Mev, where one parameter suffices to give an acceptably large α. However, at the other two energies that have been studied here it appears to be necessary to invoke the *F* wave, a conclusion in agreement with some reported[2,14] previously. The change in the sign of b_2 between 130 and 210 Mev, as well as the increasing significance of b_4 at high energy, can perhaps be explained by consideration of contributions from the $^3F_3$ and $^3F_4$ phases, to which the higher coefficients are sensitive.

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Changes in the Low-Energy Particle Cutoff and Primary Spectrum of Cosmic Rays*

PETER MEYER AND J. A. SIMPSON
Enrico Fermi Institute for Nuclear Studies, The University of Chicago, Chicago, Illinois

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The low rigidity cutoff for primary particles in the cosmic-ray spectrum reappeared in 1956. From these new results and the earlier measurements in 1948, 1951, and 1954, it is clear that the shift of the low-rigidity cutoff to a very small value is restricted in time to an interval within which solar activity reached a minimum in the 11-year solar cycle. This effect was accompanied by other changes in the primary spectrum; namely (a) the total cosmic-ray intensity and (b) the exponent for the power law spectrum, both passed through maxima near the solar minimum in 1954.

The 1956 results further support the view that these changes in the primary spectrum have their origin in a mechanism controlled by solar activity—most likely the diffusion of cosmic-ray particles through interplanetary disordered magnetic fields transported by plasma clouds of solar origin. If this is so, then only for a brief period near solar minimum is there the possibility of access to the true galactic spectrum for particles below approximately 30 Bv.

I. INTRODUCTION

IN an earlier communication we reported that the primary cosmic-ray spectrum observed at the earth had changed between 1948 and 1951. The changes include a decrease in the energy for the low-energy cutoff, an increase in the total particle intensity, and a change in the power law spectrum extending to higher energies.[1] In addition to these observations, Neher has shown that the low-energy cutoff not only changed but that it may have almost disappeared in the year 1954.[2] Since these effects appeared to be related to the general level of solar activity—the disappearance of the cutoff in 1954 corresponding to minimum solar activity—we have reinvestigated this question by making additional measurements during August 1956, when the level of solar activity had again greatly increased. We wish to report here that the low-energy cutoff has reappeared and is accompanied by further changes in the power law spectrum and total cosmic ray intensity.

We shall discuss briefly the implications of these results for the origin of the low-energy cutoff and the origin of the total intensity variations observed in the solar system.

II. EXPERIMENT

The nucleonic component intensity was measured as a function of geomagnetic latitude at high altitude. As in the case of our earlier observations the apparatus was carried by aircraft. Except for a detector modification which yields twice the counting rate of the 1954 instrument, the experimental apparatus, corrections, and tests were the same as in 1954; further details are given in reference 1.

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1 P. Meyer and J. A. Simpson, Phys. Rev. **99**, 1517 (1955).
2 H. V. Neher, Phys. Rev. **103**, 228 (1956).

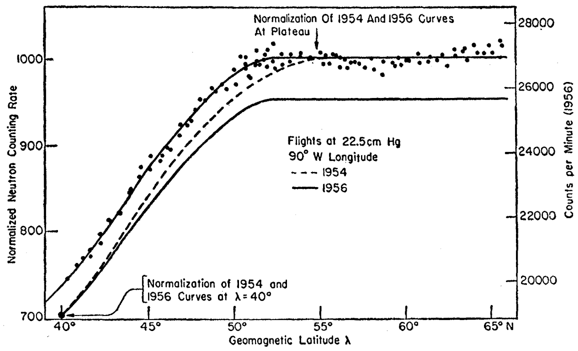

FIG. 1. The nucleonic component latitude curves for 1956 at 90° west longitude and 310 g/cm² atmospheric depth. For comparison the 90°W latitude curve for 1954 is shown as a dashed line.

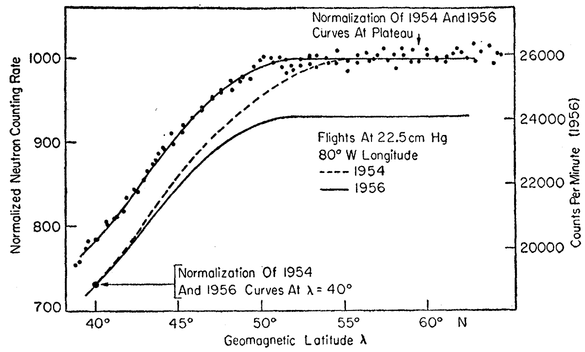

FIG. 2. The nucleonic component latitude curves for 1956 at 80° west longitude and 310 g/cm² atmospheric depth. For comparison the 80°W latitude curve for 1954 is shown as a dashed line.

The data were obtained over the identical courses flown in 1954 in order to avoid any uncertainties in defining geomagnetic latitudes or longitudes. Though the geomagnetic cutoff rigidities assigned to geomagnetic latitudes may be in error, the relative changes in measured properties of the spectrum will not suffer this difficulty. All data are for the same atmospheric depth as the measurements in 1948, 1951, and 1954; namely, 22.5 cm Hg pressure (30 000 ft pressure altitude).

Even though the frequency of large cosmic-ray intensity fluctuations was increasing throughout 1956, we were able to record data at times when the intensity changed by less than $\pm 1\%$ during each flight. Thus the latitude curves are not distorted by intensity variations.

To measure the intensity variations both during the time of the flights and over the several years during which this experiment was underway, we continuously measured the neutron intensity at Chicago ($\lambda \approx 52°$) and Climax ($\lambda \approx 48°$).

Since two flights were required to obtain the entire range of geomagnetic latitudes 40°–64°, the data were matched in the region of $\lambda \approx 52°$N.

III. CHANGES OF THE LOW-RIGIDITY CUTOFF BETWEEN 1954 AND 1956

The latitude curves for August, 1956 are shown in Figs. 1 and 2 for approximately 90° and 80° west longitude. The corresponding latitude curves measured in 1954 are included as dashed lines. Although the total cosmic ray intensity decreased between 1954 and 1956, we have normalized the 1954 and 1956 data at high magnetic latitudes in order to display the change of the cutoff latitude between these years. We conclude from Figs. 1 and 2 that the cutoff latitude has shifted $\sim 1.5°$ to a lower latitude within this time interval.

Since Neher's measurements[2] show that the rigidity cutoff near the top of the atmosphere in 1954 occurred at a much higher geomagnetic latitude than we found for the onset of atmospheric absorption, we conclude that the observed change between 1954 and 1956 is the lower limit for the true time change in geomagnetic cutoff latitude of the primary spectrum.

IV. CHANGES IN THE PRIMARY SPECTRUM BETWEEN 1954 AND 1956

In reference 1 we showed how to use the observed changes in the slopes of the nucleonic component latitude curves to describe the changes with time which occur in the primary spectrum at the top of the atmosphere, and we shall not go into detail on the methods or assumptions here. To prove that the slopes of the latitude curves were different in 1954 and 1956, we have normalized the counting rates for the two years at $\lambda = 40°$ as shown in Figs. 1 and 2. Clearly the change in slope is significant for both the 80°W and 90°W longitude curves.

If we represent the primary differential spectrum with the data obtained by Winckler in 1948 as

$$j(1948) = \frac{C}{(p/Z)^{\gamma}}, \quad \text{with} \quad \gamma = 2,$$

where p is the momentum and Z the charge number of the primary particle, then we obtained the exponent $\gamma = 2.7$ for the 1951 and 1954 spectra. In comparison with the 1954 data, the new 1956 data yield an exponent $\gamma = 2.5 \pm 0.1$. These spectra are drawn in Fig. 3. The difference in the slopes of the spectra are known more precisely than the values of γ.

V. CHANGE IN TOTAL COSMIC RAY INTENSITY BETWEEN 1954 AND 1956

The change in spectrum between 1954 and 1956 was accompanied by a decrease in the total cosmic-ray intensity, this decrease being part of the approximately 11-year change in intensity found by Forbush[3] to be inversely correlated with the 11-year solar activity cycle. An intensity decrease of about 4.3% was observed for the neutron intensity monitor at Climax, Colorado, between the times of the 1954 and 1956 measurements.

[3] S. E. Forbush, J. Geophys. Research **59**, 525 (1954).

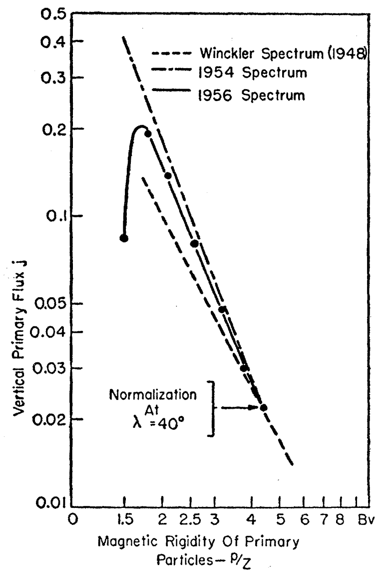

FIG. 3. The primary particle rigidity spectrum for 1956 deduced from the latitude intensity measurements shown in Figs. 1 and 2. If we assume that the differential spectrum in 1948 was represented by $j=C(p/Z)^{-\gamma}$ with $\gamma=2$, then the 1956 spectrum requires $\gamma=2.5\pm0.1$.

This decrease also appears at aircraft altitudes. By normalizing the intensity measured at $\lambda=40°$ in 1954 and 1956 (the lowest geomagnetic latitude for which there are data common to both measurements), we find that the decrease of intensity for particles within the magnetic rigidity interval $\sim$1.5 to 4.4 Bv was 4.5% using data from Fig. 1, and 6.8% from the Fig. 2 data. If we were also to include particles with magnetic rigidities above 4.4 Bv, and lower than $\sim$1 Bv, we would find that the integrated intensity decline was even greater than given for the 1.5–4.4 Bv rigidity interval—but this latter question will be considered elsewhere.

Intensity variations of large amplitude and short duration such as 27-day variations and Forbush-type decreases became progressively more pronounced throughout 1956 in contrast with the remarkably small variations observed in 1954.

We wish to distinguish the changes in both the low-rigidity cutoff and exponent γ which are associated with the gradual (11-year) changes of intensity level. We must avoid possible cutoff variations and other short time spectral changes which may be associated with the rapid, but large, Forbush decreases and 27-day intensity variations. Consequently, we observe the position of the low-rigidity cutoff and slope of the latitude curves at an intensity level which is the average for an extended period around the time of the measurements. The data for the latitude curve at 90° west longitude fulfill this condition; namely, at the time of the flight extending northward from $\lambda=40°$ to beyond $\lambda=52°$, the integrated intensity was close to the average intensity for July–August, 1956. On the other hand, the neutron intensity monitors show that the corresponding data at 80° west longitude were obtained during a short time decrease from the average cosmic ray intensity. This is apparent from the larger decrease in intensity measured above the cutoff at that time.

The change in the low-rigidity cutoff for the 80° longitude data is appreciably greater than for the 90° longitude data obtained under average intensity conditions. If the major intensity variations such as the 27-day, Forbush decreases, and 11-year variations all have a common origin, this result at 80° would not be unexpected for a temporary decrease of total intensity.[1]

VI. DISCUSSION

In Fig. 4 we summarize the changes in position of the low-rigidity cutoff measured over the period 1948–56. From reference 1, we found that our observations during 1951 and 1954 measured the lower limit of the change in position of the cutoff, since atmospheric absorption sets in at about $\lambda=57°$, and we cannot observe the effect of particles of lower rigidity than corresponds to this latitude. However, Neher has shown that there was, during 1954, no cutoff for rigidities down to $\lesssim$0.15 Bv.[2] Thus, the observations we report here for 1956 mean that:

(a) the direction for the time dependence of the low-rigidity cutoff effect has reversed;
(b) the cutoff rigidity has actually increased from the value $\lesssim$0.15 Bv given by Neher in 1954 to $\sim$1.5 Bv corresponding to the vertical cutoff for $\lambda\approx52°$.

The time changes of the cutoff are shown in Fig. 5 along with a measure of the general level of solar activity represented by the relative sunspot number. It is clear from these data that the shift of low-rigidity cutoff to a very small value is restricted to a time interval within which the solar activity reached a minimum in the 11-year solar cycle. We also note that (a) the total cosmic-ray intensity and (b) the exponent γ for the particle spectrum both passed through maxima near solar minimum in 1954. These spectral changes

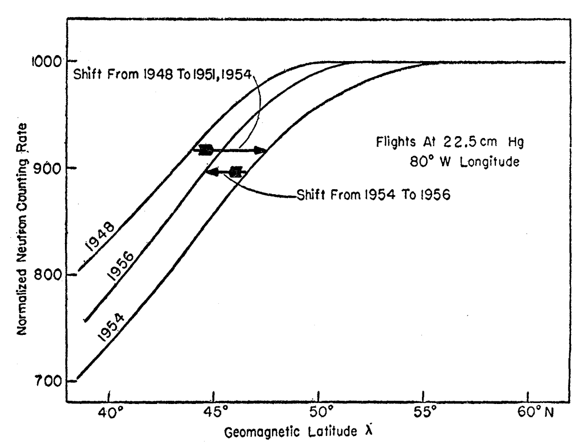

FIG. 4. The nucleonic component latitude curves for 1948, 1954, and 1956 arbitrarily normalized at latitudes >58°N in order to display the magnitude of the shifts in the low-rigidity cutoff of the cosmic-ray spectrum.

strongly support the view that they are part of the 11-year intensity variation found by Forbush[3] for higher energy particles as detected in ionization chambers. If so, then the change in low-rigidity cutoff with time is part of the phenomenon which produces the changes in the spectrum over the 11-year solar cycle.

Thus, we are led again to the conclusion we reached earlier in reference 1; namely, the mechanism producing the cutoff effect must have a solar origin rather than a galactic or terrestrial origin.[4] Galactic origin is excluded because the time scale for the observed effect is too small by orders of magnitude to be consistent with the known dynamical properties of the galaxy. Terrestrial origin is unlikely since changes of total intensity are not predicted for time-dependent changes of the geomagnetic field which might arise from external current systems. More detailed arguments on this question have already been presented in reference 1. Recent calculations by Ray also support this view.[5]

The observed properties of the cutoff effect with its spectral changes extending to energies far above 5 Bv are similar in many respects to the spectral changes which occur during a Forbush decrease or a 27-day variation; namely, the amplitude of the intensity variation is dependent upon the magnetic rigidity of the particles, the amplitude of the phenomenon is large, and a remarkable degree of isotropy prevails. Since we now believe that these short-time variations are produced by a mechanism of solar origin, it is probable that the same mechanism accounts for all cosmic-ray modulation effects in the solar system. On the basis of experiments over the past few years we have concluded that this solar mechanism modulates pre-existent cosmic radiation (e.g., galactic radiation) which reaches the earth. The most likely mechanism is the diffusion of cosmic-ray particles through interplanetary disordered magnetic fields of solar origin; models to account for the experimental evidence have been proposed recently by Morrison,[6] and by Parker[7] in this laboratory. Further experiments will make it possible both to discriminate among the various models of modulation mechanisms, and to decide whether the low-rigidity cutoff effect associated with the 11-year variations is a property of all the major intensity variations. The data we have reported for 80° west longitude suggest that this might be the case.

[4] F. Hoyle, Phys. Rev. **104**, 269 (1956), has proposed a hypothesis to account for the low-rigidity cutoff requiring a maximum cutoff effect at solar minimum. The observations we reported in reference 1 and for 1956, however, clearly exclude the mechanism he proposes.

[5] E. C. Ray, Phys. Rev. **101**, 1142 (1956).

[6] P. Morrison, Phys. Rev. **101**, 1397 (1956).

[7] E. N. Parker, Phys. Rev. **103**, 1518 (1956).

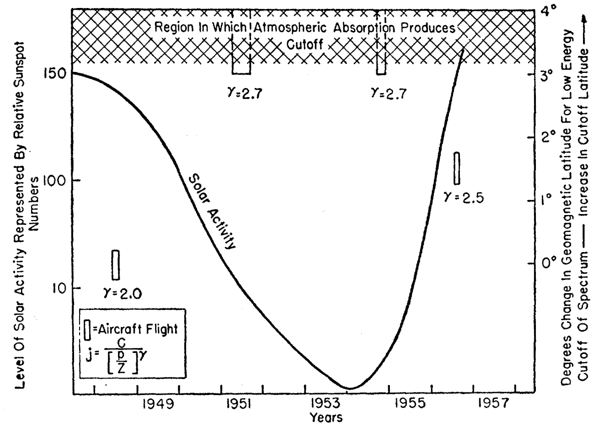

FIG. 5. The changes in cutoff latitude and exponent γ of the primary spectrum as a function of time. For comparison the level of solar activity as measured by relative sunspot number is shown over the period of the measurements.

The hypothesis for the modulation of extra-solar cosmic radiation implies that the full cosmic-ray intensity exists at all times outside the solar system, and that the spectrum observed at the earth is changed by the solar-controlled mechanism (e.g., plasma clouds containing disordered magnetic fields); the changes in intensity which occur would be decreases below the prevailing galactic intensity. If this is so, then only for a brief period near the minimum in the solar activity cycle would we have the possibility of access to the true galactic spectrum for particles below about 30 Bv.

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