EXPERIMENTS ON THE ELEVEN-YEAR CHANGES OF COSMIC-RAY INTENSITY USING A SPACE PROBE*

C. Y. Fan,† Peter Meyer, and J. A. Simpson
Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received August 10, 1960)

The total intensity of cosmic radiation reaching the earth changes with the 11-year solar activity cycle.[1] The energy spectrum of relativistic particles up to at least 20 Bev changes approximately from $E^{-2.7}$ (1954) to $E^{-2.0}$ at maximum solar activity (1957-8) with the intensity being reduced at solar maximum by a factor 2 for the relativistic particle flux,[2] and by a factor in excess of 4 for the integral flux down to ~100 Mev for protons.[3] Figure 1 shows the change in nucleonic component intensity between 1954 and 1960. Experimental evidence strongly supports the view that the spectrum at solar minimum approximates the full galactic spectrum outside the solar system, and that through an electromagnetic modulation mechanism, initiated by solar activity, the galactic particle flux having access to the inner solar system, or the earth, is greatly reduced at solar activity maximum.[2] We have performed direct experiments which prove that any mechanism changing the cosmic-ray intensity over 11 years is centered about the sun, and the scale size is >1 astronomical unit (a.u.) for the volume of space in which the cosmic-ray intensity is reduced at this period of the solar activity cycle. We also find that the gradient of cosmic-ray intensity near the orbit of Earth is so small as to suggest that modulation of galactic intensity occurs at distances much greater than the orbit of Earth.

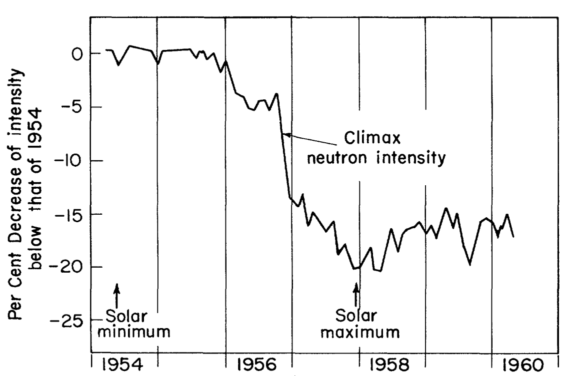

FIG. 1. Changes in the nucleonic component intensity between 1954 and 1960 at Climax, Colorado (~2.4 Bv magnetic rigidity cutoff).

The experiment consists in carrying a cosmic radiation detector from the earth to great distances in interplanetary space near the time of solar maximum. The detector measures protons above 75 Mev and, hence, integrates over that part of the cosmic-ray spectrum which changes by a factor of 2 to 4 in intensity between solar maximum and solar minimum. If the reduced intensity is restricted to the vicinity of the earth, the flux measured in interplanetary space will be greater by a factor of 2 to 4. If the volume in which there is reduced intensity is heliocentric, then there will be an intensity gradient in the direction of the sun, the magnitude of which depends greatly upon the model adopted for the solar origin of the 11-year cosmic-ray intensity variations.

Identical cosmic-ray detectors were carried by the satellite Explorer VI (launched August 7, 1959) and the space probe Pioneer V (launched March 11, 1960), and are described elsewhere.[4,5] Since this detector was not sensitive to bremsstrahlung[4] from trapped electrons in the outer radiation belts of the earth, the cosmic-ray flux was measured from less than 10 000 km to 48 000 km from Earth by Explorer VI. The data for August 9, 1959 are shown in Fig. 2. Between

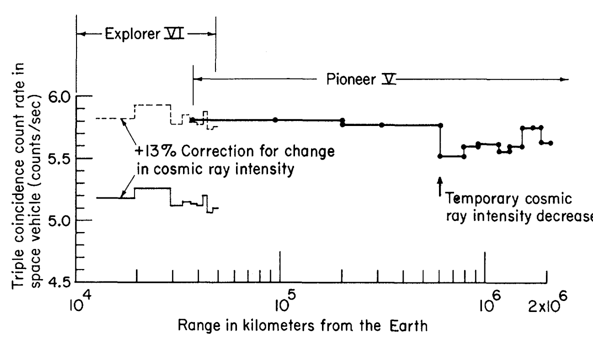

FIG. 2. Counting rate of triple coincidence events in Explorer VI satellite (August 9, 1959) and Pioneer V space probe (March, 1960). The 13% correction in Explorer VI data arises from intensity changes known to take place outside the atmosphere between August, 1959 and March, 1960 due to the 11-year cycle (see Fig. 1). Assigned errors on each interval of data are less than 1%. Pioneer IV (March, 1959) also observed constant intensity between 92 000 and 658 000 km.[8]

this date and the launching of Pioneer V on March 11, 1960, the integrated cosmic-ray intensity at the earth increased by +13% as deduced from nucleonic component monitors. The August 9, 1959 rates in Fig. 2 have, therefore, been increased by 13% for comparison with the Pioneer V data. We note that the cosmic-ray flux was approximately constant from inside the terrestrial field far into the interplanetary medium. Therefore the 11-year depression of cosmic-ray intensity is not geocentric.

We know from analysis of nucleonic component data such as shown in Fig. 1 that the cosmic-ray intensity measured at the earth as the earth moves in its orbit about the sun is not significantly dependent upon solar system longitude. Thus, at solar maximum the cosmic-ray intensity is not only depressed within the inner solar system but the depression is roughly concentric about the sun in the ecliptic plane.

Provided these intensity changes are brought about by solar modulation of the galactic flux, these results lead to the conclusion that there must be a cosmic-ray intensity gradient somewhere between interstellar space and the inner solar system. This gradient will exist in the regions of space where the electromagnetic modulation is taking place.

On the one hand, if the modulating region lies beyond the orbit of Earth (>1 a.u.) then the gradient between Sun and Earth will be very small. A model in this category would be convective removal of particles by advancing magnetic field irregularities arising from instabilities of a solar wind.[6] On the other hand, if the earth lies inside the modulation region the cosmic-ray flux will decrease as one approaches the sun. Several models, including a recent proposal of Elliot,[7] require a large, negative gradient between Sun and Earth.

One of the objectives for the space probe Pioneer V was to examine this problem. At this time we have data over the initial 50 days representing a change in solar radial distance of 0.1 a.u. (10% of the distance to the sun) which sets upper limits on the radial gradient of cosmic-ray intensity in interplanetary space. To remove the time-dependent changes of cosmic-ray intensity, we determined the ratio of the intensities in Pioneer V to the intensities at the earth represented by the nucleonic component monitor at Chicago. This ratio, normalized to unity at time of launch, March 11, is shown in Fig. 3 as a function of solar radial distance, and time. We have averaged data over intervals of two to three days for this analysis.

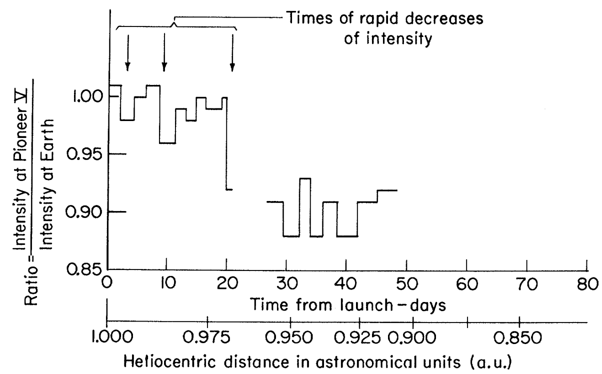

FIG. 3. The change of cosmic-ray intensity radially along the sun-earth line and relative to the intensity at the orbit of Earth. The errors assigned to these averaged intervals of data are less than 0.5%. The arrows indicate the existence of known perturbations in the low-energy portion of the cosmic-ray spectrum and data for these periods are not used in determining the intensity gradient.

It is immediately apparent from Fig. 3 that there was a sudden loss of flux of nonrelativistic particles at the time of the rapid, Forbush intensity decrease of March 31 - April 1.[5] This change in the primary spectrum persisted to the last available measurements 30 days later. The stepwise decrease in the very low energies was also detected in the Explorer VI data,[4] and will be discussed in a later publication. Smaller intensity decreases occurred at the times shown by arrows in Fig. 3. This effect is a change in spectrum which must be taken into account in measuring the gradient. There also exists the possibility that the negligible gradient observed from 0.95 a.u. to 0.90 a.u. (25th to 50th day) is the result of a space gradient plus a compensating gradual return of the low-energy particles. However, such a coincidence of effects is not likely to continue over so long a period.

We obtain a radial omnidirection intensity gradient of $-(15\pm 20)\%$/a.u. measured near the orbit of the earth and in the direction of the sun. This value is inconsistent with the existence of a positive gradient such as required for an appreciable, steady solar production of the radiation. This small but negative gradient shows that (during the period of this measurement) any electromagnetic modulating mechanism required to account for the eleven-year intensity variations is located principally outside the orbit of Earth. Such results from Pioneer V place strong constraints upon acceptable heliocentric models for the eleven-year cosmic-ray intensity variation.

We hope that additional data at later times in May may be extracted from the noisy data arising from the low signal level at these great distances.

For their contributions to the engineering and construction of our apparatus we wish to thank Mr. J. Jezewski, Mr. J. Lamport, Mr. L. Petraitis, and Mr. R. Takaki of the Laboratories for Applied Science, University of Chicago. We also appreciate the over-all engineering and management of the Pioneer V project by Dr. A. Thiel, Dr. J. Lindner, and the staff of Space Technology Laboratories. The assistance of Dr. J. Lindsay of the N.A.S.A. for the Pioneer V project and the use of the Jodrell Banks radio telescope by Professor A.C.B. Lovell enhanced greatly the results of these experiments.

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*This research was supported principally by the National Aeronautics and Space Administration, and in part by the Air Force Cambridge Research Center, Geophysics Research Directorate, and the Air Force Office of Scientific Research.

†Also Laboratories for Applied Science, University of Chicago, Chicago, Illinois.

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FORM OF THE ONE-PION EXCHANGE POTENTIAL*

G. Breit, M. H. Hull, Jr., K. Lassila, and H. M. Ruppel
Yale University, New Haven, Connecticut
(Received August 18, 1960)

The one-pion exchange potential (OPEP) has been used in calculations in nucleon-nucleon scattering by various authors employing the theoretical expression as a whole.[1] In connection with fits to data by means of adjustable phase-parameters it proved possible to make tests on the correctness of the mathematical form of the OPEP, and a brief report appears desirable. The tests were made by modifying the form of the OPEP through the introduction of additional terms multiplied by dimensionless parameters, q. Varying one of the q together with the pion-nucleon coupling constant g, an adjustment was made to a minimum value of the mean weighted square deviation from experimental data, D, resulting in the determination of the most probable values of g_0 and of the q. Three types of variation have been studied. The first two, a and b, differ only in detail, both having the approximate meaning of changing the coefficient of the spin-spin term of the OPEP containing the factor $(\vec{\sigma}_1 \cdot \vec{\sigma}_2)$ from the value 1 to $1+q$. For q_a this was literally the case. For q_b the added term was $(g_0^2/14)q_b$ times the usual spin-spin term. In the units used, $g_0^2 \cong 14$. The object in using two ways of introducing q was to provide a check. The two q are denoted below by q_S when the distinction between a and b is immaterial. A third type of variation consists in the introduction of a central potential equal to q_C times (-1/3) of the singlet-even OPEP. The computation of D for various values of g_0 and of the q gave the following results for the combined determination of g_0 and one of the q at a time.

A preliminary form of p-p scattering data fit[2] YLAM gave the pairs of values $q_S = -0.23 \pm 0.17$, $g_0^2 = 14.0 \pm 1.3$ and $q_C = -0.04 \pm 0.33$, $g_0^2 = 13.6 \pm 1.4$. In this test the parameters not varied as OPEP phase parameters were all those for $J \leq 3$ and in addition $\theta^F{}_4$, ρ_4, and K_4. The p-p data and their analysis are more accurate than their n-p counterparts and the above values may be supposed to be the more significant among those reported here.

The n-p data fit[2] YLAN2M gave the pairs of values $q_S = 0.23 \pm 0.19$, $g_0^2 = 12.8 \pm 1.8$ and $q_C = -1.0 \pm 1.2$, $g_0^2 = 15.0 \pm 1.6$. The one-pion parameters varied in this search were the same for T = 1 as in YLAM while for T = 0 the quantities not varied