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A Study of Time-Variations in Cosmic-Ray Intensity at High Altitudes*

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Twelve balloon flights with a recording cosmic-ray ionization chamber apparatus have been carried out at Chicago between October, 1938 and November, 1939. The results show marked changes in cosmic-ray intensity during this period, the maximum variation observed being about fourteen percent for the peak value of the ionization pressure curve. The changes follow in general the "world-wide" variations of cosmic rays observed at ground stations but when the high altitude results are somewhat arbitrarily corrected for such "world-wide" variations certain residual changes remain. These residual variations show a maximum in the early spring of 1939, then a sudden drop of about eight percent and lower values during the early summer with increasing values again in the autumn. Whether this represents a true seasonal effect can be determined only by further experiments. Though there is some indication that the variations are related to magnetic changes, the agreement with the theory of Vallarta and Godart is not quantitatively good.

DURING the past eighteen months a series of flights with unmanned balloons carrying cosmic-ray apparatus has been carried out at Chicago to determine whether any change with time could be observed in the intensity of cosmic rays at very high altitudes.

APPARATUS

The apparatus was of the recording type and had a mass of from 3000 to 4000 grams, the exact value depending largely upon the type of battery used for the electrometer quadrants. The ionization chamber method was used, the chamber consisting of a sphere 15 cm in diameter with 0.05-cm steel walls and filled to 10 atmospheres of argon. The most important part of the apparatus was an electrometer designed by Dr. Elmer Dershem of this laboratory. This electrometer was fitted with an especially rugged quartz suspension and this was meticulously balanced to give the same deflection with the electrometer oriented in any position. The instrument was thus rendered very insensitive to mechanical shock. A beam of light was reflected from the mirror on this instrument and the image of the light source traversed the length of a slit behind which moved a drum carrying a strip of bromide paper. The insulated system was grounded every $3\frac{1}{2}$ minutes and the electrometer voltage sensitivity was recorded on every fifth grounding.

The pressure device was of the metal bellows type, the bellows being very flexible and the steel spring very stiff. Extensive tests in a vacuum chamber on the ground showed that the barometer element would give pressure readings reproducible to within one millimeter of mercury.

* A preliminary report on these experiments was made at the Symposium on Cosmic Rays in June, 1939 and was published in Rev. Mod. Phys. **11**, 167 (1939).

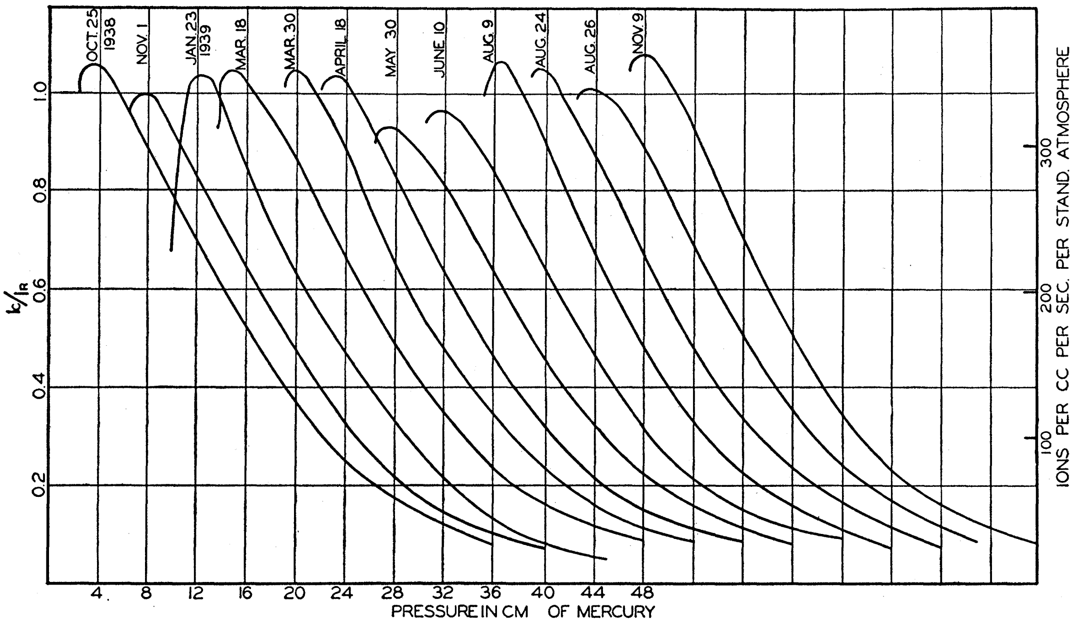

FIG. 1. Ionization due to cosmic rays relative to radium standard (I_c/I_r) as a function of pressure. Each curve has been arbitrarily shifted to the right with respect to the preceding by an amount equal to 4 cm pressure.

Slight hysteresis effects could be observed in the first barometer elements used but such effects were entirely eliminated in later instruments. No effect of temperature upon the reading of the instrument could be observed.

The temperature variation of the apparatus within the gondola was kept within reasonable limits by the usual device of a Cellophane covering with strips of silver paper to reflect a portion of the sunlight. Such a device maintained a temperature constant to within 15°C. The temperature of the apparatus was recorded by means of a bimetallic strip carrying a small mirror.

Before each flight the set was calibrated in terms of a radium standard at a standard distance and with a standard geometrical orientation. All cosmic-ray values were reckoned relative to this standard calibration. For purely relative cosmic-ray measurements there was thus avoided the necessity of knowing with great accuracy the absolute value of the electrical capacity, the timing interval or the density of the gas in the ionization chamber, although all these values were measured. An experiment to determine the effect of temperature upon the ionization chamber measurements was made by varying the temperature of the whole apparatus with the radium source in the standard position. An increase of temperature of 15°C. caused no detectible change in the length of the electrometer trace registered on the bromide paper. Thus any possible change under these conditions was less than 1 percent of the total ionization recorded.

Experimental Results

Between October 25, 1938 and November 9, 1939 twelve flights were carried out. Ten of these were made with the same apparatus which was each time recovered with a recorded trace which was usable. The other two flights were made with a second similar apparatus. The results are shown in Fig. 1 where ionization relative to the radium standard calibration (I_c/I_r), is plotted against pressure in centimeters of mercury. To avoid confusion on the diagram, each curve is arbitrarily shifted with regard to the preceding curve along the abscissa axis by a step of 4 cm pressure. A number of determinations give for the ionization produced in the chamber by the radium in the standard position a mean value of 465 ion pairs per cc per standard atmosphere of argon. If one takes the relative ionization of air to argon at one atmosphere under standard conditions to be 0.72,[1] then one obtains the value 335 for the number of pairs of ions per cc per sec. in standard air produced by the gamma-rays from the radium. If the ordinate ratios (I_c/I_r), for the curves in Fig. 1 are multiplied by this value one obtains absolute values for the ionization produced by cosmic rays. An ordinate scale for such absolute values is shown to the right of the figure.

The curves in Fig. 1 are similar in shape to ionization-pressure curves obtained by other investigators. It will be seen that in each flight sufficient altitude has been attained to outline definitely the peak of the curve. The height of the curves varies markedly from flight to flight, the maximum variation in the peak values being about fourteen percent. The corresponding change in the integrated area under the curves is about ten percent. This represents the relative change in the total energy of cosmic rays entering the earth's atmosphere. The variations in the ionization chamber readings at different pressures are shown more clearly in Fig. 2 where these values for different pressures are plotted as a function of time. For each pressure shown a mean of the corresponding ionization chamber readings for the twelve flights has been determined and the ordinate values in Fig. 2 are reckoned for each pressure in percent of this mean value. The ordinate scale in the lower left corner of the figure applies to each of the eight curves.

[1] E. F. Cox, Phys. Rev. **45**, 503 (1934).

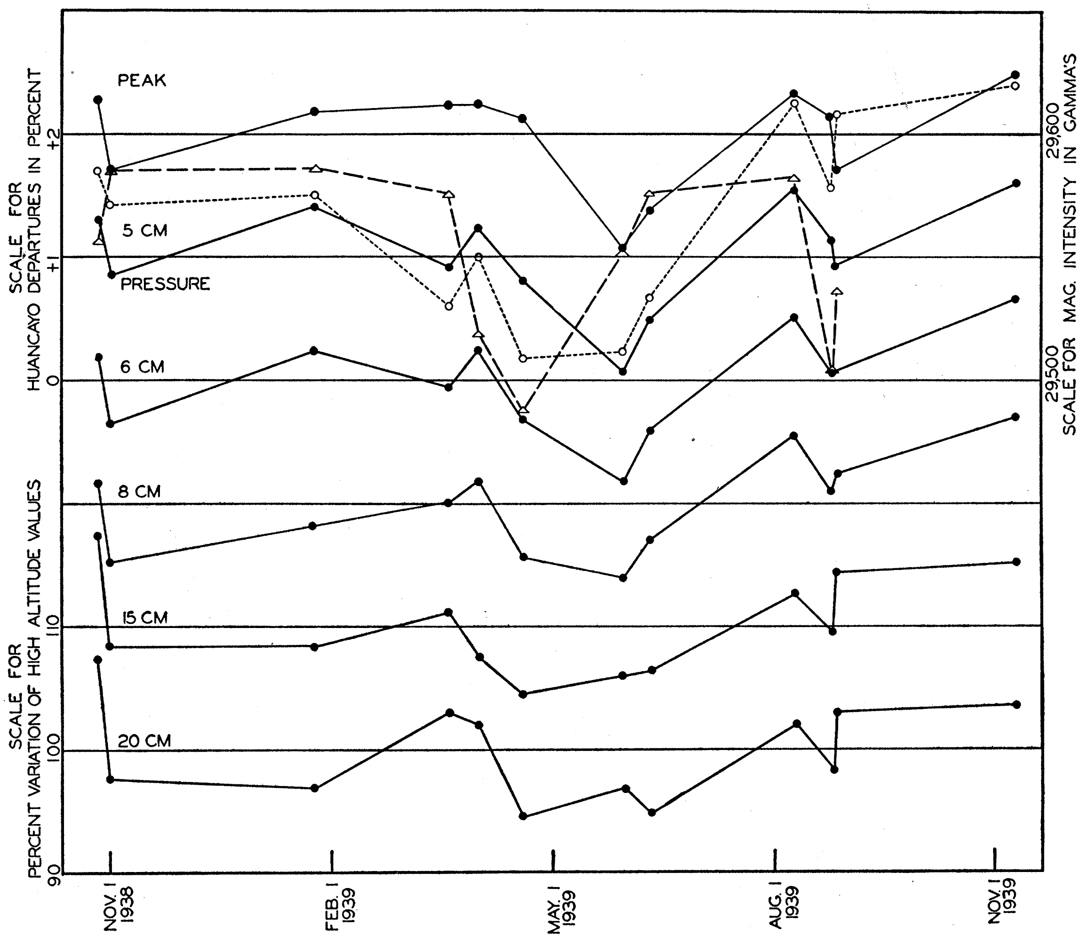

FIG. 2. Plots against time for: ●, High altitude values in percent of mean value for eight different pressures; ○, departures from mean value in percent for cosmic-ray meter at Huancayo, Peru; △, horizontal component of magnetic intensity in gammas at Huancayo Station.

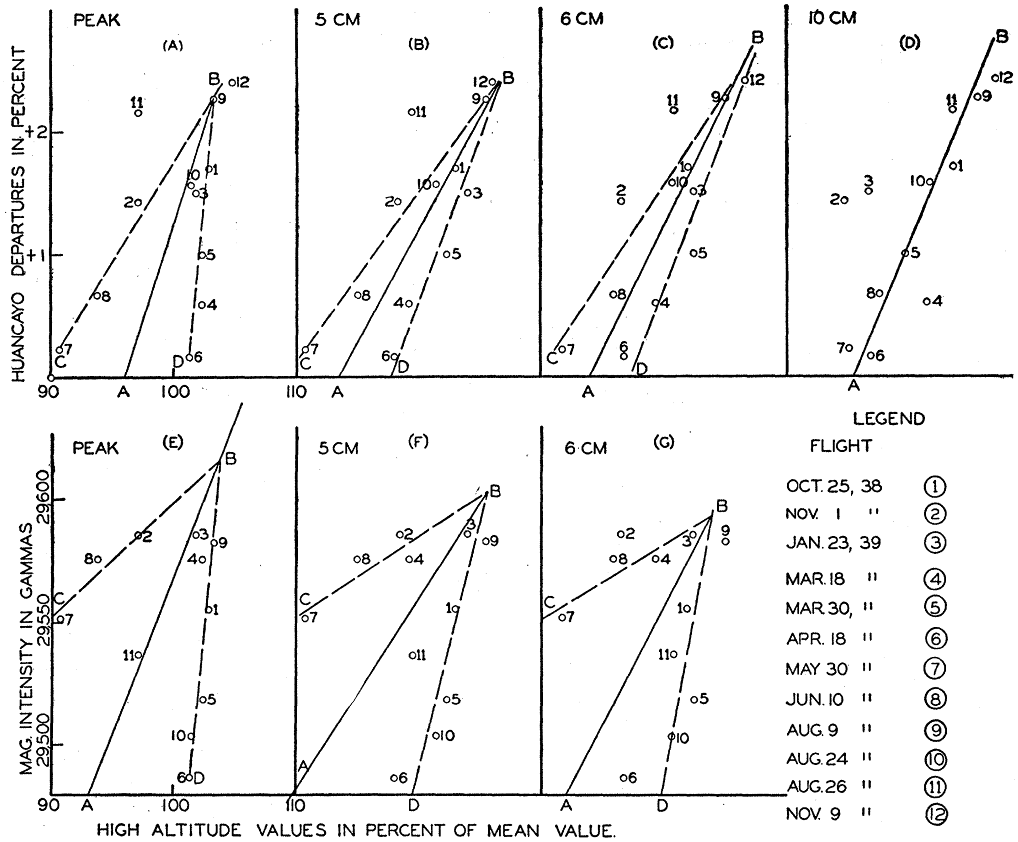

FIG. 3. In top row of diagrams, Huancayo departures are plotted against high altitude cosmic-ray values. In lower row, Huancayo magnetic intensities are plotted against high altitude values. (Lines *CB* and *DB* are *not* regression lines.)

DISCUSSION OF RESULTS

The first evidence that there might be a time change in the intensity of cosmic rays at high altitudes was obtained by investigators[2] in the laboratory of Regener. A flight in December, 1934 showed cosmic-ray intensities higher by six percent than those given by a flight a month earlier. This change was considered greater than the experimental error but was attributed to the activity of a nova. Also during the progress of the present work, papers have appeared by Millikan and Neher[3] in which they have observed similar time variations in cosmic-ray intensity at high altitudes. They observed a difference in intensity of about 9 percent between flights made at Omaha, Nebraska in September, 1937 and in December, 1938 and also a difference of about 5 percent between flights made at Saskatoon in August, 1937 and those at Bismark, North Dakota, in July, 1938. The change in intensity in each of these two cases was in the same direction as the intensity change during the same period of the "world-wide" variations which Forbush[4] has reported. The authors were thus led to suggest that the high altitude variations follow, at least to some extent, such "world-wide" variations observed on the ground. This prediction seems to be borne out in the more extensive data obtained in the present experiment.

The dotted line in Fig. 2 represents the variations observed in cosmic-ray intensity with a Model C meter[5] at the mountain station of the

[2] R. Auer, Zeits. f. Physik **111**, 559 (1939).
[3] R. A. Millikan and H. V. Neher, Phys. Rev. **56**, 491 (1939).
[4] S. E. Forbush, Phys. Rev. **54**, 975 (1938).
[5] A. H. Compton, E. O. Wollan and R. D. Bennett, Rev. Sci. Inst. **5**, 415 (1934).

Carnegie Institution at Huancayo, Peru (geomag. lat. 0.6 S; altitude, 3350 m). At this latitude the seasonal variation is negligible so the readings give directly the "world-wide" variations which Forbush and others have observed and which presumably follow changes in the magnetic field surrounding the earth. Each point represents the mean departure for a three-day period from balance of the instrument in percent of the mean cosmic-ray intensity, an average being taken of the daily mean for the day of the flight, the day before and the day after. Should one take only the mean for the day of the flight no important change would be made in the values given. It will be seen that there is a definite similarity between this curve and that for the high altitude values. The main features of the Huancayo curve are reproduced in the high altitude curves even for pressure of 15 cm and of 20 cm of mercury where the errors of experiment are much larger than for the lower pressures. It should be noted that the scale of the Huancayo values is ten times as large as that for the high altitude results so that the magnitude of the percent change in the latter is much greater.

In Fig. 2 is also plotted a curve showing variations in the horizontal intensity of the earth's magnetic field observed at the same Huancayo station. The readings are in gammas (1 gamma $=10^{-5}$ gauss) and represent also three-day means. The similarity between this curve and the high altitude curves is not as striking as for the Huancayo cosmic-ray values although the two curves present certain similar features. As has, however, been pointed out by Hess,[6] the magnetic changes measured on the surface of the earth do not necessarily present a perfect criterion by which to judge magnetic changes far out in space where the cosmic rays are most affected.

In the upper row of diagrams in Fig. 3 the high altitude values are shown plotted as abscissae against the corresponding Huancayo cosmic-ray values as ordinates for four different pressures. In the second row of diagrams the Huancayo magnetic values are plotted as ordinates. As will be seen, the experimental points do not lie very closely upon any one straight line which can be drawn through the diagram. This scatter of the points might, of course, be considered as caused by errors of experiment. This, however, would assume experimental errors far larger than it is believed exist in the data. Thus in Fig. 3(A) points 6 and 7 have about the same ordinate values but differ by more than ten percent in abscissa values. These points represent results from two of the best flight records and the probable error in these peak values is estimated to be not more than one percent. Moreover, in comparing diagrams 3(A), (B), (C), (D) where the experimental accuracy progressively decreases with increasing pressure, it may be seen that the scatter of the points from the median trace AB is worst in 3(A) where the accuracy is probably the best. The correlation coefficients for the four diagrams are, respectively, 0.49 $\pm$0.16, 0.76$\pm$0.08, 0.80$\pm$0.07, 0.74$\pm$0.09.

The points on the diagrams may be represented fairly well by the two straight lines CB and DB although the number of points available is not large enough to make certain that such a relationship is more than accidental. The fact, however, that a given change in the value of the horizontal component of the earth's magnetic field may accompany at one time a very small change in cosmic-ray intensity values and at another a very large change is not new in cosmic-ray work but is a well-known characteristic of magnetic storms. The variation of cosmic-ray intensity, as measured on the ground, may be widely different for two storms which produce similar magnetic effects.

In diagrams 3(A), (B), (C), (D) the line AB

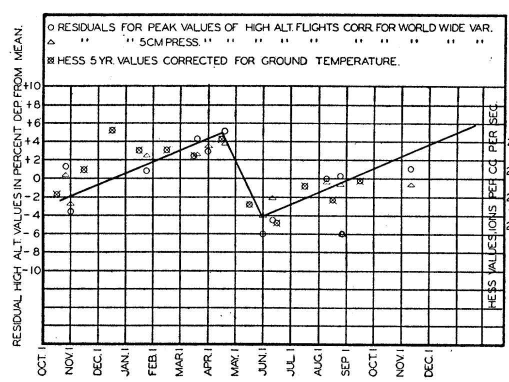

FIG. 4. Residuals from peak values and from values for 5 cm pressure, after correction for "world-wide" variations, plotted against time.

[6] V. F. Hess, Rev. Mod. Phys. **11**, 153 (1939).

has been drawn somewhat arbitrarily to represent the average trend of the plotted points. Such a line represents roughly the mean relation between Huancayo intensity values and high altitude values assuming a simple proportionality to exist. From the abscissa of each experimental point there was then subtracted the abscissa of the point on the line having the same ordinate value as the experimental point. Residual values thus obtained represent variations in the high altitude intensity values in excess of the mean variation to be expected as a result of changes in the Huancayo values. Thus these may reflect the effect upon the high altitude values of some additional disturbing factor. In Fig. 4 the the residuals thus derived from Figs. 3(*A*) and 3(*B*) are plotted as ordinates against time on the abscissa axis. A very similar curve may be obtained for the magnetic values by using in a like manner plots 3(*E*), (*F*), (*G*). As will be seen, the residual values increase continuously from October to April, drop suddenly to a minimum in the early summer and then increase slowly again. It seems difficult to fit the points on a sine curve, chiefly because of the very abrupt drop in the spring, so the two sets of points have been represented by a sort of jagged "saw-tooth" curve. Whether the variation shown here represents a true seasonal effect or not cannot be determined from the results of one year's experiments. The present experiments are being continued and should soon show whether the effect is a truly periodic one or not.

An interesting comparison may be made between the present results and those recently published by Hess.[7,8] The mean values from five years cosmic-ray intensity data taken on the Hafelekar (altitude 2300 m; 48° N mag. lat.) are shown as crossed circles in Fig. 4. Here the recorded cosmic-ray intensity values in ions per cc per sec. per atmosphere have been corrected by Hess for ground temperature variations and the resulting values are plotted against time. The values obtained by Hess follow very closely the "saw-tooth" curve representing the variation of the high altitude values. The percent variation is about eight times greater in the high altitude values. It should be noted that in the Hess data there has been no correction for "world-wide" variations as in the present results. However, presumably in a five-year mean the effect of such irregular variations would be less than in data taken over a shorter period of time.

The cause of the variations in the high altitude data as shown in Fig. 4, whether seasonal or nonseasonal, is not at once apparent. Theoretical calculations indicating a seasonal change at high altitudes have been made by Vallarta and Godart[9] and by others but the present variations do not agree well with such calculations.

It should be pointed out also that the curve in Fig. 4 does not seem to be a mere extension to high altitudes, with increased amplitude, of the seasonal effect obtained by many observers[4,6,10] at the surface of the earth. This latter curve shows a marked dependence upon air temperature with a maximum in January and a minimum in July. The phase therefore is in disagreement with the curve of Fig. 4. Thus the present experiments, within their limits of error, furnish no evidence that the seasonal effect observed in ground measurements results from any factor acting upon the cosmic rays outside of the earth's atmosphere.

If one wishes to enter the realm of speculation, one might attempt to explain the results shown in Fig. 3 in terms of variations in the earth's magnetic field combined with variations in the sun's magnetic field. Adopting such a viewpoint one might consider the variations of high altitude values along the line *DB* as caused by variations in the earth's magnetic field alone while variations along the line *CB* could be considered the combined result of simultaneous changes in the field of the sun and in the field of the earth. Epstein,[11] assuming a value of 25 gauss for the strength of the field at the magnetic poles of the sun, has shown as a result of such a field that electron rays below 1.0×10^9 ev would be completely eliminated in their passage to the earth, that rays in the range between 1.0×10^9 and 5.9×10^9 would be weakened in intensity and that rays of higher energies would be quite unaf-

[7] I am indebted to Professor Hess for making these results available to me in advance of their publication.

[8] V. F. Hess, Phys. Rev. **57**, 781 (1940).

[9] M. S. Vallarta and O. Godart, Rev. Mod. Phys. **11**, 180 (1939).

[10] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 709 (1937).

[11] P. S. Epstein, Phys. Rev. **53**, 862 (1938).

fected. At the latitude of Chicago ($\lambda=52°$N) where the threshold due to the earth's field is about 2.9×10^9 ev one might expect to find the cosmic-ray intensity at high altitudes subject to variation in either field. At high latitudes the threshold imposed by the sun's field would be the only one effective while at low latitudes the threshold imposed by the earth's field would be the predominant one.

Whether the sun's field varies in intensity as assumed above or even whether there is real evidence that the sun's field exists as a factor affecting cosmic rays are important questions still to be settled. Time variations of more than four percent in high altitude cosmic-ray intensities at Bismark, North Dakota ($\lambda=56°$ N) reported by Millikan and Neher[3] suggest the possibility that such variations persist even up to very high latitudes where the best available data indicate a cosmic ray intensity independent of latitude. A similar variation of 2 percent[12] has just been reported in sea level values at magnetic latitude 58° N during a recent magnetic storm. Such changes would seem difficult to explain on the basis of a variation in the earth's field alone. These considerations, however, only emphasize the need of further systematic high altitude experiments at high latitudes.

Conclusions

(1) During the course of a year's high altitude measurements, changes as large as fourteen percent have been observed for the maximum ordinate of the ionization-pressure curve. The corresponding maximum change in the integrated area under the curves is about ten percent.

(2) The high altitude variations follow in general the "world-wide" variations already observed at ground stations which are believed to be caused by fluctuations in the magnetic field surrounding the earth.

(3) After correction for "world-wide" variations certain residual variations remain in the high altitude values which seem to be of significance. There is an indication of combined effects of the magnetic fields of the earth and sun although no fully satisfactory explanation can be at present advanced.

(4) The establishment of the existence of time variations such as are reported here is of importance for future high altitude measurements. Thus in determining the effect of latitude or longitude on high altitude cosmic-ray intensities it is very important to be sure that no time variation has taken place during the time elapsed between the flights at the different stations. Otherwise the result obtained may have but little relation to the effect which it is desired to measure.

The writer wishes to express his thanks to Professor A. H. Compton, who first suggested the present type of experiment, for his continued interest, to Dr. Elmer Dershem whose skill in the making of the electrometers used has contributed much to the success of the work and to Dr. John A. Fleming of the Carnegie Institution who furnished both the cosmic-ray and magnetic data. He also wishes to express his appreciation for the help of Messrs. Alois Bragagnolo, Leo Seren, Ted Novey and Warren Nyer who aided in the flights. This work has been supported in part by a grant from the Penrose Fund of the American Philosophical Society and in part by the generosity of Mrs. Henry A. Strong.

[12] D. H. Loughridge and P. E. Gast, Phys. Rev. **57**, 938 (1940).