STATISTICAL STUDIES OF COSMIC RAYS AT HIGH ALTITUDES

Thesis by

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Abstract

A description of the equipment used in measuring cosmic ray intensities at high altitudes by both balloon and airplane is given. Results of a series of 15 balloon flights throughout the United States and Canada are discussed.

A B-29 airplane flight to Peru for measuring the latitude effect is discussed and conclusions drawn as to the charge of the primary cosmic rays. In particular, time variations of cosmic rays at high altitude are analyzed.

A series of B-29 flights made under identical conditions expressly for the purpose of studying time variations of cosmic rays are analyzed. It is found that there is a general pattern to the variations which might be explained by the eccentricity of the sun's magnetic dipole from the sun's rotational axis.

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Part I

Cosmic Ray Studies at High Altitudes Using Balloons

I. Introduction

During the summer of 1947, a group under the direction of Dr. H. V. Neher and Dr. W. H. Pickering conducted a series of high altitude balloon flights with cosmic ray telescopes(1,2). A detailed description of the apparatus used is given in Appendix I. To summarize, a new type of light-weight, all metal Geiger counter was used. Eight such counters connected in parallel were made into a tray and three trays were used in each telescope. The separation of the two outer trays was such that the telescope had an aperture of about 15° on all sides of its axis. This is to be compared with the apparatus previously used by Millikan, Neher, and Pickering(3,4,5) where the maximum angle from the zenith in one direction was 45° and 25° at right angles to this. The area of the trays of counters was made of such a size that the statistical errors in the counting ratio were negligible in determining the maxima of the altitude curves.

The triple coincidences were transmitted by radio to the ground where they were received, scaled down, and recorded on a moving tape. Temperature and pressure data were also transmitted and recorded on the same tape.

II. Cosmic Ray Latitude Effects at High Altitudes

A description of the results of balloon flights from seven different stations throughout the United States and Canada is given in

Appendix II. To summarize, cosmic ray telescopes for measuring the vertical intensity were sent aloft in balloons from stations approximately equally spaced between San Antonio, Texas, and Saskatoon, Canada. All sets of equipment, of which there were 25, were compared with a standard to reduce all results to a common basis. The standard sets, in turn, were compared with an accurately constructed telescope(6) which had been used to make an absolute determination of cosmic ray intensity in Pasadena. Two flights were made from each of the seven stations.

Since the publication of Appendix II, an error in the corrections has been brought to the attention of the authors. This error is in the corrections due to the accidental counting rate caused by the finite resolving time of the coincidence circuits. In the corrections previously applied, only the accidentals due to random events between each of the three trays were considered. However, there are also accidentals due to a particle going through the top two trays in true coincidence, and another time associated particle in the bottom tray. Similarly, the bottom two trays may have a true coincidence associated with a random particle in the top tray. This may be expressed by writing the accidental rate as

$$A = 3 K_a K_b K_c \tau^2 + 2(K_a K_{bc} + K_c K_{ab})\tau \qquad (1)$$

where K_a, K_b, K_c are the counting rates of tray a, b, and c; K_{ab} and K_{bc} are the true coincidence rates of the telescopes formed by trays a and b, and trays b and c, and τ is the resolving time of the electronic circuits. It is this second term which was neglected in the earlier corrections. Using the same general method as used previously, it will be assumed $K_a = K_b = K_c$ and that the counting rate of a Geiger counter is proportional to ionization chamber readings as was the case in India[3]. Using this data, one finds the constant of proportionality over a considerable range to be about 5.8 ion cm^{-3} atm^{-1}. Rewriting equation (1) to give the relative correction and considering only the second term one obtains

$$\frac{A}{K} = 2\left(\frac{K_{bc}}{K} + \frac{K_{ab}}{K}\right)\tau I \times 5.8 \tag{2}$$

where K is the counting rate of the telescope and I is the ionization reading for the corresponding altitude. It should be noted that K_{ab} and K_{bc} depend upon zenith angle distribution as well as the spacing between trays. To simplify the computations, and since these corrections amount to 7% at the very most, it will be assumed that the spacings between trays are equal, which was nearly the case, and that the zenith angle distribution goes as $\cos^2\theta$ where θ is the zenith angle. Then, using the general expression given by Montgomery[6] one finds that $K_{bc}/K = K_{ab}/K = 3.3$. Using a resolving time of 2 microseconds as before

$$\frac{A}{K} = 1.54 \times 10^{-4}\, I \tag{3}$$

By means of the ionization chamber data of Millikan, Neher and Pickering[10], one has only to apply this correction from the curves given in Appendix II to obtain the corrected curves. These corrected curves for each of the seven stations are given in Figure 1.

Figure 2 gives the corrected values for the maximum of these curves. The most prominent features of these curves are the facts that, (1) the St. George curve is below that of Fort Worth, although St. George is 3°

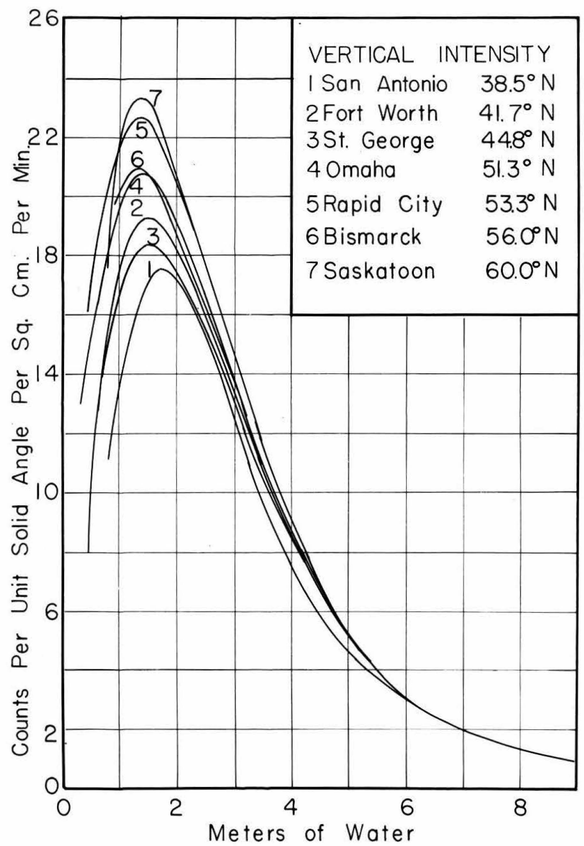

Fig. 1. Observed vertical intensity of the cosmic radiation as a function of pressure in meters of water for indicated geomagnetic latitudes.

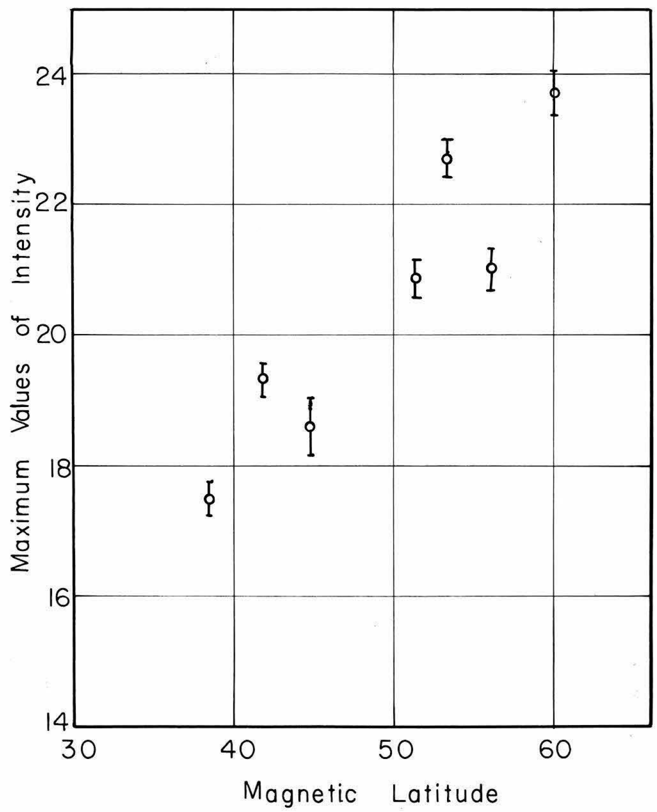

Fig. 2. Maximum vertical intensity as a function of latitude for the series of balloon flights.

magnetic latitude farther north, and (2) the Bismarck curve is below that of Rapid City although Bismarck is 3^{o} farther north also. Such a result appears to be in definite contradiction to the results of the analysis of the motion of charged particles in the magnetic field of a dipole. This analysis predicts that cosmic ray intensity should be a non-decreasing function of magnetic latitude. The over-all statistical probable errors, including the calibration against the standard are as indicated in Figure 2. It can readily be seen from this that there is a genuine discrepancy somewhere. This discrepancy is believed to be due to variations in cosmic ray intensity as a function of time. Indeed, this theory is borne out not only by those reasons stated in Appendix II, but also by additional data taken since that time.

III. Zenith Angle Telescope

Additional apparatus (not described in Appendix I) for measuring the East-West effect[7,8,9] was also constructed. This consisted of a telescope similar to those described above which was pointed at an angle of 60^{o} to the zenith instead of vertically. Windmill type vanes were provided to rotate the telescope in azimuth, at a rate of about one revolution per minute. A photo cell actuated by the sun's light through a narrow aperture determined once each revolution the telescopes azimuth angle. This signal from the photo cell was radioed to the ground in a way similar to that of the barometer and thermometer units. Thus, by interpolation, it was possible to find the azimuth angle of the cosmic ray telescope at any time.

Only one flight was made with this type of apparatus, that taking place on August 31, 1947, from Fort Worth, Texas. Upon examination of the data taken, it was found that there was no asymmetry in azimuth angle within the experimental error. This was interpreted as being due tofaulty azimuth angle determination. Additional data taken since this time, however (see Part II), indicates that the asymmetry at this latitude should be very small and probably beyond the experimental error. For these reasons, the data is now interpreted as being valid and is here presented.

Figure 3 shows the experimentally determined points averaged around the complete azimuth angle. It should be noticed that they define the curve plotted fairly well and appear to be consistant. The corrections that should be made to this curve are, (1) dead time, (2) accidentals and (3) finite opening of the telescope. As stated before, corrections for accidentals involve a knowledge of the zenith angle dependence as a function of altitude, as does correction for the finite opening of the telescope. Previously, in the corrections for the vertical intensity, this was assumed to be constant with altitude and to vary as $\text{Cos}^2\theta$. This introduced only a small error in the corrections which were themselves very small. However, this is not the case for a zenith angle of 60° as the corrections are quite large, particularly in the case of the corrections due to the finite opening of the telescope. A quick calculation as to the order of magnitude of this correction may be made at 3.1 meters of water equivalent where the zenith angle dependence is fairly well known (see Part II). This shows that the correction may amount to as much as ~ 10%. This correction may be greater at altitudes above the peak of the curve. Since the corrections due to dead time and accidentals are of approximately equal magnitude, they compensate for each other to within a percent or two. One other cause of error in the curve should be mentioned.

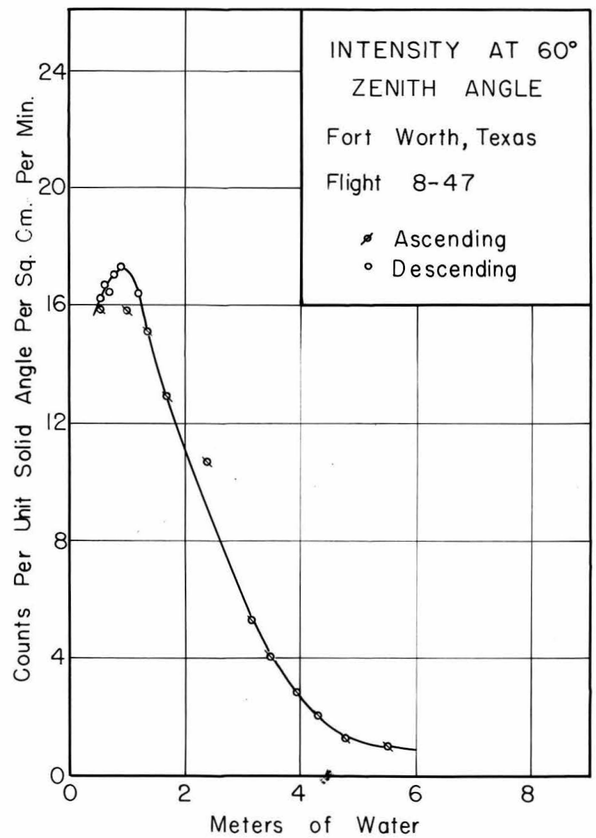

Fig. 3. Observed intensity of the cosmic radiation as a function of pressure in meters of water, for a zenith angle of 60°, at Fort Worth.

This is the increase in counting rate of the telescope due to showers (see Appendix II). This effect is believed to be small. For these reasons, no corrections will be applied to the experimental curve. Thus, one might expect the curve in Figure 3 to be of the correct shape but perhaps about 10% too high.

A number of interesting characteristics of this curve may be noted. If the equivalent depth of the atmosphere through which the particles must travel is used as the abscissa instead of the vertical depth as was done in Figure 3, then a curve as shown in Figure 4 is obtained. Plotted also on this same figure is the average of the two flights measuring the vertical intensity, made at the same locality on the previous day and on the same day. With this short time between flights, one would not expect any time variations. If the cosmic radiation were absorbed in the atmosphere by simple mass absorption, one would expect these curves nearly to coincide (except for lack of corrections as discussed above). However, one notices at the peak of the curves that the data taken at 60° zenith angle lies considerably below the corresponding vertical curve peak and also that the peak of the 60° zenith angle curve comes at a greater equivalent depth of atmosphere. It is thought that this can be accounted for by a combination of the scattering and the finite decay time of the meson as one path length is approximately twice as long as the other. A much harder fact to explain is the fact that this relation does not persist down to the lowest altitudes. Instead, one finds that the two curves cross at approximately 3 meters of water equivalent and from there on down the 60° zenith curve lies above the vertical curve. One explanation of this is that scattering in the atmosphere might be of much larger magnitude than heretofore thought. In any case, these

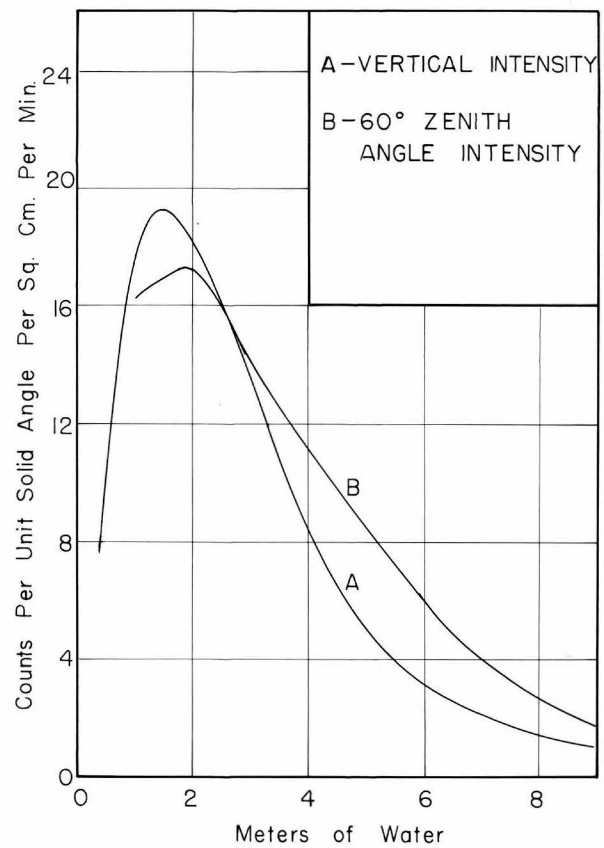

Fig. 4. Comparison of the vertical intensity and of the intensity measured at a zenith angle of 60°, as a function of equivalent depth the particles must travel through. Data taken at Forth Worth.

comparisons between the two curves can neither be explained as experimental errors, nor due to not having corrected for the finite opening of the telescope.

Winckler, Stroud, and Schenck[11] have recently reported a similar experiment which confirms the above within the limits of error.

Part II*

Cosmic Ray Studies in a B-29 Aircraft on a Trip to Peru

I. Introduction

It has been pointed out previously that comparison between balloon flight measurements of cosmic ray intensity is not possible if the flights are made a day or more apart. This unfortunate circumstance is due to the variation of the intensity as a function of time. There are at least two ways that one may obtain a consistent set of altitude curves normalized to some particular time. One of these methods is to send aloft instruments simultaneously from two different stations and then proceed from one increment of latitude to another.

Another method, perhaps easier than the first, is to make an airplane flight at one particular altitude covering a wide range of latitude in a very short time. By means of the one point obtained for each latitude, the balloon flight curves could then be normalized. One would like to obtain this normalization point as near the peak of the balloon curves as possible, this altitude corresponding to about 45,000 feet. However, as there are no available planes that can reach this altitude, it was decided to normalize at an altitude of 30,000 feet which is readily obtained by available B-29 type aircraft. From the balloon data, it is known that the intensity at 30,000 feet corresponds

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* For a more complete discussion of certain phases of this part see the article on this subject that will appear shortly in The Physical Review by H.V. Neher, W.C. Roesch, and the author. Only those parts with which the author was intimately connected are treated in detail. In particular, the sections on corrections and a great deal of the interpretations have been omitted from this discussion. Those sections marked (†) are taken directly from the article.

to about 1/2 to 2/3 of that at the maximum. Thus, this altitude should provide usable normalization data.

The flight plan was then to fly at a constant barometric pressure to the magnetic equator from as far north as possible. Landing fields mainly decided the actual course. However, in order not to become involved in any longitude effects[12] it was decided to fly on approximately a constant geomagnetic meridian in going to the equator. This was done by flying on the 80^{th} West geographic meridian which very nearly coincides with a geomagnetic meridian.

II. Experiments Performed

Although the primary purpose of these flights was to obtain data for correcting the balloon flight curves, it was also decided to perform additional correlated experiments. The north-south course of the plane readily adapted itself to east-west measurements[6,7,8] and the great weight-lifting capacity of the plane made it possible to use lead absorbers. In addition, there was to be a special high altitude flight (36,000 feet) over Peru that could be used for other experiments. A list of the experiments performed follows.†

1) Pressure Altitude 30,000 feet (310 gm cm^{-2})

   A. Latitude Effect: Continuous measurements both going and coming.

      1. Vertical radiation: Two independent telescopes; no shielding.

      2. Vertical radiation: One telescope; 10 cm of lead absorber.

      3. Vertical radiation: One telescope; 20 cm of lead absorber.

4. East-west effect at 45°: Two independent telescopes; no absorber.

5. East-west effect at 45°: One telescope; 10 cm of lead absorber.

6. East-west effect at 45°: One telescope; 20 cm of lead absorber.

7. Wide showers: Four trays of counters. Maximum extension, 3.5 meters.

8. Total radiation: Continuously recording ionization chamber. Same as used in our sea level and airplane surveys.

B. Other Experiments at 30,000 feet:

1. East-west effect at equator: Measurements made with no lead, 10 and 20 cm absorber at zenith angles of 0°, 22½°, 45°, 67½°, 90° in the east-west plane.

2. Zenith angle measurements: Made in north-south plane at 48° geomagnetic north on flight from Provo, Utah, to Springfield, Illinois, along a constant geomagnetic latitude. No absorber, 10 and 20 cm of lead absorber. Zenith angles: 0°, 22½°, 45°, 67½°, 90°. These same measurements were repeated on the east-west flight along the geomagnetic equator from longitude 80° west to Lima, Peru.

3. Side showers: To provide data on the corrections due to showers from the sides to be made to the counting rate of the counter telescopes, the center tray of counters on two telescopes was displaced sideways out-

side the telescope aperture. This was done both at northern latitudes and at the equator.

2) Pressure Altitude 36,000 feet (235 gm cm^{-2}) over Peru:

A. Azimuthal experiments: Two hexagonal courses flown, one hexagon rotated 30° with respect to the other, thus giving data every 30° in azimuth. Measurements made with no lead, 10 cm and 20 cm of lead absorber. Zenith angles: 0°, 22½°, 45°, 67½°.

B. Wide showers also measured.

3) Miscellaneous Experiments:

A. Counting Rate versus Air Pressure: At nearly all times when the plane was ascending, all telescopes were turned vertically and records were kept of outside air pressure versus time.

B. Calibration Checks: On several occasions on the flight, down and return, all telescopes were turned vertically and long runs were made for intercomparison.

III. Description of Apparatus

The cosmic ray apparatus used in these experiments consisted essentially of three parts: (1) the cosmic ray telescopes, (2) the scaling circuits, and (3) the recording equipment.

(1) Cosmic Ray Telescopes

The cosmic ray telescopes, with slight modifications, were of the type previously described and used in balloon type experiments. In general, they consisted of three trays containing eight Geiger tubes per tray connected in triple coincidence. Each tray had an effective area of approximately 600 cm^2, the spacing between extreme trays being about 3/4 of a meter. This spacing between trays was reduced from the previously used value of one meter in order to facilitate using the same frame for two telescopes, and to increase the counting rate of the telescope. Thus, three of the telescope frames contained four trays of Geiger tubes, the top three trays being connected in triple coincidence as one telescope and the bottom three trays connected so as to form another telescope. Lead was placed between the bottom two trays (Figure 5) to measure absorption in the lower telescope. Table I gives a description and the dimensions of each of the telescopes. In one case, lead was also inserted between the middle two trays as well as between the bottom two trays.

The amplifiers and coincidence circuits were the same as those used previously. The output pulse was taken from a cathode follower and transmitted through a coaxial line to the centrally located scaling circuits. A power supply of the regulated type was provided to supply the circuits. However, in order to insure continued operation of the apparatus in case of failure of either, the power supply or the source of power, means for battery operation was provided. This provision proved to be quite valuable on a number of occasions. The high voltage for the Geiger tubes was obtained from batteries as previously.

Each of the telescope frames was completely enclosed in twenty-mil aluminum for electrical shielding and physical protection. The telescopes for measuring intensities at various zenith angles (Nos. 4,5 and 6,7) were mounted to rotate about a center line of the airplane as shown in

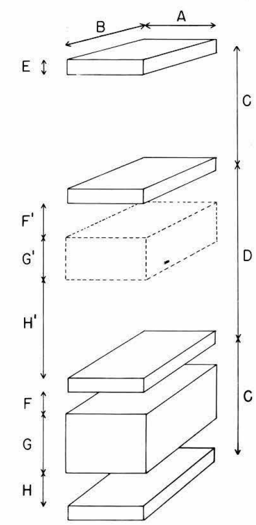

Fig. 5. Typical cosmic ray telescope used in airplane flights. Actual dimensions are given in Table 1.

TABLE I

Tel. No.	Type	Lead	F	F'	G	G'	H	H'
4 5	E - W E - W	None 10 cm	11	-	11	-	10	-
6 7	E - W E - W	None 20 cm	6	-	6	-	20	-
8 9	Vertical Vertical	10 cm 20 cm	9	22	10	10	10	13

For all units A = 23.1 cm

B = 25.8

C = 32

D = 80

E = 3

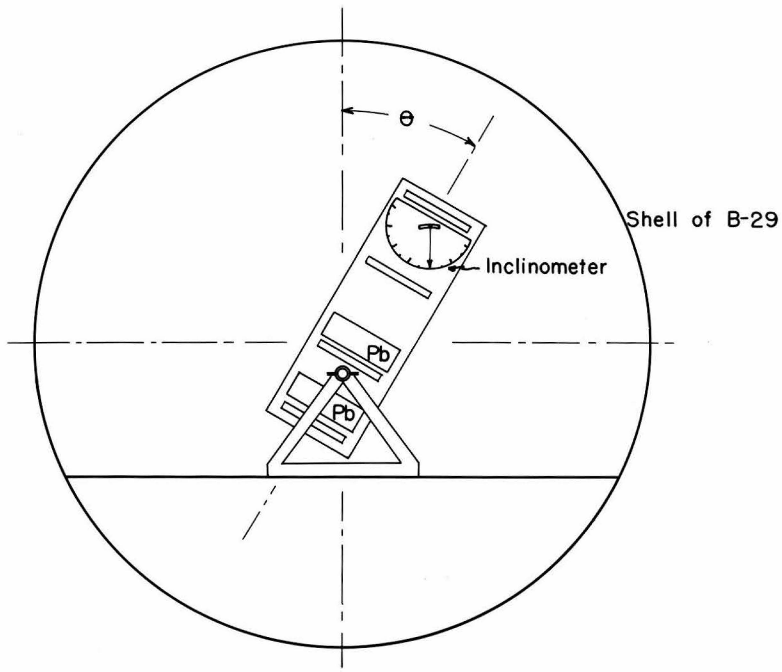

Fig. 6. Pictorial sketch showing method of mounting cosmic ray telescopes in airplane.

Figure 6. Since in two of the telescopes the weight of the lead was over 200 kg. it was necessary to use quite heavy construction. The zenith angle was obtained by means of a bubble glass and protractor as is also illustrated in Figure 6. This method of obtaining the zenith angle proved to be accurate to about $\frac{1}{2}^{\circ}$, and was satisfactory.

(2) Scaling Circuits

Apparatus was constructed to scale the counting rates of each of the telescopes by a factor of four. It can be shown by simple considerations that this scaling ratio of four is just sufficient to reduce the number of counts missed to a neglible amount at the maximum counting rates. If K is this maximum counting rate and τ is the resolving time of the mechanical recorder, then the probability that n counts will occur in the time interval is given by Poisson's law. Thus, the efficiency may be written as

$$\mathcal{E} = 1 - \frac{(K\tau)^n}{n!} e^{-K\tau} \qquad (4)$$

where, in this case, n is the scaling ratio minus 1, i.e., 4 - 1 = 3. Using the maximum counting rate as 800 counts per minute and τ as 0.016 sec. (60 cycle response) one finds the efficiency to be about 99.9% which is sufficient for this experiment. A similar analysis for the rest of the circuits shows that the other parts have even higher efficiencies.

Battery type tubes were used in the scaling circuit to conform to the rest of the circuits and make complete battery operation possible. The scaling circuit consisted of a multivibrator pulse-shaper, two scale of two circuits, and an output multivibrator for driving a Cyclotron Specialties Register*. The circuit diagram is shown in Figure 7. The

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* Manufactured by Cyclotron Specialties Co., Moraga 9, California

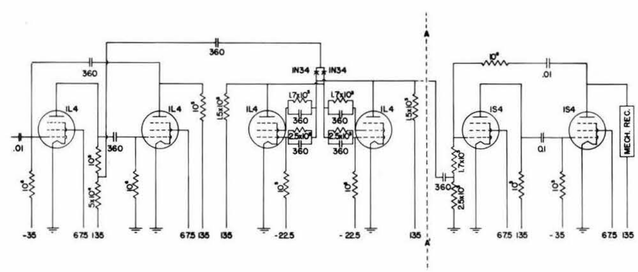

Fig. 7. Circuit diagram of scaling circuit used.

input multivibrator is of the standard type using two 1L4 vacuum tubes. A positive pulse at the input trips the multivibrator which gives a uniform negative pulse to the scale of two circuit regardless of the size or shape of the input pulse. This pulse-shaping circuit was necessary as considerable attenuation and distortion was found to take place in the fairly long coaxial lead connecting the coincidence circuit to the scaling circuit. The scale of two circuit is of the conventional plate feed type except that 1N34 crystal diodes are used for isolation purposes instead of conventional vacuum diodes. Although this eliminated the use of four additional tubes per scaling circuit, the practice is in general not recommended as much time and effort was spent replacing crystals that went bad in use. In the output circuit, it was found necessary to use 1S4 tubes in order to pass the relatively large currents necessary to drive the mechanical registers. The frequency response of the complete unit without the register connected was measured to be approximately 50 KC.

Ten units of this type were built up in the form of plug-in units to facilitate rapid change in case of failure. Two inputs were provided on each unit, one of which was used to test the circuit at frequent intervals by means of a standard frequency. A neon bulb indicator was also placed on each unit so that in case of failure, attention was immediately called to this unit.

All these precautionary measures proved quite valuable in flight, as it was necessary for the two operators to keep this circuitry of almost 200 vacuum tubes and 152 Geiger tubes in operation.

(3) Recording Circuit

The readings of all the registers were photographed at one minute intervals by a 35 mm motion picture camera tripped by means of a clock operated relay. The time as well as other experimental data were also photographed in order to have as much of the data on the film as possible.

(4) Auxiliary Apparatus

A) A shower experiment (Figure 8) was performed using four trays in quadruple coincidence. The circuit for this unit was made by adding another channel to one of the coincidence circuits used in balloon work. This was necessitated as the accidental rate of the triple coincidence circuit would have been appreciable for the very low counting rate of the shower experiment. It was not necessary to scale this counting rate.

B) The pressure altitude of the plane was obtained by two methods: (1) the plane's altimeter, and (2) a recording barograph. The plane's altimeter was calibrated by the Air Force personnel in terms of the standard altitude[13] prior to the flight. Readings of this altimeter were taken at frequent intervals. A Friez aircraft continuously recording barograph, placed in the bomb bay, gave a continuous record of the pressure altitude. This barograph was calibrated in a vacuum tank in the laboratory and checked, within the experimental error, the plane's altimeter. The actual altitude of the plane was obtained by means of a radar altimeter whenever the flight was over water.

C) A Neher type electroscope[14] was run continuously during all the flights. Caution was taken to place it as far as possible from any radioactive dials.

IV. Internal Calibrations †

All telescope data were adjusted by suitable correction factors to

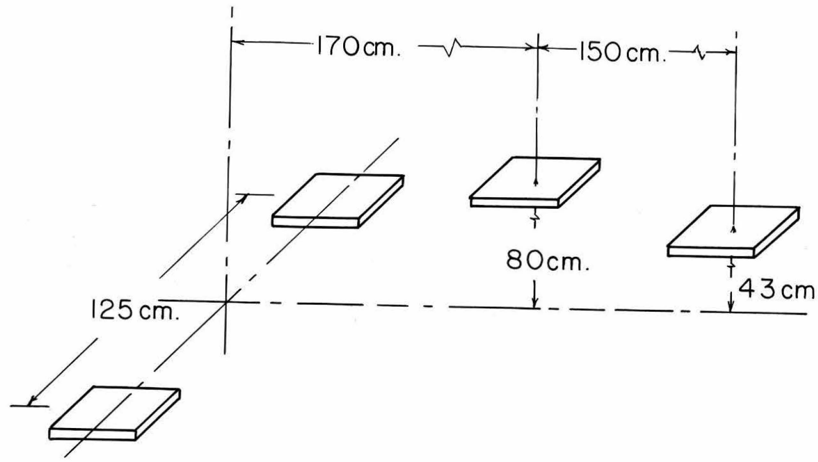

Fig. 8. Pictorial view showing position of trays for measuring wide showers. Arbitrary reference plane is 87 cm. above the floor of the plane, and the center tray is attached to the overhead.

read what No. 1 (one of the vertical, unshielded telescopes) would have read in the same circumstances. These calibration factors were determined as follows:

On several occasions, both on the ground and in the air, the four unshielded sets were measuring the same radiation while the cosmic ray intensity was constant for a sufficient time to yield an accurate ratio between counting rates. There is no significant difference between the two methods of comparing the rates. Averaging the ratios so obtained using the reciprocals of the probable errors as weighting factors provided the calibration factors.

For the calibration of the telescopes containing lead absorber, data taken in the plane while on the ground were used. These data gave the counting rate with the lead removed but with the iron boxes which held the lead still in place. An experiment in which iron sheets were inserted between the trays of the unshielded telescopes gave the necessary correction for the metal boxes, so that the above counting rates could be compared with those of set No. 1.

This last procedure failed in one case due presumably to the failure of a counter in the set. However, on other occasions its counting rate could be compared with another set with the same absorber.

The results of the internal calibrations were as follows:

Set No.	Ratio of No. 1 to this Set
3	0.979 ± 0.004
4	0.981 ± 0.007
5	1.037 ± 0.009
6	1.000 ± 0.007
7	1.037 ± 0.006
8	1.011 ± 0.006
9	1.019 ± 0.016

(Set No. 2 was used to measure extensive showers.)

The indicated probable errors are those computed from statistical errors in the calibration. The above comparison gives a good experimental check of the similarity of the geometries of the various telescopes.

V. Corrections and Reduction to Absolute Units

The following is a list of corrections to the different arrangements that need to be considered:

A. Accidental counting rates.

B. Dead time of counters.

C. Effect of side showers.

D. Variation in pressure (altitude).

E. Efficiency of recording circuit.

F. Variation in zenith angle of the east-west sets.

G. Effects of finite telescope aperture.

H. Effect of finite thickness of counter walls and absorption in walls of plane.

After the above corrections are applied, the resultant counting rate must be reduced to standard units. Comparing our geometry with that used by Montgomery[9], we arrive at the result that our counting rates must be multiplied by 0.0208 to reduce them to particles per sq. cm. per steradian per minute. If we, on the other hand, assume that the intensity of cosmic rays at sea level has not changed since Montgomery's determination at Pasadena, we obtain a factor of 0.0205. The mean, or 0.0206, will be used.

IV. Flight Procedure

The flight plan is given in Table II. It should be noted that on the flights north and south along the 80° meridian, there was an overlapping of consecutive flights. This allowed a normalization between flights, if this was found necessary. On the flight to Chicago from Inyokern, California, the starting point, the plane was flown at 30,000 feet along an approximate constant geomagnetic latitude between Provo, Utah, and Springfield, Illinois. The only other special flights were the high altitude flight over Peru and a shuttle flight over Chicago just before returning to Inyokern. The return trip to Inyokern was made at low altitude. † The procedure during flights was as follows:

(1) All telescopes were pointed vertically while gaining altitude and while descending for all flights. The rate of rise was about the same as for the balloon flights we made in the past. This gave additional data at several latitudes on the counting rate versus pressure with and without lead absorber.

(2) The dials of the 9 registers, besides being photographed every minute, were read visually every 10 minutes and the rates of counting

TABLE II

Flight No.	Date	Time (GCT)	From	Route
4	May 26, 1948	0334 - 1004	Inyokern	Provo, Utah, and Springfield Illinois
5	May 29, 1948	1146 - 2100	Chicago	To 54° N, 80° W, then South along 80° W
6	June 2, 1948	1522 - 2334	Tampa	South along 80° W
7	June 4, 1948	0945 - 1839	Panama	South along 80° W
8	June 6, 1948	1505 - 2130	Lima, Peru	High alt. above Lima
9	June 8, 1948	1537 - 2324	Lima Peru	North along 80° W
10	June 9, 1948	1738 - 0130	Panama	North along 80° W
11	June 10, 1948	2044 - 0328	Tampa	North along 80° W
12	June 12, 1948	1758 - 0118	Chicago	Shuttle over Illinois and Wisconsin
13	July 1, 1948	1405 - 2240	St. Louis	Back to Inyokern at low altitude

computed immediately to give a constant check on the behavior of the equipment.

(3) Frequent checks were made on the apparatus not only while in the air but on the ground. An oscilloscope was used to determine the behavior of both Geiger tubes and circuits. Interruptions caused by these failures were in all cases never serious.

(4) During the flights north and south, the two observers shifted the two frameworks holding the four east-west telescopes every ten minutes from 45° East (or West) to 45° West (or East). Approximately 3 seconds of time were necessary to make this shift.

(5) During the azimuthal flight over Peru at 2.35 m of water equivalent, the east-west sets were tipped to a given angle with the vertical and left there for two full hexagonal courses of 360°. Two full hexagonal courses were again flown with the two sets tipped at other angles. The two successive hexagons were rotated 30° with respect to each other to permit readings every 30° in azimuth. The time of flight along each side of a hexagon was approximately 10 minutes.

(6) A constant check was maintained on the reading of the altimeter and the heading of the plane. An inter-phone system permitted communication at any time with the pilots as well as other members of the crew.

(7) The position of the plane was determined by an experienced navigator.

(8) While flying over water the actual height of the plane was frequently determined with the radio altimeter.

VII. Experimental Results

1)[†] Latitude Effect of the Vertical Radiation:

a) The counting rates of the two vertical telescopes without absorber, as a function of geomagnetic latitude, are given in the upper curve of Figure 9. Each point on the curve represents the average of the two sets each averaged for a 30 minute interval of time. At the northern latitudes, each point is determined by nearly 50,000 counts giving a statistical probable error of about ± 0.3%. Thus, the error in each point from the number of counts is given approximately by the radii of the circles (or dots). No corrections have been applied to these data.

The open circles represent the results of the trip south and the solid circles for the trip north. It is seen that, in general, the agreement is quite good indicating that the absolute value of the radiation did not change appreciably in the intervening 4 to 11 days (see Table II). There is, however, an indication of some fluctuations on the return flight at about 50° North as seen in Figure 9.

b) The latitude effects taken with the two telescopes with 10 and 20 cm of lead between the second and third trays of counters are given in the top curves of Figure 10 (a) and (b). The open and solid points again represent the values going south and north respectively. Since only one telescope was used for each curve, the statistical probable error over the 30 minute period at the northern latitude was ± 1% or about one-half the radius of a circle (or dot).

2)† <u>Latitude Effect of the East-West Effect</u>:

In Figures 9 and 10, the lower pairs of curves give the results obtained with the counter telescopes pointed east and west, without and with lead, respectively. Again the average for each point was over three intervals of 10 minutes each. The data without lead were the averages of two independent telescopes, each alternatively pointing 45° East half the

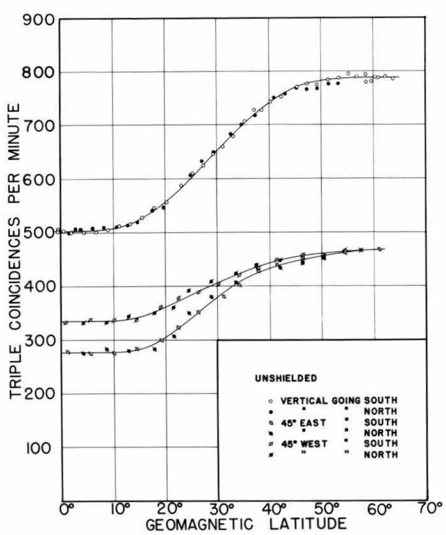

Fig. 9. The upper curve gives the vertical intensity as measured for the latitude covered. The lower curves give the intensity at 45° west and 45° east, respectively. Each point represents the average value over a half hour period. These measurements were made with no lead absorber.

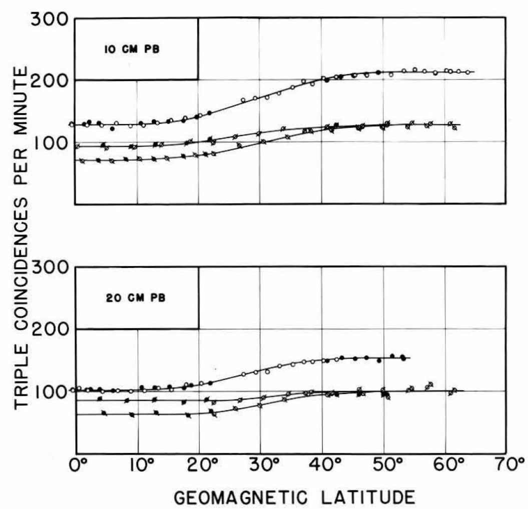

Fig. 10. The upper curve gives the vertical intensity as measured for the latitude covered. The lower curves give the intensity at 45° west and 45° east, respectively. Each point represents the average value over a half hour period. These measurements were made with 10 and 20 cm of lead absorber.

time and 45° West the other half of the time. Thus, each point without lead represents the counting rate obtained from about 28,000 counts at the northern latitudes.

The data with 10 and 20 cm of lead were obtained with a single telescope for each. The statistical probable error in each point is thus about $\pm 1.2\%$ or again about one-half the radius of one of the circles (or dots).

It should be noted that in certain regions of the curves with lead, as shown in Figure 10, some of the data are missing. These gaps are due to failure of the equipment, but fortunately do not appear to effect the general behavior of the curves.

The above results on the latitude effect without and with lead are now corrected for side showers and multiplied by the factor 0.0206 to reduce the data to particles cm^{-2} min^{-1} $steradian^{-1}$. The reduced curves are given in Figures 11 and 12. The side shower correction applied to the telescopes without lead amounted to, at northern latitudes, a reduction of 12.8% for the readings of the vertical telescopes and 18.5% for those tipped at 45° to the vertical*.

3) <u>Latitude Effect of the Total Radiation</u>:

The results obtained from the ionization chamber, reduced to ions cm^{-3} sec^{-1} at one atmosphere of air are given in Figure 13. The error in each point is approximately $\pm 1.5\%$ as determined from the scatter of the readings of the five-minute individual discharges on the film.

4) <u>East-West Effect at the Equator</u>:

The results of the measurements made on the east-west effect at the

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* For a full account of the method used in obtaining these values, see W.C. Roesch, Ph.D. Thesis, California Institute of Technology (in press).

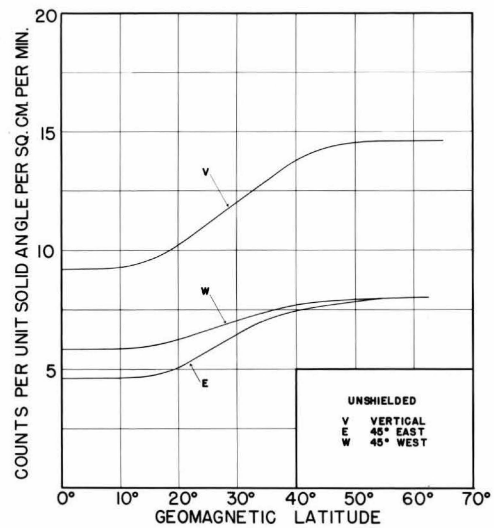

__Fig. 11.__ The same data as given in Figure 9, after reduction to absolute units.

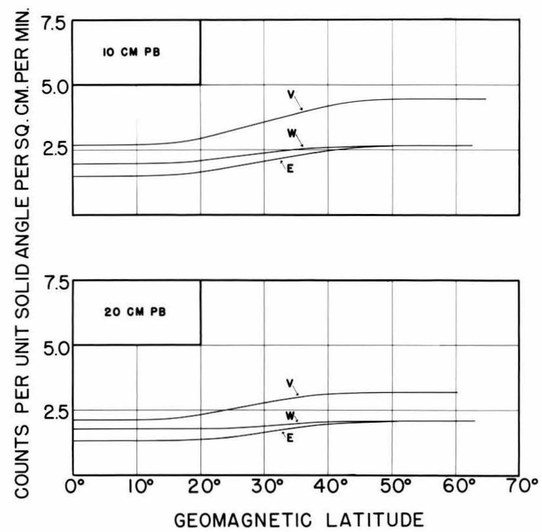

Fig. 12. The same data as given in Figure 10, after reduction to absolute units.

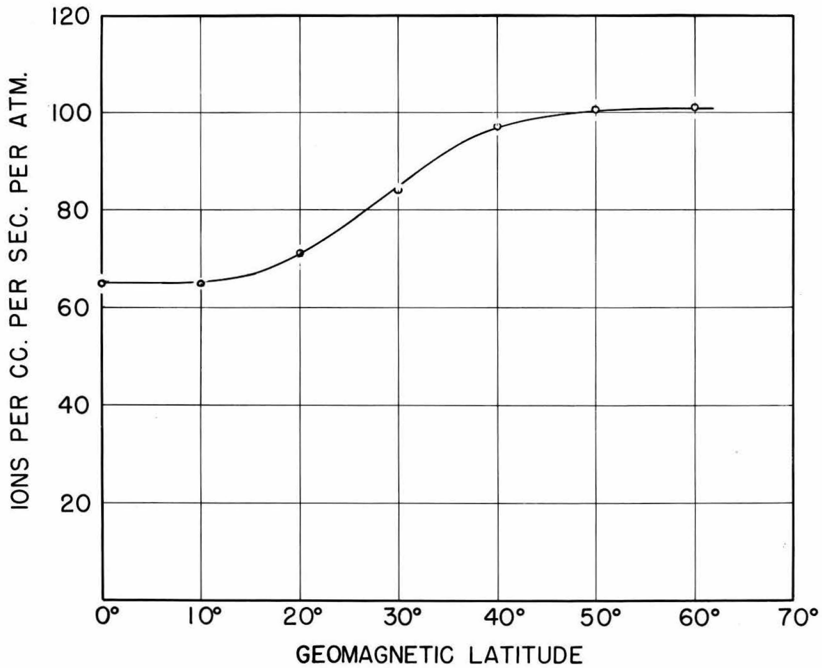

Fig. 13. The latitude effect as measured with a Neher type ionization chamber.

equator are included in Appendix III[15].

5) Azimuthal Effect at the Magnetic Equator:

Figures 14 and 15 show the variation in intensity as a function of azimuth angle for various zenith angles with and without lead absorbers respectively. Each point gives the counting rate averaged over a ten minute period. This results, for example, for no lead absorber in an error of ± 0.7% for each point at zenith angle of 45°. In the case of the telescopes with lead, the error is about three times this amount.

6) Remaining Results:

Results were also obtained on the following measurements which, however, will not be presented here.

a) Measurements on wide showers as a function of latitude.

b) Measurements on wide showers as a function of altitude.

c) Intensities as a function of zenith angle at northern latitudes.

d) Intensity as a function of altitude.

e) Altitude of the airplane as a function of latitude for constant air pressure.

VIII. Discussion of Results

From an inspection of the experimental data presented above, a number of interesting conclusions may be drawn without going into a detailed analysis of the data. These results are as follows:

1) Latitude Effect at the Vertical

a) An inspection of Figures 9, 10, 11, 12 and 13 shows that the variations of the vertical intensity both with and without lead absorber as well as the total radiation as measured with an ionization chamber, are a continuously increasing smooth functions of lati-

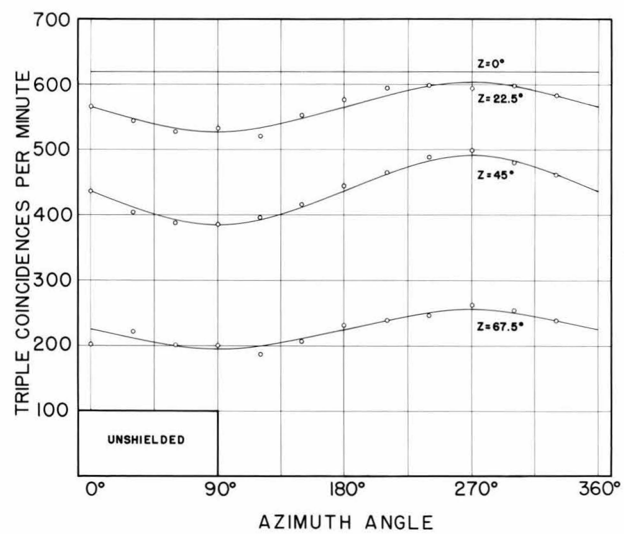

Fig. 14. Azimuthal effect measured at an altitude of 36,000 feet over Peru without lead absorber.

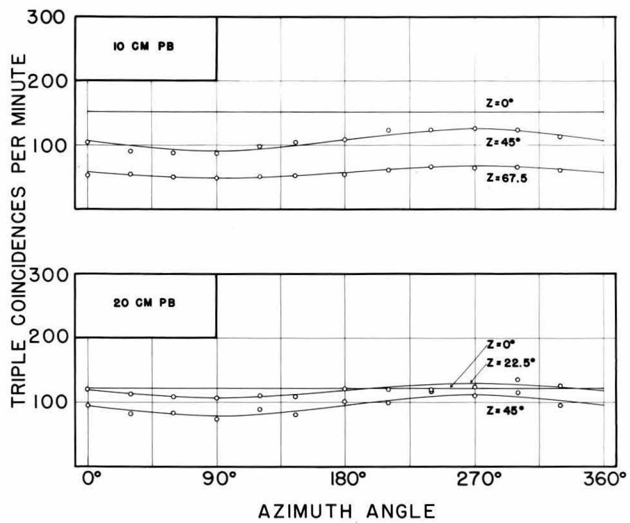

Fig. 15. Azimuthal effect measured at an altitude of 36,000 feet over Peru with 10 and 20 cm. of lead absorber.

tude for a constant atmospheric depth. The fact that these curves are continuously increasing is to be expected, as was stated in Part I. The smoothness of the curves indicates that the momentum spectrum of the primary incoming particles is also a smooth curve. This is not what was expected by Millikan, Neher, and Pickering[10] on the basis of the atom annihilation theory.

b) Further inspection shows that there is approximately the same ratio between penetrating and non-penetrating radiation at the equator as at northern latitudes, i.e., there is the same latitude effect for each.

c) As was originally stated at the beginning of this Part, the main purpose of this experiment was to obtain data which would permit a normalization of the curves given in Part I as well as additional balloon type data obtained by Millikan, et al[3,10]. The data given in Figures 11 and 13 proved satisfactory for this purpose. A more detailed account of time variations will be treated below, but let it suffice here to say that the curves given in Figures 11 and 13, though made over a period of 11 days, did not change appreciably during this period. Direct evidence for this is indicated in Figure 9 where the experimental points are plotted and no essential difference is noticed between the flight south and the flight north.

The normalization was accomplished by multiplying all values at a given latitude by a factor which made the point at 3.10 meter of water equivalent (30,000 feet) agree with that given in Figure 11. It is thought that this procedure is justified by the similarity of the altitude curves for adjacent latitudes. A consistent set of altitude curves permits the determination of the primary momentum distribution[3] of the incident cosmic rays for a range of about 2 to 15 Bev/c.

2) East-West Effect

a) An account of the east-west effect at the equator is given in Appendix III. To summarize, the conclusion is drawn that it is not necessary to assume a different primary particle to account for the penetrating and soft components at the equator and that it is likely that one kind of incident, positively charged primary particle will suffice.

b) The east-west curves given in Figures 11 and 12 are consistent with the analysis of the motion of a positively charged particle in the field of a magnetic dipole as given by Vallarta[12]. This indicates also that in the momentum range considered in this analysis, the number of negatively charged particles is small with respect to the number of positively charged particles, if any negatively charged particles enter into the primary component of cosmic rays at all.

3) Azimuthal Effect at the Equator

From the data given in Figures 14 and 15 combined with the data given by Vallarta, it is possible to make an analysis of the momentum distribution over a range of 9 to 33 Bev/c. This, combined with the measurements made at the vertical, carries the momentum distribution determination over a total range of 2 to 33 Bev/c. The smoothness of the curves indicates that this distribution is also smooth and continuous.

IX. Time Variations*

A study of the variation of cosmic ray intensity at sea level and on mountains as a function of time has been carried on by Forbush[16,17] for a considerable number of years with a Compton type ionization chamber. The general conclusions from this type of investigation is that there are at least four types of variations. Two of these, the (1) diurnal and (2) annual variations are thought to be understood to at least a fair degree. Attempts have been made to explain these by a combination of a change in the earth's magnetic field due to ionization changes in the upper atmosphere, and by a change in the path length through the atmosphere due to atmospheric heating. Another type of variation is of the type (3) measured by Neher and Roesch[18] and is characterized by an associated solar flare. The remaining variations, (4) are grouped together for simplicity and as yet no definite periodicity has been found or satisfactory explanation has been put forth. These variations at sea level may amount to a few percent over a few months or less.

Since the flights took place in considerably less than a month, it is impossible to investigate any annual variations; however, any effects from each of the other three may be investigated. In inspecting any of the data taken on these flights, particular emphasis was placed on the vertical intensity with no lead absorber and ionization chamber data. This is justified by the following:

(1) These two measurements are statistically more accurate than any of the other measurements.

(2) If the variations are due to changes in the primary momentum

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* For some excellent papers on this subject, see the report on the Symposium on Cosmic Rays held at the University of Chicago, June, 1939. (Rev. Mod. Phys. 11, 122-296 (1939))

distribution, one would expect any variations that do show up to be larger percentage-wise in the two measurements chosen.

(3) A comparatively large amount of data is available on both the vertical intensity and ionization density.

(4) Interpretation of the two measurements chosen is the simplest, and possible formulation of a theory as to the causes for these variations is promising.

An examination of the flight data for diurnal variations yields a negative result within the experimental error which may be placed at 1 to 2%. Excellent opportunity for detection was afforded on Flight No. 4, from Inyokern to Chicago, as this flight was made during the night and over a constant magnetic latitude. No change in intensity was detected while on this constant magnetic latitude, nor were the values measured appreciably different from those measured a day and a half later on another flight at the same magnetic latitude.

With the generous cooperation of Dr. Nicholson of the Mount Wilson staff, an examination of both the solar activity and the magnetic intensity during the flight was made. The period was characterized by low solar activity and only nominal magnetic disturbances. One solar flare of magnitude 2* actually occured while the airplane was at altitude on June 9, at 2052 to 2058 G.C.T. No abnormalities, however, were observed in any of the cosmic ray measurements made at this time.

In order to provide better curves for close examination, Figure 16 and 17 are given. Figure 16 gives the individual ten minute averages of the two vertical sets without lead for the complete flight south and

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* Solar flares are classified as, (1) small, (2) large, and (3) extraordinarily large.

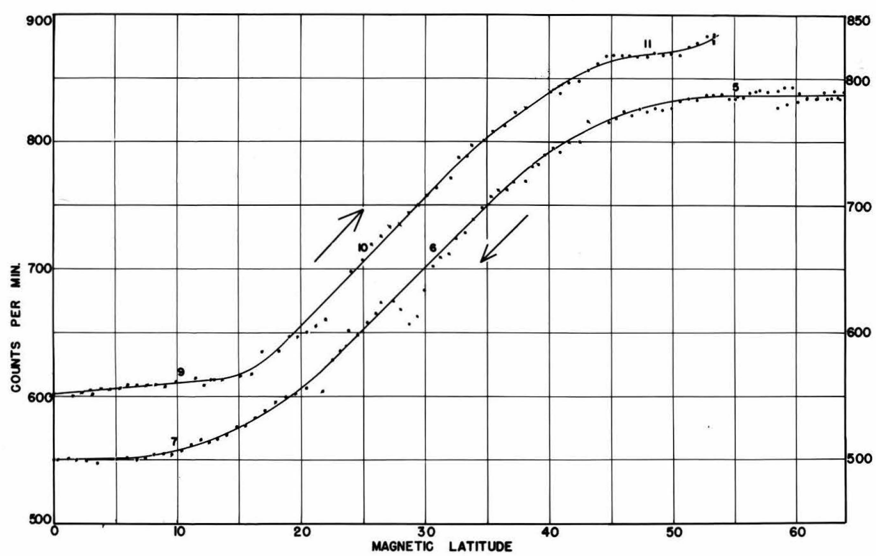

Fig. 16. Detailed plot of vertical intensity as a function of magnetic latitude. Each point represents the average of the two telescopes, without lead, over a 10 minute period. The flight numbers are given adjacent to the data taken on that flight. To enable an easy comparison, the data going north has been displaced 50 units. The flights going north and south read from the left and right scales respectively.

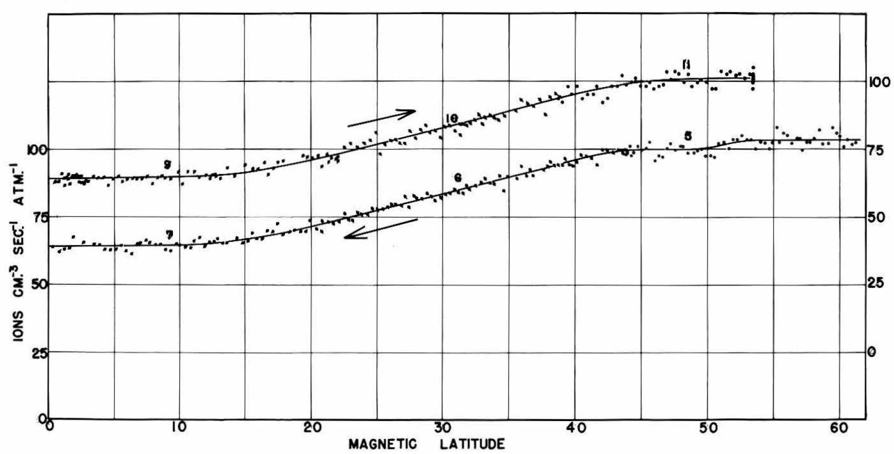

Fig. 17. Detailed plot of the ionization density as a function of magnetic latitude. Each point represents the average value for a 5 minute period. The flight numbers are given adjacent to the data taken on that flight. To enable an easy comparison, the data going north have been displaced 25 units. The flights going north and south read from the right and left scales respectively.

north. Figure 17 gives corresponding data for the ionization chamber over five minute averages. It can be seen from these curves that there is remarkable agreement between the flights to and from Peru, except for a few isolated instances. In particular, the comparison is quite satisfactory except for discrepancies at Northern latitudes. This discrepancy manifests itself in the same manner in both the vertical counting rate and ionization chamber data by Flight No. 11 being about 2% below the corresponding Flight No. 5. Thus, it appears that these erratic variations are predominant at northern latitudes. This is the same conclusion arrived at in Appendix II.

Part III

Latitude Dependence of Cosmic Rays at 33,000 Feet*(19)

I. Introduction

In an attempt to continue the study of time variations of cosmic rays at northern latitudes, a series of eight flights to be made as nearly identical as possible was planned. By making these flights over the knee of the latitude curve, i.e., over the region where the intensity ceases to increase with latitude, it was hoped that some sort of a systematic variation could be detected.

The equipment used in these flights was identical with that used on the flights to Peru and consisted of only two cosmic ray telescopes and a Neher type ionization chamber. The telescopes were without lead absorber and were maintained in a vertical position. This reduction in the total amount of equipment was mainly necessitated by space limitations in the airplane. For this reason, also, the two telescopes were put into a single frame by interleaving the Geiger counter trays. In this way, the frame contained six trays of Geiger tubes which made up two otherwise completely independent telescopes. The recording method was changed only in that visual readings were taken instead of photographic. Battery operation was used throughout the flights because the plane's power was fully used by other equipment and no other power was available.

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* The material in this part was presented at the Winter Meeting (1949) of the American Physical Society at Berkeley.

II. Description of Flights

Flights

A series of eight flights were made on the dates shown in Table III.

TABLE III

Flight No.	Date	Time of Starting	Time of Finishing
B-1-48	July 20	1300 GCT	2100 GCT
2	July 26	1700 GCT	2200 GCT
3	July 28	1600 GCT	2200 GCT
4	August 11	1700 GCT	2300 GCT
5	August 12	1700 GCT	2300 GCT
6	August 17	1800 GCT	2200 GCT
7	September 23	2000 GCT	2300 GCT
8	October 21	1700 GCT	2400 GCT

It was planned that all flights should be made flying north and south on the 117 West Meridian between the borders of Canada and Mexico at an altitude of 33,000 feet standard atmosphere (2.70 meters of water equivalent). This altitude was primarily determined by other experiments being performed at the same time by other occupants of the plane. All flights, except Number 5, were made as planned. Due to engine trouble, Flight No. 5 was made at an altitude of 30,500 feet (3.00 meters of water equivalent). For this same reason, Flight No. 7 was terminated prematurely.

III. Experimental Results

1) Telescope Data

Figure 18 shows the average of the counting rates for the two telescopes taken over ten minute intervals plotted as a function of geographic latitude. For convenience in comparison of the different curves, they have been plotted one below another using depressed ordinates. The crossed circles are those points obtained while going north, the plain circles while going south. The readings of the individual telescopes were at all times consistent with each other. This consistency was one of the main ways of determining that both telescopes were functioning properly. By averaging the two readings, better statistical accuracy is obtained than considering either of the two telescopes separately. No corrections of any sort have been made to the points plotted. This will not prevent an analysis from being carried out on this data as any corrections that must be applied will very nearly be the same for each point plotted and will only amount to a few percent.

If we assume that the points plotted should define a smooth curve, the scatter of the points is mainly due to two causes. The first and most definitely calculable is that due to the finite number of counts in each time interval. The second cause for the scattering is the altitude variations of the plane. An effort was made in flying the plane to never be off more than $\pm$ 100 feet. From noting the altimeter reading at frequent intervals, the mean probable error in altitude on a typical flight was found to be 40 feet. It is believed that errors due to the altimeter which responds to changes of altitude of ten feet, is negligible, as comparisons could be made between the three different altimeters in the plane. By using altitude curves obtained with balloons, the probable error for each point can then be computed and is approximately ½%. This is mainly due to altitude variations and is given by the size of the

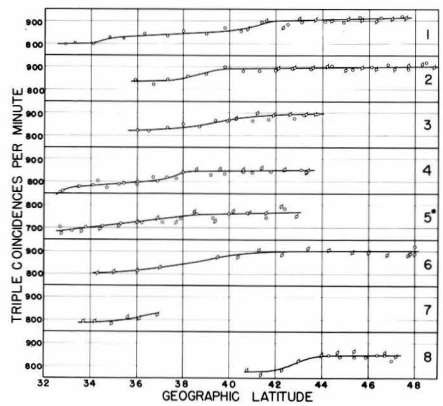

Fig. 18. The counting rates of the average of the two cosmic ray telescopes plotted as a function of geographic latitude for ten minute intervals. Note that Flight 5 was made at an altitude of 30,500 feet, all others at 33,000 feet standard atmosphere. Crossed circles are going North, circles going South.

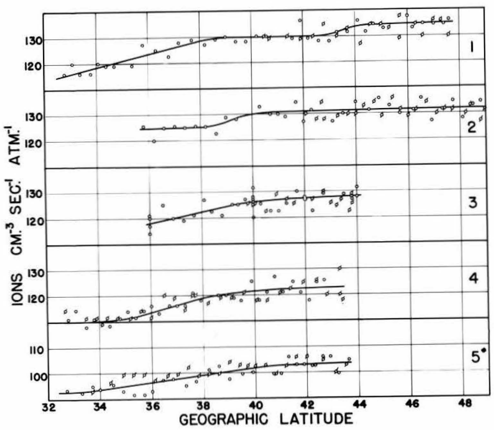

Fig. 19. The ionization as a function of geographic latitude is plotted for five minute intervals as obtained by a Neher electroscope. Crossed circles are going North, circles are going South.

circles in Figure 18.

The curves through the points have been drawn in by eye as seemingly giving the best fit to the points. This subject of curve fitting will be discussed in more detail later.

2) Electroscope Data

Figure 19 shows the corresponding data taken with the Neher type ionization chamber. Here the probable error of each point is due to the inaccuracies in measuring the rate of discharge trace on the recording film, and the variations of altitude of the plane as before. The predominant error in this case is not the plane's altitude but is the film measurement. It should be noted that in averaging the ionization over a five minute period, the number of particles passing through the chamber is large enough to reduce the statistical error to a negligible amount.

Again the curves drawn have been fitted by eye. It should be noted that there are only five flights for the electroscope data. This is due to the film jamming on the beginning of the sixth flight and escaping detection until after the completion of the last flight.

IV. Statistical Analysis of Data

In drawing the curves through the points plotted in Figures 18 and 19, a considerable amount of personal factor enters into just how the actual curves should be drawn. For example, the way Flight No. 1 was drawn for the telescope data, it appears that there are two, and possibly three plateaus in this curve. That is, there are regions where there is little change in intensity over a considerable range of latitude. The way Flights 2 and 4 have been drawn also seem to indicate a plateau characteristic, but it is noticed that the plateaus start and end at different latitudes. This same characteristic also appears in the ionization chamber curves which correspond quite closely to the vertical intensity curves.

To find out if one was justified in drawing the curves with plateaus and to obtain the best fit to the experimental points, a statistical study of the above data was carried out. The method used is that known as the X^2 (Chi square) test[21] which has been developed to a considerable extent for testing hypotheses about frequency distributions. In this particular application, certain simple analytic curves were chosen and then the probability of their validity tested. This is done by comparing the mean square deviation of the experimental points to the theoretical mean square deviation (sometimes called, expected mean square deviation).

1) The X^2 Test

Let us define X^2 in the usual way as

$$\chi^2 = \sum_{i=1}^{n} \frac{(m_i - \bar{m})^2}{\bar{m}} \qquad (4)$$

where m_i is the difference of the value of the ordinate (counting or ionization rate) of the i^{th} point from the value given by the curve at the corresponding latitude, $\bar{m}$ is the expected mean square deviation of the points from the mean, and n is the total number of points defining the curve. Then, the probability of obtaining a sample of m's for which X^2 is greater than an assigned X^2, say X_o^2, is given by*

$$P(\chi^2 > \chi_o^2) = \int_{\chi_o^2}^{\infty} \frac{(\chi^2)^{\frac{d-2}{2}} e^{-\frac{1}{2}(\chi^2)}}{2^{\frac{d}{2}}\,\Gamma(\frac{d}{2})} \, d(\chi^2) \qquad (5)$$

where d is the degrees of freedom of the system and $\Gamma(\frac{d}{2})$ is the gamma

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* For a derivation of this expression, see for example, reference 21.

function defined in the usual way by

$$\Gamma(x) = \int_0^\infty e^{-t} t^{x-1} \, dt \tag{6}$$

It is obvious that X^2 is never negative and may vary from 0 (when there is no difference between the observed and expected deviation) to very large values. As X^2 varies from 0 to ∞, the probability P given by (5) decreases from 1 to 0. Fisher[22] has prepared a table of this integral for a wide range of X^2 and d, and says:

> In preparing this table we have borne in mind that in practice we do not want to know the exact value of P for any observed X^2, but, in the first place, whether or not the observed value is open to suspicion. If P is between 0.1 and 0.9 there is certainly no reason to suspect the hypothesis tested. If it is below 0.02 it is strongly indicated that the hypothesis fails to account for the whole of the facts. We shall not often be astray if we draw a conventional line at 0.05, and consider that higher values of X^2 indicate a real discrepancy.

2) Application of the X^2 Test

The choice of the type of curve to assume as well as the number of experimental points will determine the degrees of freedom d. The more complex the curve chosen, the fewer the degrees of freedom. This may be expressed as $d = n - r$ where r is the restrictions on the degrees of freedom. For a straight line $r = 1$, for a parabola $r = 2$, for t straight lines $d = n - (2t - 1)$, etc. Thus, it can be seen that analytic curves must be chosen if the degrees of freedom are to be determined, and the complexity increases enormously as the more complicated analytic expressions are fitted to the experimental points by a least square method.

The expected deviation may be obtained by two methods for the counter data. One method is to compute the probable error from the counting rates and from estimates of the plane's variation in altitude, as was explained previously, and then to divide this probable error by 0.67 to obtain the standard deviation. If this is done, the standard deviation, which is the expected deviation, is found to be 7 counts per minute for a counting rate of 900 counts per minute. The other method of obtaining the expected deviation is to use data obtained when the counting rate of the sets should have followed a normal distribution about a constant mean value. An excellent opportunity for this sort of an analysis was afforded by the data taken while flying east and west over a short course on both sides of the 117 West Meridian at 40.8° N Latitude on Flight No. 3. This shuttling back and forth took place for over two hours and was identical with other flights except that there was no change of latitude during this time and one would expect the mean intensity to be constant. Using this data and the usual definition of standard deviation, i.e.

$$\overline{SD} = \left[\sum_{i=1}^{n} \frac{m_i^2}{n} \right]^{\frac{1}{2}} = \overline{m} \qquad (7)$$

one obtains a value of 8.2 counts per minute. This is in good agreement with the other value given above. Similar analysis on the electroscope by the second method yields an expected deviation of 2.6 ions $cm^{-3}sec^{-1}atm^{-1}$.

Due to the nature of the curves and for simplicity, an attempt was made to fit the experimental data by a series of straight lines. As an example of the procedure used, a detailed account of the analysis given Flight No. 1 is presented.

3) <u>X^2 Test of Flight No. 1</u>

Figure 20 shows a plot of the experimental points for the counter telescope on a greatly enlarged scale. Also shown are the three combinations of straight lines which were chosen to be analyzed. These consist of:

A. Single straight line.

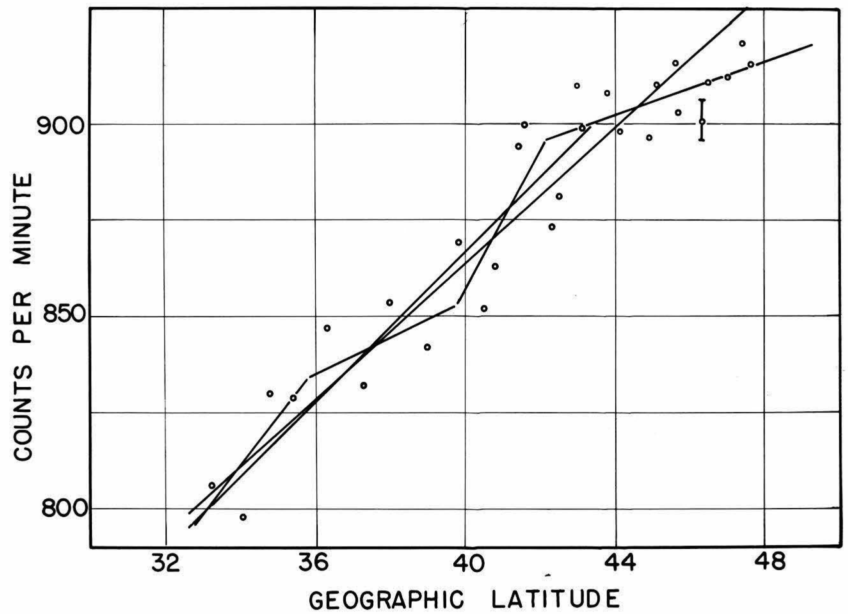


Fig. 20. A detailed plot of the experimental points of the vertical intensity measured on Flight No. 1. The straight line fit to these points are shown (see text).

B. Two straight lines.

C. Four straight lines.

A first fit of these curves was obtained by the method of first plotting the average of three adjacent points at its average position. This method of first approximation reduces the scatter of the points and as long as the curve is fairly smooth, does not hide any effects. The straight lines were then fitted by trial and error to a least square fit. Since there are thirty points, the degrees of freedom are 29, 27, and 25 and X^2 was computed to be 54.8, 43.5 and 40.0 respectively. Using the table of Fisher, the probability P was found to be, (A) 0.001, (B) 0.01, and (C) 0.015. Recalling that Fisher stated that any values of P below 0.02 were definitely open to doubt, it appears that the solutions tried did not follow any acceptable normal distribution. Fortunately, this is the only flight in which this dilemma was encountered and there appears to be no acceptable explanation to offer. If more than four straight lines were used to attempt a fit, the degrees of freedom decrease so as to lessen the probability P still further.

Figure No. 21 for the ionization data on the same flight is perhaps a better example in that values of P of 0.27 and 0.21 were obtained for the series of four and two straight lines respectively. Thus, according to Fisher, there is a satisfactory fit to the experimental points by either of the two curves, although the four line fit has a higher probability of being correct.

4) Results of X^2 Test

A summary of the results of each of the flights is as follows:

Flight No. 1 could be fitted by either two or four connected straight lines with approximately equal probabilities of being correct for

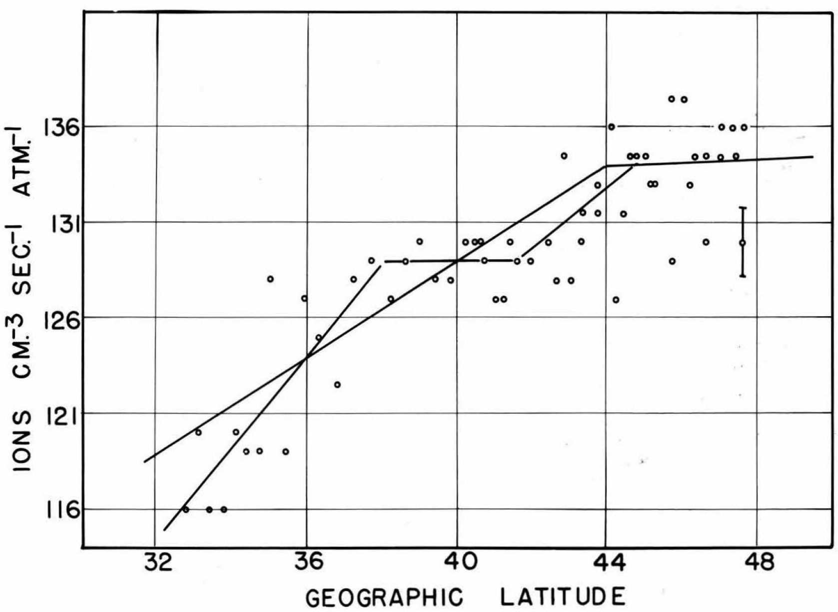


Fig. 21. A detailed plot of the experimental points of the ionization density measured on Flight No. 1. The straight line fits to these points are shown (see text).

both the electroscope and counter data. However, the probabilities in the case of the counter data were considerably lower than that of corresponding probabilities obtained on other flights. In other words, if one is to fit the counter data by straight lines, the scatter in the points is more than one is led to expect statistically. Fortunately, this is the only case in which this occurred.

Flight No. 2 was, in both cases, fitted very well by two straight lines.

Flight No. 3 could be fitted, in both cases, with almost equal probabilities of being the correct fit, by either two straight lines or a single straight line.

Flight No. 4 was, in both cases, fitted very well by two straight lines.

Flight No. 5 was, in both cases, fitted reasonably well by two straight lines, though the electroscope data going North seemed to differ considerably from corresponding readings going South. The exact reason for this is not known, the average of the two being taken to represent this flight. The data on this flight were normalized to 33,000 feet from 30,500 feet by previous data.

Flight No. 6 was fitted reasonably well by two straight lines for the counter data. No electroscope data were taken for this or the remaining flights.

Flight No. 7 was a short flight and accordingly yielded nothing of interest.

Flight No. 8 was discarded as unreliable, as only one telescope was operated at any time and that was found to have a bad counter after the flight.

Thus, in order to obtain a consistency among the different flights, it was decided that the two straight line fits would be used to represent

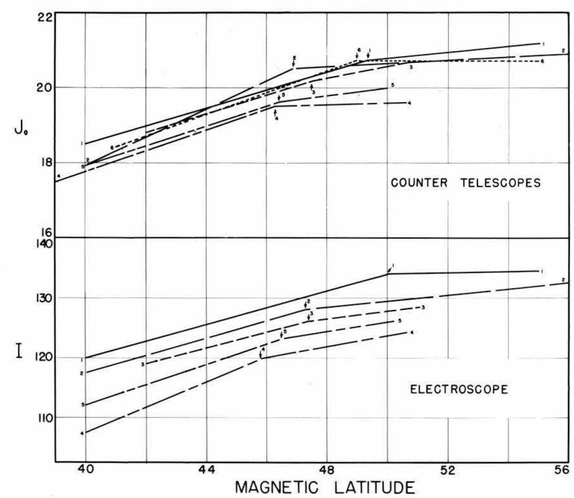


Fig. 22. Best fit curves obtained from the data presented in Figures 18 and 19. Counter data have been corrected for dead time and accidentals and changed to the units of ionizing particles per square centimeter per steradian per minute (J_o). Electroscope data are given in units of ions per cubic centimeter per second per atmosphere (I_o).

each flight. This is shown in Figure 22, where the geographic latitude has been replaced by geomagnetic latitude and the counting rates have been corrected for dead time and accidentals, and converted to ionizing particles per square centimeter per steradian per minute. By choosing this set, it can be seen that a fair degree of consistency is obtained between the counter data and corresponding electroscope data.

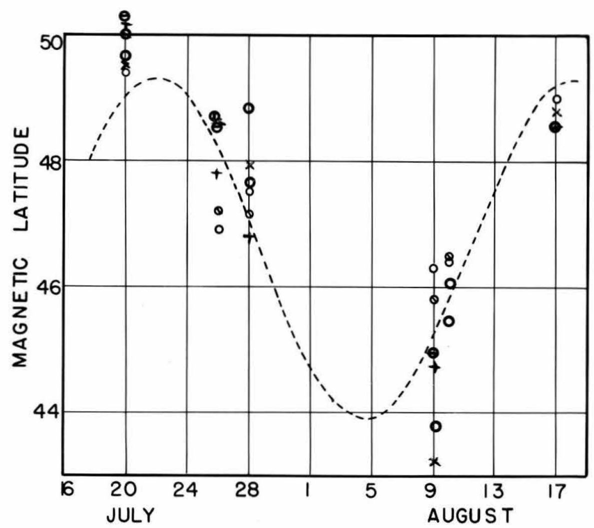
The conclusion therefore reached is that there is no reason to believe that the experimental data warrants the drawing of the curves with plateaus as was done in Figures 18 and 19.

5) Discussion of Results

A close examination and comparison of the curves given in Figure 22 shows a general tendency of the two measurements to vary in a definite manner. For example, it is noticed that Flight 1 in both the counter and electroscope data has the break in the straight lines farther north than any of the other flights. Similarly, it also is the highest of the curves given. In order to emphasize this tendency, Figure 23 is presented. This figure shows the relative differences between the curves for the different parameters as a function of the time of the flight. These parameters are, (1) magnetic latitude of the breaks in the curves, (2) amplitude at 42° N, and (3) 50° N magnetic latitude. It can be seen that there is a tendency of the points plotted to follow a general pattern. Though there is no reason to expect a periodicity from this data, a sine wave has been plotted through the points. Further discussion of this curve will be given later.

V. The Differential Numbers Spectrum

It is a well known fact[23] that the latitude effect combined with



<u>Fig. 23</u>.

○	- Counter data	-	Latitude variation of knee
⊘	- Ionization data	-	" " " "
⊖	- Counter data	-	Intensity variation at 42° N
⦶	- Ionization data	-	" " " "
×	- Counter data	-	" " " 50° N
+	- Ionization data	-	" " " "

Points showing the general behavior of the curves given in Figure 22 as a function of time. The open and crossed circles are for the variation in latitude of the knee of the latitude curve. The scale is given to the left. The other points show the relative variations of intensity at 42° and 50° North magnetic latitude between the different flights. These are plotted to an arbitrary scale.

the analysis of a charged particle in the field of a magnetic dipole[12] may be used to find a measure of the differential numbers spectrum[24]. In order to obtain an exact solution of this spectrum for the primary cosmic ray particles, it is necessary to know the following:

1) The latitude effect outside the earth's atmosphere instead of at a depth of 2.70 meters of water equivalent, (2) the nature of the incident particles, and (3) the exact solution to the motion of charged particles in the earth's magnetic field. As none of the above are known to any great degree of certainty, a modification of the above was performed by making certain assumptions.

Vallarta[12] has recently published a partial solution to the problem of the motion of charged particles in the field of a magnetic dipole. For both high and low latitudes the least momentum, p, that a singly charged particle must have in order to penetrate through the earth's magnetic field in the vertical direction at the geomagnetic latitude λ is fairly well determined. This momentum is determined by the simple shadow cone for high latitudes and by the Störmer cone for low latitudes. For the intermediate latitudes, the exact solution is not well known, but by the theory of the main cone[25] at least an upper limit for the momentum necessary for vertical entry is obtained. The region between these two solutions known as the region of penumbra is then an unknown region where only certain momentum between the two limits are allowed. Fortunately, the data on these flights were all taken at fairly northern latitudes where the simple shadow cone theory should apply quite well. Thus, if we assume the particles are positive, singly charged, and that the simple shadow cone theory applies for the region under consideration, then the momentum for first vertical entry is very nearly given by[23]

$$p = 15 \cos^4 \lambda \qquad (Bev/c) \tag{8}$$

This analytic expression checks to within better than a percent or two the curves given by Vallarta for the region of latitudes under consideration. Equation (8) is plotted in Figure 24, as is its derivative with respect to latitude.

Now let us define J_o to be the vertical intensity in units of particles steradian^{-1} cm^{-2} min^{-1}, where this is the intensity measured by a cosmic ray telescope and is a function of latitude λ, atmospheric depth h, and path length through the atmosphere ℓ. Then if j(p) is the intensity of primary cosmic rays outside the atmosphere, we may write

$$\frac{\partial J_o}{\partial p} = K(p,h,\ell)\,\frac{\partial j(p)}{\partial p} \tag{9}$$

where K(p,h,ℓ) is the multiplicity factor*, i.e., it is the gross, over-all, average ratio of the change in the number of particles at some atmospheric depth to the corresponding change in the number of primary particles that would occur for a differential change of the limiting momentum of entry, and $\frac{\partial j(p)}{\partial p}$ is the differential numbers spectrum of the primary radiation which is usually taken to be proportional to $p^{-2.5}$ (24). From (9) we see that

$$\frac{\frac{\partial J_o}{\partial \lambda}}{\frac{\partial p}{\partial \lambda}} = K(p,h,\ell)\,\frac{\partial j(p)}{\partial p} \tag{10}$$

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* The multiplicity factor may be defined in a variety of ways. Some authors define it by the expression

$$J_o = \int_{p_o}^{\infty} K(p,h,\ell)\, j(p)\, dp$$

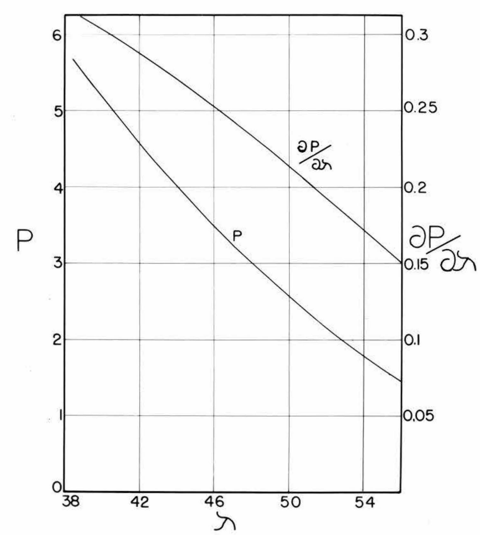

Fig. 24. Curve showing latitude of first vertical entry of singly charged particles of momentum p (Bev/c) as well as the derivative of this curve with respect to latitude in units of p per degree latitude.

where

$$\frac{\partial P}{\partial \lambda} = -60 \cos^3 \lambda \sin \lambda \tag{11}$$

which is plotted in Figure 24.

Figure 25 gives the average value of J_o and $\frac{\partial J_o}{\partial \lambda}$ as obtained from the six flights. It is noticed, first of all, that since we are primarily interested in $\frac{\partial J_o}{\partial \lambda}$, in this type of analysis the results depend upon the absolute value of J_o only to second order effects. This should be mentioned as J_o has not been corrected for side showers, this correction amounting to about 10%.

Another fact that should be noted is that though from the statistical analysis of the curves given in Figure 22 the slopes are always finite, $\frac{\partial J_o}{\partial \lambda}$ in Figure 25 is zero north of 53° N. This has been drawn this way because it was not possible to determine from the small amount of data available at the most northern latitudes if the counting rates did keep rising. However, excellent data on this subject was obtained on Flight No. 5 of the Peru trip (Part II, Figure 18) when a flight was made all the way up to 64° N. Though this flight was made at 30,000 feet instead of 33,000 feet as the other flights, this difference should not play an important role in the conclusions drawn. On this flight, the rise was less than ½% for the 10 degrees above 54° N. Thus, it was concluded that $\frac{\partial J_o}{\partial \lambda}$ should be zero, north of somewhere around 53 or 54° N. An extrapolation of the well determined points further up on the curve gave the zero intercept.

The results of dividing the curve of Figure 25 by that of Figure 24 in compliance with (10) yields the result given in Figure 26. This shows the product of the differential numbers spectrum of the primary particles

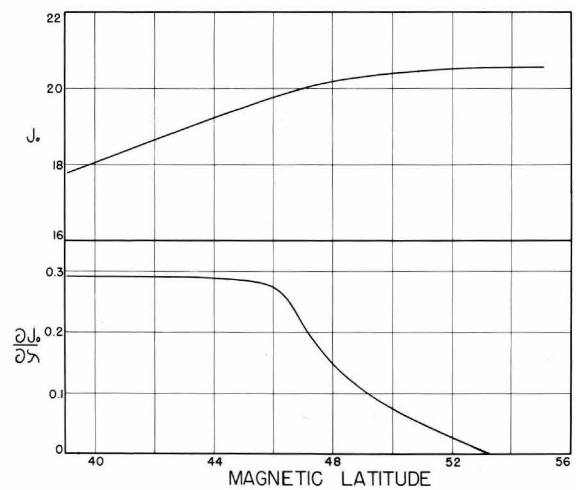

Fig. 25. The average of the counter data for the first six flights is shown as well as its derivative with respect to latitude in units of J_o per degree of latitude.

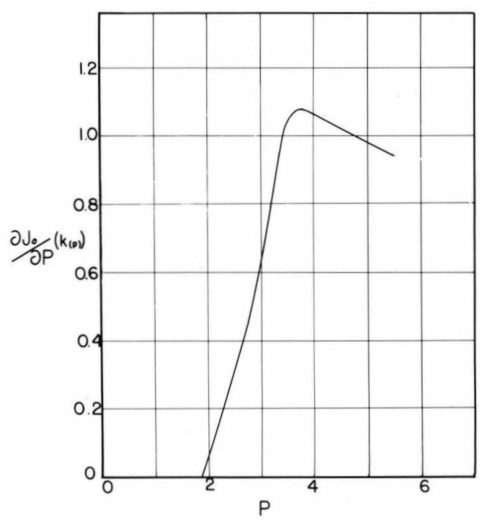

Fig. 26. The differential numbers spectrum times the multiplicity k(p) at 33,000 feet as plotted from the data of Figure 24 and 25.

$\frac{\partial j}{\partial p}$ and the multiplicity factor K(p) for the altitudes at which the flights were flown. An interesting feature of this curve is the way the curve falls off rapidly for momentum below 3.5 Bev/c and reaches zero at about 2 Bev/c. Since the curve is a product of two functions, either one, or both might be the cause for the product going to zero.

If the primary incident particles were protons(26), and one knew the processes by which the atmospheric secondary radiation was produced, an attempt might be made to see if any of the effects of 1.5 Bev protons could be detected at 33,000 feet. It is known though, that if losses to the incident protons were only ionization losses, protons with energies less than 1 Bev could certainly penetrate the atmosphere down to 33,000 feet. However, the processes taking place at the top of the atmosphere rapidly filter out the incident protons, as very few(24) are found at altitudes of 30,000 feet. Thus, one would expect the original energy of the proton to be divided among many particles which would then be able to dissipate this energy more rapidly by ionization than the single proton could have done by itself. Reasoning along the same line by a different approach, one may arrive at the same result. That is, if there were latitude effects at higher altitudes, one would expect the only reason they did not occur at the flight altitude was that the particles were absorbed in the atmosphere before they reach the deeper depths. This is indeed the case as born out by the data of Millikan et al.,(10) where a continual increase was measured with the ionization chamber as they proceeded north, i.e., they observed no northern plateau at very high altitudes.

The conclusion is therefore drawn that the reason the curve given in Figure 26 goes to zero at less than 2 Bev/c momentum is the multiplicity K(p) is zero for a depth of atmosphere of 270 g cm^{-2} (33,000 feet).

VI. Discussion of Solar Cut-Off

Janossy postulated in 1937[28] that a plateau in the latitude curve in the far northern region could be explained by the permanent magnetic field of the sun preventing particles below a certain minimum momentum from reaching the earth. Although it has been stated previously, that the plateau obtained in the latitude curves for this series of flights is believed to be due to the low energy protons not having any measurable effect at the altitude of the flights, a consideration of the effects of the sun's cut-off will be presented for completeness. It is to be emphasized that this type of analysis holds only if the conclusions reached above, about the reason for plateau, are false. Besides this objection, there are at least two others that may be raised which warrant serious consideration.

1) The first of these concerns the nature of the origin of the cosmic radiation and its distribution in interstellar space. Briefly, this analysis probably will not hold unless the cosmic radiation approaches the sun (and the earth) isotropically[25]. This assumption has recently been questioned by new theories of the origin of cosmic radiation by Alfven[28], Fermi[29], and Teller[30].

2) Another objection to the consideration of a solar cut-off is the question of whether or not the sun even has a permanent magnetic field[31]. Although much time and effort has been spent on attempting direct measurements by the Zeeman effect, the present conclusion, to the knowledge of the author, is that there is no evidence of the sun having a permanent magnetic field[32].

Regardless of these possible serious objections, if one does assume, that (1) the sun has a permanent dipole magnetic field, (2) the cosmic radiation approaches the sun isotropically, and (3) the plateau in the latitude curve is due to the solar cut-off, then an analysis may be made. Using the method of Epstein[33] and performing only a first approximation, it can be shown that the fraction of the number of particles that will be able to reach the earth is

$$f = \frac{1}{2}\left[1 - 0.2275\left(\frac{H}{pc}\right) + 0.953\left(\frac{H}{pc}\right)^{\frac{1}{2}}\right] \qquad (11)$$

for the dipole moment of the sun perpendicular to the plane of the ecliptic. H is the polar magnetic field of the sun in gauss and p is the particle momentum in Bev/c. This has been plotted in Figure 27 for various values of H and it can be seen that for a polar field of 50 gauss, no particles with less than 2 Bev/c momentum could reach the earth. This is in fair agreement with possible values of polar fields that have been measured by direct methods, but have since been severely criticized and rejected[32].

VII. Time Variations

Returning again to the subject of time variations, an interesting explanation for the variations found (Figure 23) may be given. Vallarta and Godart[34] have shown theoretically that the sun can produce a variation of cosmic ray intensity with a period of 27 days. If the solar magnetic dipole does not coincide with the solar axis of rotation, the solar magnetic latitude of the earth must change with a period equal to the period of rotation of the sun, which is 27 days. It is for this reason that the dotted curve with a periodicity of 27 days has been placed on Figure 23. Although other experimenters[35] have found a variation in

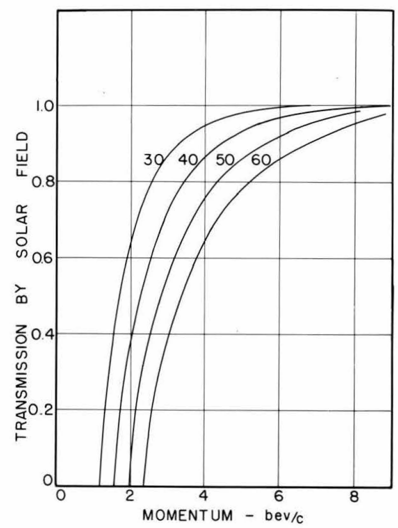

Fig. 27. The fraction of the singly charged particles of momentum p which would reach the earth is plotted for various polar magnetic fields of the sun.

intensity with a period of 27 days, this is the first evidence of a change in the position of the knee of the latitude curve with this same period. This is not strange, however, but is rather to be expected. This may be easily understood by again considering the solar cut-off curves (Figure 27) and imagining these to be shifted back and forth as the earth effectively moves back and forth over a range of the sun's latitude about the sun's magnetic equator. If the eccentricity of the sun's dipole moment were known (if the sun has a magnetic dipole field) a possible comparison as to amplitude of the variation might be made. The calculations necessary for this have been done by Vallarta[34] by using a superposition of the sun's field on that of the earth. Since none of these factors are known to any definite degree, only an order of magnitude calculation will be made.

One other fact that should be noted is that the sun's rotational equator is inclined to the plane of the ecliptic by 7°. This inclination is such that early in September the axis is pointing in the direction of the earth. Consequently, during the first part of June (and December) the earth passes through the equatorial plane of the sun. At this time, the apparent motion of the earth is symmetric about the sun's magnetic equator. This will give the smallest amplitude for the shift of the knee of the latitude curve[12,34]. In the first part of September (and March) the maximum shift will occur as the apparent motion of the earth will be about the 7° North (or South) magnetic latitude of the sun.

If we assume (1) the sun's polar field is 50 gauss, and (2) the eccentricity of the sun's dipole to be 6°, then we may compute the amplitude to expect for the change in the knee of the curve. Using Vallarta's curves[12] for momentum of first entry and a scale change, it is found that the change in momentum of first entry amounts to about 0.05 Bev in June and 0.15 Bev in September. This corresponds (Figure 24) to a change in latitude of about $\frac{1}{4}^{\circ}$ and $3/4^{\circ}$ respectively.

The flights took place in July and August or about midway between the time of minimum and maximum effect. Comparison with the observed amplitude of 3° (Figure 23) is not entirely satisfactory. However, so many of the variables are open to question that it is hard to venture an intelligent explanation as to which of the assumptions is not valid.

It might be thought possible to check the phase of the sun against the phase of the cosmic ray variations. This is exceedingly difficult as the position of the dipole pole of the sun was only thought to be known at certain times and an extrapolation to the actual time of the flights is very poor. This is because different portions of the sun rotate at different rates. The period of rotation of 27 days is nearly a mean for the mid-latitudes of the sun[36].

VIII. Conclusions

From the data presented and analyses performed, the following conclusions are drawn: (1) There is no reason to expect that the latitude effects measured exhibit the plateau characteristics that one might assume at a casual inspection of the experimental points. (2) There is a general pattern to the time variations of the various flights. This shows up in both the intensity and in the shift of the knee of the latitude curve. A possible explanation for this is the eccentricity of the magnetic dipole moment of the sun in which case a 27 day variation fits the experimental data quite well. (3) The reason for the northern plateau which occurs at about 53° N magnetic latitude at 33,000 feet is due to the primary particles of momentum below 2 Bev/c not having any effect down at 33,000 feet. (4) If the last conclusion is not true, which is highly unlikely, then the northern plateau can be explained as the cut-off due to the sun's magnetic field. This would place the value of the polar field at the surface of the sun at about 50 gauss.

Appendix I

A New Cosmic-Ray Telescope for High Altitudes

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A cosmic-ray telescope is described having an angular resolution of approximately ±15°. The distance between the two outermost trays, each containing 8 Geiger counters, is 1 meter. The area of each tray is approximately 24×24 cm². Triple coincidences modulate a transmitter and the signals, including those giving the air pressure and temperature of the instrument, are recorded on the ground. The counting rate is such that at the peak of the curve the relative probable error during a 4 minute interval is about 1.5 percent.

Accidental counts are found to be nearly negligible at all altitudes and latitudes, but some correction needs to be made for loss in efficiency because of the inherent dead time of the counters. An absolute determination of cosmic-ray intensity at the vertical at Pasadena was made in order to express the results as nearly as possible independently of the apparatus used.

I. INTRODUCTION

The cosmic-ray instrument used by Millikan, Neher, and Pickering[1–3] from 1939–1942 in their exploratory work on the variation with latitude of cosmic rays coming in near the vertical, suffered from the major defect of collecting the radiation from too large an angle. With the counters then used, the choice had to be made between a small solid angle giving a low rate of counting or a larger solid angle giving a higher counting rate with its smaller statistical error. The extreme solid angle used was 45° in one direction from the vertical by 25° in the other. The counting rate at the maximum of the curves taken in the United States was such that over a period of four minutes the probable error was about ±1 percent.

In redesigning the equipment it was thought desirable to keep the counting rate at least as high as in the previous equipment, and to reduce the angle of collection to something like 15° on all sides of the vertical. To accomplish this, required sensitive counter areas of approximately 600 cm², in the shapes of squares, with a separation between outside areas of about 1 meter.

To achieve the above with an instrument of a minimum weight and at the same time to have the required degree of accuracy and reliability was the problem we set for ourselves.

II. GENERAL DISCUSSION OF REQUIREMENTS

1. Weight

In planning an extended series of flights in regions where winds must be contended with, it is very desirable to keep the number of balloons to a minimum. Two balloons can be handled nearly as easily as one, and their use means that after one bursts, the other will remain to lower the instrument back to earth and serve as a temporary marker, thus facilitating recovery. Two good, 2000-g balloons, which are the largest commercially available at the present time, will lift a load of 8 kg to about 85,000 ft., which for our purpose was sufficiently high. It was therefore desirable to keep the total load, including 1800 cm² of counter area, batteries, amplifiers, transmitter, wrapping, and a suitable framework, down to at least this figure.

2. Accidentals

The counting rate for a single counter could be estimated approximately from previous flights with electroscopes[4, 5] and counters.[1] With the size of counter and counter area used, 2200 counts per second per tray were expected as a

[1] H. V. Neher and W. H. Pickering, Phys. Rev. 61, 407 1942).
[2] H. V. Neher and W. H. Pickering, Rev. Sci. Inst. 13, 143 (1942).
[3] W. H. Pickering, Rev. Sci. Inst. 14, 171 (1943).
[4] I. S. Bowen, R. A. Millikan, and H. V. Neher, Phys. Rev. 53, 855 (1938).
[5] Robert A. Millikan and H. V. Neher, Proc. Am. Phil. Soc. 83, 409 (1940).

maximum. To keep the number of accidentals to less than 1 percent, it was necessary to have a resolving time of about 2×10^{-6} sec., even though triple coincidences were used.

3. Efficiency

Loss in efficiency may be caused by at least two factors. (a) Failure of a counter to respond to the passage of an ionizing particle at low counting rates. (b) A similar failure at high counting rates. The first may occur when a particle passes near the edge of a counter when the product of path length and the pressure of the gas is such that there is some chance of not producing at least one ion pair. The second will occur because of the fact that the counter is dead for a short time after a discharge occurs.[6] This dead time varies somewhat with the gas pressure, the geometry of the counter, and applied potential but is from 1 to 2×10^{-4} sec. for the average counter.

For a single counter, if τ_0 is the dead time and N ionizing particles per unit time on the average pass through the counter, the relative number missed will be $N\tau_0$ and the efficiency, ϵ, will be $(1-N\tau_0)$.

Since the over-all efficiency of an n-fold coincidence set is ϵ^n, if the counters are all similar and counting at the same rate, it is desirable to keep n as small as possible consistent with accidentals and other requirements.

4. Power Supply for Counters

In the Geiger counter apparatus used by Millikan, Neher, and Pickering[1,2] for balloon

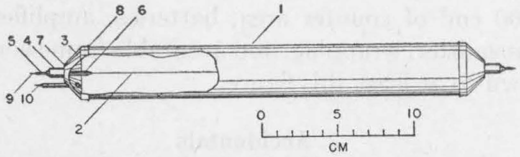

FIG. 1. Light weight Geiger counter: 1. Metal cylinder is formed from copper plated sheet steel, 0.025-cm thick. The joint is a locked seam that is silver soldered together simultaneously with 7 and 8; 2. tungsten wire, 0.0025 cm in diameter; 3. copper plated steel caps; 4. Kovar eyelet containing glass bead; 5. small Kovar tubing; 6. glass covering to Kovar tubing; 7, 8. silver soldered joints; 9. pinched when wire is taut, then silver soldered; 10. tubulation. Copper tubing is pinched to a feather edge to seal. Weight of completed counter, 90 g; sensitive area, 80 cm².

[6] H. G. Stever, Phys. Rev. 61, 38 (1942).

work a light weight, high voltage supply employing a buzzer, transformer, and rectifier was used. Such a supply was found to be impractical for the present work because of the high current demands of 24 counters each counting at a maximum rate of 250 sec.$^{-1}$ The current drain at this counting rate was about 25×10^{-6} ampere for this number of counters—a current drain much too large for the high voltage supply used previously.

The development of light weight dry cells has now made it possible to use batteries with a cost in weight of about 1.6 g per volt. The use of such batteries has the very great advantage that the potential on the counters is maintained constant throughout the flight.

5. Mounting

It is highly desirable from every point of view so to mount the components that are to be carried aloft that on landing a minimum of damage will be done. In the series of flights reported in the following article the returned instruments could usually be connected to the proper power supplies, and they would immediately start to count at a rate in close agreement with that before being sent up.

6. Temperature

In the previous flights a double covering of Cellophane and black paper provided a sufficient equilibrium between heat gained from sunlight and heat lost that during a flight the temperature of the instrument varied less than ±5°C. On these flights, presumably because of the much larger ratio of surface to mass, the temperature range was usually about ±10° from that at take-off. Such small variations in temperature guarantee nearly laboratory conditions during the course of the flight.

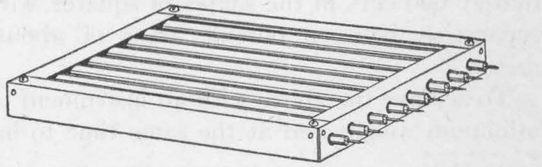

FIG. 2. Eight counters were mounted rigidly in a framework to form a sensitive area of 600 cm². Three of these trays were used to count triple coincidences. The weight of each tray was 850 g.

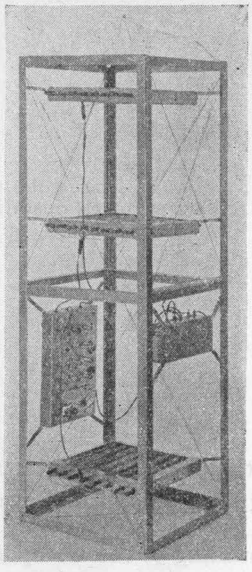

FIG. 3. The components were shock mounted in an aluminum framework. The weight of the whole assembly including 1800 cm² of counter area was 8 kg.

7. Pressure of the Air

An aeroid barometer measured the change in pressure relative to the pressure at ground level at take-off. A more satisfactory instrument for low pressures would be one that measured pressures with respect to a good vacuum. In the flights made with this equipment the errors in the determination of the air pressure were often larger than the uncertainty in the cosmic-ray intensity.

III. DESCRIPTION OF THE APPARATUS

1. Counters

From considerations of weight, ruggedness, and ease of construction it was decided to use metal-walled counters. It was found that sheet steel with a wall thickness of 0.025 cm was sufficient, when bent into the form of a cylinder 3.3 cm in diameter and the seam locked, to withstand atmospheric pressure even when baked at 300° to 400°C. When the steel is copper plated the whole may be silver soldered together in a hydrogen atmosphere.

The small metal tube through the glass beads at the ends permitted a tungsten wire of any desired size to be threaded through after the silver soldering was completed. Actually a tungsten wire 0.0025 cm in diameter was used. While the wire was taut the ends of the small metal tubes were pinched shut and then dipped into molten silver solder.

The tubulation for evacuating and filling with the desired gases was copper tubing. It was found possible to seal this by pinching it to a feather edge with a properly constructed tool.

The techniques used in the construction of the counters at all times maintained a clean, copper surface inside free from oxides or other contamination. All heating was done in hydrogen or in the presence of other reducing gases so that no liquids at any time were introduced.*

A group of 36 of these counters was silver soldered to a metal manifold and baked at a temperature of about 300°C for half an hour while a good vacuum, using diffusion pumps, was maintained. This was considered sufficient to drive most of the gases, especially oxygen, from the walls.

When cold, the counters were filled, first to a pressure of about 1 cm of Hg with the complex hydrocarbons of the commercial organic liquid called petroleum ether, then 99.8 percent pure argon was introduced to a pressure of 12 cm. A potential of 750 volts was applied to one of the counters of the group, and the total pressure reduced until the threshold occurred at this potential. The resultant pressures were about 0.6 cm of Hg of organic vapor and 6 or 7 cm of argon. This filling procedure has the advantage of exposing the freshly de-gassed copper surface first to the organic vapor. Since the adsorbed gases on the surfaces inside a counter play an important role in their behavior this order of filling seems desirable.

The counters in a given group prepared in the above manner had thresholds within about 10 volts out of 750 volts of each other. The lengths of the plateaus varied but were usually more than 250 volts.

In Fig. 1 is an isometric drawing showing the main features of the counters.

Of about 700 counters made, 600 passed initial tests satisfactorily. Some 25 percent of these were found to develop defects later, mostly because of leaks.

Eight of these counters were held rigidly in an

* A more detailed account of these techniques will be published elsewhere.

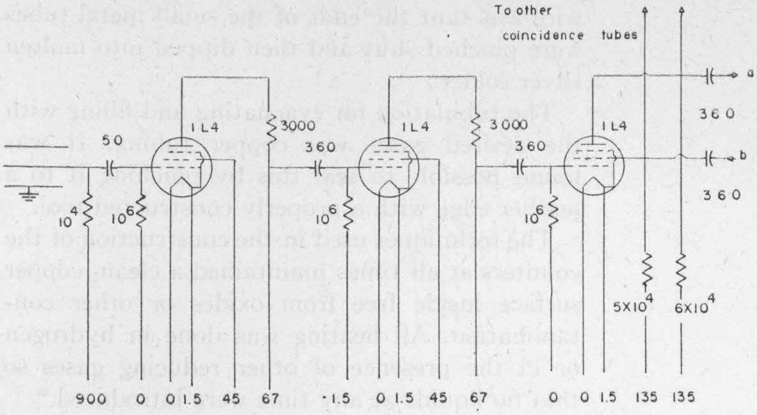

FIG. 4. One of the three amplifier channels operating into a coincidence tube.

aluminum framework as shown in Fig. 2. The counters in each tray were all connected in parallel to form a sensitive area of about 600 cm². The spacing between counter walls was held to a minimum. If the spacings between counters in their trays occurred at random with respect to the spacings in the other trays, then the effect on triple coincidences will be three times as great as the decrease in area of a single tray would indicate.

The total weight of each tray with its 8 counters was 850 grams. It is estimated that this is from $\frac{1}{2}$ to $\frac{1}{3}$ the minimum weight that could be achieved using glass walled counters of the same sensitive area.

2. Barometer and Thermometer

The barometer and thermometer units were the same as those used in former years.[7,8] This Olland method of modulating a transmitted radio signal is well adapted to the requirements necessary for transmitting pulses caused by cosmic rays. Methods of calibrating and the type of received signal are described in reference 8.

3. Mounting of the Components

An aluminum framework 120-cm high and 38-cm square was made up of 90° angle pieces, as shown in Fig. 3. The strength of the framework and bracing were such that when the instrument was returned to earth by one balloon the components were completely protected against injury. On at least one occasion when both balloons were observed to burst the instrument when returned had a bent frame but the vital parts were undamaged.

The counter trays, the common mounting for the amplifiers and barometer unit and the high voltage batteries were all shock mounted with springs.

4. The Circuits

Electronic circuits generally similar to those previously described were used with the sub-

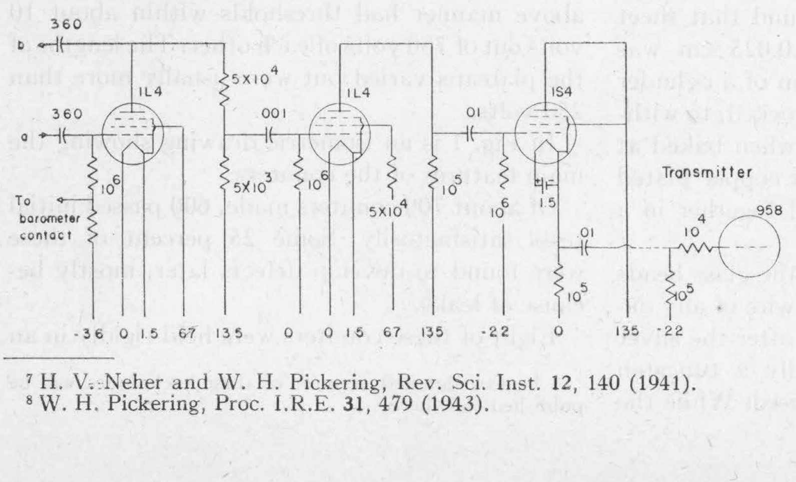

FIG. 5. Multivibrator and modulator unit for feeding transmitter tube.

[7] H. V. Neher and W. H. Pickering, Rev. Sci. Inst. 12, 140 (1941).
[8] W. H. Pickering, Proc. I.R.E. 31, 479 (1943).

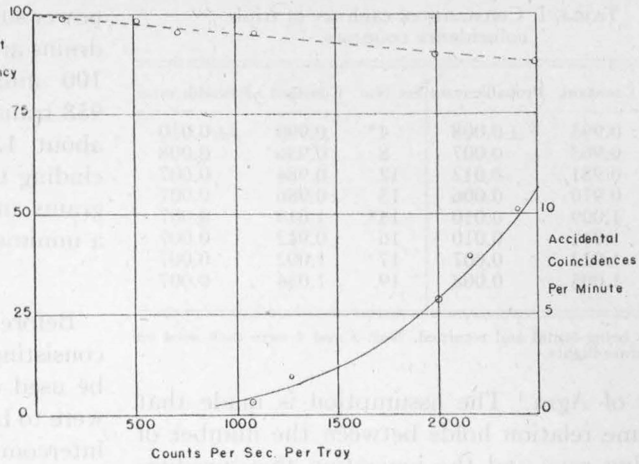

FIG. 6. Lower curve shows the rate for accidental triple coincidences as a function of the total counting rate of each tray. Upper curve shows the efficiency for real coincidences for the same total counting rates.

stitution of miniature tubes and the change from twofold to threefold coincidences. Figure 4 shows one of the three channels consisting of two resistance coupled amplifier stages followed by a coincidence tube in the normal Rossi arrangement. To obtain a pulse sufficiently large to operate the coincidence tubes and at the same time sufficiently short to reduce accidentals to a negligible value, two stages of amplification were used. This also gives the correct polarity of pulse. The voltage gain of the amplifier was 3 or 4, the output pulse was about 2 microseconds long, and the limiting action resulted in an output pulse nearly uniform in size for a variation of a factor of 2 in size of the input pulse.

Figure 5 shows the remainder of the electronic circuit with the exception of the transmitter which is separately mounted. (Points marked with the letters *a* and *b* in Fig. 4 connect to the corresponding points of Fig. 5.) The output of the multivibrator stage following the coincidence tubes is fed through a phase inverting and isolating amplifier and then a cathode follower to the transmitter. The multivibrator pulse length is approximately 50 microseconds, and the recovery time about 200 microseconds so that no correction to the experimental counting rates of less than 1000 per minute need be made for the resolving time of the multivibrator. The series resistance of 10,000 ohms in the transmitter grid circuit limits the peak plate current to approximately 20 milliamperes, at which current the maximum r-f power is obtained for the "*B*" voltage (135 volts) used.

The barometer and temperature signals were transmitted in the same manner as in the equipment used in 1941–42. The barometer unit with clock mechanism and bimetallic strip was mounted on rubber grommets at one end of the twelve tube chassis which contains all the electronic circuits exclusive of the transmitter. This unit weighed 650 grams, including the barometer unit. It was suspended on springs slung between two of the legs of the aluminum frame work cage (see Fig. 3).

The performance of the electronic circuits was investigated in detail with particular regard to the over-all efficiency and the accidental rate. To obtain the efficiency loss resulting from the "dead time" of the counters, measurements of coincidence counting rates were made for various total counting rates as controlled by the proximity and shielding of a thorium source. The accidentals were obtained with similar stimulation when the counter trays were arranged so that no one particle could traverse all three trays, a small correction being made for the constant background rate caused by showers. The rate of accidental counts was subtracted from the rate of real coincidences for a given total counting rate of each tray. The ratio of this rate to the rate attributable to real coincidences obtained at low total counting rates of each tray gives the efficiency. Figure 6 shows the curve of percentage efficiency *versus* total counting rate for a tray of eight counters.

The total counting rates to be encountered could be estimated from the data obtained with comparable electroscope and single counter

TABLE I. Constants of each set of triple coincidence counters.

Set No.	Constant	Probable error	Set No.	Constant	Probable error
1	0.995	±0.008	4*	0.990	±0.010
3	0.963	0.007	8	0.936	0.008
3*	0.981	0.012	12	0.984	0.007
3*	0.970	0.006	15	0.986	0.007
3*	1.009	0.010	15*	1.019	0.007
4	1.011	0.010	16	0.942	0.007
4*	1.022	0.007	17	1.002	0.007
4*	1.005	0.008	19	1.034	0.007

* After being found and returned. Nos. 3 and 4 were each used on four separate flights.

flights of Agra.[1] The assumption is made that the same relation holds between the number of incoming rays and the ionization they produce in an electroscope at high latitudes as that observed in India. Under this assumption the estimated total counting rates per tray would vary from 1080 $\sec.^{-1}$ at San Antonio to 2200 $\sec.^{-1}$ at Bismarck as a maximum.

The number of accidentals is given, in a triple coincidence arrangement, by $A_{123}=3\tau^2N_1N_2N_3$, where A_{123} is the number of accidental triple coincidences and N_1, N_2, N_3 are the respective counting rates of the individual trays of counters. The resolving time τ thus computed gave a value of approximately 2 microseconds. This result was checked by measuring accidental double coincidences. In Fig. 6 the theoretical curve of accidentals for a resolving time of 2 microseconds is shown, together with some experimental points. At the maximum counting rates met experimentally, the accidental rate is less than one percent of the real coincidences obtained, and at most counting rates it is negligible.

The stability of the electronic circuits was investigated with reference to changes in the parameters such as B voltage supplies, filament voltages, various bias voltages, and the circuit components. Stable operation was found to occur over large ranges of these variables.

The apparatus was physically designed so that gaseous discharges would not occur at high altitudes. Tests were made at pressures lower than the minimum to be expected and possible points of discharge were shielded or immersed in paraffin. It was also found necessary to cover the Geiger counter beads with pressure tight wax to prevent discharges over the glass.

Commercial dry batteries were used for the power supplies of the electronic circuits. Filament drains are 50 milliamperes for each 1L4 tube and 100 milliamperes each for the 1S4 and the 958 transmitting tube. The total "B" drain was about 12 milliamperes. The battery pack, excluding the Geiger counter supply, totalled 1400 grams and sufficed to operate the instrument for a minimum of four hours.

V. CALIBRATION

Before the flights started two complete sets consisting of selected counters were set aside to be used only for comparison with the sets that were to be sent up. These two standard sets were intercompared at frequent intervals. The calibrating procedure consisted in operating simultaneously three sets, usually consisting of one of the standards and two of the sets that were to be used. Triple coincidences were recorded. Care was taken to be sure that the roof overhead had low absorption and presented the same appearance to all three sets. Approximately 15,000 counts were used to find the constant by which the readings of the set being calibrated needed to be multiplied to reduce them to that of the standard. As an indication of the similarity of geometry the constants of the individual sets are given in Table I. The probable errors given include the statistical error in the counts recorded by the standard set.

The counting rates on the ground varied from about 22 per minute near sea level to 28 at the higher locations.

In calibrating, i.e., in comparing the sets to be flown with one of the other standard sets, the same high voltage batteries for the counters were used as were used on the flight. This was considered quite desirable, as it eliminated one uncertainty that was present in equipment used in past years. In fact, it was only necessary to substitute a prepared set of batteries to supply the power required by the amplifier tubes for

TABLE II. Determination of the absolute intensity of cosmic rays at the vertical in Pasadena.

	Total No. of counts	Mean barometric pressure	j^*
Ends protected	72,000	29.42 in. of Hg	0.727
Effective length determined	22,500	29.21	0.729

* j is the number of ionizing rays per unit solid angle $\min.^{-1}\ \mathrm{cm}^{-2}$ at the vertical in Pasadena. Elevation = 240 meters above sea level.

the power supply used in the calibration and transfer the connection from the mechanical recorder to the 2.0-meter wave-length transmitter and the set was ready for launching, except for wrapping.

To reduce the rates of the individual sets not only to a common basis but also to a value which had more of an absolute meaning, the counting rate out-of-doors at Pasadena was determined for a counter set of known solid angle and compared with the standard sets. The solid angle was determined by two methods which will be described in more detail elsewhere. Briefly, the first method consisted of covering the spaces between counters with other counters and then making a known length of the counters by placing another at right angles across the ends. This then determined the sensitive area completely except for small unknown regions at the corners. The other method consisted of measuring the effective length of the counters, as was done by Street and Woodward[9] and by Greisen and Nereson.[10] The results from the two methods are given in Table II.

[9] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).

[10] K. Greisen and Norris Nereson, Phys. Rev. **62**, 316 (1942).

The value of the number of ionizing particles per unit solid angle per minute per square cm, j, determined in this way agrees quite well with that of Greisen.[10,11] This value has not been corrected for side showers. Preliminary determinations of this effect indicates it introduces not more than a three percent error. The value of j needs no correction for accidentals or loss in efficiency as each correction at sea level was well within the experimental error.

Use of the Equipment

Twenty-five complete sets of the equipment described above were constructed, and twenty flights were made in the summer of 1947 at seven stations in the United States and Canada. The results of these flights are reported in the following article.

The authors wish to take this opportunity of thanking Professor R. A. Millikan for the aid and encouragement he has given this development. Also, we wish to thank Mr. Maurice Rattray for his assistance in making the apparatus. We gratefully acknowledge the financial assistance of the Carnegie Institution of Washington.

[11] Kenneth Greisen, Phys. Rev. **61**, 212 (1942).

Appendix II

Recent Studies of the Cosmic-Ray Latitude Effect at High Altitudes

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With an improved Geiger counter telescope, having an angular aperture of about ±15° from its axis, a series of balloon flights was made in August and September, 1947, at seven stations extending from San Antonio, Texas, to Saskatoon, Canada. The axis of the telescope in all cases was oriented in a vertical direction. All sets of equipment were compared with a standard to reduce all results to a common basis. The standard sets, in turn, were compared with an accurately constructed telescope which had been used to make an absolute determination of cosmic-ray intensity at the vertical in Pasadena.

Two flights were made from each of the seven stations. The agreement between flights made within a few hours of each other at a given station is very good. Results from two flights made at a given station several days apart are not in general as consistent. Likewise, no monotonic increase of the radiation with increase of latitude was observed. Evidence is presented for rather large fluctuations at high altitudes of the lower energy components of cosmic rays. Some of the reasons for these fluctuations are discussed.

I. INTRODUCTION

IN 1939–1940 Millikan, Neher, and Pickering made a series of balloon flights in India using Geiger counters in vertical double coincidence.[1,2] These flights were made at three different magnetic latitudes 3°, 17°, and 25°N. The significant results were that within the uncertainty of the measurements there was no change in the radiation coming in near the vertical from 3° to 17° while in going to 25°N there was an increase of 21 percent. This was interpreted as meaning that in the primary energy spectrum there were relatively few, if any, particles lying within the energy range from 17 down to 15 Bev. Likewise, the increase in going from 17° to 25° was interpreted as being due to primary charged particles in the energy range 15 down to 12.5 Bev.

To extend these measurements to other latitudes a series of similar observations was made in 1941–42 in Mexico and the United States.[3] Those in Mexico were made at Acapulco (Mag. lat. 25.6°N), Valles (Mag. lat. 31°N) and Victoria (Mag. lat. 33°N). It was found at that time that there was little if any increase in going north from 25.6° to 31°. This was again interpreted as due to a deficiency in the primary radiation in the energy range 10.3 to 8.6 Bev. At Victoria the radiation had definitely increased over its value at Valles, showing that the primary spectrum contained appreciable numbers of particles of energies in the range 8.6 to 7.5 Bev. Several flights at Pasadena showed a pronounced increase over the value obtained at Victoria and this was evidence that the primary spectrum contained particles lying between 7.5 and 5.8 Bev.

In extending the observations farther north, two stations, St. George, Utah, and Pocatello, Idaho, were chosen where one flight at each location was made in March, 1942. The results of these flights showed that within the rather large experimental uncertainties there was a marked increase of about 14 percent at the maximum of the curves in going from Pasadena to St. George, but no increase from St. George to Pocatello. This latter plateau was interpreted as meaning that there were no particles in the energy range from 4.4 to 2.9 Bev.

To check this apparent distribution of particles in the primary energy spectrum and to extend the observations as far north as seemed practical, a new series of flights has been made at seven stations extending from San Antonio, Texas to Saskatoon, Canada. These flights were made with improved equipment of higher resolving power and, in an attempt to minimize secular changes, the whole series was completed

[1] H. V. Neher and W. H. Pickering, Phys. Rev. 61, 407 (1942).
[2] R. A. Millikan, H. V. Neher, and W. H. Pickering, Phys. Rev. 61, 397 (1942).
[3] R. A. Millikan, H. V. Neher, and W. H. Pickering, Phys. Rev. 63, 234 (1943).

in a little under four weeks during August and September, 1947.

II. APPARATUS AND PROCEDURE

A detailed description of the apparatus used appears in the preceding paper of this journal. To summarize, a new type of light-weight, all-metal Geiger counter was used. Eight such counters connected in parallel were made into a tray and three trays were used in each telescope. The separation of the two outer trays was such that the telescope had an aperture of about 15° on all sides of its axis. This is to be compared with the apparatus previously used where the maximum angle from the zenith in one direction was 45° and 25° at right angles to this. The area of the trays of counters was made of such a size that the statistical errors in the counting rates were negligible in determining the maxima of the curves.

The triple coincidences were transmitted by radio to the ground where they were received, scaled down, and recorded on a moving tape. Temperature and pressure data were also transmitted and recorded on the same tape.

In choosing stations from which to send up our balloons we were governed by the availability of helium or hydrogen and by the desire to get a good representation of latitudes. The stations finally selected are given in Table I.

In the period August 27 to September 24, 1947, two successful flights were made at each of these stations except Saskatoon where one good flight was made and only a few good points were obtained around the maximum of the curve for the second flight. The stations were visited in the order given except for St. George. We had intended making flights from Oklahoma City, Oklahoma, but were prevented from doing so by high winds. On the return trip to Pasadena we made two flights from St. George to fill in this gap. The launchings were actually made from sites which were isolated, so that our receiver would not pick up ignition noise from passing cars, and which were located so that the equipment would land in settled territory and have a good chance of being returned to us. Of the 20 instruments sent up 17 have been returned. Of these, two were those released from St. George, Utah, and almost certainly came down in very rugged country. The average geomagnetic latitude during a flight is quite well represented by that of the stations given above, since the balloons did not drift far from an E-W line.

Before each flight the counter telescope to be flown was placed beside a standard set and the two permitted to count until the ratio between their counting rates had been determined to within 1 percent. After returning to Pasadena the standard set was compared with a carefully constructed telescope having a known geometry which had been used to make an absolute determination of the vertical counting rate out-of-doors in Pasadena. It was then possible to reduce all measurements to an absolute value. The counting rates during the flights were corrected for efficiency and accidentals.

Figure 1 illustrates some of the procedures in inflating the balloons and in launching the instrument. Dr. Millikan was a most valuable member of the expedition and took an active part in much of the preparation.

III. DATA

In Fig. 2 are presented the results of these experiments. The number of counts received per unit solid angle per square centimeter per minute from the vertical direction is plotted against the depth below the top of the atmosphere in meters of water equivalent. The number of counts will differ from the number of ionizing rays because of the effects of showers for which no corrections were made.

Counts were averaged over four minute intervals. For the exponentially changing rates encountered, calling this average the counting rate at the middle of the interval causes an error of a few tenths of a percent at the most. The probable error in the counting rate due to the finite number of counts recorded was about 1.5

TABLE I. Flight stations.

Station	Mag. lat.
San Antonio, Texas	38.5°N
Fort Worth, Texas	41.7
St. George, Utah	44.8
Omaha, Nebraska	51.3
Rapid City, South Dakota	53.3
Bismarck, North Dakota	56.0
Saskatoon, Canada	60.0

percent at the maximum of the curve for a four minute interval. Errors resulting from correcting for efficiency and accidentals should be less than 0.5 percent. Errors in reference to the standard should be about 1.0 percent.

In reducing the counting rates to an absolute value, it is assumed that side showers are relatively unimportant. If it is desired to find the number of ionizing particles coming in from the vertical per unit solid angle per cm^2 per minute, the effect of upward radiation and showers from the top must also be taken into account. However, since in this paper we are concerned mostly with relative values of flights at different stations, we will assume that over the range in energies here dealt with these effects are roughly proportional to the total radiation and, hence, will not affect appreciably the comparison of the different flights.

The pressure data on the whole are quite satisfactory in these experiments. However, much of the uncertainty in these flights can probably be traced to errors in the barometer. It seems quite likely that the reason for curve 7, Fig. 2, at Saskatoon crossing curve 5 at Rapid City at a pressure of about 0.1 atmosphere was a faulty barometer. Also curve 1 of Fig. 2 at San Antonio appears to be shifted to the right at the lower pressures when compared with the other curves. This may be due again to a faulty barometer.

An idea of the precision attained in these experiments can be obtained from Figs. 3 and 4. Here the experimental points for Bismarck and Rapid City are shown before they were corrected for accidentals and efficiency. It will be noted that the points for any one flight sharply define a curve for that particular flight. Furthermore, the two flights at either of these stations agree very closely. The curves after correction for efficiency and accidentals are also given in Figs. 3 and 4. The efficiency correction is about 7 percent at the maximum, the accidental correction less than 1 percent.

IV. DISCUSSION OF RESULTS

The most prominent features of the curves in Fig. 2 are: (1) the St. George curve is below that of Fort Worth, although St. George is 3° mag-

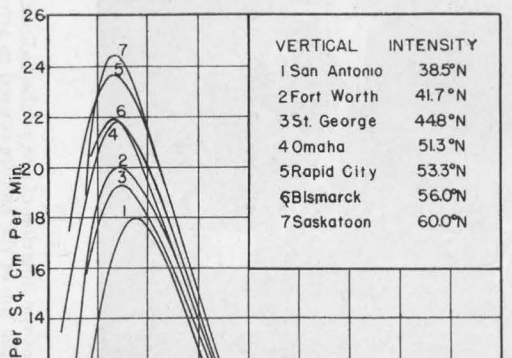


FIG. 2. Observed vertical intensity of the cosmic radiation as a function of pressure in meters of water, for indicated geomagnetic latitudes.

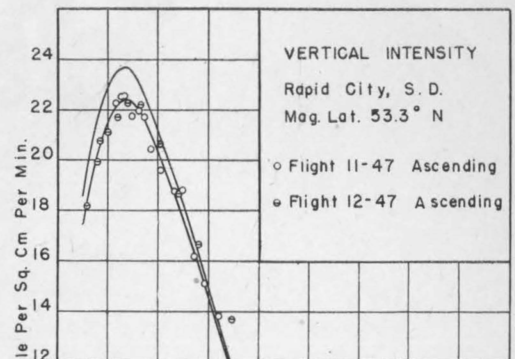
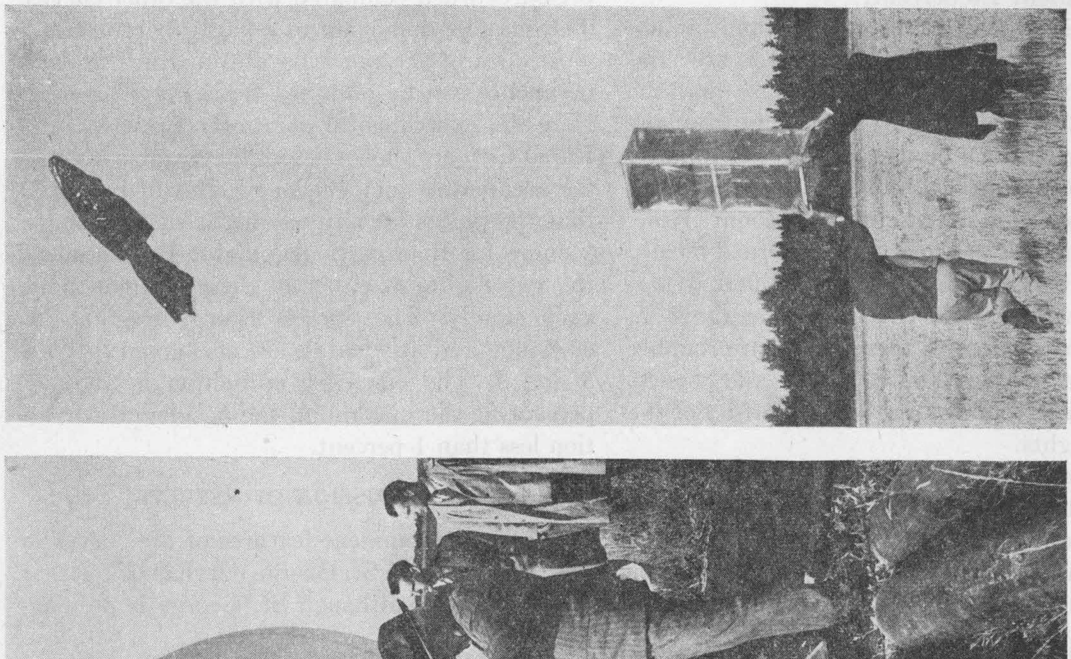


FIG. 3. Experimental data for Rapid City, S. D. The upper curve shows the result of correcting for accidentals and efficiency.



(a) (b)

FIG. 1. (a) Final stages of the inflation of one of the balloons. H. V. Neher and R. A. Millikan in foreground. (b) Releasing the instrument. The flag near the top of the picture is used to attract attention to the instrument after it returns to earth. The metal frame and cellophane wrapping completely enclose the counters, amplifiers, etc.

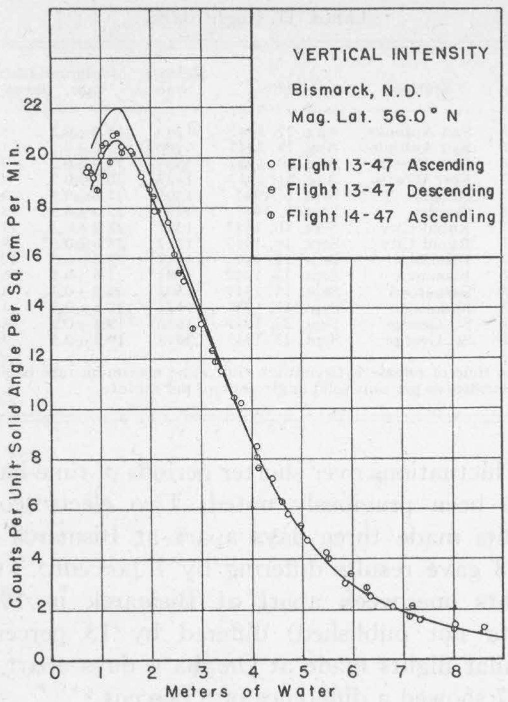


FIG. 4. Experimental data for Bismarck, N. D. The upper curve shows the result of correcting for accidentals and efficiency.

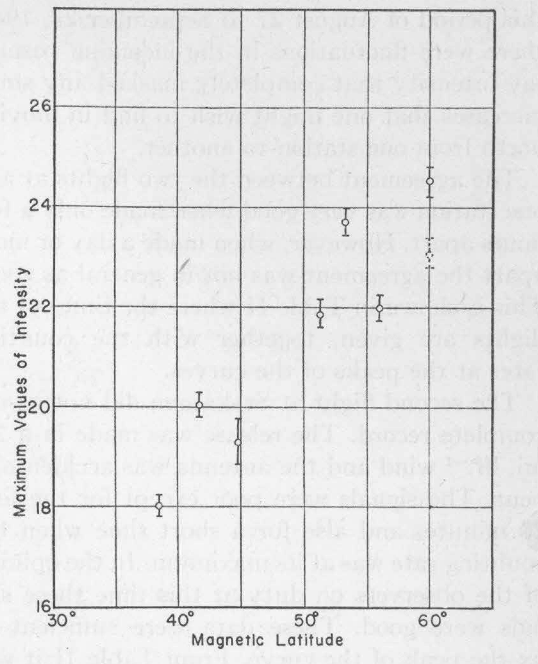


FIG. 5. Maximum vertical intensity as a function of latitude. The two flights at Saskatoon, lat. 60°N are shown separately. The lower point corresponded to a flight of questionable reliability.

netic latitude farther north, and (2) the Bismarck curve (56°N) is below that for Rapid City (53°N). Such a result appears to be in definite contradiction to the results of the analysis of the motion of charged particles in the magnetic field of a dipole. This analysis predicts that cosmic-ray intensity should be a non-decreasing function of magnetic latitude. Figure 5 shows the effect more clearly. There we have plotted the maximum counting rates against latitude. The indicated probable errors are estimated from the uncertainties of the counting rates, the calibration against the standard, and the uncertainty in the efficiency and accidental corrections.

We have chosen the maxima of the curves as a measure of the amount of radiation coming in instead of the areas under the curves since small uncertainties in barometric pressure will affect the differences in the areas quite markedly but will have no influence on the peaks.

The probable error given for St. George is larger than the others. This is caused by the fact that both of the standards were accidentally damaged before the calibrations were made at this station. One was damaged only slightly and was taken as the standard at this location. Checks indicate that if there were changes they were less than about 2 percent. This large probable error makes it possible to say that perhaps the counting rate simply did not increase between Ft. Worth and St. George, rather than that there was a decrease. However, we also note that the flights at St. George were made three weeks after those at Ft. Worth.

The decrease from Rapid City to Bismarck cannot, we believe, be explained as experimental error. In discussing the data we have pointed out the limits of accuracy. This decrease is well outside these limits. The constant checks on all apparatus make it very doubtful that it was out of order at any time either at Rapid City or Bismarck. At no time during any of the flights did we have occasion to think that any of the counters had failed. Reference to Table I of the preceeding article will show that several sets were used for more than one flight and when returned the calibration was always within a percent or two of that obtained before the flight.

The evidence from Fig. 5, then, is that during this period of August 27 to September 23, 1947, there were fluctuations in the incoming cosmic-ray intensity that completely masked any small increases that one might wish to find in moving north from one station to another.

The agreement between the two flights at any one station was very good when made only a few hours apart. However, when made a day or more apart the agreement was not in general as good. This is shown in Table II where the times of the flights are given, together with the counting rates at the peaks of the curves.

The second flight at Saskatoon did not give a complete record. The release was made in a 25-mi. hr.$^{-1}$ wind and the antenna was accidentally bent. The signals were poor except for the first 20 minutes and also for a short time when the counting rate was at its maximum. In the opinion of the observers on duty at this time these signals were good. These data were sufficient to fix the peak of the curve. From Table II it will be noticed that the value at the maximum for the second flight is 5.6 percent lower than the flight made two days earlier. Because of lack of data at other elevations this flight is not included in the Saskatoon curve of Fig. 1 and is shown dotted in Fig. 5.

Such fluctuations over longer periods of time are known from electroscope data taken with balloons in former years. In 1938 flights at Bismarck showed more radiation coming in than at Saskatoon the year before.[4] Also, the maximum value at Bismarck was 30 percent higher in 1940 than in 1938.[5] Smaller variations have been found at Omaha and even as far south as Oklahoma City. The maximum of the ionization curve was 14 percent higher at the time of measurement at the latter station in 1940 than in 1938.[5] However, at the two times flights have been made at San Antonio with electroscopes, 1936 and 1940, the same maximum values were found. These observations have been interpreted as time fluctuations of primary particles incident on our atmosphere in the lower energy range—the higher energy particles remaining essentially constant. (See reference 5).

[4] Robert A. Millikan and H. V. Neher, Proc. Am. Phil. Soc. **83**, 409 (1940).

[5] Robert A. Millikan, H. V. Neher, and William H. Pickering, Carnegie Inst. of Wash. Year Book, No. **43**, 56 (1943–44).

TABLE II. Flight data.

Flight	Station	Date	Release time	Maximum rate	Instrument No.
4-47	San Antonio	Aug. 27, 1947	1242	18.0±0.2	8
5-47	San Antonio	Aug. 28, 1947	1300	18.0±0.2	1
6-47	Fort Worth	Aug. 30, 1947	1537	19.9±0.2	3
7-47	Fort Worth	Aug. 31, 1947	1428	20.3±0.2	4
9-47	Omaha	Sept. 6, 1947	1205	21.6±0.3	4
10-47	Omaha	Sept. 8, 1947	1221	22.1±0.3	3
11-47	Rapid City	Sept. 10, 1947	1307	23.8±0.3	17
12-47	Rapid City	Sept. 10, 1947	1722	23.6±0.3	19
13-47	Bismarck	Sept. 12, 1947	1347	22.2±0.3	12
14-47	Bismarck	Sept. 12, 1947	1701	21.6±0.3	16
15-47	Saskatoon	Sept. 15, 1947	1301	24.5±0.3	4
18-47	Saskatoon	Sept. 17, 1947	1431	23.1±0.3	4
19-47	St. George	Sept. 23, 1947	1616	19.4±0.5	15
20-47	St. George	Sept. 23, 1947	2318	19.2±0.5	3

The time of release is Greenwich time. The maximum rate is given in coincidences per unit solid angle per cm² per minute.

Fluctuations over shorter periods of time have also been previously noted. Two electroscope flights made three days apart at Bismarck in 1938 gave results differing by 7 percent.[4] Two flights one week apart at Bismarck in 1946 (data not published) differed by 13 percent. Similar flights made at Omaha 4 days apart in 1937 showed a difference of 5 percent.[6]

In seeking a reason for these fluctuations we first investigated the behavior of the earth's magnetic field and the sun during this period. Through the kindness of Dr. S. B. Nicholson of the Mt. Wilson Observatory we were given access to the data taken at Mt. Wilson. While the records showed considerable activity of both the sun and earth during this time there were no magnetic storms on the earth and no flares on the sun of major importance. Sunspots were prominent, since the sun was near the peak of its 11-year sunspot cycle, but none were particularly large during this period. We conclude from this study that if activity of the sun or changes in the earth's field were responsible for the variations at the high altitudes observed they were much greater than the usual fluctuations found at sea level.

To study further the nature of these fluctuations we examined ground level records of cosmic-ray intensity as measured with an ionization chamber at Cheltenham, Maryland (50.1° N. mag.). (These data were made available through the courtesy of Dr. S. E. Forbush of the Carnegie Institution of Washington.) At the time of the

[6] I. S. Bowen, R. A. Millikan, and H. V. Neher, Phys. Rev. **53**, 855 (1938).

flights at St. George these records show a sea-level ionization significantly lower than during the other flights. Indeed a preliminary analysis shows that if one assumes a factor of 10 in the amplitude of the fluctuations at high altitude for all the flights as compared with the shielded ionization chamber at Cheltenham the apparent inconsistencies of Fig. 5 nearly all disappear.

In March 1942 no change in cosmic rays coming in near the vertical was measured between St. George and Pocatello.[3] The flights reported here show a 12 percent increase between St. George and Omaha, Omaha being at about the same magnetic latitude as Pocatello. Likewise a 14 percent increase was found between Pasadena and St. George in 1942. In August and September 1947 no increase was found between Ft. Worth and St. George, Ft. Worth being at nearly the same magnetic latitude as Pasadena. We are now engaged in a program of analyzing data from balloon flights of past years to determine if these and other inconsistencies may disappear when ground level measurements are taken into account.

Other observers have reported no change at very high altitudes in the radiation coming in near the vertical north of certain magnetic latitudes. Johnson[7] in 1938 reported no increase within his observational uncertainties between Minnesota (56°N) and Churchill, Canada (69°N). Likewise, Dymond[8] in 1939 made several balloon flights at 85°N magnetic and found no increase over that reported by Pfotzer[9] at 49°N. We should like to point out that comparisons of flights taken at different times may not be valid and the apparent agreement between such flights may be fortuitous.

[7] T. H. Johnson, Phys. Rev. **54**, 151 (1938).
[8] E. G. Dymond, Proc. Roy. Soc. **171A**, 321 (1939).
[9] G. Pfotzer, Zeits. f. Physik **102**, 23 (1936).

V. CONCLUSIONS

The results of 14 flights taken at seven more or less evenly spaced stations extending from San Antonio, Texas, to Saskatoon, Canada, indicate that fluctuations in the primary particles were quite pronounced during the period August 27 to September 23, 1947. These fluctuations were such as to hide any small increase one might hope to find in going north from one station to another. No plateau at northern latitudes was found. However, it may have been masked by the observed erratic behavior of the incoming radiation. No apparent correlation was found between the observed fluctuations and the activity of the sun or magnetic storms on the earth. There does, however, appear to be a correlation between fluctuations of cosmic rays at high altitudes and those found at sea level. The study of these variations in cosmic rays would require a large number of flights made over an extended period of time. The increment from one latitude to another could be obtained by sending instruments aloft simultaneously from two stations.

We wish to express our appreciation to Dr. R. A. Millikan, who accompanied us on this expedition, for his assistance and encouragement during the course of these experiments. The authors also wish to express their appreciation for the welcome given us by the University of Saskatchewan and the help of Professor E. L. Harrington, who was largely responsible for the success of our work in Canada. We gratefully acknowledge the financial assistance of the Carnegie Institution of Washington that made these experiments possible. Our thanks are also due the U. S. Weather Bureau for supplying us with helium for our balloons, and the individual members of the Bureau, who were of so much assistance at each of the stations in the United States.

Appendix III

Note on the East-West Effect*

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December 27, 1948

IN a recent flight to Peru in a B-29, continuous measurements were made at 3.10 equivalent meters of water barometric pressure (approximately 30,000 feet) of the intensity of cosmic-ray particles at the zenith, 45° west and 45° east. In addition the azimuthal variation was measured over Peru (magnetic latitude zero) at 2.35 m of water (approximately 38,000 feet) for zenith angles of $22\frac{1}{2}°$, 45°, and $67\frac{1}{2}°$. These measurements were made with both 10 cm and 20 cm of lead placed between the counters as well as with *no lead* absorber.** Because of the important bearing that such measurements have on the nature of the primary radiation, some of the preliminary results at the equator are herein reported.

Johnson and Barry[1] measured a west excess at a zenith angle of 60° of only 7 percent above 5 cm of Hg at 20° geomagnetic latitude north. Since this could be accounted for in terms of the asymmetry in the penetrating component measured near sea level, it was concluded that there was no asymmetry in the soft component and hence that the soft component was due to equal numbers of primary positive and negative electrons. The penetrating component was identified as arising from primary protons.

Janossy and Nicolson[2] agree with this conclusion reached by Johnson, namely that the absence of a large east-west effect at high altitudes argues for two different kinds of primary particles at the equator.

The east-west effect in the penetrating component at intermediate latitudes and altitudes has recently been measured by Schein, Yngre, and Kraybill.[3] In the geomagnetic latitude range 27°–31° north, they report an asymmetry at 45° zenith angle of 0.46 ± 0.07, at a pressure altitude of 34,500 feet, in the particles that can penetrate 22 cm of lead.

In the experiment here reported the asymmetries in both the hard and soft components were measured. The telescopes were the same as used previously by us,[4] except the extreme angles were changed to include $\pm16°$ in zenith angle and $\pm20°$ in azimuth. Counting rates at the vertical with no absorber were about 500 per minute at the equator at an atmospheric pressure corresponding to 3.10 m of water (32,000 feet). The experiment was performed at approximately 0° geomagnetic latitude and 76° west geographic longitude.

Table I. East-west asymmetry over Peru, zenith angle 45°.

M of water equivalent	Thickness of Pb absorber	West excess* (%)
3.1	0	23.3 ± 1.1
	10	27.6 ± 1.3
	20	30.4 ± 1.5
2.35	0	29.1 ± 1.4
	10	33.0 ± 1.6
	20	35.4 ± 1.7

* Computed from the difference between west and east divided by the average.

Table I gives a summary of the results at 45° zenith angle. The counting rate has been corrected for dead time of the counters, accidental counts, and for side showers. An indication of the magnitude of the shower correction was obtained by displacing the center tray of counters out of line. A detailed account of these corrections will be published elsewhere.

The following conclusions are drawn from the data in Table I: (a) That at these altitudes the west excess in the total radiation is nearly as large as in the penetrating component. (b) That the percentage asymmetry is increasing with altitude. The fact that the percentage west excess is greater for the more penetrating radiation together with the fact that it decreases with decreasing altitude may be due to scattering suffered by the lower energy particles.

More complete data at the higher altitude were taken. The percentage west excess as a function of zenith angle with and without lead absorber is plotted in Fig. 1. This brings out quite clearly the near equality in the asymmetry of the penetrating and soft components.

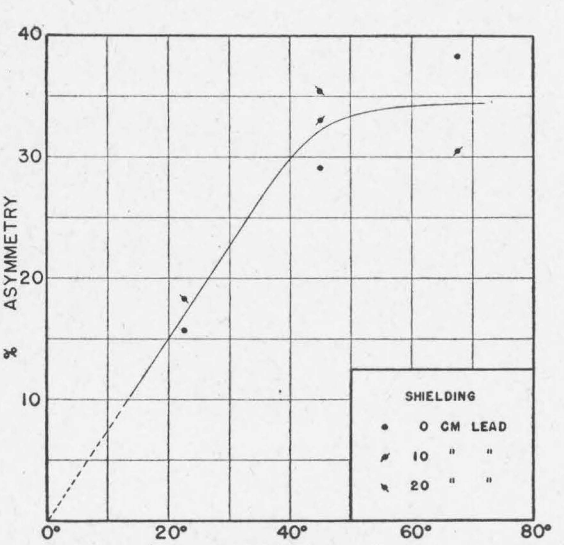

Fig. 1. The west excess in percent as a function of zenith angle with and without lead absorber.

The conclusion to be drawn is, that as far as these experiments are concerned, it is not necessary to assume a different primary particle to account for the penetrating and soft components at the equator and that it is quite likely that only one kind of incident, positively charged particle will suffice.

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** Data of 2.35 m of water and zenith angle of $22\frac{1}{2}°$ are missing for 10 cm of Pb and at $67\frac{1}{2}°$ for 20 cm of Pb because of lack of time.

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