The Cosmic-Ray Intensity above the Atmosphere*

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In a series of flights of Aerobee and V-2 rockets at geomagnetic latitude $\lambda = 41°$N, single Geiger counters and Geiger counter telescopes have been employed to measure the total intensity of cosmic rays above the appreciable atmosphere. The directional intensity j, averaged over the upper hemisphere, is found to be 0.120 ± 0.009/sec./cm²/steradian, constant from 55-km altitude to the highest altitude reached of 161 km. This result is an experimental upper limit to the primary intensity of charged particles at this latitude.

I. INTRODUCTION

IN a previous report,[1] we presented measurements on the counting rate of a single Geiger counter from ground level to 161 kilometers in altitude. (See Fig. 1, reproduced from reference 1.) It was found that a substantially flat plateau intensity exists above about 55 km.

An interpretation of the plateau counting rate in terms of charged particle intensity was given.

This paper contains further comments on the previous results and a description of subsequent single counter and coincidence telescope measurements, made at high altitude by means of the new American sounding rocket, the Aerobee, and by means of another V-2.

Inasmuch as a single Geiger counter is perhaps the most sensitive practical indicator of either an attenuation or multiplication of the cosmic-ray intensity, it seems justified to consider the experimental figure of 55 km as the upper bound of the appreciable atmosphere in cosmic-ray considerations. This is especially true for a cylindrical counter with axis approximately vertical; for such a counter has its maximum sensitivity to rays entering the atmosphere at grazing incidence and, hence, traversing the greatest path length in the atmosphere. In what follows, we shall refer to measurements above this altitude as having been made "above the atmosphere."

All results herein have been obtained in rockets fired from the White Sands Proving Ground, Las Cruces, New Mexico. Although in some flights as much as 1° of latitude is traversed, the geomagnetic latitude of the launching site, $\lambda = 41°$N, is adopted for convenience since there is no indication that present results justify more refined consideration.

No determination of the quantitative importance of secondaries emerging from the earth's atmosphere has been made. Rossi[2] has recently contributed an illuminating discussion of the nature of this problem.

II. REMARKS ON THE SINGLE GEIGER COUNTER MEASUREMENTS IN V-2 NO. 30 FIRED ON JULY 29, 1947

In reference 1, it was assumed that the inner ends of the glass skirt which surrounded the 3-mil anode wire of the Geiger counter defined the effective length of the counter. This length was 15.2 cm. Subsequently, we have determined the effective length of tubes from the same batch by the experimental method of Street and Woodward.[3] A typical curve (for the actual counter flown in V-2 No. 35 described in Section III) is shown in Fig. 2. The experimental effective length is 13.5 cm. In accordance with the universal finding of other workers, the effective diameter has been taken, as before, as the internal diameter of the metal wall of the counter, 2.38 cm. Thus, ascribing the mean plateau counting rate of 22.4 counts/second to a cosmic-ray flux isotropically distributed over the upper hemisphere, zero over the lower hemisphere, a revised value for the directional intensity

$$j = 0.13/\text{sec./cm}^2/\text{steradian}$$

is obtained.

* This work was supported by the Navy Bureau of Ordnance under Contract NOrd 7386.

[1] J. A. Van Allen and H. E. Tatel, Phys. Rev. **73**, 245 (1948).

[2] B. Rossi, Rev. Mod. Phys. **20**, 537 (1948).

[3] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934); K. Greisen and N. Nereson, Phys. Rev. **62**, 316 (1942); S. A. Korff, *Electron and Nuclear Counters—Theory and Use.* (D. Van Nostrand Company, Inc., New York, 1946), pp. 138, 139.

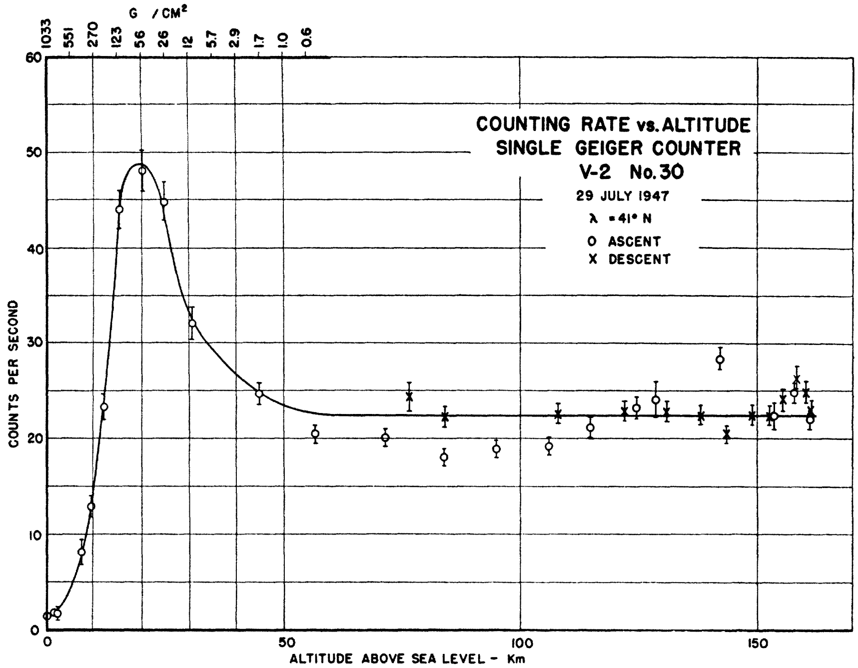

FIG. 1. Counting rate of a single Geiger counter as a function of altitude.

III. SINGLE COUNTER DATA FROM THE FLIGHT OF V-2 NO. 35 FIRED ON MAY 27, 1948

In V-2 No. 35, a single counter of the same batch as the one of V-2 No. 30 was used. Its physical location in the rocket was identical with that of reference 1. But in this case, the coincidence bundle of counters was considered no longer necessary and only one scale-of-eight circuit was used. Missile-borne electronics, telemetering, timing, missile tracking, etc. were similar to the previous flight.

The counting rate was determined in preflight tests on the ground at White Sands (altitude 1.22 km above sea level, pressure 890 g/cm²) as 1.72 ± 0.06/sec. with counter axis horizontal. In the 90 seconds just preceding take-off, a rate of 1.60 ± 0.10/sec. was recorded over the telemetering system; during this latter period the counter axis was vertical.

The rocket was fired at 7:16 A.M. on May 27, 1948. Fuel cut-off was accomplished at 64 seconds after launching; at this time, the velocity was 1400 m/sec., inclination of the trajectory 8° to the vertical, altitude 39.6 km above sea level. Summit altitude of 140 km was attained at 210 seconds. Explosive break-up of the missile was

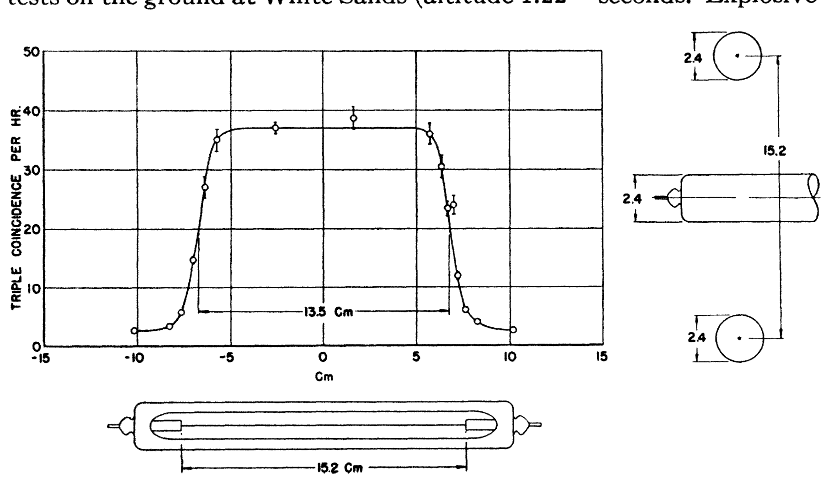

FIG. 2. Schematic arrangement for determining effective length of a Geiger tube for fast particles and plot of results for the single tube used in V-2 No. 35.

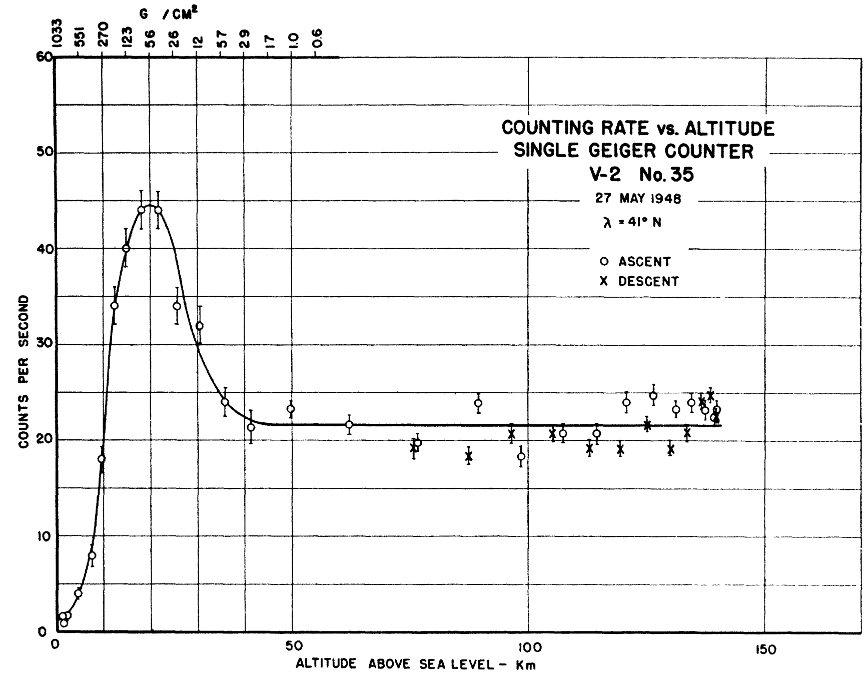

FIG. 3. Counting rate as a function of altitude of a single Geiger counter carried in a V-2 rocket.

performed at 341.6 seconds. The roll period of the missile during its unpowered flight was 50 seconds; the missile axis departed from the near-vertical direction very slowly, probably not exceeding a zenith angle of 90° up to 335 seconds. Precise information on this aspect of the flight will not be available for several months. Tracking by photo-theodolite, radar, and photo-telescopes was very good throughout flight. An exceptionally clean telemetering record was obtained, making possible continuous reading of data from 90 seconds before take-off to 335 seconds of flight time.

Figure 3 exhibits the counting rate of the single counter as a function of altitude above sea level.

The counting rate curve resembles in all important respects the one obtained in V-2 No. 30. The counting rate at the Regener-Millikan-Pfotzer maximum appears slightly lower and the average plateau counting rate is likewise slightly lower, being 21.6 ± 0.2/sec., based on 5736 counts in the time interval 70–335 seconds. A detailed analysis of the distribution of time intervals between successive scale-of-eight pulses showed excellent agreement with the statistical theory of Alaoglu and Smith,[4] thus giving further confidence in the flight operation of the Geiger counter and the scaling circuit.

[4] L. Alaoglu and N. M. Smith, Jr., Phys. Rev. **53**, 832 (1938).

IV. SINGLE COUNTER DATA FROM THE FLIGHT OF AEROBEE A5 ON MARCH 5, 1948

The Aerobee is a new American rocket specifically designed for use in upper atmospheric investigations. It has been developed for the Navy Bureau of Ordnance and the Office of Naval Research by the Aerojet Engineering Corporation and the Douglas Aircraft Company under the technical supervision of the Applied Physics Laboratory of the Johns Hopkins University. By means of it, a useful payload of 70 kg of equipment can be transported to an altitude of about 115 km. The equipment is contained in a thin ogival-shaped aluminum nose cone at the forward end of the rocket.

Radio transmission of data is provided by a small 85-mc telemetering set of six channels, developed by this laboratory. The system of tracking, timing signals, etc. is similar to that used for the V-2's, except that, thus far, no radar beacon has been carried by the Aerobee.

The firing of the Aerobee is conducted by the U. S. Naval Unit, White Sands Proving Ground. The Physical Science Laboratory of the New Mexico College of Agriculture and Mechanic

Arts operates the telemetering ground stations and reduces tracking and telemetered records.

Aerobee A5 was fired from the White Sands Proving Ground at 3:51 P.M. March 5, 1948 on a near-vertical trajectory. The altitude-time curve is shown in Fig. 4. The instrumentation cone contained two pieces of cosmic-ray equipment (Fig. 5).

(a) A single Geiger counter (11 in Fig. 5) of the same batch as used in V-2's Nos. 30 and 35 was located on a fiber structure near the point of the nose cone. Precautions were taken, as before, to reduce to a minimum the amount of material in the immediate vicinity of the counter.

(b) A pair of crossed wide-angle triple-coincidence telescopes, *AOB* and *XOY*, was located in the after portion of the nose cone. The axes of these two telescopes were at right angles to each

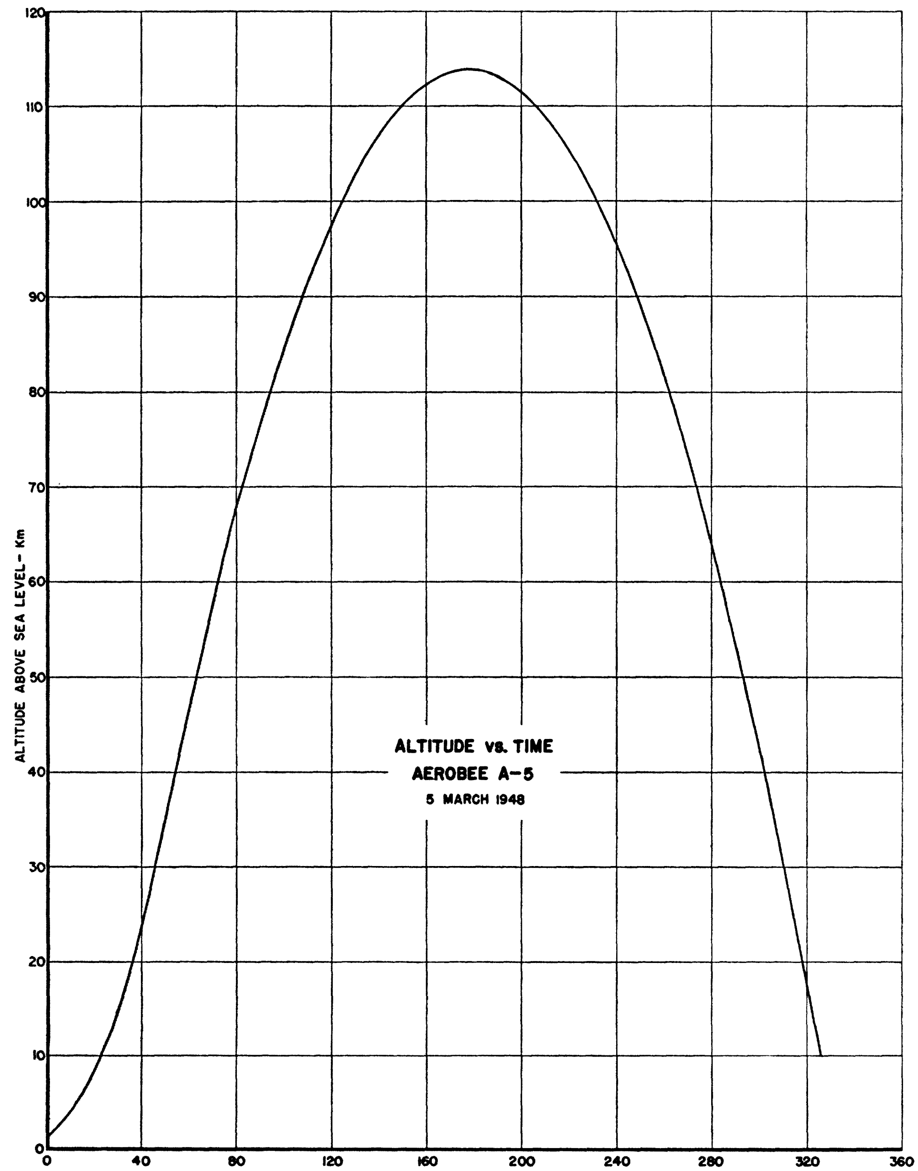

FIG. 4. Plot of altitude above sea level *vs.* time for Aerobee A5. This curve is based in part on external tracking data and in part on cosmic-ray data as discussed in the text. Disintegration of the rocket structure occurred at altitude 10 km on the descending branch of the curve.

other; the plane of their axes included the axis of the rocket. The inclination of the telescope axes was 45° to the rocket axis.

Necessary batteries, electronic chasses, etc., occupied the remaining volume of the cone. Three arrays of 1P42 photoelectric cells were located in the periphery of the rocket to measure, by means of the sun, azimuth and zenith angles during flight.

At fuel exhaustion, which occurred 48 seconds after launching, the zenith angle of the rocket axis was 10°; the roll period was 1.13 seconds. Thereafter, the roll period maintained a constant value; the longitudinal axis of the rocket precessed with a period of about sixty seconds in an approximate cone of about 15° half-angle. This angular motion, with the nose generally upward, persisted until about 260 seconds flight time. Beginning at about this time, the axis of the rocket assumed a larger and larger zenith angle. Complete inversion had occurred and the axis had become parallel to the trajectory with the nose downward by about 290 seconds.

A complete telemetering record was obtained from 55 seconds before take-off to 326 seconds flight time, with the exception of a total of 11.5 seconds during the inversion period. This loss of signal was presumed a result of nulls in the radiation pattern of the rocket-borne antenna. At 326 seconds, altitude 10 km, the missile broke up and no data were obtained beyond this time.

A plot of the counting rate of the single Geiger counter *vs.* altitude above sea level is shown in Fig. 6. For the first time we were successful in "closing the curve" back through the maximum at about 20 km.

The photo-theodolites provided a good knowledge of the trajectory almost to fuel burn-out; but the velocity at fuel burn-out and, therefore, the complete trajectory were not accurately determined. Figure 6 was prepared by first plotting the counting rate data *vs.* time of flight. This curve was then folded so as to bring the maxima into coincidence. The altitudes of the counting rate maxima on the ascending and descending portions of the trajectory were *assumed* the same. With due regard for the variation of g with altitude and for aerodynamic drag, the altitude-time curve of Fig. 4 was then arrived at by trial and error calculation. The curve so produced was well within the determination of it provided by the tracking data. (This is believed to be the first practical application of cosmic-ray data to the determination of a rocket trajectory.) Finally, the counting rate *vs.* time of flight curve was converted to an altitude basis (Fig. 6) by the use of Fig. 4.

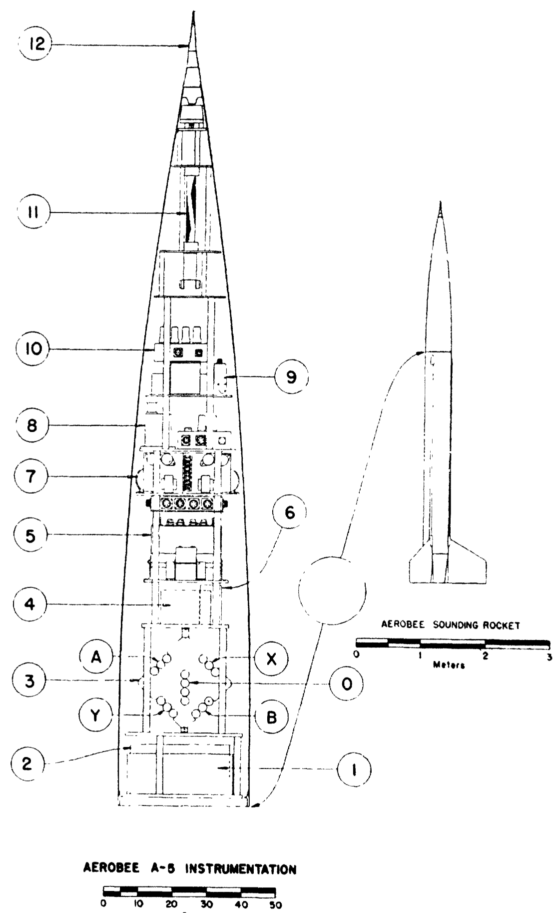

FIG. 5. Arrangement of equipment in Aerobee A5. The instrument cone is shown in large scale and the relationship of the cone to the entire rocket is indicated by the smaller drawing on the right. A, O, B, X, Y are individual Geiger counter trays of the cosmic-ray telescopes AOB and XOY and associated guard counters. 11 is the single Geiger counter whose output pulses were transmitted. Other principal items of equipment are as follows: 1, telescope coincidence circuits; 2, telemetering sub-carrier audio modulator; 3, telescope assembly; 4, emergency fuel cutoffreceiver; 5, lead storage batteries; 6, rf-telemetering transmitter; 7, dynamotors and filters for B^+ supply to circuits; 8, motor and commutator for commutating orientation photo-cells; 9, high voltage battery for Geiger counters; 10, scale-of-eight circuit; 12, telemetering antenna, insulated from body of missile. Sea-level atmospheric pressure maintained by aluminum nose cone 1.0 mm thick. Arrays of photo-cells not shown, but located aft of nose cone in forward skirt of rocket structure.

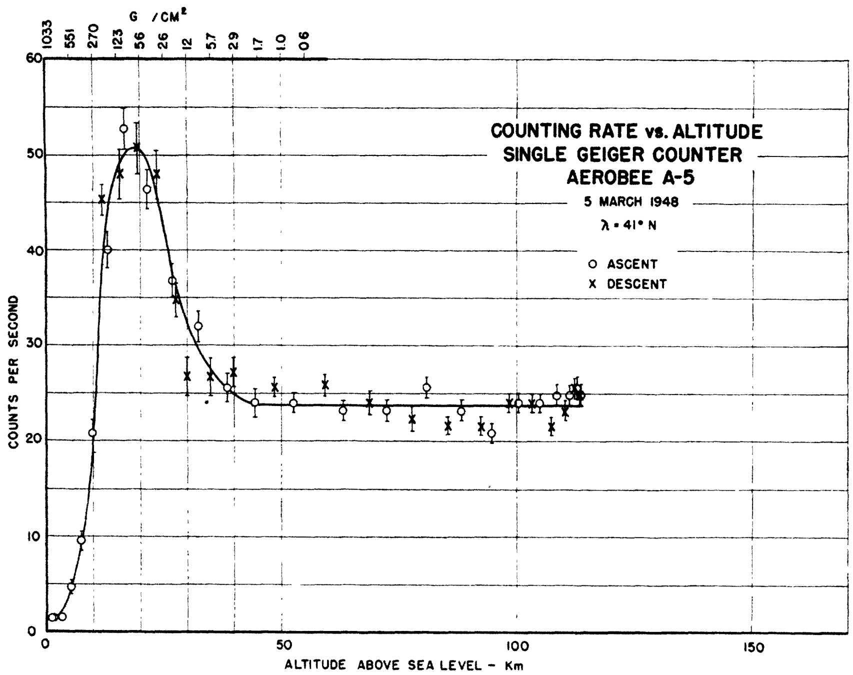

FIG. 6. Counting rate as a function of altitude of a single Geiger counter carried in an Aerobee rocket.

Again, substantially the same counting rate *vs.* altitude curve was obtained.

The counting rate of 1.45 ± 0.11/sec. was recorded during the 55 seconds previous to take-off. A peak counting rate of 51/sec. occurred at a 19-km altitude and a mean plateau rate of 23.7 ± 0.2/sec. was found for 227 seconds of record in the period 60 to 300 seconds. As in previous sections, the error indicated is the statistical probable error. Possible systematic errors are discussed in a later section.

V. COINCIDENCE TELESCOPE MEASUREMENTS IN FLIGHT OF AEROBEE A5—MARCH 5, 1948

The general arrangement of the two threefold coincidence telescopes is shown in Fig. 5. A more detailed view of the geometry of the counters is contained in Fig. 7. The aluminum nose cone of the rocket, which surrounded all the instrumentation, had a thickness of 1.0 mm. The Geiger tubes in the telescope were of the same batch as those used in the single counter apparatus discussed in previous sections. Thus, an average traversal of the telescope involved penetration through about 0.4 g/cm² of Al and 4.0 g/cm² of Cu. The perpendicular separation between midplanes of counter trays X and Y or A and B was 17.2 cm. The respective telescopes XOY and AOB were as nearly identical as practical.

The following coincidences were formed electronically with standard type circuits with a resolving time $\tau = 10\mu s$,

AOB
XOY
AOB (X and/or Y) *or* XOY (A and/or B).

The latter type coincidence requires simultaneous passage of at least two particles through the telescope array.

On the telemetered record (8 cm/sec.) additional identification of the multiple particle events was accomplished with a resolving time of about 0.007 sec. Thus, it was possible to list coincidences in the following five categories,

(1) AOB
(2) AOB (X or Y)
(3) XOY
(4) XOY (A or B)
(5) $XOYAB$.

In order to interpret the telescope counting rate in terms of directional intensity, it is necessary to calculate the geometric factor for the telescope. The counting rate N of an idealized threefold coincidence set of three parallel rectangular plane counters of effective length l, width a, separation between outer planes s is given by

$$N/e^3j=(a^2l/s) \text{ arc } \tan(l/s), \quad (1)$$

for a/s small, e absolute efficiency of each counter, j directional intensity in particles/sec./cm²/steradian, constant over the aperture of the telescope and "downward" only. The wide-angle telescope AOB (or XOY) may be considered as composed of nine simple component telescopes (refer to Fig. 7) with a/s small. First, formula (1) was applied to each of the component telescopes; then a correction[5] for the actual cylindrical shape of the counters was calculated analytically and added to the first approximation. The nine corrected factors were then summed to give the geometric factor for the entire telescope. The result for isotropic intensity (applicable to plateau counting rate above the atmosphere) was

$$N/e^3j=28.1\pm0.7 \text{ cm}^2 \text{ steradian}, \quad (2)$$

in which N is observed coincidences/sec., j is in particles/sec./cm²/steradian, and e is the counting efficiency of each tray. The value of e includes the intrinsic efficiency and the loss of counts as a result of counter dead time; it is, therefore, dependent on the counting rate. On the high altitude plateau $e^3=0.96$; at the Pfotzer maximum, 0.92; on the ground, 0.98. The error indicated in Eq. (2) is believed to be such as to almost certainly encompass the true value of the geometric factor.

For the interpretation of preflight counting rates of the telescope in a laboratory on the ground, the geometric factor for the telescope is somewhat lower than that computed above. Utilizing the theorem of Greisen[5] and assuming that at White Sands for any azimuth $j(\theta) = j(0°) \cos^2\theta$, where θ is the zenith angle, we find for the axis of our telescope vertical

$$N(0°)/e^3j(0°)=25.1\pm0.7 \text{ cm}^2 \text{ steradian}, \quad (3)$$

and for the axis of the telescope at $\theta=45°$,

$$N(45°)/e^3j(45°)=25.7\pm0.7 \text{ cm}^2 \text{ steradian}. \quad (4)$$

At altitudes intermediate between ground level and 55 km, the geometric factor for the telescope will lie between the value of Eq. (3) and that of Eq. (2) because of progressive change of zenith angle distribution from $\cos^2\theta$ to approximately isotropic. No detailed quantitative interpretation of data at intermediate altitudes is given in this paper.

Accidental coincidences were estimated by the formulas of Schiff[6] taking into account all possible modes of generation of accidental coincidences. The principal contribution comes from events of the type: true coincidence of OY overlapping an unrelated count of tray X. On the high altitude plateau, it was estimated that

$$(\Delta N)_{XOY}=0.04 \text{ accidentals/sec.} \quad (5)$$

The rate of accidental fourfold electronic coincidences and the rate of incorrect identifications on the telemetered record were estimated to be negligible.

In the preflight runs, all classes of accidentals were negligible.

Table I contains a summary of preflight telescope data and directional intensities $j(0°)$ and $j(45°)$ calculated from them with the use of formulas (3) and (4). Agreement of the calculated intensities with accepted values[2] is satisfactory.

In flight, the counting rates (1)–(2)–(5) and

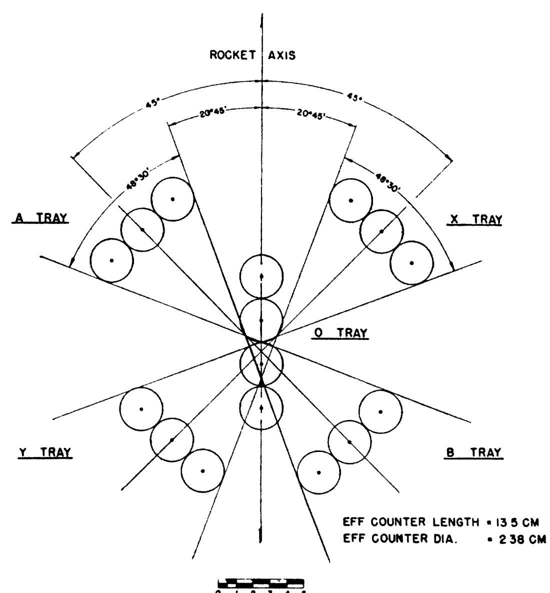

FIG. 7. Scale drawing of end view of telescope. Perpendicular distance between trays A and B or between X and Y 17.2 cm.

[5] Compare K. Greisen, Phys. Rev. **61**, 212 (1942).

[6] L. I. Schiff, Phys. Rev. **50**, 88 (1936).

TABLE I. Ground data with telescopes XOY and AOB—White Sands Proving Ground.

$\lambda = 41°N$	Nominal pressure 890 g/cm²		Alt. 1.22 km
Nominal telescope zenith angle	Observed counting rates		
	Av. (1)–(2)–(5) and (3)–(4)–(5)	Av. (2) and (4)	(5)
0°	19.9±0.4/min.	1.0±0.2/min.	0.8±0.2/min.
45°	10.9±0.2	0.6±0.1	0.3±0.1

Calculated intensities:
$j\,(0°) = 0.0135 \pm 0.0006$/sec./cm²/steradian
$j\,(45°) = 0.0072 \pm 0.0003$/sec./cm²/steradian

TABLE II. High altitude plateau data.

Category	No. of counts
(1)	975
(1)–(2)	808
(1)–(2)–(5)	666
(3)	1046
(3)–(4)	842
(3)–(4)–(5)	700

Rate of Telescope AOB, less all recorded multiple particle events $= 2.91 \pm 0.07$/sec.
Rate of Telescope XOY, less all recorded multiple particle events $= 3.06 \pm 0.08$/sec.
Average net rate per telescope $= 2.99 \pm 0.05$/sec.

(3)–(4)–(5) *vs.* time of flight were statistically indistinguishable. The averages of these two counting rates *vs.* altitude are plotted in Fig. 8, using Fig. 4 to convert time to altitude. The peak of this curve occurs at about 16 km, somewhat lower than for the single counter curves; likewise, the plateau appears to commence at an altitude of about 40 km. Both of these differences from the single counter curves may be reasonably attributed to the restricted range of zenith angles around 45° in which the telescope would accept counts. Thus, the effective amount of atmospheric material "above" the telescope is less, at every altitude, than that "above" a single counter.

Table II summarizes plateau data for 228.5 seconds during the period 60–300 seconds.

VI. DISCUSSION OF DATA

Referring to Sections II, III, and IV, it is seen that there are certain minor differences among the single counter results of the three flights. There is a temptation to identify these differences with the recent results of the California Institute of Technology group[7] on the fluctuations of cosmic-ray intensity within the atmosphere. However, because of possible systematic differences of effective counter length and spurious counts during the various flights, we do not believe that

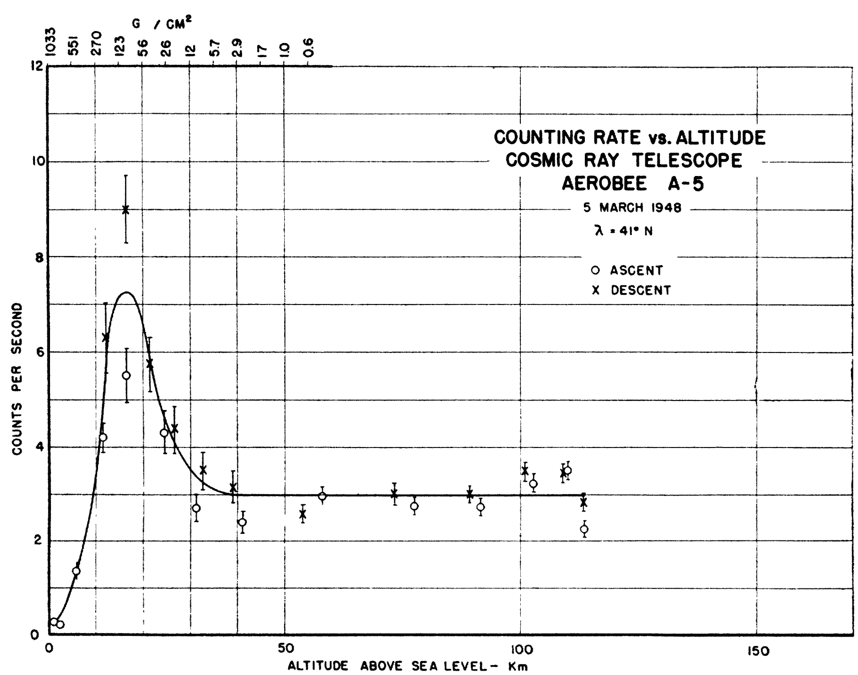

FIG. 8. Counting rate as a function of altitude of a cosmic-ray telescope carried in an Aerobee rocket.

[7] A. T. Biehl, R. A. Montgomery, H. V. Neher, W. H. Pickering, and W. C. Roesch, Rev. Mod. Phys. **20**, 353, 360 (1948).

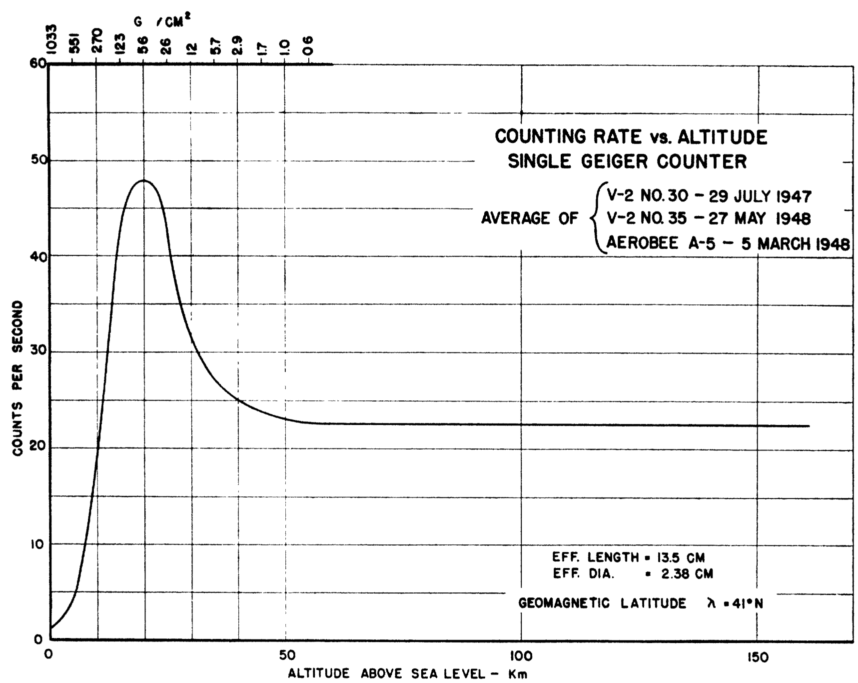

FIG. 9. Smoothed composite curve of all single counter data.

our single counter data justify such refined consideration. The three sets of data have, therefore, been combined into a single smooth curve (Fig. 9).

There do appear to be significant undulations in the individual plateau data of the separate flights. In each case, these undulations are generally correlated with the zenith angle of the rocket axis. In reference 1, it was proved that in a hemispherically symmetric field of flux, the counting rate of a single counter is independent of orientation; further, it was found experimentally that the extraneous influence of material in the rocket was negligible for our arrangement so that neither a reduction resulting from shadowing nor an augmentation caused by multiplication could occur in any orientation of the rocket. It is, therefore, suggested that the observed undulations, if indeed significant, constitute evidence for the lack of hemispherical constancy of the directional intensity above the atmosphere. A semi-quantitative idea of the directional, i.e., telescopic, properties of a single cylindrical counter may be obtained from Fig. 10, in which is plotted the counting rate per unit uniform flux per unit solid angle of a conical field of flux of half-angle α, the axis of the cone lying along the axis of the counter. As is well known, a cylindrical counter is considerably more sensitive to flux perpendicular to its axis than to flux parallel to its axis. Further discussion of this question is deferred until a subsequent report on the azimuthal and zenith angle dependence of intensity above the atmosphere, as obtained by detailed analysis of the telescope data from the flight of Aerobee A5. Section V of this paper deals only with the over-all summary of the telescope data.

The average plateau counting rate from Fig. 9 is 22.6/sec. If this rate be ascribed to a directional cosmic ray intensity of charged particles j, uniform over the upper hemisphere, zero over the lower hemisphere, then we calculate

$$j = 0.131 \pm 0.005/\text{sec.}/\text{cm}^2/\text{steradian}$$

as a final result of this series of measurements.

We now proceed to discussion of the telescope measurements. Minimizing the amount of material in the vicinity of a single counter is of essential importance in obtaining true intensity measurements in the upper atmosphere and above the atmosphere; in measurements with telescopes, surrounding material is even more troublesome. In early V-2 flights of this laboratory, a telescope

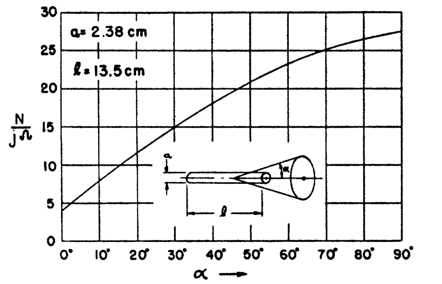

FIG. 10. Plot of counting rate N of a single cylindrical Geiger counter per unit uniform flux j per unit solid angle of a conical field of flux of half angle α. The field of flux is considered "solid" with the center line parallel to the axis of the counter.

patterned after that of Schein, Jesse, and Wollan[8] was used; each tray of our telescope consisted of two tubes instead of one. The C tray was electrically divided into two. Also a set of guard counters alongside of the B tray was provided. On the plateau above the atmosphere, only about 15 percent of "in-line" events ABC or BCD were found to be *unassociated* with side counts or double counts in the split tray.[9] The rate of multiple particle events increases very rapidly in the upper atmosphere, approximately as $\exp(-h/150)$ where h is the pressure in g/cm.[2] These events seem to be primarily a result of bursts from the primaries themselves.[8–11] Inasmuch as a typical path through the above-mentioned telescope was 100 g/cm^2 of lead for a ray from any direction, not necessarily within the solid angle of the telescope, it is not surprising that this is so. The *NRL* group has reported a similar situation in their high altitude measurements with leaded telescopes.[12–18] In the Aerobee telescope (Figs. 5, 7), a special effort was made to reduce the amount of proximate material.

The measure of success in this effort may be judged from Table II of Section V. Multiple particle events (which are, of course, of great interest for their own sake in other investigations) were reduced far below their previous predominance. Yet the telescope measurements were still not as clean as would be desired, since roughly one-third of AOB or XOY events were associated with guard counts. The average rate of category (1) and category (3) events on the plateau, disregarding the guard counts, is

$$4.42\pm0.07/\text{sec.}$$

per telescope. The average *net* rate per telescope, after subtraction of all recorded associated multiples, is

$$2.99\pm0.05/\text{sec.}$$

Bursts caused by particles whose paths lie outside of the telescope geometry spuriously increase the counting rate of the telescope; bursts caused by particles whose paths lie within the telescope geometry are properly included in the "true" rate of the telescope. Thus, it may reasonably be believed that the true rate of such a telescope in free space lies between the two rates just calculated. Inasmuch as most of the nearby material lay outside of the solid angle of the telescope, we have chosen the *net* rate as the best experimental determination of the true rate of the telescope in free space. At the worst, this rate is probably not more than a few percent too low. Using the geometric factor of Section V and making the minor corrections for inefficiency and accidentals, we have finally

$$j=0.109\pm0.006/\text{sec./cm}^2/\text{steradian}$$

from the telescope measurements on the plateau.

As described in Section IV, the angular motion of the telescope axes on the plateau was, in detail, rather complicated; in over-all view, however, it is felt that the upper hemisphere was scanned with reasonably uniform weight. Thus, the above

[8] M. Schein, W. P. Jesse, and E. O. Wollan, Phys. Rev. **57**, 847 (1940). See also M. Schein, E. O. Wollan, and G. Groetzinger, Phys. Rev. **58**, 1027 (1940); and especially M. Schein, M. Iona, Jr., and J. Tobin, Phys. Rev. **64**, 253 (1943); and for a general summary M. Schein and D. J. Montgomery, *Problems in Cosmic Ray Physics*, (1946), Princeton lectures.

[9] J. A. Van Allen, H. E. Tatel, and R. P. Petersen, *High Altitude Research Using the* V-2 *Rocket* (Applied Physics Laboratory, Johns Hopkins University Report No. 81, edited by L. W. Fraser and E. H. Siegler), pp. 62–64.

[10] H. E. Tatel and J. A. Van Allen, Phys. Rev. **73**, 87 (1948).

[11] J. A. Van Allen, Sky and Telescope **VII**, 7 (1948).

[12] S. E. Golian, E. H. Krause, and G. J. Perlow, Phys. Rev. **70**, 223 (1946).

[13] S. E. Golian, E. H. Krause, and G. J. Perlow, Phys. Rev. **70**, 776 (1946).

[14] G. J. Perlow and J. D. Shipman, Jr., Phys. Rev. **71**, 325 (1947).

[15] S. E. Golian and E. H. Krause, Phys. Rev. **71**, 918 (1947).

[16] G. J. Perlow, Phys. Rev. **72**, 173 (1947).

[17] E. H. Krause and S. E. Golian, Phys. Rev. **72**, 173 (1947).

[18] G. J. Perlow, Phys. Rev. **73**, 1218 (1948).

determination refers to the average directional intensity over the upper hemisphere. As before, we have here tacitly assigned any flux from the lower hemisphere to the upper hemisphere.

The directions of the two telescopes AOB and XOY were rapidly interchanged in flight by the rotation of the rocket. Their average counting rates were within reasonable statistical agreement (Table II).

The intensity result from the single counters is probably a little high because of spurious counts; the intensity result from the telescopes is probably a little low due to excessive subtraction of multiple particle events. Therefore, lacking a better procedure, we have arbitrarily combined with equal weight the final single counter determination of $j=0.131\pm0.005$ and the telescope determination of $j=0.109\pm0.006$. Thus,

$$j=0.120\pm0.009/\text{sec./cm}^2/\text{steradian}$$

is our best value for the average directional intensity above the appreciable atmosphere in the 55–161-km altitude band at geomagnetic latitude $\lambda=41°$N. The assigned error is intended to indicate the values between which we believe the true average intensity almost certainly lies.

VII. GENERAL DISCUSSION

Our value of $j=0.120\pm0.009/\text{sec./cm}^2/\text{steradian}$ is an experimental upper limit to the average directional intensity of *charged* cosmic-ray primaries at the latitude of these experiments. From the systematic studies of the latitude effect[19] by Millikan and associates, it is already known that the primary intensity of charged particles is indeed of this order of magnitude.

Secondaries emerging from the atmosphere and executing orbits in the earth's magnetic field undoubtedly contribute in some measure to the measured intensity above the atmosphere.

It has often occurred to others and to us that the extraneous secondaries should be easily absorbable. Some of our results and the results of Perlow and Shipman[14] with leaded telescopes have been so interpreted. Yet the complexity of the counting situation in leaded telescopes in the high atmosphere (see Section VI) has led us to a considerable caution in conclusions from such apparently straightforward results.

It may be mentioned that Primakoff[20] has obtained a series of counting rate curves with balloon-borne telescopes containing different amounts of absorber. His curves for telescopes containing various thicknesses of lead from 0 to 10 cm converge to the same counting rate at the top of the atmosphere and lead to the conclusion that the easily absorbable component is negligible at about 37 km.

In view of the conflicting evidence, we feel that there is thus far, no satisfactory experimental determination of the importance of secondaries.

Low energy (for example 10^7) γ-radiation would produce a much greater counting rate in a single counter than in a coincidence telescope. Since the intensity results by the two distinct methods are, with due regard for the probable magnitude and sign of systematic errors, in substantial agreement, it may be concluded that there is no significant contribution of such γ-rays. However, an intensity of the order of $1/\text{sec./cm}^2/\text{steradian}$ would probably escape detection.

It is not clear that such an argument can be used to exclude important contributions from γ-rays of energies like 10^9 ev. A telescope such as that used in the Aerobee flight would have a detection efficiency for γ-rays of this energy similar to that of a single counter. This detection efficiency would be only a few percent; however, there seems to be no basis for excluding a large intensity of γ-rays of such energy.

Auxiliary experiments with detectors of high γ-ray efficiency are planned.

Appreciable intensities of γ-rays of energies greater than 5×10^9 ev appear to be ruled out by the experiment of Hulsizer.[2]

In consideration of the general theory of the effect of the earth's magnetic field on the trajectories of charged particles passing through it, it may be concluded that the intensity plateaus observed in rocket flights of up to 160-km peak altitude are *not* of indefinite extension. The portion of the intensity resulting from charged primaries will, at all geomagnetic latitudes below

[19] See, for example, the excellent summary of L. Janossy, *Cosmic Rays* (Oxford University Press, London, 1948).

[20] Second semi-annual report of the work of the Bartol Research Foundation of the Franklin Institute under Contract N6ori-144 with the Office of Naval Research, September 15, 1947.

say 50°, slowly rise with increasing altitude—approaching asymptotically, at "altitudes" many times the radius of the earth, the free space intensity in the astronomical vicinity of the earth. At all latitudes, except at $\lambda=90°$, the contribution of secondaries—"cosmic-ray albedo" of the earth's atmosphere—should progressively diminish with increasing altitude due to their inability to escape from the earth's magnetic field.

Comparisons with related work of other investigators will now be made. Biehl, Montgomery, Neher, Pickering, and Roesch[7] have recently reported vertical intensity measurements at various latitudes. The highest altitude point (38 g/cm^2) on their curve 2 for Fort Worth, Texas, $\lambda=41.7°$N yields a vertical intensity $j=7.7$/min./cm^2/steradian or 0.13/sec./cm^2/steradian, almost identical with our value above the atmosphere. It is, of course, not known how much farther the curve of Biehl *et al.* would have continued to fall if the balloon had risen higher.

It may be noted that the zenith angle dependence of total intensity within the atmosphere[21, 22] combines with the directionality of a single vertical counter to cause a single counter curve to peak at a considerably higher altitude and to likewise level at a considerably higher altitude than the curve for a vertical narrow angle telescope.

Pfotzer's original measurements[23] with a vertical coincidence telescope may be noted. His corrected counting rate at the highest altitude attained (27 g/cm^2) was 125 counts in 4 minutes. A reasonable extrapolation of his curve to zero pressure would be 115 counts in 4 minutes. The geometric factor for his telescope can be roughly figured as

$$A_1A_2/r^2=(4.5)^2(5)^2/(12)^2=3.5 \text{ cm}^2 \text{ steradian.}$$

Thus, the extrapolated intercept would correspond to a vertical intensity of approximately 0.14/cm^2/sec./steradian, at $\lambda=49°$.

Primakoff[20] and co-workers have made similar measurements; however, we have not been able to find a description of the geometry of their telescope.

[21] W. F. G. Swann, Rev. Mod. Phys. **11**, 242 (1939).
[22] J. F. Jenkins, Bull. Am. Phys. Soc. **23**, No. 3 1948, Washington Meeting Abstract EA3.
[23] G. Pfotzer, Zeits. f. Physik **102**, 23.40 (1936).

It may be noted that all the above-quoted results are subject to a greater extraneous contribution of secondaries than are the rocket measurements.

Golian and Krause[15] in a V-2 telescope experiment have found a ratio of intensity above the atmosphere to vertical sea level intensity of 11.5 for the "total" radiation and 9.0 for the "hard" component.

Our corresponding ratio for the total intensity is

$$0.120/0.011=11.$$

VIII. CONCLUSION

By means of single Geiger counters and coincidence telescopes of Geiger tubes carried by rockets to high altitudes at geomagnetic latitude $\lambda=41°$N, a constant value of cosmic-ray intensity above 55 km has been clearly demonstrated. An upper limit to the directional intensity of charged cosmic-ray primaries, averaged over the upper hemisphere, has been determined. This upper limit is $j=0.120\pm0.009$/sec./cm^2/steradian.

IX. ACKNOWLEDGMENTS

The conduct of experiments in rockets involves operations on such an extensive scale that it is very difficult indeed to give adequate credit to all participants.

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The Aerobee was developed and built by the Aerojet Engineering Corporation and the Douglas Aircraft Company. The U. S. Naval Unit of the White Sands Proving Ground is in charge of field operations in firing the Aerobee.

We have been assisted in field work by the

Naval Unit, the Army Technical Section, and the General Electric Group, all of the White Sands Proving Ground. The Physical Science Laboratory of the New Mexico College of Agriculture and Mechanic Arts has carried a major share of the technical field work for the Aerobee in the conduct of preflight telemetering tests, flight telemetering, and in the reduction of tracking and telemetered data.

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This series of experiments was originally planned in conjunction with Dr. H. E. Tatel, now at the Department of Terrestrial Magnetism of the Carnegie Institution.

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The Properties of Cosmic Radiation at Very High Altitudes*

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The variation of the vertical cosmic-ray intensity as a function of altitude has been investigated in a series of free-balloon ascents with standardized quadruple-coincidence-counter trains containing various amounts of interposed absorber, to a maximum thickness of 7.5 cm Pb. The curves thus obtained converge at the "top of the atmosphere." A maximum occurs in the curve with 4 cm of Pb, but disappears with 6 cm of Pb. Cosmic-ray absorption curves at various altitudes above that corresponding to an atmospheric pressure of 250 mm of Hg are plotted from the data, as are integral and differential distributions-in-range. The relative stopping powers of carbon and lead are also available from the data.

Disturbing effects such as those arising from side showers and scattering appear to be negligible. An extrapolation procedure, which leads to results consistent with those of other experiments, provides a new picture of the composition of the cosmic rays in the atmosphere. With heavier particles $(P+M)$ displaying a maximum intensity at a higher altitude than electrons (E), the conclusions drawn from the present investigation are compatible with a primary radiation consisting of protons (and possibly heavier nuclear particles) producing mesotrons which subsequently give rise to the electronic component.

Comparison of the results reported here with those of Schein and Allen indicate an absorption of primaries, by a process other than ionization, in thicknesses of Pb between 7.5 and 18 cm.

I. INTRODUCTION

ONE of the most widely used methods of investigating the nature and properties of cosmic-ray particles is based upon measurements of their absorption in matter. Although this technique has been pursued extensively near sea level, at great depths, and on mountain peaks, no experiments designed to obtain data of this type have been performed, even at altitudes accessible to aircraft. In the course of investigations of mesotron production, conducted by Schein, Wollan, and Groetzinger[1] in airplanes, and of the latitude effect of the penetrating component by Bhabha, Aiya, Hoteko, and Saxena,[2] and by Gill, Schein, and Yngve,[3] *intensity vs. altitude* curves have been determined with various counter arrangements embodying several different thicknesses of interposed lead. However, the authors do not regard the results as being

* These investigations have been supported by the Office of Naval Research. Although the observations reported here were obtained at geomagnetic latitude 52°N, considerable experience in the techniques was obtained during The Joint National Geographic Society—Army Air Forces Eclipse Expedition to Bocaiuva, Brazil, during May, 1947.

[1] M. Schein, E. O. Wollan, and G. Groetzinger, Phys. Rev. **58**, 1027 (1940).

[2] Bhabha, Aiya, Hotenko, and Saxena, Phys. Rev. **68**, 147 (1945).

[3] P. S. Gill, M. Schein, and V. Yngve, Phys. Rev. **72**, 733 (1947).