spin of $8(\hbar)$ for the 3.1-hr isomer. Since this result agrees with the directly measured value, the present experiment serves as evidence for the validity of decay schemes based on calculations of internal conversion coefficients by Rose *et al.*[8,18]

From the shell model two possible proton-neutron configurations are possible for the excited isomer Cs^{134m} compatible with the measured spin of $8(\hbar)$. These are[19] $1g_{7/2}$, $1h_{11/2}$, and $2d_{5/2}$, $1h_{11/2}$. Using a two-nucleon wave function, one arrives at the expression of Bellamy and Smith[4] for the magnetic moments of odd-odd nuclei, from which the moments associated with these states are calculated to be -0.36 and $+2.90$ nm, respectively. Possibly a mixed configuration, as suggested by de-Shalit and Goldhaber,[20] of these two states may account for the measured result of $+1.10$ nm.[21]

An empirical method for estimating moments of odd-odd nuclei stems from proposals[22] that the spin contributions to the magnetic moment of the odd nucleons are suppressed from their respective free particle values when the neutron and proton are in the nucleus. Following this suggestion, we may take the effective intrinsic moment of the odd neutron and odd proton in Cs^{134m} to be -1.4 and 1.5 nm, respectively, using the graph prepared by Bloch.[22] Introducing these values into the same two-nucleon calculations, we find fair agreement with experiment in the result of $+0.8$ nm computed for the $g_{7/2}$, $h_{11/2}$ configuration. The $d_{5/2}$, $h_{11/2}$ proton-neutron configuration gives the much higher value of $+2.1$ nm for the nuclear moment.

[18] Rose, Goertzel, and Swift (privately circulated tables).
[19] Mayer, Moszkowski, and Nordheim, Revs. Modern Phys. **23**, 315 (1951).
[20] A. de-Shalit and M. Goldhaber, Phys. Rev. **92**, 1211 (1953).
[21] The suggestion of a mixed configuration in Cs^{134m} was first made by Cohen and Gilbert, reference 15.

ACKNOWLEDGMENTS

We wish to thank J. A. Dalman for his ingenious design work and assistance in performing the experiments, H. W. Ostrander for his design of many parts of the apparatus, and M. Hamermesh, D. E. Nagle, and D. Kurath for stimulating discussions.

[22] F. Bloch, Phys. Rev. **83**, 839 (1951); H. Miyazawa, Progr. Theoret. Phys. (Japan) **6**, 263 (1951); A. de-Shalit, Helv. Phys. Acta **24**, 296 (1951).

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Cosmic-Ray Intensity above the Atmosphere at High Latitudes*†

L. H. Meredith,‡ J. A. Van Allen, and M. B. Gottlieb
Department of Physics, State University of Iowa, Iowa City, Iowa
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The total charged particle cosmic-ray intensity above the atmosphere has been measured with thin-walled Geiger counters (total effective stopping power of apparatus and residual atmosphere 0.5 g/cm² of aluminum) carried in balloon-launched rockets at geomagnetic latitudes 54.3° N, 62.1° N, 71.9° N, and 86.7° N. The respective values of unidirectional particle intensity averaged over the upper hemisphere are: $\bar{J}=0.44\pm0.01$, $\leq 0.50\pm0.05$, $\leq 0.50\pm0.05$, and $=0.48\pm0.01$ (cm² sec sterad)$^{-1}$. These results are consistent with the complete or nearly complete absence of primary cosmic rays having a magnetic rigidity less than 1.7×10^9 volts.

I. INTRODUCTION

A. Purpose

The purpose of this investigation was to make an absolute measurement of the total intensity of charged primary cosmic rays down to the lowest feasible value of magnetic rigidity R—in this case down to a value of R of about 0.2×10^9 volts.

The intensity of low-rigidity cosmic rays is of interest for several reasons, *viz.:* (a) They may constitute a significant portion of the primary beam. (b) The presence or absence of low-rigidity primaries may provide a crucial test of any proposed mechanism for the astrophysical origin and propagation of cosmic rays. (c) A specific aspect of (b) may be a definitive test of the magnitude of the magnetic dipole moment of the sun. (d) It is of aeromedical interest to know the radiation intensity which will be encountered in flight at high altitudes and in the vicinity of the earth.

B. Necessary Geographic Location

The theoretical properties of the geomagnetic field as a magnetic spectrometer are summarized by Alpher.[1] A special feature of the theory is that the critical value of magnetic rigidity R_c, which a particle must possess in order to reach the top of the atmosphere at a specified location, diminishes with increasing geomagnetic lati-

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‡ Present address: U. S. Naval Research Laboratory, Washington 25, D. C.

[1] R. A. Alpher, J. Geophys. Research **55**, 437 (1950).

tude λ and approaches zero as λ approaches 90° north or south. For vertical incidence at high latitudes, the critical value of magnetic rigidity is given to good accuracy by the Störmer relation:

$$R_c = 14.8 \cos^4\lambda, \tag{1}$$

where R_c is measured in units of 10^9 volts (i.e., in Bv).

It is therefore important to make experimental measurements at the highest possible latitudes in order to extend knowledge of the low-rigidity portion of the primary spectrum.

In the present paper, geomagnetic latitudes[2,3] in the centered-dipole representation are denoted by λ′; and in the eccentric-dipole representation, by λ.

C. Necessary Altitude

While the earth's magnetic field determines the geographic position at which measurement of the intensity of any low-rigidity primaries must be made, absorption by the earth's atmosphere determines the minimum altitude necessary.[4,5]

Present-day balloon techniques seldom provide measuring conditions at an atmospheric pressure depth of less than 10 g/cm². This depth is equal to the ionization range of a vertically arriving proton of 0.46-Bv rigidity, for example. A useful summary of the limitations of balloon-borne apparatus can be obtained as follows: The ionization ranges h of stripped nuclei of specified rigidity and of various atomic numbers Z can conveniently be obtained from the graphs of Rossi.[6] Then the minimum magnetic rigidity R_c which a particle must possess to arrive vertically at a specified geomagnetic latitude λ can be calculated with Eq. (1). By means of these two sets of data one can then list the geomagnetic latitude at which the value of R_c for vertical incidence corresponds to the air range h for vertical travel down through the residual atmosphere to the apparatus. Such a listing (Table I) may be said to give the geomagnetic latitude "equivalent" to a given atmospheric depth (or absorber thickness).

On the reasonable assumption that primaries of these low values of rigidity (and energy) are unable to make their existence evident (as by production of long range secondaries) at depths greater than their ionization ranges, it is evident from Table I that it is fruitless with present day balloon techniques to attempt measurements on the proton component of the primary beam at latitudes higher than 65°; or on the heavy components, at latitudes higher than about 52–56°, depending upon the value of Z.

TABLE I. Geomagnetic latitudes such that R_c for vertical incidence corresponds to ionization range h for representative stripped nuclei.

Primary nucleus \ h	0.5 g/cm²	10 g/cm²	20 g/cm²
H	70°	65°	63°
He	66	60	58
N	64	56	54
Mg	63	55	52
Ca	62	53	50
Fe	61	52	48

In particular, there is no reasonable prospect that balloon measurements will extend the known primary spectrum to magnetic rigidities less than 0.5 Bv for any component.[4]

II. EXPERIMENTAL MATTERS

A. Attainment of High Altitudes

In order to extend knowledge of the primary spectrum to lower rigidities we have employed the Iowa balloon-launched rocket ("rockoon") technique.[5,7]

B. Nature of the Apparatus

In choosing between a single Geiger counter and a Geiger counter coincidence telescope for these measurements we were led to adopt the former by several practical considerations:

(a) The angular motion of free-flying rockets in a near vacuum is usually complex and unpredictable. For this reason it is necessary to provide auxiliary instrumentation—such as a magnetometer and an array of photoelectric cells—for continuous aspect measurement in order to be able to interpret directional measurements.[8] Such complexity entails considerable technical difficulty of achievement in the small pay-volume and pay-load available.

(b) The statistical accuracy of telescope data from a brief rocket flight, after necessary subdivision into intervals of azimuthal and zenith angles, is not high.

(c) The stopping power of a telescope is almost inevitably several times greater than that of a single counter.

(d) Single Geiger counters have been shown to provide reliable absolute measurements of total charged particle intensity. A statistical accuracy of about 1 percent in the intensity above the appreciable atmosphere can be obtained in a typical rocket flight. Furthermore, a single Geiger counter is a sufficiently isotropic detector that it is unnecessary to know its orientation during

[2] S. Chapman and J. Bartels, *Geomagnetism* (The Clarendon Press, Oxford, 1940), Vol. 2.

[3] Vestine, Laporte, Lange, Cooper, and Hendrik, Carnegie Institution of Washington Publication 578, 1947 (unpublished); and Vestine, Laporte, Lange, and Scott, Carnegie Institution of Washington Publication 580, 1947 (unpublished).

[4] J. A. Van Allen and S. F. Singer, Nature **170**, 62 (1952).

[5] J. A. Van Allen, Nuovo cimento **10**, 630 (1953), a preliminary account of part of the present work.

[6] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1952), pp. 40, 41.

[7] J. A. Van Allen and M. B. Gottlieb, *Rocket Exploration of the Upper Atmosphere*, edited by R. L. F. Boyd and M. J. Seaton (Pergamon Press, London, 1954), pp. 53–64.

[8] J. A. Van Allen, *Physics and Medicine of the Upper Atmosphere*, edited by C. S. White and O. O. Benson, Jr., (University of New Mexico Press, Albuquerque, 1952), pp. 412–431.

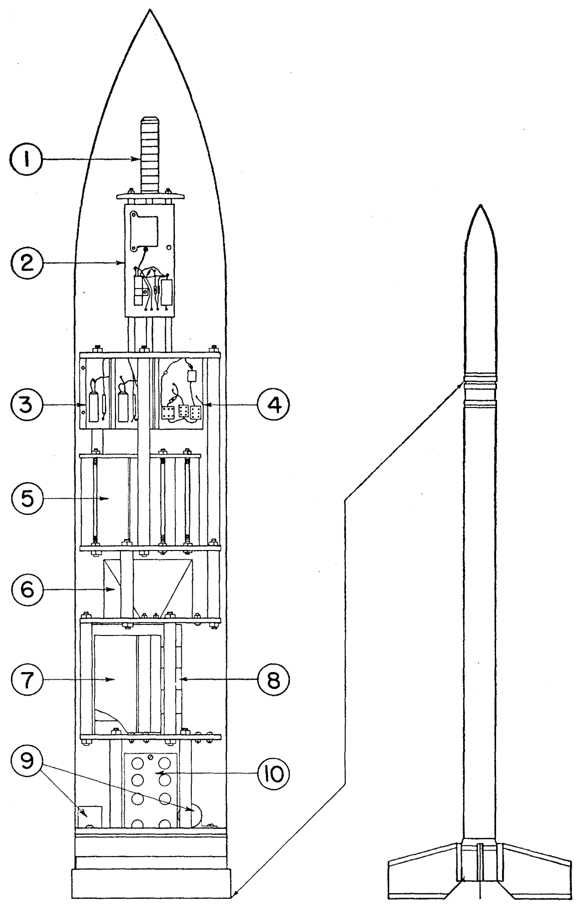

FIG. 1. Physical arrangement of equipment in the rocket. Diameter of nose shell was 6.5 inches. 1. Single Victoreen 1B85 Geiger Counter. 2. Thin fiber plate and cathode follower. 3. Scale-of-thirty-two circuit. 4. Variable frequency audio-oscillator (sub-carrier oscillator) which frequency modulates the radio transmitter. 5, 6, 7, 8, and 9. Miscellaneous batteries for circuit power. 10. Radio telemetering transmitter.

the high-altitude portion of the rocket flight, where the incidence of the radiation is only mildly anisotropic.

C. Geometric Factor of the Geiger Counter

The Victoreen 1B85 Geiger counter was selected for these measurements principally because of its thin wall (30 mg/cm^2 of aluminum).

The average unidirectional intensity over the upper hemisphere is defined by

$$\bar{J}=\frac{1}{2\pi}\int_0^{2\pi}\int_0^{\pi/2} J(\theta,\varphi)\,\sin\theta d\theta d\varphi, \tag{2}$$

wherein $J(\theta,\varphi)$ is the unidirectional intensity at zenith angle θ, azimuthal angle φ, and where it is understood that any upward moving radiation is arbitrarily assigned to the θ, φ of its reversed trajectory.

The counting rate N of a Geiger counter may be written as

$$N=\epsilon G\bar{J}. \tag{3}$$

The efficiency is denoted by ϵ and the geometric factor G is, in general, a function of the angular distribution of the radiation, the orientation of the counter, and its effective length l and effective diameter a.

The value of G for a cylindrical counter of any orientation in a field in which the unidirectional intensity is isotropic over one hemisphere, zero over the other is

$$G_{\text{iso}}=0.5\pi^2 al(1+a/2l). \tag{4}$$

It is easily shown that, for the observed angular distributions of radiation above the atmosphere at various latitudes and for the l/a ($\sim$3.5) of our counters, the quantity

$$N/\epsilon G_{\text{iso}} \tag{5}$$

does not differ from the true $\bar{J}$ by as much as 1 percent in a typical rocket flight. Hence we are justified in using Eq. (3) with $G=G_{\text{iso}}$ for the calculation of $\bar{J}$ from the observed counting rate N on the high altitude plateau.[9–11] This simplification does not obtain, of course, within the lower atmosphere where the angular distribution of radiation intensity is markedly anisotropic.

In order to calculate $\bar{J}$ from N we then must know a, l, and ϵ. It has been found by other investigators[12,13] that the effective diameter of a Geiger counter is within 0.01 cm of its physical inside diameter. The physical inside diameter of the 1B85's was measured to be 1.91 ± 0.01 cm and the effective diameter was taken to be

$$a=1.91\pm0.02 \text{ cm}. \tag{6}$$

The effective lengths of individual Geiger counters and their efficiencies were determined experimentally.[14] A tabulation of effective lengths and of the quantity ϵG_{iso} is given in Table II.

In view of the earlier discussion, $\bar{J}$ above the atmosphere was calculated from the observed counting rates on the high-altitude plateau by using Eq. (3) with $G=G_{\text{iso}}$. The corrections for counter dead-time and loss of counts in the circuits were negligible.

It was necessary to use a different set of instrumentation for each rocket flight as no recovery was attempted. The individual sets were intercompared by measuring the counting rate of each set when a standard radioactive source was placed a standard distance from it. The counting rates of the individual sets were proportional to the effective length of the Geiger counter used within the statistical uncertainty of 0.5 percent.

[9] J. A. Van Allen and H. E. Tatel, Phys. Rev. **73**, 245 (1948).
[10] Gangnes, Jenkins, and Van Allen, Phys. Rev. **75**, 57 (1949).
[11] G. J. Perlow and C. W. Kissinger, Phys. Rev. **81**, 552 (1951).
[12] J. C. Street and R. H. Woodward, Phys. Rev. **46**, 1029 (1934).
[13] K. Greisen and N. Nereson, Phys. Rev. **62**, 316 (1942).
[14] Miscellaneous experimental details are described by L. H. Meredith, Doctoral Dissertation, State University of Iowa, 1954 (unpublished).

D. Radio Telemetering System

Throughout the balloon-borne phase and the free-flight phase of the rocket's flight, the counting rate of the Geiger counter was transmitted to a receiving station on the launching ship[15] by a radio telemetering system. The Geiger counter pulses were fed directly to a cathode follower and from this to a scale of thirty-two circuit.[16] Pulses from this scaler were used to shift the frequency of a 3900-cps subcarrier oscillator. The oscillator output then frequency modulated a 76 megacycle per second rf transmitter. The transmitting antenna consisted of two portions of the rocket itself: the nose shell (about 36 in. in length) was electrically insulated from the afterbody. The transmitter was arranged to produce an rf potential difference between these two portions, giving a quite suitable radiation pattern with cylindrical symmetry about the rocket axis.

At the receiving station the rf signal was received by a directional two-stack Yagi antenna and fed to a Clarke Instrument Company 167-J high quality FM receiver. The receiver's audio-frequency output was put through a band-pass filter to a discriminator. This discriminator yielded a voltage pulse for each transient audio-frequency shift. These pulses were amplified by a Brush Electronics Company BL-905 amplifier and then recorded on the moving paper strip of a Brush BL-202 inking oscillograph. A simultaneous recording was made on the same paper strip of time signals which occurred at five second intervals. This telemetering system was similar to that described by Coor.[17]

E. Physical Arrangement

The physical arrangement of the equipment in the rocket is shown in Fig. 1. The equipment was mounted on circular plates which were $\frac{3}{8}$ in. thick. The upper three of these plates were of Dow metal while the lower one, which supported the lead storage battery, was of steel. The plates were supported by $\frac{1}{2}$ in. diameter brass posts. To prevent corona the nose shell was sealed pressure-tight with an "O"-ring to maintain sea-level pressure throughout flight.

TABLE II. Effective lengths and geometric factors of Geiger counters.

Flight number	Counter effective length (cm)	ϵG_{iso} (cm^2 steradian)
White Sands	6.70±0.08	70.7±1.1
S.U.I.-2	6.60±0.08	69.8±1.1
S.U.I.-4	6.60±0.08	69.8±1.1
S.U.I.-5	6.60±0.08	69.8±1.1
S.U.I.-23	6.20±0.08	66.1±1.1

[15] The U. S. Coast Guard Cutter Eastwind (WAGB-279), an icebreaker.

[16] Rugged subminiature tubes (Raytheon CK5678's) were used in a circuit adapted from one kindly sent us by J. A. Simpson.

[17] T. Coor, Doctoral Dissertation, Princeton University, 1948 (unpublished).

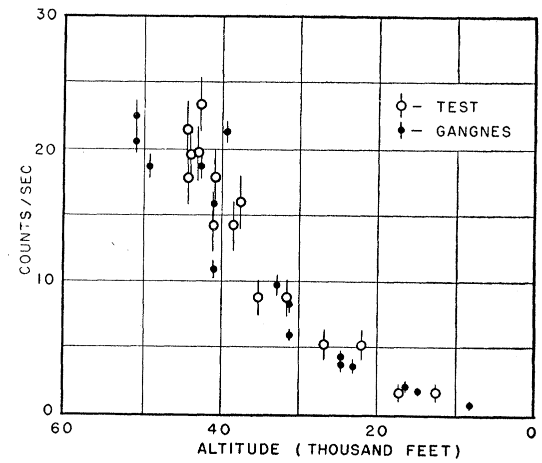

FIG. 2. Comparison of test flight results (open circles) of present equipment at White Sands, New Mexico with previous results (solid circles) at same location. See text and reference 10.

From Fig. 1, it can be seen that the Geiger counter was located at the apex of the instrumentation and was well isolated from any masses of material. The polystyrene supporting disk at the lower end of the counter was 2 in. in diameter and 0.2 in. in thickness. The aluminum nose shell was 0.050 in. in thickness. These thicknesses were judged to be the minimum values sufficient to provide the necessary strength.

Minimum thicknesses were desired for two reasons. The first was to reduce the contribution of locally produced secondaries to the measured counting rate. In this connection it should be mentioned that the body of the rocket subtended less than 2 percent of the total solid angle seen by the Geiger counter. The second was to reduce to the lowest practical value the amount of material which a particle must traverse before reaching the active volume of the Geiger counter. It was for this latter purpose that thin walled Victoreen 1B85 Geiger counters were selected. By means of detailed path length calculations on the exact physical arrangement it was found that the minimum thickness of material which a particle had to traverse to reach the active volume of the counter was 0.4 g/cm^2. With the rocket in nose-up aspect 90 percent of the radiation experienced a path length of less than 0.5 g/cm^2; whereas in nose-down aspect, 60 percent experienced a path length less than 0.5 g/cm^2. Hence we adopted 0.5 g/cm^2 of aluminum as the effective apparatus thickness.

F. Preliminary Flights

An initial test firing of one complete set of instrumentation was made in a Deacon rocket nearly identical with those later to be used in the flights at northern latitudes. The rocket was launched from a short tower mounted on the ground at the White Sands Proving Ground. The firing was conducted by the staff of the Naval Ordnance Missile Test Facility at 0645 M.S.T. on June 26, 1952. Operation of the equipment was

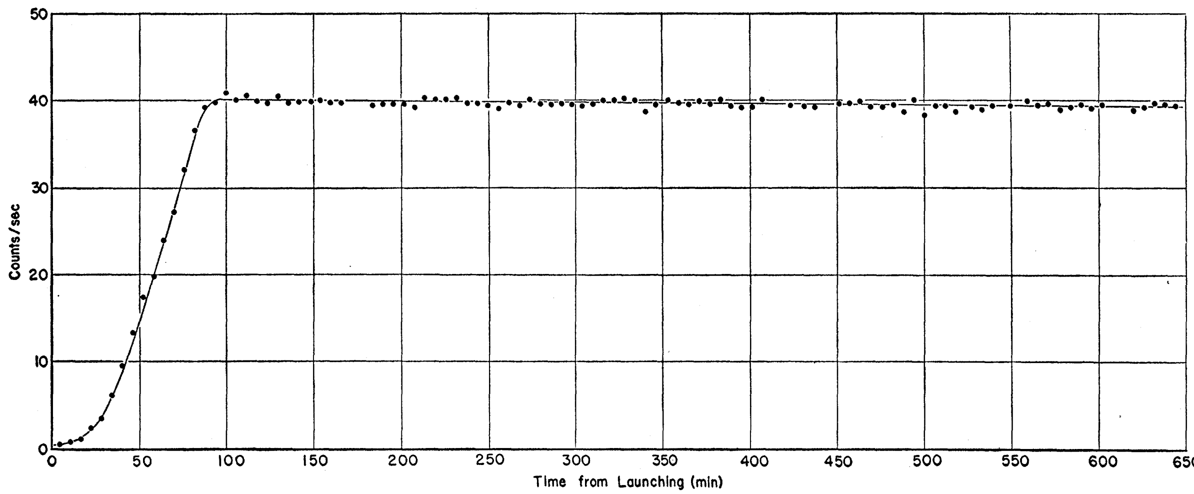

FIG. 3. Counting rate data obtained in a balloon-rocket flight in which the rocket failed to fire. $\lambda = 87°$ N. S.U.I.-2 of August 24, 1952.

satisfactory. The observed counting rate of the Geiger counter as a function of altitude is shown in Fig. 2; tracking data furnished by the N.O.M.T.F. were used in converting the observed counting rate *vs* time data to an altitude above sea level basis.

Also shown for comparison on Fig. 2 are similar data previously obtained by Gangnes, Jenkins, and Van Allen[10] at the same location. These previous results, obtained with a single Geiger counter of different dimensions, were normalized on an absolute basis to the size of a 1B85 counter by using the appropriate geometric factors. There is seen to be satisfactory agreement between the two sets of data.

A flight test on how long the entire system would operate properly on the batteries used was obtained in a balloon rocket flight made at $\lambda = 87°$. In this flight the rocket failed to fire due to a defective firing circuit. Figure 3 shows the results obtained. It can be seen that

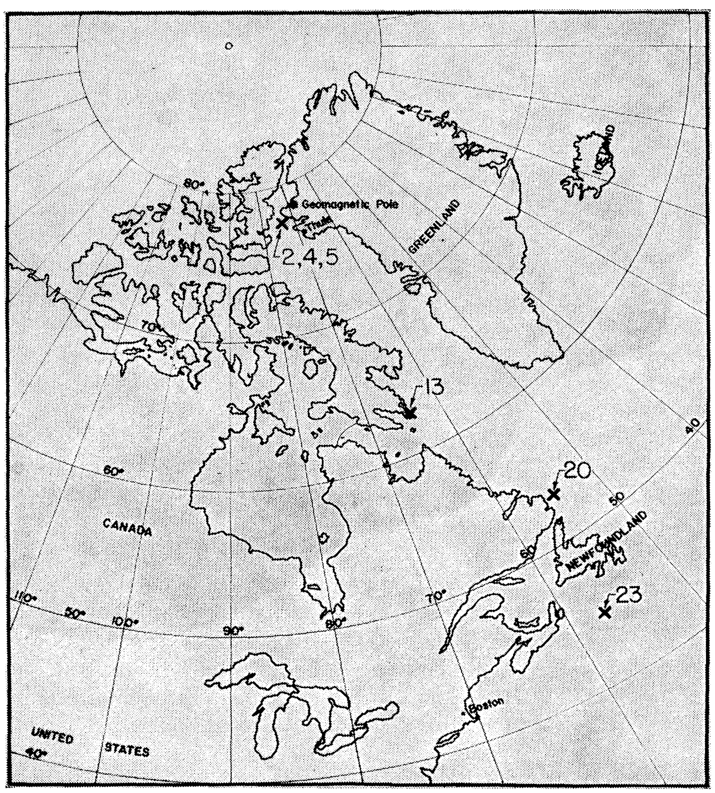

FIG. 4. Chart showing geographic location of rockoon flights.

TABLE III. General flight data.

Flight No.	S.U.I.-2	S.U.I.-4	S.U.I.-5	S.U.I.-23
Geographic latitude and longitude of balloon launching	77° 31′ N 73° 30′ W	77° 32′ N 73° 29.5′ W	77° 21′ N 73° 29′ W	44° 33′ N 57° 03′ W
Geomagnetic latitude of balloon launching				
(a) Per centered dipole	88.5°	88.5°	88.5°	56.5°
(b) Per eccentric dipole	86.7°	86.7°	86.7°	54.3°
Time of rocket firing	Rocket did not fire. Balloon launched at 0334 G.C.T.	0830 G.C.T.	1917 G.C.T.	1510 G.C.T.
Date	24 Aug. 1952	29 Aug. 1952	29 Aug. 1952	3 Sept. 1953

for nine hours the counting rate was nearly constant at 39.5 counts/second. The small counting rate decrease was attributed to a slow descent of the balloon and rocket. During this period the rocket altitude was about 21.3 km (45 g/cm^2). This flight also demonstrated the adequacy of the arrangements for maintaining the temperature of the rocket in the range of proper operability. In addition, the data are of value for comparison with data from subsequent rocket flights.

The termination of the data was caused by the fading of the transmitter signal. This could have been caused by the passage of the apparatus over the radio horizon or by a transmitter battery failure. In either case Fig. 3 shows the system could operate on the batteries used for at least 10.7 hours after launching. The complete system was set in operation about a half hour before launching. For the flights in which the rocket fired the total time of operation of the equipment was an hour and a half to two hours. The system then had a safety factor in its length of operation of about six.

III. RESULTS

A. General Flight Data

The locations of the launchings of the "rockoon" flights are shown in Fig. 4. In this figure, the number

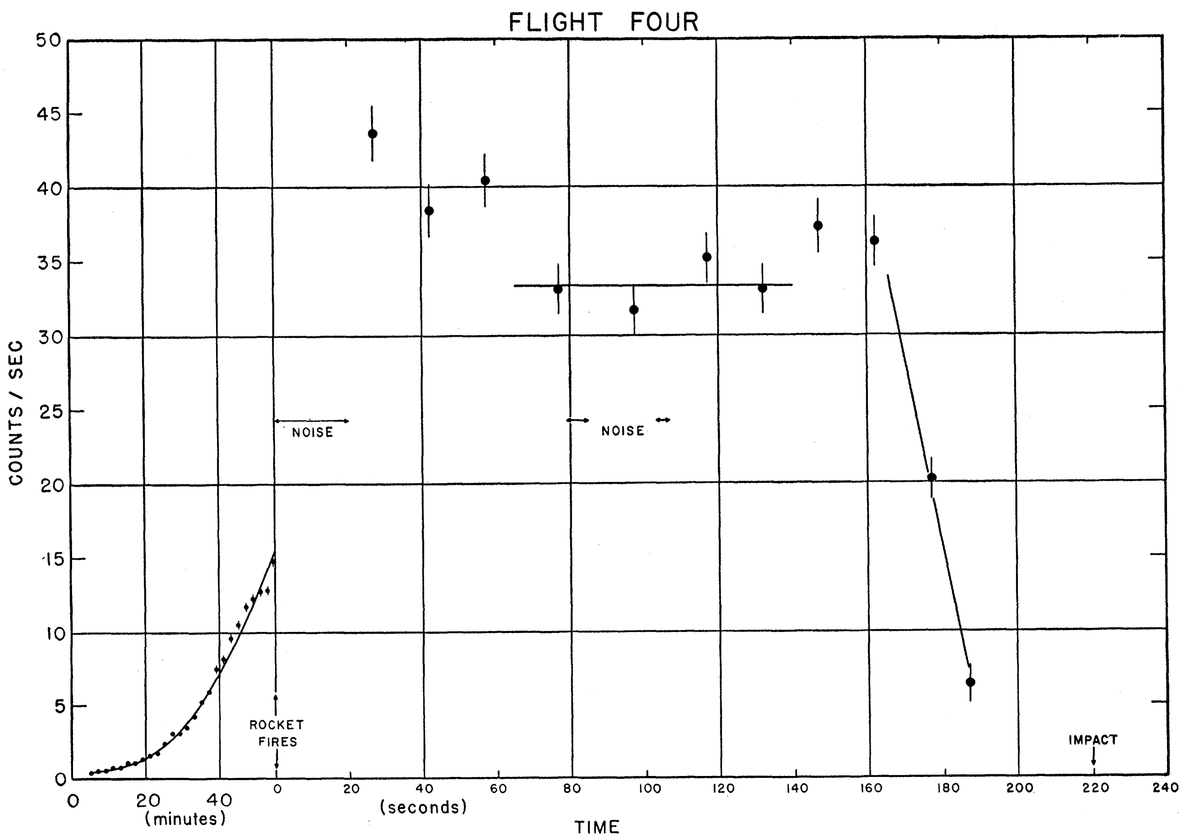

FIG. 5. Counting rate of single Geiger counter as a function of time of flight. S.U.I.-4 of August 29, 1952. $\lambda = 86.7°$ N. For the first 54 minutes the rocket was being lifted by a General Mills Type 551 balloon. The remainder of the data was recorded during flight of the rocket to high altitude and return to the sea. Note 60-fold expansion of time scale during latter period.

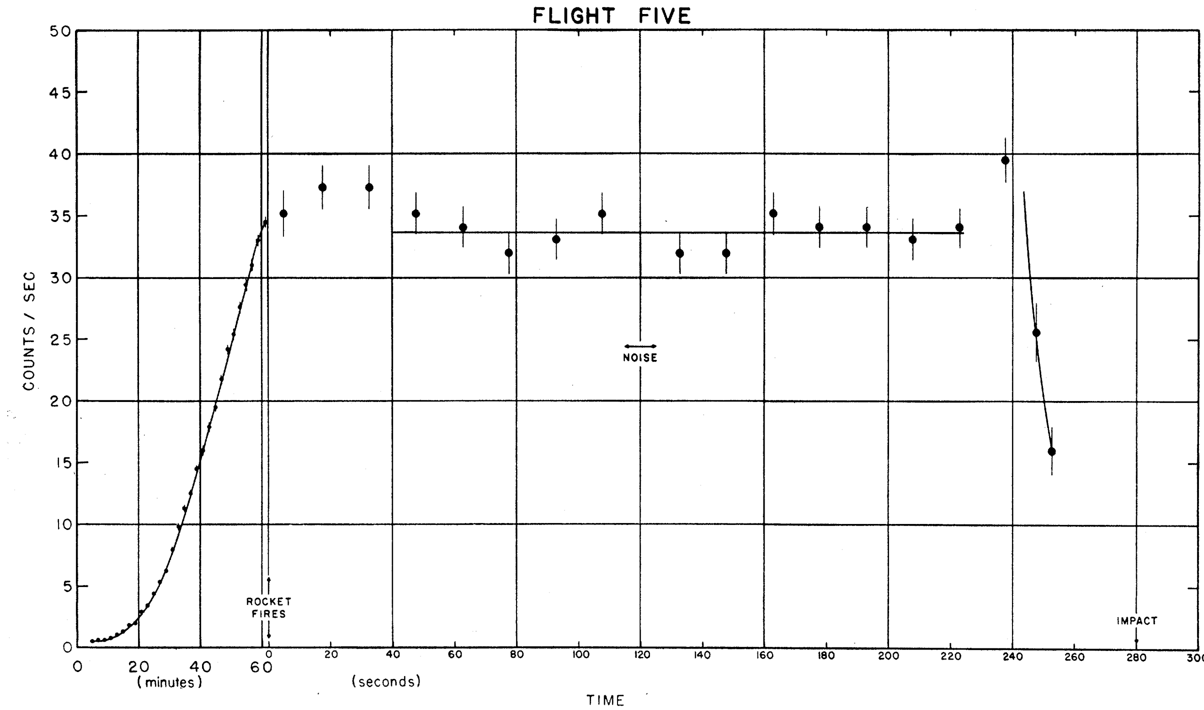

FIG. 6. Counting rate of single Geiger counter as a function of time of flight. S.U.I.-5 of August 29, 1952. $\lambda = 86.7°$ N. Rocket fired at 62 minutes after release of rocket-balloon system from ship.

two indicates the launching position of the previously described flight in which the rocket failed to fire. Numbers four, five, and twenty-three give the locations at which successful single counter rocket firings were made. A summary of the data relevant to the time and location of these flights is given in Table III.

In Table III geomagnetic latitudes are given in both the centered- and eccentric-dipole approximations. The latter is taken to give the true geomagnetic latitude, λ.

The latitude of the flights given in Table III are those at which the rockoons were launched. In every case the rockoon drifted approximately along a line of constant geomagnetic latitude. Also, the flight duration before the rocket fired was only about an hour. For these two reasons the geomagnetic latitude of firing was taken to be the same as the latitude of launching.

B. Observed Counting Rates and Discussion of Validity

In Figs. 5, 6, and 7 are shown the counting rates observed in flights four, five, and twenty-three, respectively. To better exhibit the data, the time scale for the period after the rocket fired has been expanded by a factor of sixty over that used during the balloon portion of the flight. Brief portions of the flight during which noise due to poor radio reception obscured the scaler pulses have been designated by "noise." In all other portions of the flight an excellent clear record was obtained. That all the pulses were from the scaler was verified by their characteristic height and shape and also by the appearance of a small pulse of the opposite polarity between each scale of thirty-two pulse. This small pulse corresponded to a scale of sixteen.

From Figs. 5, 6 and 7 it can be seen that after the rocket fires the counting rate goes through two maxima. These are separated by a plateau region in which the counting rate is constant. The interpretation of these counting rate curves is that the two maxima correspond to the passage of the rocket through the Regener-Pfotzer transition maximum on the ascent and descent respectively. The constant counting rate on the plateau is interpreted[9] as being due to the cosmic ray intensity above the appreciable atmosphere.

Under the primitive circumstances of the flights no facilities were available for tracking the rocket in its flight. Such tracking is not essential to these experiments, of course. Nonetheless, a worthwhile validity check on the time duration of the high-altitude plateaus can be made by an approximate ballistic calculation. In the case of flights four and five, the firing altitude was estimated by comparing the Geiger counting rate at the instant of firing with the rate in similar flights which were equipped with radio sonde barographs. The subsequent altitude-time curve was then calculated numerically[18] assuming vertical flight and using the rocket performance characteristics and drag data obtained in the White Sands flight previously mentioned.

[18] The authors are indebted to Mr. E. C. Ray and Mr. R. M. Missert for these calculations.

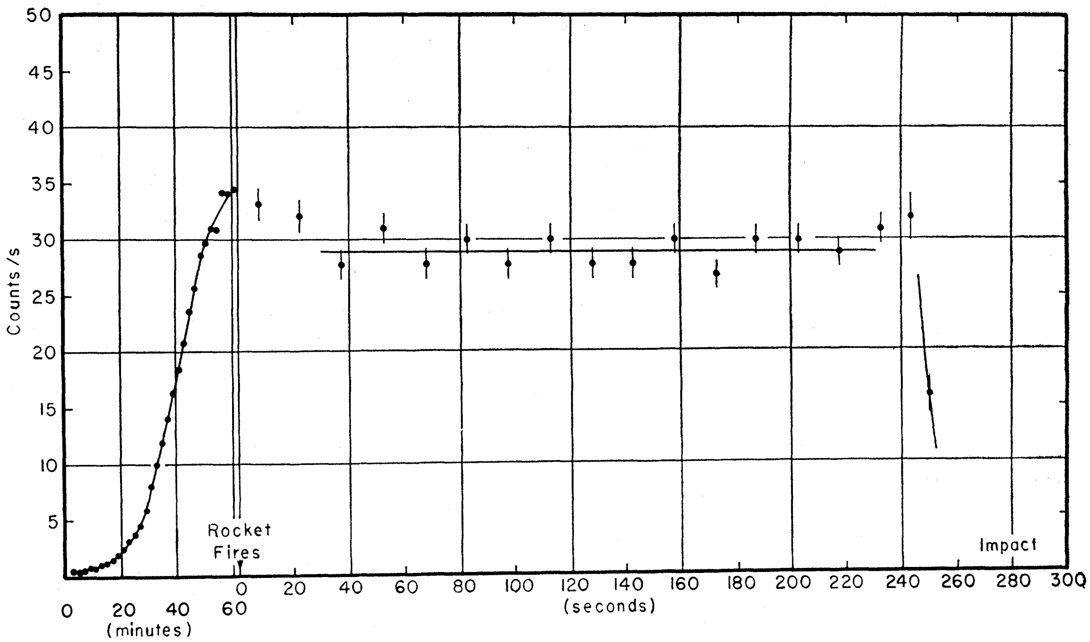

FIG. 7. Counting rate of single Geiger counter as a function of time of flight. S.U.I.-23 of September 3, 1953. $\lambda = 54.3°$ N. Rocket fired at 62 minutes after release of rocket-balloon system from ship.

The firing altitude of Flight 23 was known from radio sonde data. Pertinent results of these calculations are tabulated in Table IV. Also included in this table are the observed plateau durations as found from Figs. 5, 6 and 7. It is evident that the observed plateau durations are in adequate agreement with the calculated flight time above 50 km. The onset of the high-altitude plateau has been previously found[10] to occur at just this altitude (at lower latitudes).

A further over-all check was made by plotting the distribution of time intervals between successive pulses on the plateau. This distribution was in excellent agreement with that expected from a scale-of-thirty-two circuit whose input was a Poisson distribution of individual pulses with constant average rate of arrival; and it was in definite disagreement with the broader distribution to be expected from any significant occurrence of bursts of corona, microphonism, intermittent circuit operation, etc.

The satisfactory agreement of the data for the up and down legs of the flight is also a good indication of trustworthiness.

The greater time duration of the transition maximum on the ascent than on the descent of Flights 5 and 23 is attributable to lack of precision of knowledge of the firing time of the rocket and to the three second accelerative period of the rocket on the ascent. No sharply defined telemetering indication of the instant of firing occurred; the firing time was crudely estimated from the more rapid time-rate-of-change of the intensity of the rf telemetering signal which occurs during the rocket phase of the flight. A precise determination of the firing time is, of course, not essential to the accuracy of the plateau data.

Our own data provide no information as to whether the flights were made at times when the cosmic-ray intensity differed appreciably from its average value. But Simpson[19] has kindly informed us of the neutron intensities at Climax, Colorado, at the times of our flights. These neutron intensities are given in Table V. Neher and Forbush[20] have demonstrated that the fluctuations in the rate of ionization at high balloon altitudes are closely correlated with the fluctuations in neutron intensity at Climax. The fractional fluctuation of the former is two to three times as great as that of the latter. The last line of Table V was calculated using a factor of three in order to obtain a generous estimate. Thus Table V shows that our omnidirectional intensities above the atmosphere (Flights 4, 5 and 23) probably do not differ from their long term average values by more than one percent. No explicit correction was applied to our data.

C. Hemispherical Average Unidirectional Intensity at $\lambda = 86.7°$ N

The counting rates on the plateau of Flights 4 and 5 are 33.3 ± 0.8 and 33.6 ± 0.5 counts per second respectively, being in agreement within their small statistical uncertainties. (Geometric factors of respective counters identical.) Combining these results with proper relative weight we obtain a plateau counting rate of 33.5 ± 0.4

[19] J. A. Simpson (private communication).
[20] H. V. Neher and S. E. Forbush, Phys. Rev. 88, 889 (1952).

TABLE IV. Observed and calculated ballistic data.

Flight number	S.U.I.-4	S.U.I.-5	S.U.I.-23
Altitude of launching of rocket above M.S.L.	11.0 km	17.4 km	20.1 km
Calculated summit altitude above M.S.L.	55 km	90 km	98 km
Calculated duration of rocket's flight above 50 km	64 sec	181 sec	198 sec
Measured plateau duration	76 sec	184 sec	200 sec

counts per second. Then using Eq. (3) and the values of ϵG_{iso} from Table II, we obtain

$$\bar{J}=0.48\pm0.01\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (7)$$

at $\lambda=86.7°$ N. This is the absolute value of the hemispherical average unidirectional intensity above the appreciable atmosphere in the sense of Eq. (2).

D. Hemispherical Average Unidirectional Intensity at $\lambda=54.3°$ N

Similarly, from the observed counting rate of 28.8 ±0.4 counts per second on the high-altitude plateau of Flight 23, we obtain

$$\bar{J}=0.44\pm0.01\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (8)$$

at $\lambda=54.3°$ N. The errors indicated in (7) and (8) encompass statistical counting errors and errors in knowledge of ϵG_{iso}.

E. Hemispherical Average Unidirectional Intensity at $\lambda=62.1°$ N and $\lambda=71.9°$ N

Two other successful rockoon flights (S.U.I.-20 and S.U.I.-13) of identical apparatus were made during the 1953 expedition. The flights at $\lambda=62.1°$ N and 71.9° N respectively were made in the auroral zone. Inasmuch as the results of these flights have provided direct evidence for a considerable intensity of low-energy radiation (apparently of auroral character) above 50 km, a separate communication has been devoted to their detailed presentation.[21] But they also provide values of $\bar{J}$ pertinent to the present investigation. The values are less accurate than those quoted in the preceding sections but are worthy of inclusion. They are

$$\bar{J}\leq0.50\pm0.05\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (9)$$

at $\lambda=62.1°$ N, and

$$\bar{J}\leq0.50\pm0.05\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (10)$$

at $\lambda=71.9°$ N.

F. Comparable Previous Results in this Latitude Region

Comparable values of $\bar{J}$ have been previously derived from results of directional coincidence telescope measurements at $\lambda=52.2°$ N and $\lambda=59.3°$ N. These measurements were made with Aerobee rockets on a cruise of the U.S.S. Norton Sound (AV-11) in January, 1950 in the Pacific Ocean and the Gulf of Alaska.[5] Apparatus stopping powers were about 3 g/cm² of copper and aluminum. The results were:

$$\bar{J}=0.31\pm0.03\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (11)$$

at $\lambda=52.2°$ N, and

$$\bar{J}=0.41\pm0.03\ (\mathrm{cm^2\ sec\ steradian})^{-1} \qquad (12)$$

at $\lambda=59.3°$ N.

IV. SUMMARY AND DISCUSSION

A. Tabular Summary of Observed Data

The values of $\bar{J}$ above the atmosphere (7), (8), (9), (10), (11), (12) and others previously reported[10,22] are

TABLE V. Neutron intensity data at Climax, Colorado (after Simpson).[a]

Flight No.	S.U.I.-2	S.U.I.-4	S.U.I.-5	S.U.I.-23
Firing time	Aug. 24, 1952 (See Table III)	Aug. 29, 1952 0830 G.C.T.	Aug. 29, 1952 1917 G.C.T.	Sept. 3, 1953 1510 G.C.T.
Average neutron intensity during hour of measurement	0530 to 1330: 3550	0800 to 0900: 3593	1900 to 2000: 3597	1500 to 1600: 3627[b]
Long term average hourly rate[c]	3589.8	3589.8	3589.8	3639.7[b]
Percent difference between neutron intensity during flight and average value	−1.1%	+0.09%	+0.20%	−0.35%
Presumed percent difference between measured and average charged particle intensities above atmosphere	−3.3%	+0.3%	+0.6%	−1.0%

[a] See reference 19.
[b] These rates were measured with a different pile than that in use during Flights 2, 4, and 5. The rate has, however, been normalized to the pile used at the time of Flights 2, 4, and 5. This normalization has an uncertainty of ±0.5 percent.
[c] For Flights 2, 4, and 5 this rate was obtained by averaging the neutron intensity for the period July 24–September 1, 1952. For Flight 23 the rate was the average neutron intensity for the period spanned by ±20 days of the firing day.

[21] Meredith, Gottlieb, and Van Allen, Phys. Rev. 97, 201 (1955).
[22] J. A. Van Allen and A. V. Gangnes, Phys. Rev. 78, 50 (1950).

summarized in Table VI and plotted in Fig. 8. The reader is cautioned to distinguish the raw experimental value of $\bar{J}$ above the atmosphere from the vertical intensity $J(0°)$ and from the best direct estimate of the primary intensity J_P.

B. Remarks on Interpretation

It is evident that there is only a slight increase in total cosmic-ray intensity above the atmosphere as one goes north of $\lambda = 55°$ N. In this respect our results are concordant with those of Carmichael and Dymond,[23] Pomerantz and McClure[24] and Neher, Peterson, and Stern.[25] In particular, the ionization chamber work of Neher and his associates places the latitude knee at $\lambda' = 58°$ N or $\lambda = 57°$ N. By virtue of the considerably reduced stopping power of our apparatus plus residual atmosphere (total of 0.5 g/cm^2) in contrast to that of previous balloon investigators (10 to 15 g/cm^2), it is now possible to extend considerably and to make more certain the low-rigidity end of the primary cosmic-ray spectrum.

Several general points should be noted:

(1) The interpretation of all gross "latitude effects" into information pertaining to the rigidity (or energy) spectrum of the primary radiation has essential dependence on geomagnetic theory.[1] If presently accepted geomagnetic theory is found to contain important omissions or errors then the interpretation will be correspondingly in error.

(2) Our measurements are limited in temporal extension and may not provide a full picture of long term conditions.

(3) Single Geiger counters measure effectively the omnidirectional intensity. Hence the observed values of $\bar{J}$ previously reported comprise comparable contributions from primary radiation and from secondary radiation (atmospheric "albedo"). That is, we may write

$$\bar{J} = \bar{J}_P + \bar{J}_A, \qquad (13)$$

where the subscripts P and A denote primary and albedo radiation respectively.

(4) Total intensity measurements such as the present ones are of no useful significance with respect to heavy primaries ($Z > 2$) due to the low relative intensity of heavies in the primary beam. Rather, they pertain to the major components—protons and alpha particles. A separate investigation of the low-rigidity end of the spectra of heavy primaries is reported elsewhere.[26]

(5) Even if there is a cutoff in the spectra of the principal components of the primary radiation at a magnetic rigidity $R_{\min}$—corresponding to the geomagnetic cutoff in the vertical direction at some latitude λ—it is predicted by geomagnetic theory that $\bar{J}_P$ will continue to increase substantially as one goes to higher latitudes than λ. This expected increase is due to the progressive opening up of the "earth's shadow cone." At latitudes such as $\lambda = 55°$ the shadow cone is responsible for much higher values of R_c at large zenith angles than the vertical value. Only at $\lambda = 90°$ does R_c go to zero for all θ and φ.

(6) For analytical purposes it is helpful to consider the albedo radiation at any point above the atmosphere to be divided into two categories: (a) "splash albedo," upward moving secondary radiation arising from nuclear collisions of primaries in the atmosphere and (b) "re-entrant albedo," downward moving secondary radiation of the same origin which has been unable to escape from the earth's field and which is therefore returning to the atmosphere.

(7) The intensity of splash albedo is calculable, in principle, from data on the angular distribution and intensities of primaries, on the cross sections for interaction, on the multiplicity, angular distribution, energies and nature of the secondaries, etc. Unfortunately, the existing experimental data are still too meager to permit a satisfactory calculation. Nonetheless, it is illuminating

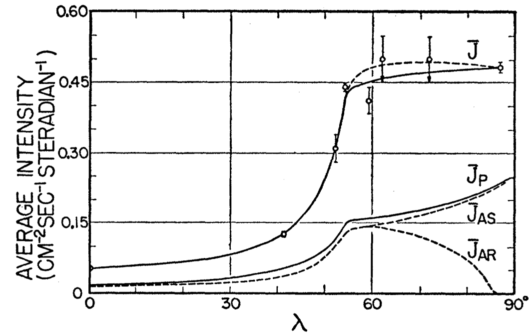

FIG. 8. Summary plot of observed total unidirectional intensity (averaged over upper hemisphere) $\bar{J}$ above the atmosphere at various latitudes, and the analysis into primary radiation $\bar{J}_P$, splash albedo $\bar{J}_{AS}$, and re-entrant albedo $\bar{J}_{AR}$. $\bar{J} = \bar{J}_P + \bar{J}_{AS} + \bar{J}_{AR}$. See Sec. IV of text.

TABLE VI. Observed unidirectional intensity above the atmosphere averaged over upper hemisphere.

Geomagnetic latitude—λ	$\bar{J}$ (cm^2 sec steradian)$^{-1}$	Reference
0	0.053±0.002	a
41° N	0.120±0.009	b
52.2° N	0.31 ±0.03	c
54.3° N	0.44 ±0.01	d
59.3° N	0.41 ±0.03	c
62.1° N	0.50 ±0.05	e
71.9° N	0.50 ±0.05	e
86.7° N	0.48 ±0.01	d

[a] See reference 22.
[b] See references 9, 10, 11.
[c] See reference 5.
[d] See present paper.
[e] See reference 21.

[23] H. Carmichael and E. G. Dymond, Proc. Roy. Soc. (London) **A171**, 321 (1939).
[24] M. A. Pomerantz and G. W. McClure, Phys. Rev. **86**, 536 (1952) and references to previous work therein.
[25] Neher, Peterson, and Stern, Phys. Rev. **90**, 655 (1953).
[26] Ellis, Gottlieb, and Van Allen, Phys. Rev. **95**, 147 (1954).

to carry out even a very crude calculation. This we have done along the following lines: the average angular distribution of grey and minimum-ionizing secondary tracks and their average multiplicity according to high-altitude balloon data of Salant, Hornbostel, and Blau[27] were adopted; the interaction mean free path of primaries in air was taken to be 100 g/cm^2; and all secondaries were taken to have an air range of 150 g/cm^2. From consideration of the generally forward collimation of the secondaries in an elementary act, it is evident that most of the splash albedo arises from primaries which are incident on the atmosphere at large zenith angles. By the same token, the intensity of the splash albedo is a minimum in the vertical direction; its intensity at large zenith angles is several times greater. In a specific calculation for isotropic incidence of primaries, we find that the contribution of albedo (splash) to the average intensity above the atmosphere is

$$\bar{J}_{AS}=0.3\bar{J}_P. \tag{14}$$

The bulk of the contribution comes from primaries arriving at zenith angles greater than 60°.

(8) The fate of the splash albedo in the earth's magnetic field is either return to the top of the atmosphere (thus becoming re-entrant albedo) or escape to infinity. In a valuable discussion of this matter Treiman[28] has shown that all splash albedo which originates at latitude λ and which does not satisfy the geomagnetic conditions for escape will return to the atmosphere at approximately the same latitude (in either the same or opposite hemisphere of the earth), the breadth of the zone of reentry being dependent on the magnetic rigidity of the radiation and on the angle of "emission." In a typical case this zone has a width of one or two degrees of latitude. Treiman conjectures that the re-entrant albedo returns more or less isotropically. Yet it is possible to see that in some simple cases (e.g., near the equator) that albedo which leaves at a large zenith angle will likewise return at a large zenith angle. Thus, it is reasonable to believe that there is some persistence of direction, though the tendency is toward isotropy of reentry. In view of the essential lack of interchange of albedo from one latitude to another and in consideration of the magnetic rigidities of typical secondaries one may conclude that approximately the ratio

$$\bar{J}_{AR}/\bar{J}_{AS}=1 \quad \text{for} \quad \lambda<55°, \tag{15}$$

wherein the subscript AR denotes albedo (re-entrant), and the subscript AS, albedo (splash). Toward higher latitudes, the ratio of $\bar{J}_{AR}/\bar{J}_{AS}$ progressively diminishes due to increasing ease of escape from the geomagnetic field until

$$\bar{J}_{AR}=0, \quad \text{at} \quad \lambda=90°. \tag{16}$$

These considerations are essential to our interpretation of the variation of $\bar{J}$ with λ.

(9) The total unidirectional intensity above the atmosphere *in the vertical direction* contains the least contribution of albedo, and therefore represents the best simply observable approximation to the true primary intensity at any latitude. Absolute measurements of the vertical unidirectional intensity above and near the effective top of the atmosphere have been reported by a number of workers.[29–31] The results of these measurements can be well represented[31] by the integral number-rigidity spectrum:

$$J(>R)=0.48R^{-1.1}, \quad 2\ \text{Bv}\leq R\leq 15\ \text{Bv}, \tag{17}$$

where $J(>R)$ gives the intensity in units of (cm^2 sec steradian)$^{-1}$ of particles whose magnetic rigidity exceeds $R(\equiv pc/Ze)$ Bv. Or, in the corresponding range of energy[29] (making the approximation $Z/A=1$ for all constituents),

$$J(>E)=0.37E^{-0.9}, \tag{18}$$

where E is kinetic energy in Bev and the units of J are as in (17).

It is a matter of great importance to determine experimentally the fraction of the vertical unidirectional intensity which is albedo. The experimental difficulties are formidable; but there are several investigations[32,33] at $\lambda'=40°$, 41° which make it reasonable to assume that about 0.85 of the total vertical unidirectional intensity is true primary radiation and about 0.15 of the total is albedo of splash and re-entrant types. We shall make the further tentative assumption that this proportion is independent of latitude.

C. First Trial Interpretation: No Spectral Cutoff

On the basis of the foregoing considerations it is assumed specifically that the integral primary spectrum is given by

$$J_P(>R)=0.41R^{-1.1}, \tag{19}$$

or by

$$J_P(>E)=0.31E^{-0.9}. \tag{20}$$

For a first trial interpretation it is further assumed that there is *no spectral cutoff*—e.g., spectra (19) and (20) continue to hold below the rigidity, or energy, for which they have been determined and do, indeed, hold for $R\rightarrow 0$, or $E\rightarrow 0$. Then, by using the details of geomagnetic theory and the range limitations of our apparatus, it is possible to calculate the expected latitude dependence of observable $\bar{J}_P$. The effective apparatus

[27] J. Hornbostel (private communication).
[28] S. B. Treiman, Phys. Rev. **91**, 957 (1953).
[29] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[30] M. Vidale and M. Schein, Nuovo cimento **8**, 1 (1951).
[31] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950); **80**, 116 (1950).
[32] S. E. Golian and E. H. Krause, Phys. Rev. **71**, 918 (1947); G. J. Perlow and J. D. Shipman, Phys. Rev. **71**, 325 (1947); Perlow, Davis, Kissinger, and Shipman, Phys. Rev. **88**, 321 (1952).
[33] J. R. Winckler and K. Anderson, Phys. Rev. **93**, 596 (1954).

thickness was 0.5 g/cm^2 of aluminum. This corresponds to the ionization range of a proton of kinetic energy 19 Mev or magnetic rigidity 0.19 Bv. The hemispherical average *primary* intensity, in the sense of Eq. (2) and as observable with our apparatus was calculated omitting any contribution from albedo. Such calculations give a lower limit of the total $\bar{J}$ to be expected under the prevailing assumption. The results of these calculations are that the extrapolated spectrum (19) leads to a lower limit of the expected intensity at $\lambda=87°$ of about *five times* that observed, and that the extrapolated spectrum (20) leads to a lower limit of expected intensity about *seventeen times* that observed.

Hence, without further refinement, we conclude that the assumptions of this section—namely no low-rigidity spectral cutoff and no change of spectral form at low rigidities—are overwhelmingly false.

D. Second Trial Interpretation: Sharp Spectral Cutoff at $R=1.7$ Bv

The assumption is now made that the integral primary spectrum is given by

$$\begin{aligned} &J_P(>R)=0.41R^{-1.1}, \quad 1.7\text{ Bv}\leq R<\infty; \\ &J_P(>R)=(0.41)(1.7)^{-1.1}=0.23, \quad R\leq 1.7\text{ Bv}. \end{aligned} \tag{21}$$

The foundations for this assumption are to be found in reference 31.

For simplicity of calculation, the spectral assumption of this section has been formalized in Eqs. (21) to a perfectly sharp break at $R=1.7$ Bv (vertical geomagnetic cutoff at $\lambda=54°$). It may well be that a rounding of the spectrum from 1.8 to 1.2 Bv, and then a complete flatness below 1.2 Bv, for example, are more natural and may be supported eventually by more detailed experiments in the appropriate latitude range.

The resulting curve of expected $\bar{J}_P$ *vs* λ is plotted in Fig. 8.

Also shown in Fig. 8 are two dashed curves representing the latitude dependence of $\bar{J}_{AS}$ and $\bar{J}_{AR}$. At latitudes less than 55° it was assumed that $\bar{J}_{AR}=\bar{J}_{AS}$. (This is equivalent to the assumption that all albedo particles have a magnetic rigidity less than 1.6 Bv.) And, of course,

$$\bar{J}=\bar{J}_P+\bar{J}_A=\bar{J}_P+\bar{J}_{AS}+\bar{J}_{AR}. \tag{22}$$

North of $\lambda=55°$, a continuation of the $\bar{J}_{AS}$ curve has been estimated by assuming that $\bar{J}_{AS}$ is proportional to the intensity of primary radiation arriving at zenith angles greater than 60°. Finally, the curve of $\bar{J}_{AR}$ north of 55° has been drawn so that

$$\bar{J}_{AR}=\bar{J}-\bar{J}_P-\bar{J}_{AS}. \tag{23}$$

The fall-off of $\bar{J}_{AR}$ north of 55° is seen to be generally plausible; and in fact $\bar{J}_{AR}$ falls to nearly zero at $\lambda=90°$, as it must, though this requirement was nowhere introduced in the analysis.

It seems most remarkable that the true fall-off of $\bar{J}_{AR}$ with latitude should occur in just such a way as to so nearly compensate for the concurrent increase of $\bar{J}_P+\bar{J}_{AS}$. There is, however, a suggestion of an upward bulge in the measured values of $\bar{J}$ in the vicinity of $\lambda=70°$. If this bulge persists in more accurate measurements (which are currently underway), it may be related to the similar one reported by Neher *et al.*[25] and may simply reflect the imperfection of the above mentioned cancellation.

A specific prediction of the foregoing interpretation is that the *vertical* intensity above the atmosphere at $\lambda=90°$ is 0.29 (cm^2 sec sterad)$^{-1}$. No experimental evidence on this matter is available as yet.

Figure 8 and the foregoing discussion demonstrate that the experimental results are consistent with a primary spectrum which is sharply cut off at $R=1.7$ Bv [Eq. (21)].

In view of fundamental uncertainties in the higher rigidity portion of the primary spectrum, in the production of albedo, and in the details of geomagnetic theory, it is very difficult to make a precise conclusion as to the absence of primaries of magnetic rigidity less than about 1.7 Bv. Nonetheless, Fig. 8 presents the physical situation as presently understood and is probably substantially correct.

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Fig. 4. Chart showing geographic location of rockoon flights.