# High-Altitude Intensities of the Medium and Heavy Cosmic-Ray Nuclei and of the Star-Producing Component over a 25-Hour Interval*

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Results are reported on a study of the hourly averaged values of intensity of medium and heavy cosmic-ray nuclei and of the star-producing component over a day and night interval, at an average atmospheric depth of 15 g/cm². The equipment was carried aloft by a Skyhook balloon on August 6, 1954 from Minneapolis, Minnesota (geomagnetic latitude 55°N). A large, thin-walled spherical pulse-ionization chamber served as the detecting instrument. Approximately 125 000 of these cosmic-ray events were recorded over the 25-hour flight interval; thus, statistical counting rate fluctuations were reduced substantially below those previously attained in this field. Analysis shows that approximately one-half of the counting rate at 15 g/cm² can be ascribed to the medium and heavy nuclei, the remainder being reasonably accounted for as arising from the star-producing component.

No variation is observed in the hourly averaged counting rate of pulses of size greater than 6 Mev throughout the flight, to within the combined statistical and experimental uncertainties of ±4 to 6% during the daytime, and ±8 to 10% during the night.

## I. INTRODUCTION

A THIN-WALLED spherical pulse-ionization chamber has been employed to investigate the temporal variation of the intensities of the medium and heavy cosmic-ray nuclei ($Z \geqslant 6$) and of the intensity of the star-producing component. Intensities were recorded continuously over a 25-hour interval at atmospheric depths of 12 to 22 g/cm². Related work has been reported in which photographic emulsions,[1–5] a scintillation counter,[6] an ionization chamber as in the present experiment,[7] and a proportional-counter cloud-chamber combination[8] were employed.

The special virtue of a large, spherical ionization chamber for such time-variation studies lies in the large number of the medium and heavy cosmic-ray nuclei which can be recorded in a form that is convenient for analysis. Thus, statistical uncertainties can be reduced by an order of magnitude over those obtained to date with the more widely used photographic emulsion techniques. A correspondingly more critical view of the temporal behavior of the primary radiation is obtained.

The data are recorded continuously on a moving film on which are superimposed an accurate time base and a record of the atmospheric-pressure altitude level. An empirical determination of the altitude dependence of the radiation is obtained from the counting-rate data on the rise to altitude; this makes possible a direct correction of the data for any variations in floating pressure-altitude which take place during the flight. A continuous absolute pulse-height energy-loss calibration level is maintained throughout the flight through the use of a source of monoenergetic alpha-particle activity ($Po^{210}$) inside the chamber.

In return for the high counting rates from the ion-chamber, one must accept a loss of resolution among the various primary charge groups, due both to the spherical geometry of the chamber, and to its detection characteristics. The data are then to be interpreted as pertaining to the total medium and heavy particle intensities, without detailed resolution in $Z$.

Moreover, there is an appreciable "background" counting rate present, which arises from the disintegrations produced by the nucleonic component in the chamber gas, wall, and surrounding materials.[9] The temporal variation of the rate of events in the chamber is thus a composite of the temporal variation of the contribution due to stars (mainly caused by primary protons and alpha particles and their nucleonic progeny[10]) and that due to the medium and heavy nuclei. In principle, the respective contributions from these two classes of events to any observed temporal variation can be distinguished by observing the dependence of the variation upon pulse height and upon atmospheric depth. No provision for such analyses was made in the present experiment. While it is planned to make use of these ideas in future work, the present data must be understood as referring to the temporal variation of the composite of the two contributions.

In general then, a spherical ion-chamber as employed here has the advantage of yielding much smaller statistical uncertainties in the observations as compared with those obtainable at present with photoemulsions, but sacrifices to some extent the more direct interpretation of results obtained with the latter.

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1 J. J. Lord and M. Schein, Phys. Rev. **78**, 484 (1950); **80**, 304 (1950).
2 Freier, Anderson, Naugle, and Ney, Phys. Rev. **79**, 206(A) (1950); **84**, 322 (1951).
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6 E. P. Ney and D. Thon, Phys. Rev. **81**, 1069 (1951).
7 M. A. Pomerantz and G. W. McClure, Phys. Rev. **84**, 1252 (1951).
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9 These disintegrations will be referred to hereafter as "stars"; they produce chamber pulses which are electronically indistinguishable, in the present technique, from the pulses due to the medium and heavy primary particles.
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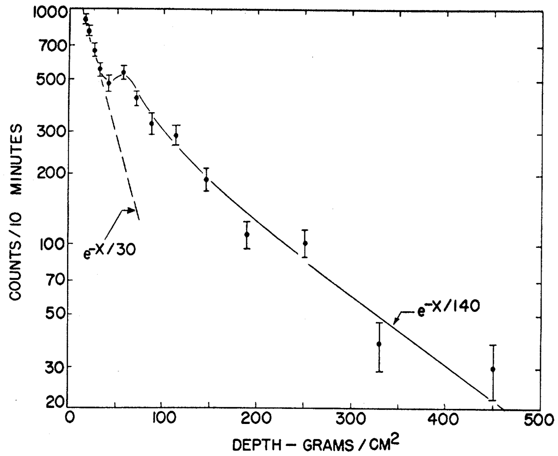


FIG. 1. Ionization-chamber counting rates as a function of atmospheric depth for pulses of height greater than 6 Mev.

## II. IONIZATION CHAMBER AND ASSOCIATED INSTRUMENTATION

The fast ionization chamber was similar in design to that described by Ellis, Van Allen, and Gottlieb.[11] The chamber was 30.5 cm in diameter, with a copper wall of 0.4 g/cm$^2$ average thickness. The filling gas was argon (99.6% pure, further purified over hot metallic calcium) at 1.20 atmospheres pressure at 0°C. Electron collection times were of the order of 3 microseconds. A built-in Po-$\alpha$ source provided an absolute pulse-height calibration of the complete system throughout the flight. The output pulses from the chamber were amplified, stretched, and displayed on a cathode-ray tube for photographic recording within the gondola.

## III. FLIGHT INFORMATION

The equipment was carried to altitude by a General Mills balloon, under the auspices of Project Skyhook of the Office of Naval Research. Launching took place at Minneapolis, Minnesota at 7 A.M. (CST), August 6, 1954; cutdown occurred at 10 A.M. August 7, over Rapid City, South Dakota.

The balloon altitude was maintained between 15 and 12 g/cm$^2$ during the daylight hours, but dropped to approximately 22 g/cm$^2$ during the night.

A clear ion-chamber record and time-pressure data were obtained throughout.

## IV. COUNTING RATES DURING THE RISE TO ALTITUDE

The variation of the counting rate with atmospheric depth for pulses of size greater than 6 Mev as observed during this flight is shown in Fig. 1. Several features of the data are of interest.

(a) The apparent absorption mean free path of the detected radiation (i.e., the depth over which the counting rate drops by a factor of $1/e$), for depths greater than 150 g/cm$^2$, is in agreement with previous work, and is consistent with the belief that the counting rates at these depths arise predominantly from the star-producing component.[12]

(b) The counting rate maximum around 55 g/cm$^2$ has not been detected directly with ionization chambers of this type before at these latitudes,[13] but seems to be statistically significant.

(c) The rapid increase in counting rate which occurs at small depths can be accounted for in a reasonable way as arising from the direct traversals of medium and heavy primary nuclei through the chamber (see Sec. V below). The counting rates from these nuclei obtained with the present detector rose to several thousand per hour at the highest altitudes reached (12 g/cm$^2$).

## V. CALCULATION OF EXPECTED MEDIUM AND HEAVY PRIMARY-PARTICLE COUNTING RATES

The theory appropriate to the calculation of the counting rates to be expected in a spherical ionization chamber in a specified cosmic-ray beam has been developed by Ellis, Van Allen, and Gottlieb,[11] and was followed here with modifications necessary to extend the calculations down into the atmosphere, as outlined below.

An isotropic flux of medium and heavy nuclei at infinity was assumed, of absolute values as given by emulsion results.[14] The integral number-rigidity spectrum chosen was of the form

$$J_Z(>R)=k_Z R^{-1.1}, \qquad (1)$$

where $J_Z$ is the intensity of nuclei with charge $Z$ per m$^2$ sec steradian with magnetic rigidity greater than $R$, and $k_Z$ is a constant. The expected flux at the top of the atmosphere as a function of zenith angle and azimuth was then found using the results from geomagnetic theory as summarized by Alpher.[15]

The calculations were then extended to several successive depths in the atmosphere by a step-wise integration over azimuthal and zenith angles. In these calculations account was taken of ionization losses, nuclear interactions and fragmentation effects. The mean free paths for nuclear interaction were based on the reported emulsion results of the Rochester group.[16] The diffusion equations as presented by Noon and Kaplon,[17] together with their associated fragmentation probabilities, formed the basis for the fragmentation calculations.

[11] Ellis, Van Allen, and Gottlieb, Phys. Rev. **95**, 147 (1954).

[12] B. Rossi, *High-Energy Particles* (Prentice-Hall, Inc., New York, 1950), p. 438 ff.

[13] T. Coor, Jr., Phys. Rev. **82**, 478 (1951); see also G. N. Whyte, Phys. Rev. **82**, 204 (1951).

[14] Kaplon, Peters, Reynolds, and Ritson, Phys. Rev. **85**, 295 (1952).

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

[16] B. Peters, in *Progress in Cosmic-Ray Physics* (Interscience Publishers, Inc., New York, 1952), p. 210.

[17] J. H. Noon and M. F. Kaplon, Phys. Rev. **97**, 769 (1955).

The calculations show that approximately one-half of the counting rate observed at 15 g/cm² can be ascribed to direct traversals of the medium and heavy nuclei, while the fraction drops to one-third at 22 g/cm², an indication of the importance of reaching and maintaining sufficiently high altitudes in these studies. The calculated ratio of heavy to medium nuclei detected at 15 g/cm² was 0.6, while at 22 g/cm² the ratio was 0.4.

It may finally be noted that these calculations are well confirmed on an empirical bases by the observed variation of the total counting rate with altitude as given in Fig. 1, providing one assumes a variation of star-rate with altitude of the form found by Lord in his photographic emulsion studies.[10]

## VI. CORRECTIONS TO THE DATA AT ALTITUDE

### (a) Altitude Corrections

Corrections to the counting rates necessitated by changes in altitude of the balloon about the mean altitude of 15 g/cm² were made with the aid of the counting rate data of Fig. 1 and the pressure record furnished by a temperature-compensated Olland-cycle aneroid barometer. Maximum uncertainty introduced in the counting rates from these corrections was $\pm 3\%$.

### (b) Corrections for Electronic System Variations

As noted previously, the $\alpha$-particle source provided an absolute pulse-size reference level for the entire system (equivalent to 5.0 Mev). Examination of the pulse-height distributions at selected times throughout the flight established this reference level and the pulse heights were referred to it. The level varied less than 10% in height during the day, but a large decrease occurred during the night (40% decrease in electronic system gain). Resolution of the data at these smaller heights was not as good as at higher pulse heights and the Po-$\alpha$ level was somewhat less well-defined. This additional uncertainty resulted in an increase of the uncertainty limits to $\pm 10\%$ for the night-time data points.

### (c) Geomagnetic Latitude Effects

During the course of the flight the balloon had a uniform southwesterly drift, resulting in an excursion of 1.5° in geomagnetic latitude and 15° in geomagnetic longitude.[18] The corrections to the counting rates to be considered for this change in coordinates are twofold, arising from the change in the intensities of the primary medium and heavy nuclei with latitude and longitude, and from the change of the star-producing component with latitude and longitude. Upper limits to the changes to be expected in these two components have been determined as follows.

(*1*) *Medium and heavy nuclei.*—The number-rigidity spectrum of Eq. (1) would predict a decrease of approximately 18% in the vertical intensity of the medium and heavy nuclei at the top of the atmosphere, for the above change in geomagnetic latitude and longitude.[19] For an atmospheric depth of 15 g/cm², we have used the ionization range in air *versus* magnetic rigidity curves for various $Z$ as given in reference 11, together with our own calculations of the expected intensity of these nuclei at various zenith angles, to deduce a corresponding decrease in the medium and heavy nuclei counting rates of approximately 5% at this depth. We note that since our measurements were made not far from the knee of the latitude curve,[11] the actual number-rigidity spectrum may be somewhat flatter than that given by Eq. (1); hence our estimate here of the counting-rate change represents an upper limit for the latitude effect of the medium and heavy nuclei.

(*2*) *Star-producing component.*—The experimental data of Coor and Whyte[13] indicate that the star-producing radiation detected by ion-chambers of this type at high altitudes does not rise as rapidly with increasing latitudes as the primary spectrum given by Eq. (1). From their data, and from the summary of extensive neutron data at high altitudes as presented by Soberman,[20] we have deduced an upper limit of 12% for the possible change in the star-counting rates for the given excursion in latitude and longitude.

Combining the above estimates for the change in counting rate with latitude and longitude of the primary medium and heavy nuclei and the star-producing component, an *upper* limit of 9% is obtained for the corresponding change in the total counting rate over the flight interval. A *lower* limit of zero for the latitude effect would apply here if the "knee" of the star-producing radiation intensity detected by the chamber at 15 g/cm² lay below the latitudes traversed in this experiment.

In view of the uncertainties in the latitude-longitude effect, no explicit correction has been applied to the final data. This point will be discussed further in Sec. VII in the light of the experimental results.

## VII. FINAL CORRECTED RESULTS AND DISCUSSION

The hourly averaged counting rates over the 25-hour interval at altitude are presented in Fig. 2, corrected to a constant atmospheric-pressure level of 15 g/cm² and a constant pulse-height energy-loss level of 6 Mev. The Po-$\alpha$ calibration level was determined at bi-hourly intervals during the daytime hours, and at three points in the night-time data. The uncertainty limits represent the combined statistical counting rate and experimental altitude and gain correction uncertainties as discussed in Sec. VI. There are no variations evident outside of the combined statistical and experimental uncertainties of $\pm 4$ to 6% during the daytime hours, and $\pm 8$ to 10% during the night.

[18] A. G. McNish, J. Terrestrial Magnetism and Atmospheric Elec. **41**, 37 (1936).

[19] F. Jory, Phys. Rev. **102**, 1167 (1956).

[20] R. K. Soberman, Phys. Rev. **102**, 1399 (1956).

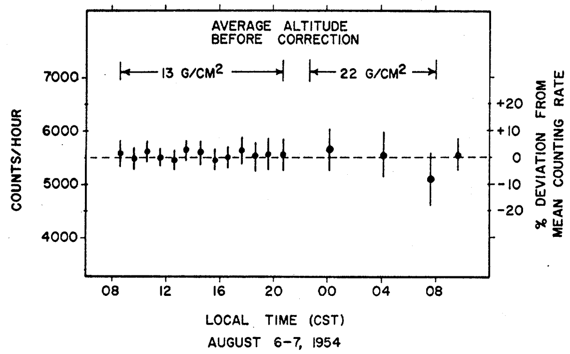


FIG. 2. Counting rates as a function of time, for pulses of height greater than 6 Mev, corrected to a constant atmospheric depth of 15 g/cm$^2$.

*Geomagnetic correction.*—No correction has been applied to the data for the change in geomagnetic coordinates of the balloon during the flight, inasmuch as the exact correction is uncertain, as discussed in Sec. VIC. However, from the data in Fig. 2, it may be seen that the counting rates for the first 13 hours are consistent, within the statistical uncertainties, with a constant counting rate, and that the value of the counting rate in the late morning of the next day is in agreement with the average of the previous daytime values. This experimental evidence appears to favor a considerably smaller latitude-longitude effect than the upper limit of 9% over the flight interval as deduced in Sec. VIC.

*Character of the detected radiation.*—On the basis of the analysis in Sec. V, these results are to be construed as showing the temporal behavior over a day-night interval of the following composite sample of the cosmic radiation: (a) For primary nuclei with charge $Z \geqslant 6$, the ratio of contributions of heavy ($Z \geqslant 10$) to medium ($6 \leqslant Z \leqslant 8$) nuclei was approximately 0.6 during the day, and 0.4 during the night. (b) For locally produced stars, the contribution from such stars was approximately equal to that from direct traversals of medium and heavy nuclei during the day, and twice as great during the night.

*Ground-level data.*—Neutron-monitors are the most sensitive instruments for the detection of the lower rigidity (<10 Bv) primary radiation and the star-producing radiation at ground-level stations[21]; these data are therefore the most appropriate for comparison with the high-altitude results presented here. Data from the high-altitude neutron-monitors at Climax (geomagnetic latitude 48°N, longitude 45°W)[18] for the flight period have been kindly furnished by Dr. J. A. Simpson. No fluctuations greater than ±1% are in evidence.

## VIII. CONCLUSIONS

From the final corrected data as presented in Sec. VII, Fig. 2, and the discussion therein, the following conclusions may be drawn.

(1) No variations are present in the hourly averaged ion-chamber counting rates throughout the 25-hour interval at high altitudes, outside of the combined statistical and experimental uncertainties of ±4 to 6% during the daytime hours, and ±8 to 10% during the night-time hours. The data are understood as applying to a sample of the cosmic-ray beam consisting of approximately equal contributions from the primary medium-heavy nuclei and the star-producing radiation (Sec. V).

(2) In conjunction with the ground-level data from neutron monitors during that period (Climax) and the previous high-altitude day-night results on the star-radiation of Lord and Schein,[1] and the high-altitude day-night total intensity and fast-neutron results of Bergstrahl and Schroeder,[22] the present data support the belief that there is no large, *systematic* diurnal variation of the intensities of medium and heavy nuclei. Furthermore, no large variations of a *sporadic* nature were observed during the 25-hour flight period on August 6–7, 1954.

## IX. ACKNOWLEDGMENTS

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[22] T. A. Bergstrahl and C. A. Schroeder, Phys. Rev. **81**, 244 (1951).