Cosmic-Ray Heavy Nuclei at the Geomagnetic Equator*

D. D. KERLEE AND O. K. KRIENKE, JR.
Seattle Pacific College Institute for Research, Seattle, Washington

J. J. LORD
Department of Physics, University of Washington, Seattle, Washington

AND

M. E. NELSON
Department of Physics, College of Puget Sound, Tacoma, Washington

(Received October 16, 1959)

The flux of primary cosmic-ray heavy nuclei has been measured with a sandwich of C–2 and G-5 emulsions near the island of Guam, magnetic latitude 4°N. The emulsions were exposed at about 101 000 ft for 7.3 hours and the calculated fluxes at the top of the atmoshpere in particles/m²-sec-sr were found to be:

Li, Be, B	(L nuclei)	0.26 ± 0.05,
C, N, O, F	(M nuclei)	0.66 ± 0.10,
$Z\geqslant10$	(H nuclei)	0.37 ± 0.09.

This flight took place on February 12, 1957, about a year prior to the sun spot maximum; however, there is no evidence within statistical error for any changes in the composition of the primary heavy nuclei.

INTRODUCTION

THE primary cosmic-ray charge spectrum has been measured extensively by various investigators at geomagnetic latitudes between 30°N and the polar regions[1–4] and at depths ranging from 3 to 25 g/cm² below the top of the atmosphere.[1–4] Flux values extrapolated to the top of the atmosphere differ primarily in the values quoted for the abundance of L nuclei ($Z=3,4,5$) and are influenced probably by the variation of the general solar activity.[3]

Flux determinations near the magnetic equator have been given for $M(Z=6,7,8,9)$ and $H(Z\geqslant10)$ nuclei[5–9] but there is little information on the $L(Z=3,4,5)$ nuclei.[9]

In the present work the charge distribution and flux values were obtained near the geomagnetic equator (4°N). Resolution of particles with $Z>3$ was based on grain density measurements in underdeveloped C-2 emulsions. Delta-ray measurements in G-5 emulsions were carried out but did not give nearly the accuracy obtained with the C-2 emulsions. Corrections based on the well-known diffusion equations were made to obtain the flux values at the top of the atmosphere.

EXPERIMENTAL PROCEDURE

A. Emulsion Stack for the Detection of Heavy Nuclei

The heavy nuclei utilized in this experiment were detected in an emulsion stack consisting of 18 type G-5 Ilford stripped emulsions, 4×4 inches, 400 microns thick. In addition 6 type C-2 emulsions, 200 microns thick were placed in the second, fourth and sixth positions from each end of the stack. The plane of the emulsions was maintained vertical in a pressurized aluminum container with wall thickness 0.35 g/cm².

The G-5 emulsions were processed in the usual manner; however, the C-2 plates were underdeveloped so that it would be possible to count grains for tracks as heavy as those due to iron nuclei. The C-2 emulsions were developed in a standard Amidol developer diluted to 2.5% of normal strength. The development was carried out at 7°C for 40 minutes.

B. Exposure

The emulsion stack was exposed by free balloon from the vicinity of the island of Guam on Flight No. 739, Project EQUEX, on February 12, 1957. The rise time of the balloon from sea level to 102 000 feet was 2.1 hours and the flight time was about 7.1 hours at an average of 101 000 feet, where the mean average atmospheric depth is 10.3 g/cm². The time of descent was 0.6 hour.

The entire flight at altitude was at a geographic latitude of 13.4±0.1 degrees north or 4 degrees magnetic north.[9]

* This work was supported in part by the National Science Foundation, the Office of Naval Research, and the U. S. IGY Project.

[1] S. F. Singer, *Progress in Cosmic-Ray Physics*, edited by J. G. Wilson (Interscience Publishers, Inc., New York, 1958), Vol. 3.
[2] M. V. K. Appa Rao, S. Biswas, R. R. Daniel, K. A. Neelakanton, and B. Peters, Phys. Rev. **110**, 751 (1958). (A summary of previous work is given in this paper.)
[3] P. S. Freier, E. P. Ney, and C. J. Waddington, Phys. Rev. **113**, 921 (1959).
[4] H. Aizu, Y. Fujimoto, S. Hasegawa, M. Koshiba, I. Mito, J. Nishimura, K. Yokoi, and M. Schein (private communication).
[5] R. E. Danielson, P. S. Freier, J. E. Naugle, and E. P. Ney, Phys. Rev. **103**, 1075 (1956).
[6] H. J. Taylor, M. Sitaramaswami, and P. N. Krishnamoorthy, Proc. Indian Acad. Sci. **36** (1952).
[7] D. Lal, Proc. Indian Acad. Sci. **A38**, 93 (1953).
[8] C. J. Waddington, Suppl. Nuovo cimemto **8**, 518 (1958).
[9] W. R. Webber, Suppl. Nuovo cimento **8**, (1958).

C. Scanning Techniques

The entire surfaces of both outside emulsions of the stack were scanned by two observers using microscopes with a magnification of 250 diameters. All tracks were recorded which appeared to have an ionization greater than four times the minimum. Protons and alpha particles producing high-energy jets were used to determine grain density limits and as a check on the plate orientations during the flight.

As a check on scanning efficiency one of the outside emulsions of the stack was entirely scanned by another observer. On the basis of this rescanning, the scanning efficiency was calculated to be 93%.

As a result of the scanning, 800 tracks were found which had a dip angle in the emulsion less than 33.7° and appeared to have negligible multiple scattering in the first emulsion. Tracks were considered to be due to relativistic primaries if they could be followed through at least 12 emulsions with negligible change in track density and had angular deviation less than 2°. A total of 112 tracks met the above criteria.

D. Charge Determination

Determination of the charge of the heavy nuclei was made by grain density measurements in the *C*-2 and *G*-5 emulsions. Grain density saturation prevented reliable charge calibrations beyond $Z=3$ in the *G*-5 emulsions, but grain density measurements in the *C*-2 emulsions could be carried out up to at least $Z=26$ as can be seen in Fig. 1. Fragmentation of one heavy nucleus made it possible to get good cross calibration of tracks in the *C*-2 and *G*-5 emulsions for a charge as low as $Z=2$.

The charge calibration for tracks due to particles with $3\leqslant Z\leqslant 8$ was obtained from the tracks of slow protons stopping in the *C*-2 emulsions. This calibration was carried out in the manner described by Appa Rao et al.[2] The calibration for $Z>8$ was obtained from the fragmentation of heavy nuclei. The resulting charge calibration relations can be seen by the inspection of Fig. 1. As a check on the calibration, delta ray and gap counts were made on many of the tracks. While these determinations were in agreement with the grain density measurements, in this experiment the grain density method was much more accurate and was used for all charge assignments. In some cases it was difficult to find the $Z=3$ tracks in the *C*-2 emulsion and charge assignments were made from the G-5 emulsions.

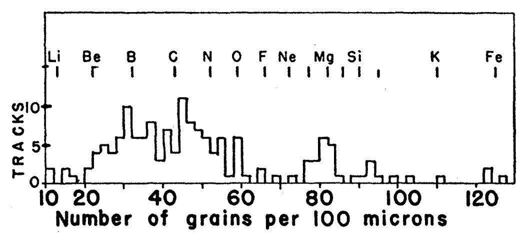

FIG. 1. Grain density distribution of heavy nuclei.

TABLE I. Time-altitude relation for the balloon flight.

Average elevation of balloon in g/cm²	39.5	26.1	17.0	12.0	10.4	10.2	9.9
Time spent at the average elevation (hours)	0.17	0.17	0.17	0.17	5.0	0.33	1.67

CHARGE DISTRIBUTION AND FLUX DETERMINATION

In Fig. 1 the histogram gives the grain density distribution of all tracks found and ascertained to be high-energy multiply charged particles with atomic numbers greater than two. The atomic number assignments are given at the top of the figure. This distribution represents the flux of particles at an average elevation corresponding to 10.3 g/cm² of residual atmosphere.

The flux of primary cosmic-ray heavy nuclei at the top of the atmosphere of the earth was determined from certain tracks selected from the distribution in Fig. 1. The tracks utilized in this determination had zenith angles less than 60° and dip angles less than 33.7°.

The conventional notation of L nuclei (Li, Be, and B), M nuclei (C, N, O, and F), and H nuclei ($Z\geqslant 10$) will be used to designate the convenient grouping of heavy nuclei.

The flux calculation was carried out by the method described by Bradt and Peters. The fragmentation probabilities $P_{ML}=P_{HL}=0.25$ were used in agreement with the observations of Freier, Ney, and Waddington.[3] The collision mean free paths in air for L, M, and H nuclei were taken to be 33, 30, and 22 g/cm², respectively. To avoid errors arising from the finite rise time of the balloon to its ceiling elevation, a numerical integration of the flux was carried out over the time intervals listed in Table I.

Using the procedures outlined above, the calculated fluxes at the top of the atmosphere are given in the first row of Table II. The flux values obtained by other workers in experiments near the equator are included in Table II.

The abundance of the various elements in the heavy nuclei component is shown in Fig. 2. This distribution represents the abundance at an average elevation of 10.3 g/cm²; however, the Li, Be, and B due to fragmentation have not been included. Thus, the distribution in Fig. 2 is very close to that at the top of the atmosphere.

CONCLUSIONS

It has been noted by Waddington[10] and Peters[2] that there are more than likely serious errors in a great deal of the data on the charge calibration of the heavy nuclei,

[10] C. J. Waddington, Phil. Mag. 2, 1059 (1957).

TABLE II. Flux of heavy nuclei near the equator.

Experiment	Magnetic cut-off in Bev per nucleon	Date	Flux in particles/m²-sec-sr L (Li, Be, B)	M (C, N, O, F)	H ($Z\geqslant 10$)
Present work	7.6	February, 1957	0.26±0.05	0.66±0.10	0.37±0.09
Waddington[a]	7.6	February, 1957	...	0.95±0.11	0.35±0.08
Webber[b]	7.6	February, 1957	0.44±0.19	1.02±0.26	0.52±0.17
Lal[c]	7.0	...	...	1.3 ±0.25	0.25±0.06
Taylor[d]	7.1	Fall 1950	...	1.45±0.30	0.33±0.08
Danielson[e]	5.7	September, 1953	...	0.68±0.06	0.21±0.05

[a] See reference 8.
[b] See reference 9.
[c] See reference 7.
[d] See reference 6.
[e] See reference 5.

particularly in the region around C, N, and O. In this experiment a charge calibration error of one half unit of atomic number would change the flux values in Table II by amounts less than the statistical errors. However, as can be seen through inspection of Fig. 1, a half unit error in charge calibration would produce serious changes in the charge distribution given in Fig. 2.

It was of interest in this experiment to determine if the ratio of the flux of L to M nuclei was a function of the energy of the heavy nuclei. As shown in Table II, L/M in this experiment is 0.39 ± 0.10 at the top of the atmosphere. The measured value of L/M at an atmospheric depth of 10.4 g/cm² was 0.59 which is in agreement with the observation of Webber[9] at the same latitude. Comparison of the results of this experiment and that of Webber[9] can be made with observations corresponding to lower energy through inspection of the results shown in Fig. 3 of the paper of Appa Rao et al.[2] Although the statistical uncertainties in the measured values of L/M are large, it appears that the values at $\lambda=4°$ are about 40% higher than those at $\lambda=41°$. A value of L/M of 0.35 implies a traversal of about 4.5 g/cm² of interstellar hydrogen.[11] The above 40% increase would imply a traversal of about 0.8 g/cm² of hydrogen while the energy of the heavy nuclei increases from 1.5 to 7.6 Bev per nucleon.

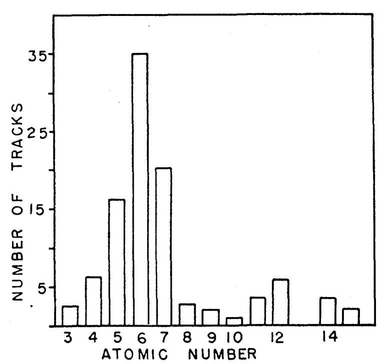

FIG. 2. Charge distribution of heavy nuclei.

ACKNOWLEDGMENTS

It is a pleasure to thank the Office of Naval Research for the balloon flights in connection with project EQUEX. For their assistance in scanning, the authors are grateful to Craig Becker, Orison Cain, Charles Chiu, Merlyn Danskin, Lyle Durland, Paul Hsu, Philip Ogden, and Joan Pentilla.

[11] B. Peters, Suppl. Nuovo cimento 8, 556 (1958).