Primary Cosmic-Ray Proton and Alpha Flux near the Geomagnetic Equator*

FRANK B. McDONALD
State University of Iowa, Iowa City, Iowa
(Received July 29, 1957)

The vertical flux of primary protons and of alpha particles has been measured at Guam, Marianas Islands ($\lambda=3°$N) using a Čerenkov scintillation detector carried to a residual pressure of 6.1 g/cm^2 by a Skyhook balloon. The primary alpha flux, $J_{0\alpha}$ was found to be, $J_{0\alpha}=18.0\pm2$ particles/m^2-sec-sterad at 0 g/cm^2 atmos depth. The flux of primary protons, J_{0p} was found to be, as an upper limit (without returning albedo correction), $J_{0p}=115\pm12$ particles/m^2-sec-sterad at 0 g/cm^2 atmos depth, and as a lower limit (with returning albedo corrections), $J_{0p}=95\pm12$ particles/m^2-sec-sterad at 0 g/cm^2 atmos depth. This flight completes an extensive latitude survey of the alpha and proton components by this laboratory using identical detectors at all latitudes. The alpha energy spectrum can be represented from 0.150 Bev/nucleon to 7.3 Bev/nucleon by

$$J_{0\alpha}(\geqq E)=-(1.5)(415)\int_E^\infty\frac{[1-\exp(-80E'^3)]}{(1+E')^{2.5}}dE' \quad \text{particles/m}^2\text{-sec-sterad,}$$

where $J_{0\alpha}(\geqq E)$ is the vertical flux of primary alphas with kinetic energy $\geqq E$ (measured in Bev/nucleon). This energy spectrum is in excellent agreement with the measured low-energy alpha differential energy spectrum. Above 0.35 Bev/nucleon the alpha energy spectrum is accurately represented by $J_{0\alpha}(\geqq E)=415/(1+E)^{1.5}$ particles/m^2-sec-sterad. The proton energy spectrum in the latitude range 0–41°N (15.2–4.0 Bev/nucleon) is well represented by $J_{0p}(\geqq E)=6600/(1+E)^{1.5}$ particles/m^2-sec-sterad. Thus the flux of protons and alphas has the same energy dependence over a wide range of energies. Values of the flux of splash albedo at $\lambda=3°$N are given and estimates are made of the magnitude of the returning albedo correction.

I. INTRODUCTION

A ČERENKOV scintillation detector has been flown on a Skyhook balloon flight from Guam, Marianas Islands. This flight was part of the United States Office of Naval Research 1957 Equatorial Expedition. The experiment completes an extensive latitude survey of the proton and alpha primary cosmic-ray flux and energy spectrum by this laboratory using identical detectors at all latitudes. The Čerenkov scintillation detector, which has been previously described,[1,2] is uniquely suited for such an investigation. It has been shown that direct measurements of the primary alpha energy spectrum independent of geomagnetic theory can be obtained in the kinetic energy range 0.150 to 0.800 Bev/nucleon with this detector.[1,2] Flights at 41°N have demonstrated that the charge resolution is even better at higher energies. It was felt that a flight near the geomagnetic equator would be invaluable in determining whether the alpha energy spectrum previously measured at low energies could be extended to higher energies. Except for the recent emulsion experiment of Shapiro, Stiller, and O'Dell[3] at 11°N, there does not seem to be a good measurement of the α flux near the equator. In addition the values of the proton flux obtained at low latitudes are somewhat puzzling. The data of Vernov and Charakhchyan[4] and McClure[5] using techniques with more positive identification of high-energy particles give appreciably lower flux values than the Geiger-counter telescope data of Winckler *et al.*[6] and of Van Allen and Singer.[7] The work of Anderson[8] in the vicinity of 11°N using a Čerenkov counter has indicated that substantial corrections to telescope data are necessary for upward moving particles and slow secondaries. Also, most balloon data would seem to require a large correction for the effects of the residual atmosphere above the telescope, but this has been applied only in the cases of McClure, and Vernov and Charakhchyan. However, these experiments could not directly correct for splash albedo. It was felt that an experiment at the equator which would distinguish the singly charged particles incident at the top of the atmosphere from slow secondaries and splash albedo might resolve the disparity in proton flux values.

The Čerenkov scintillation counter was carried to an altitude of 114 000 feet (6.1 g/cm^2) on January 30, 1957, and floated level for a period of $5\frac{3}{4}$ hours (Fig. 1). The performance of the equipment was excellent throughout the flight and data were obtained for the complete duration. Good resolution was obtained at altitude of the fast downward-moving singly charged particles and of the alpha particles. The principal results of this flight are the following:

$\lambda=0$, $J_{0\alpha}=18.0\pm1.9$ particles/m^2-sec-sterad at 0 g/cm^2 residual atmos.

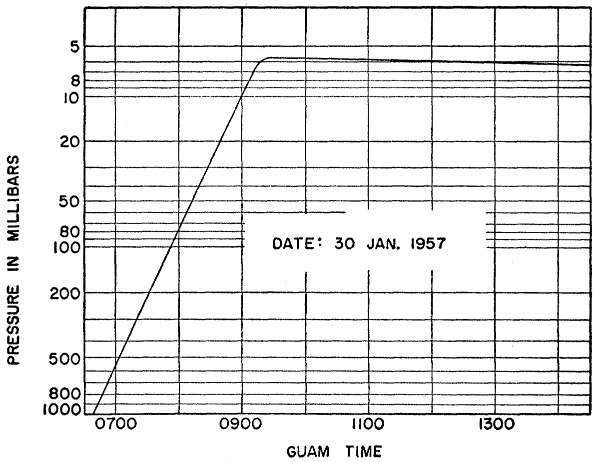
Upper limit: $J_{0p}=115\pm12$ particles/m^2-sec-sterad at 0 g/cm^2 residual atmos.

Lower limit: $J_{0p}=95\pm12$ particles/m^2-sec-sterad at 0 g/cm^2 atmos depth.

$J_{0\alpha}$ is the flux of alpha particles at the top of the

* Assisted by the joint program of Office of Naval Research and the U. S. Atomic Energy Commission.

[1] F. B. McDonald, Phys. Rev. **104**, 1723 (1956).
[2] F. B. McDonald, Phys. Rev. **107**, 1386 (1957).
[3] Shapiro, Stiller, and O'Dell, Bull. Am. Phys. Soc. Ser. II, **1**, 319 (1956).
[4] S. N. Vernov and A. N. Charakhchyan, Doklady Akad. Nauk S.S.S.R. **91**, 487 (1953).
[5] G. W. McClure, Phys. Rev. **96**, 1391 (1953).
[6] Winckler, Stix, Dwight, and Sabin, Phys. Rev. **79**, 656 (1950).
[7] J. A. Van Allen and S. F. Singer, Phys. Rev. **78**, 819 (1950).
[8] K. A. Anderson, Ph.D. thesis, University of Minnesota, 1955 (unpublished).



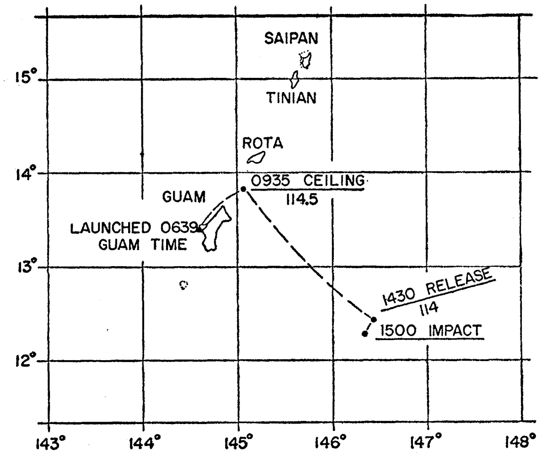


FIG. 1. Time altitude curve and trajectory of equator flight (Flight 11) launched on January 30, 1957. Coordinates on map are Geographic.

atmosphere and J_{0p} is the flux of fast singly charged particles incident at the top of the atmosphere.

If the cutoff energy at Guam is 7.3 Bev/nucleon, then the alpha-particle energy spectrum of

$$J_{0\alpha}(\geqq E)=415/(1+E)^{1.5} \text{ particles/m}^2\text{-sec-sterad.}$$

[$J_{0\alpha}(\geqq E)$ is the flux of α particles with kinetic energy $\geqq E$. (E is measured in Bev/nucleon)] is valid in the region 0.300 to 7.3 Bev/nucleon. A modification of this formula is suggested in Sec. IV in order to obtain better agreement with the very low-energy portion of the α spectrum. In addition it appears that the proton and alpha fluxes have the same energy dependence over a range of proton energies of 4.0 to 15 Bev/nucleon. The flux of splash albedo with energy greater than 0.8 M_0c^2 is 19 ± 3 particles/m²-sec-sterad and has a steeply rising energy spectrum. The remainder of this paper will deal with the results which have been summarized above.

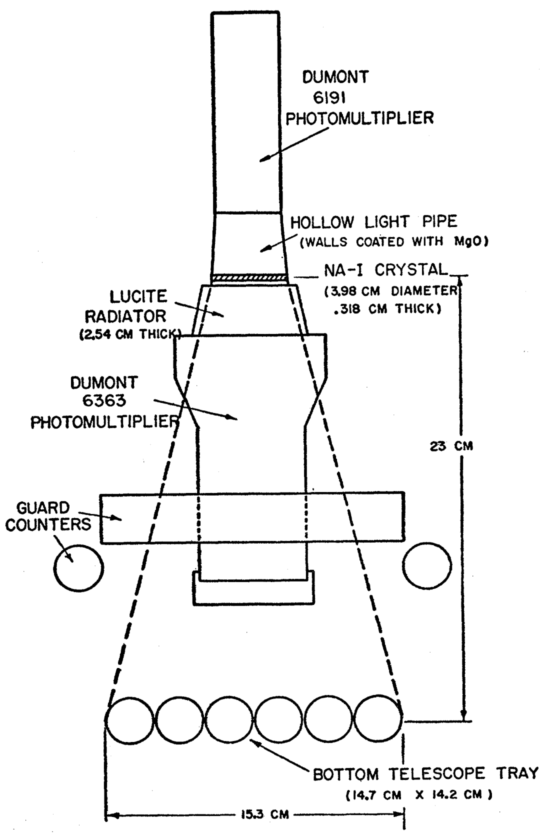


FIG. 2. Schematic drawing of telescope.

II. EXPERIMENTAL APPARATUS

The Čerenkov scintillation detector used was identical to those previously described.[1] Briefly, the detector consisted of a NaI(Tl) crystal scintillation counter, a Lucite Čerenkov counter, a tray of Gieger counters, and a ring of guard counters (Fig. 2). A coincidence is formed by a particle traversing the scintillation crystal and the lower tray of Gieger counters. For each particle which triggers the telescope, the pulse heights from the Čerenkov counter and from the scintillation counter are recorded. A notation is also made if more than one counter in the bottom tray or if one of the ring of guard counters is triggered for a given event. The data are reduced by measuring for each coincidence the pulse heights from the Čerenkov counter and from the ionization detector and recording these on a suitable two-dimensional data grid. The theoretical resolution as β, the particle velocity, is varied from 1 to $1/n$ (320 Mev/nucleon) is shown in Fig. 3 for $Z=1$, 2. At the equator the minimum β for primaries is >0.98. One would therefore expect to find primaries of a given Z concentrated in the region of low ionization loss and high Čerenkov pulse height.

The response of the scintillation counter is independent of the direction in which the particle traverses the telescope. However, for the same value of β, the

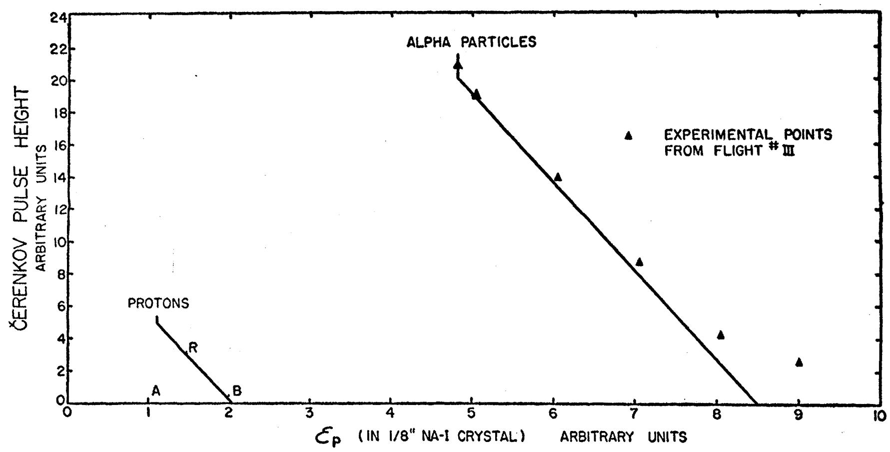


FIG. 3. Plot of Čerenkov pulse height in 1-in. Lucite radiator *vs* the most probable energy loss for protons and alphas in a $\frac{1}{8}$-in. NaI crystal. Fast upward moving albedo particles will be along line *A–B*.

Čerenkov output for upward moving particles is much less than for downward moving particles because of the directional properties of the Čerenkov radiation. Pulse heights from fast splash albedo should be confined to the line *A–B* in Fig. 3. Singly charged particles with $E<320$ Mev which traverse the telescope in either direction should be along the $\mathcal{E}_P$ axis and have zero or very small Čerenkov pulse height. In the low-energy region it is impossible to distinguish the direction in which the particle is moving. There is no direct way to separate the fast returning albedo from true primaries in this experiment.

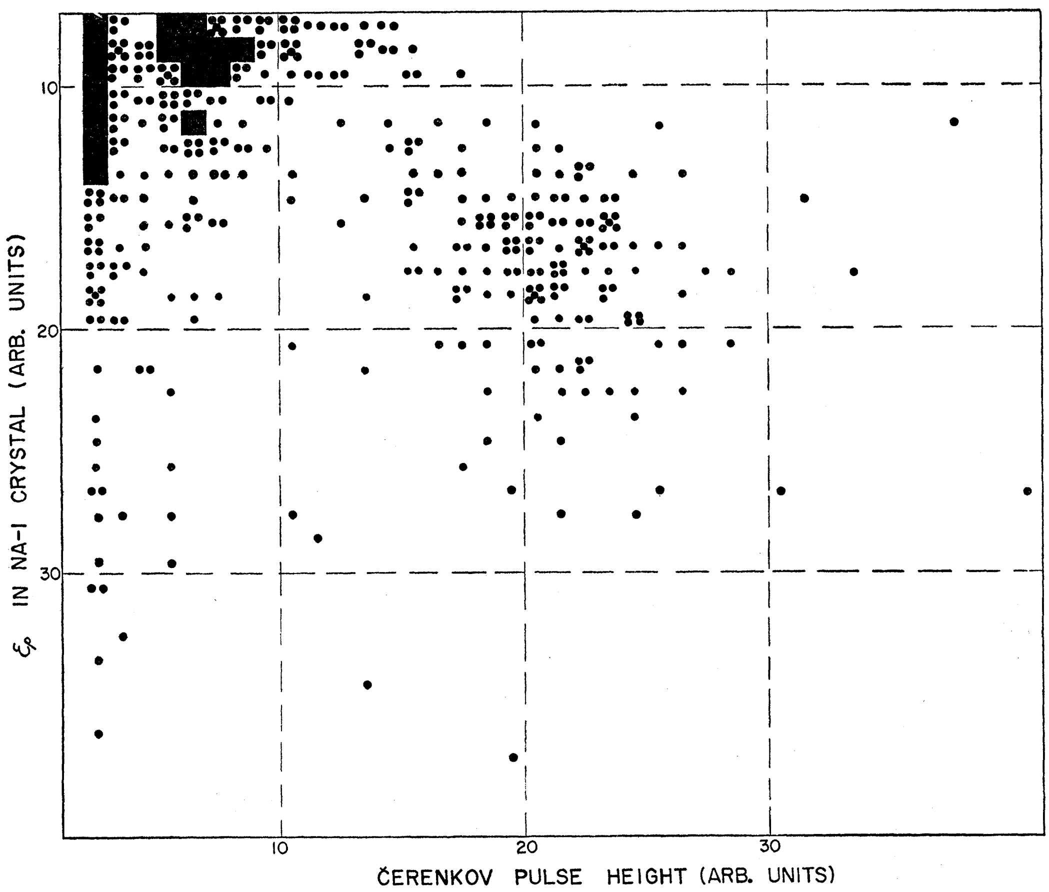


FIG. 4. Plot of energy loss in the crystal *vs* Čerenkov pulse height for each recorded event with an energy loss greater than twice minimum ionization. All multiple particle and shower events have been excluded.

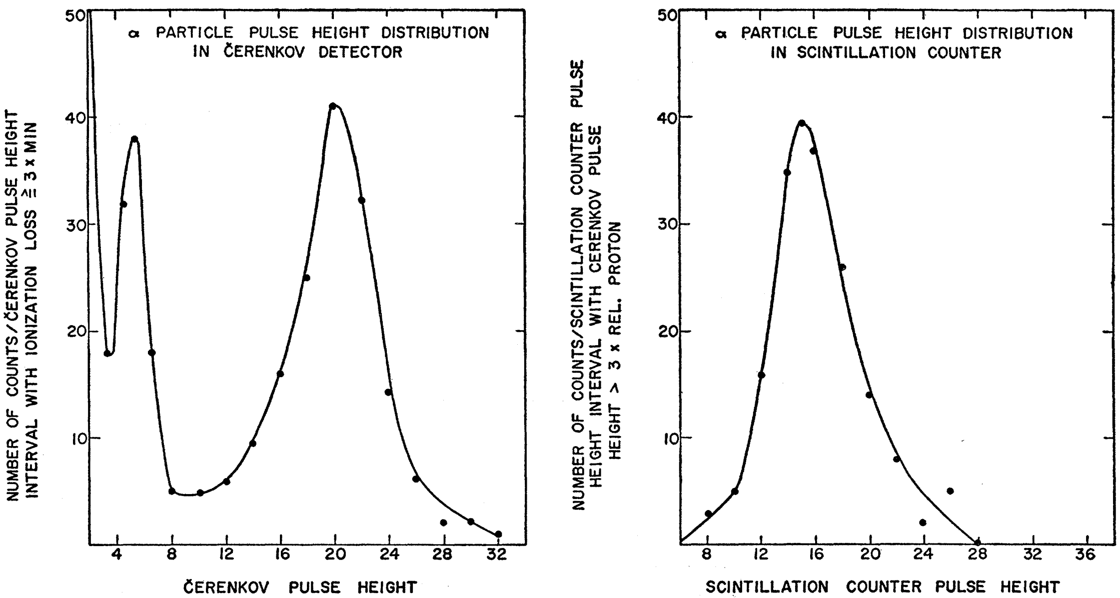


FIG. 5. Plot on left is Čerenkov distribution of all events with an ionization loss greater than 3× minimum ionization. Peak at low value of Čerenkov pulse height is due to slow protons, the middle peak is due to the Williams-Landau tail of fast protons, and the third peak is the resolved alpha peak. The plot on the right is the scintillation counter pulse-height distribution of events with Čerenkov pulse height greater than 3× that of a proton with $\beta\approx 1$.

III. PRIMARY ALPHA-PARTICLE FLUX NEAR THE GEOMAGNETIC EQUATOR

The two-dimensional distribution of counts in the α region obtained at 6 g/cm^2 residual atmosphere is shown in Fig. 4. This plot gives the value of energy loss in the crystal *vs* Čerenkov pulse height for each event with an energy loss greater than twice minimum ionization. With the exception that all shower and multiple particle events have been excluded, no corrections have been applied to these data. This plot reveals a well-resolved group of particles in the region where the alpha particles are expected to be. The data can best be reduced by studying the Čerenkov distribution of those events with an ionization loss greater than 3× minimum ionization. In a similar fashion the ionization distribution of those events with Čerenkov pulse height greater than that of a proton with $\beta\cong 1$ can be studied. The two distributions obtained in this manner are shown in Fig. 5. It is clearly seen that the alpha peak is well resolved. The excellent peak-to-valley ratio of both distributions for low values of pulse height and the manner in which they go to zero for large pulse height values indicate a minimum of background in the alpha region. The Čerenkov distribution in the left plot of Fig. 5 has three well-defined peaks. The unresolved peak with low value of Čerenkov pulse height is produced by slow protons. The second peak is due to the Williams-Landau tail of the proton energy-loss distribution. The peak with a Čerenkov pulse height of 20 is the alpha peak.

It is necessary to apply a small background correction similar to the one previously described.[1] With this correction applied, there were 159±13 counts in the α distribution recorded in a 5-hour period. This represents the number of α particles which traverse the telescope without producing an interaction or high-energy δ ray. The background correction adds a ±4% error to the actual number of counts. The pertinent α data and additional corrections are summarized below:

Number of α counts/sec at 6.1 g/cm^2 = 0.0089±0.007;
Telescope geometric factor = 6.85±0.25 cm^2-sterad;
Atmospheric depth = 6.1 g/cm^2;
Amount of material in telescope (air equivalent) = 8 g/cm^2;
Mean free path = 45±4 g/cm^2;
+5±2% δ-ray correction;
−4±1% correction, for α's produced by fragmentation of heavy nuclei in 6.1 g/cm^2 atmosphere above telescope.

Applying these corrections leads to a value of the alpha flux at the top of the atmosphere, $J_{0\alpha}$, of

$$J_{0\alpha}=18.0\pm 2 \text{ alphas/m}^2\text{-sec-sterad.}$$

The δ-ray correction is necessary as it is possible for particles traversing the telescope to produce knock-on electrons which trigger one of the Geiger counters. This results in events being classified as multiple-particle events. A spurious increase in counting rate might result from particles traversing the top two elements of the telescope and triggering the lower tray with a δ ray but the ring of guard counters (Fig. 2) greatly reduces this effect.

It is difficult to assign a cutoff energy to the alpha flux value previously quoted in view of the current con-

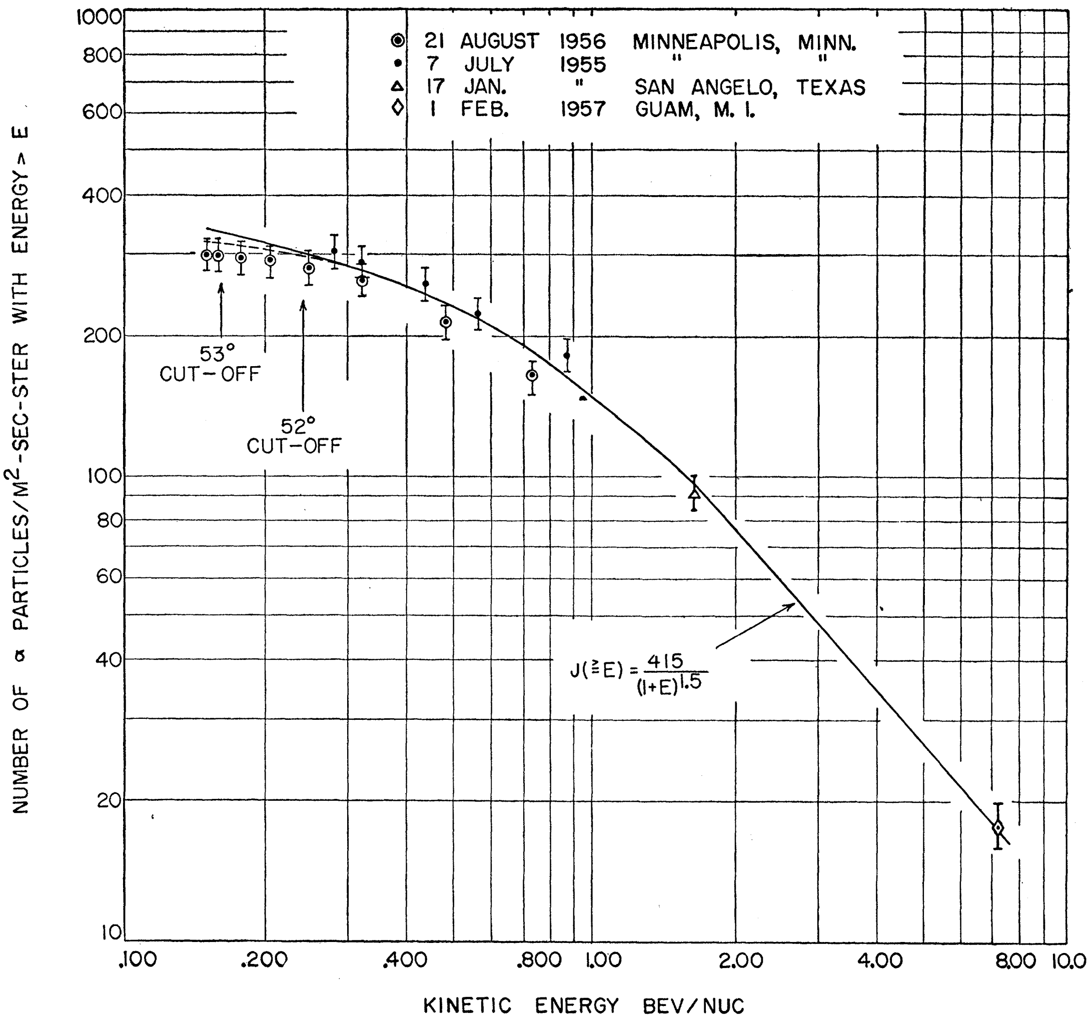


FIG. 6. Alpha integral energy flux data from four Skyhook flights with Čerenkov scintillation detector. The dotted curve represents the function

$$J_{0\alpha}(\geqq E)=\int_E^\infty \frac{-(1.5)(415)[1-\exp(-80E'^3)]dE'}{(1+E')^{2.5}}.$$

At $E>350$ Mev/nucleon this is identical with $J_0(\geqq E)=415/(1+E)^{1.5}$ which is shown as a solid line.

fusion regarding the applicability of conventional geomagnetic theory to the study of cosmic rays. The work of Simpson, Katzman, and Rose,[9] Fowler and Waddington,[10] Freier, Ney, and Fowler,[11] and McDonald[2] clearly indicates that measured cosmic-ray coordinates and cutoff energies do not agree with those calculated from conventional geomagnetic theory. Probably the best estimate can be obtained by calculating a new cutoff energy on the basis of the equator shift proposed by Simpson *et al.* This procedure leads to a vertical cutoff rigidity at Guam of 16.3 Bv, which corresponds to an α cutoff energy of 7.3 Bev/nucleon. This value must be regarded as tentative until more definitive experiments on cutoff rigidities at low latitudes can be performed.

[9] Simpson, Katzman, and Rose, Phys. Rev. **102**, 1648 (1956).
[10] P. H. Fowler and C. J. Waddington, Phil. Mag. **1**, 637 (1956).
[11] Freier, Ney, and Fowler, Bull. Am. Phys. Soc. Ser. II, **2**, 191 (1957).

IV. ALPHA-PARTICLE ENERGY SPECTRUM

To construct an α energy spectrum over the range 0.150 to 7.3 Bev/nucleon the results of 4 Skyhook flights with the Čerenkov-scintillation detector will be used. These include the equator flight, one flight from San Angelo, Texas ($\lambda=41°$N) and two flights from Minneapolis, Minnesota. With the two latter flights it was possible to make direct measurements of the energy spectrum in the region 0.150 to 0.800 Bev/nucleon. The α flux values and energy spectrum data from the four flights are summarized in Table I and the integral flux values are plotted in Fig. 6. It is observed that a good fit is obtained over the region 0.300 to 7.3 Bev/nucleon

TABLE I. Summary of alpha-particle measurements with Čerenkov scintillation detection.

E Kinetic energy (Bev/nucleon)	$J_{0\alpha}(\geqq E)$ [No. of primary α particle/m²-sec-sterad with kinetic energy $\geqq E$]
Flight 3, July 7, 1955, λ=55°N [Minneapolis, Minn.]	
0.280	306±25
0.320	294±25
0.436	261±20
0.563	225±20
0.883	183±18
Flight 8, August 21, 1956, λ=55°N [Minneapolis, Minn.]	
0.153	298±25
0.161	297±25
0.204	290±25
0.249	278±20
0.316	260±20
0.350	250±20
0.487	±16
0.730	±14
Flight 1, January 17, 1955, λ=41°N	
$J_{0\alpha}(E\geqq 1.65$ Bev$)=90\pm 9$ particles/m²-sec-sterad	
Flight 11, January 30, 1957, λ=3°N	
$J_0(E\geqq 17.3$ Bev$)=18.0\pm 2$ particles/m²-sec-sterad	

with an integral energy spectrum of the form

$$J_{0\alpha}(\geqq E)=[415/(1+E)^{1.5}]\ \alpha \text{ particles/m}^2\text{-sec-sterad}, \quad (1)$$

where $J_{0\alpha}(\geqq E)$ is the vertical flux of primary cosmic-ray alphas with an energy greater than E (measured in Bev/nucleon).

However, this spectrum does not fit the measured integral and differential energy spectrum data in the region below 300 Mev/nucleon. The low-energy differential energy spectrum data are plotted in Fig. 7. This spectrum has a maximum in the vicinity of 325 Mev/nucleon and decreases as one goes to lower energy. The simple power spectrum of Eq. (1) predicts a continuously increasing differential energy spectrum as the energy is decreased. However, it is found that excellent agreement (Fig. 5) is obtained with a differential spectrum of the form:

$$\frac{dJ_{0\alpha}}{dE}=-\frac{(1.5)(415)}{(1+E)^{2.5}}[1-\exp(-80E^3)] \text{ particles/m}^2\text{-sec-sterad-Bev.} \quad (2)$$

The value

$$J_{0\alpha}(\geqq E)=\int_E^\infty \frac{-1.5(415)[1-\exp(-80E'^3)]}{(1+E')^{2.5}}dE' \text{ particles/m}^2\text{-sec-sterad} \quad (3)$$

is in agreement with the experimental data over the region 0.150 to 7.3 Bev/nucleon. The α differential energy spectrum of Fowler, Waddington, Freier, Ney, and Naugle[12] is also in good accord with Eq. (2). The exponential term in Eq. (3) is completely negligible for $E>0.350$ Bev/nucleon and in this region Eq. (3) is essentially identical to Eq. (1). Equation (2) was derived in an empirical manner and the significance of the exponential term is not understood at the present time.

The four Skyhook flights considered in this section took place over a two-year period. Neutron monitor counting rates are available at λ=0°, 42°,[13] and 56°[14]

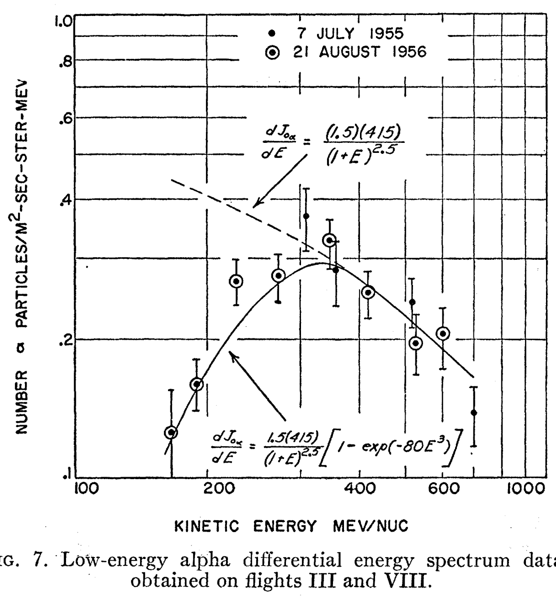


FIG. 7. Low-energy alpha differential energy spectrum data[1,2] obtained on flights III and VIII.

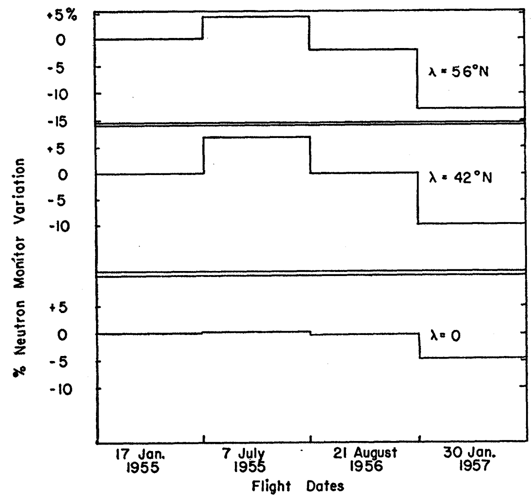


FIG. 8. Sea level neutron monitor data for four days on which flights used in Fig. 6 and Table I were made. The λ=0 and 42° data are from the University of Chicago stations at Huancayo, Peru, and Sacramento Peak, New Mexico. The λ=56° data are from the University of New Hampshire station at Mount Washington, New Hampshire.

[12] Fowler, Waddington, Freier, Naugle, and Ney, Phil. Mag. 2, 157 (1957).

[13] The λ=0° and 42° data are from University of Chicago stations at Huancayo, Peru, and Sacramento Peak, New Mexico, and were communicated to the author by Dr. J. A. Simpson, University of Chicago.

[14] The λ=56° data are from the University of New Hampshire's Mount Washington Station and were communicated to the author by Dr. John Lockwood, University of New Hampshire.

on each of the flight days. These data are summarized in Fig. 8. There is a decrease in the neutron level in August, 1956, and January, 1957. This is clearly reflected in the α data at 55°. However, the January 30, 1957 equator neutron level decreased only 6% from the January 17 and July 7, 1955 flight days. To a crude approximation this corresponds to a 9% decrease in the alpha flux. Actually the errors introduced by time variations would seem to be less than the experimental errors.

V. PROTON FLUX NEAR THE GEOMAGNETIC EQUATOR

The task of measuring primary cosmic-ray flux values is much more difficult for protons than for multiply charged particles. The interaction of primaries with air nuclei produce many fast, singly charged secondaries. Some of these secondaries move in an upward direction and constitute the "splash albedo." The earth's magnetic field acts on the splash albedo and a portion of it will re-enter the earth's atmosphere and will be termed "returning albedo." The copious production of fast secondaries, which are difficult to distinguish from primary protons, and the albedo problem greatly complicate the determination of the primary proton flux.

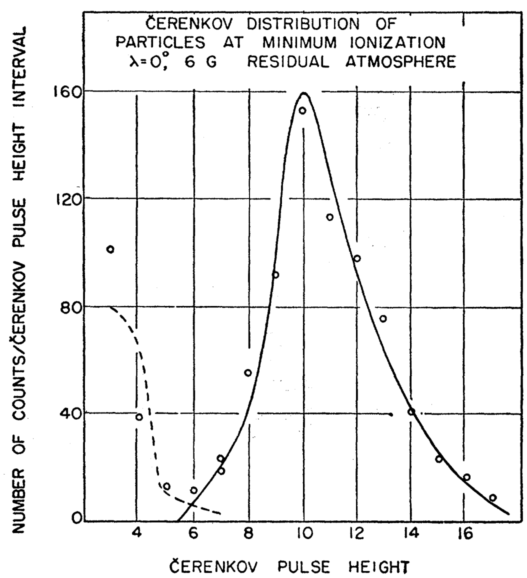


FIG. 9. Circles represent the Čerenkov pulse-height distribution of particles at minimum ionization obtained at 6.1 g/cm² residual atmosphere. The solid line is the sea level μ-meson distribution normalized to the same area. The dotted line is the sea level μ-meson distribution obtained with an inverted telescope. This gives the Čerenkov distribution of fast albedo particles. Again the curves have been normalized to the same area.

It was pointed out in Sec. II that the fast splash albedo is readily identifiable because of the gross directional properties of the Čerenkov counter. The Čerenkov distribution at 6.1 g/cm² of particles at minimum ionization (kinetic energy$>M_0c^2$) is shown in Fig. 9. The solid line represents the normal sea level μ-meson distribution. The dotted line represents the sea level μ-meson distribution obtained by inverting the detector. This gives the pulse-height distribution of upward moving particles. The sea level distributions have been normalized so that they contain the same number of counts as the data obtained at 6.1 g/cm² residual atmosphere. The resolution of incident fast, singly charged particles and of splash albedo appears to be good and there is excellent agreement between the sea level distributions and the data obtained at altitude. This would indicate a minimum of background events are included in the altitude data. As multiple particle events have been excluded from all distributions, a correction is necessary for those particles which produce interactions in the block and have thus been removed from the distributions. The resolution achieved is not surprising in view of the individual resolution of the three different

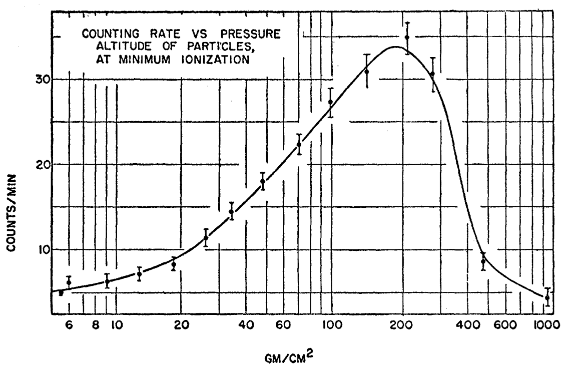


FIG. 10. Counting rate of particles at minimum ionization *vs* pressure altitude.

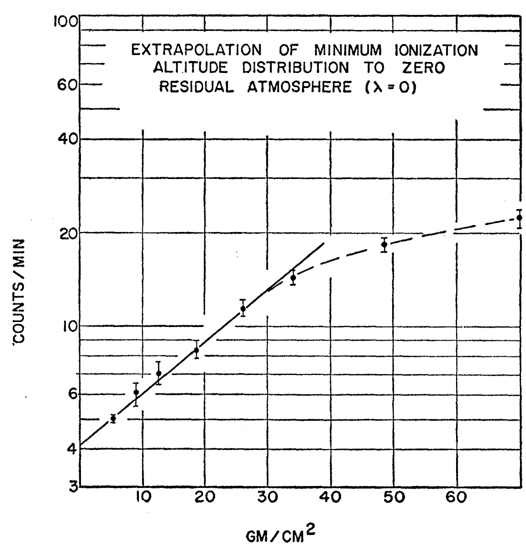


FIG. 11. Extrapolation of flux of particles at minimum ionization to 0 atmospheric depth. The counting rate curve appears to have constant slope from 6 to 34 g/cm².

TABLE II. Proton and total flux values near the geomagnetic equator.

Geomagnetic latitude, location, and date	Observer	Experimental technique	Atmos depth	Absorber	Total flux particles/ m^2-sec-sterad	Proton flux [if measured directly]	Total flux corrected for α-particle contribution
$\lambda=0$, Peru, June, 1949	Winckler *et al.*[a]	Vertical telescope	15	3 cm Pb	270 ± 10		260 ± 10
$\lambda=0$, Peru, March, 1949	Van Allen and Singer[b]	Vertical telescope	Rocket altitude	0	280 ± 40		260 ± 40
$\lambda=3°$N, India, 1953	Pomerantz[c]	Vertical telescope	14	4 cm Pb	240 ± 20		230 ± 20
$\lambda=3°$N, India, 1953	Rao *et al.*[d]	Vertical telescope	Extrapolated to 0 atmos depth	10 cm Pb	227		217
$\lambda=10°$N, Galapagos, 1953	McClure[e]	Ionization chamber +telescope	Extrapolated to 0 atmos depth	4 cm Pb	260	145	
$\lambda=2°$S	Vernov and Charakhchyan[f]	Nuclear interactions in Pb	Extrapolated to 0 atmos depth	10 cm Pb		150	
$\lambda=3°$N, Guam, January, 1957	McDonald	Čerenkov scintillation	Extrapolated to 0 atmos depth	0		115–95	

[a] See reference 6.
[b] See reference 7.
[c] M. A. Pomerantz, Phys. Rev. **95**, 531 (1954).
[d] See reference 15.
[e] See reference 5.
[f] See reference 4.

detectors the particles are required to traverse. Slow secondaries will have zero or very small Čerenkov pulse heights similar to the splash albedo but will have a greater value of energy loss. There was a distinct paucity of downward moving particles in the kinetic energy range $0.3M_0c^2-0.8M_0c^2$. This fact greatly facilitates analysis of the data.

The best method of correcting for the production of fast secondaries above the telescope is based on the altitude distribution of the flux of incident fast particles (Fig. 10). The ratio of the counting rate at the Pfotzer maximum to the rate at altitude is somewhat higher than that obtained by Winckler[6] in his equatorial flights. However, Rao *et al.*[15] have shown that the counting rate in the vicinity of the Pfotzer maximum is a function of the amount of material in the telescope. If the high altitude portion of Fig. 8 is replotted with a linear pressure scale and logarithmic counting rate scale (Fig. 11), the counting rate curve has a constant slope in the region 6–35 g/cm^2. With a uniform slope over such a wide range, one can confidently extrapolate over the small interval 6 to 0 g/cm^2. This procedure leads to a -18% correction. The very high altitude reached by the balloon greatly reduces the magnitude of the extrapolation. At the present time it is not possible to isolate the returning albedo. However, in Sec. VI limits will be set on the amount of returning albedo.

The data relevant to the proton flux are summarized below:

Counting rate of fast downward moving particles at 6.1 g/cm^2$=0.084\pm0.002$ counts/sec;
Telescope geometric factor$=6.85\pm0.25$ cm^2-sterad;
Amount of material in telescope (air equivalent) $=8$ g/cm^2;
Proton interaction mean free path in air (calc)$=68$ g/cm^2;
Correction from 6.1 g/cm^2 to 0 g/cm^2$=-18\%$.

[15] Rao, Balasubrahmanyan, Gokhale, and Pereira, Phys. Rev. **91**, 764 (1953).

These corrections give a proton flux value of

Upper limit: $J_{0p}(E\geqq15.3\text{ Bev})=115\pm12$ particles/m^2-sec-sterad (without returning albedo correction).
Lower limit: $J_{0p}(E\geqq15.3\text{ Bev})=90\pm12$ particles/m^2-sec-sterad (with maximum returning albedo corrections; see Sec. VI).

These values have been corrected for the particles which have been removed by the production of nuclear interactions in the telescope. It is felt that these two flux values set realistic limits on the proton flux that existed above Guam on January 30, 1957. The total flux values and proton values obtained in other experiments near the geomagnetic equator are summarized in Table II. The data of McClure and of Vernov and Charakhchyan are in fair agreement with the present work and would be in close agreement if corrected for albedo. The telescope data of Winckler and of Van Allen and Singer give total flux values which are more than a factor of two greater than the value quoted in the present work. However, the total counting rate obtained with the Čerenkov scintillation detector at 18 g/cm^2 was 320 particles/m^2-sec-sterad. This value is 20% greater than the flux measured by Winckler at this altitude. Thus when splash albedo and slow secondaries are eliminated and an extrapolation to the top of the atmosphere is made, a significantly lower flux value results.

In a similar fashion a proton flux value of $J_{0p}(E\geqq4.0\text{ Bev})=570$ particles/m^2-sec-sterad was obtained with a Čerenkov scintillation counter flight made from San Angelo, Texas on January 17, 1955. This flux agrees well with the proton flux measured by Perlow *et al.*[16] with rockets at the same latitude. Their detector was a double proportional counter telescope with lead absorbers and Geiger counter trays interspersed below the telescope.

The uncertainties in the returning albedo spectrum make it difficult to fit the proton energy spectrum data

[16] Perlow, Davis, Kissinger, and Shipman, Phys. Rev. **88**, 321 (1952).

with the same accuracy achieved with the alphas. It is of interest to see if the high-energy proton spectrum has the same energy dependence as the alphas. Indeed it is found that the proton spectrum can be represented quite accurately (Fig. 12) with an integral energy spectrum of the form

$$J_{0p}(\geqq E)=6600/(1+E)^{1.5} \text{ particles/m}^2\text{-sec-sterad.}$$

This spectrum can certainly not be extended to proton energies below 1.5 Bev. It is possible that a modification of the form suggested in Eqs. (2) and (3) (Sec. V) will be applicable. However, in the region $\lambda=0$ to $41°$ it appears quite definite that the alpha particles and protons have the same energy spectrum. This conclusion will not be altered by moderate changes in geomagnetic cutoff energies.

VI. SPLASH ALBEDO MEASUREMENTS

The flux of fast upward moving particles at 6.1 g/cm² can be obtained from the Čerenkov distribution of minimum ionization particles (Fig. 8) and will be characterized by zero or very small Čerenkov pulse height. The sea level meson distribution with the detector inverted is fitted to the distribution located in the region of small Čerenkov pulse height. This gives a fast splash albedo flux of $J_{\text{splash albedo}}(E\geqq 0.8M_0c^2)=19\pm3$ particles/m²-sec-sterad where M_0 is the mass of the splash albedo particle under consideration (probably confined to e, μ mesons, and protons).

In a similar fashion the number of upward moving particles with energy between 0.3 and $0.8M_0c^2$ is $J_{\text{splash albedo}}(0.3\leqq E\leqq 0.8M_0c^2)=12\pm2$ particles/m²-sec-sterad. Anderson's equatorial splash albedo flux value was 67 ± 15 particles/m²-sec-sterad at 18 g/cm² using a Čerenkov counter. It is felt that the Čerenkov scintillation apparatus with its two detectors gives a more positive means of identifying splash albedo.

The work of Winckler and Anderson[17] at 41°N indicated that splash albedo was essentially isotropic at high altitudes. This means that to a crude approximation the vertical fast splash albedo flux measured in this experiment is an upper limit of the amount of returning albedo flux. Since the vertical splash albedo appears to have a steep energy spectrum and decreases with increasing altitude, it is probable that the fast re-entry albedo is significantly less than 20 particles/m²-sec-sterad.

The flux of slow secondary protons in the range 100–300 Mev was measured to be $J_{\text{slow proton}}(100 \text{ Mev}\leqq E\leqq 300 \text{ Mev})=13\pm3$ particles/m²-sec-sterad.

[17] J. R. Winckler and K. A. Anderson, Phys. Rev. **93**, 596 (1954).

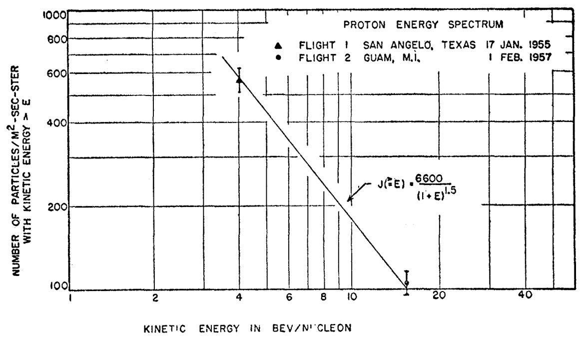


Fig. 12. Proton integral energy spectrum in region $\lambda=0$–41°N.

CONCLUSION AND DISCUSSION

The value of $J_{0\alpha}=18\pm2$ particles/m²-sec-sterad of this experiment is 25% lower than the value obtained by Shapiro, Stiller, and O'Dell using emulsions flown near the Galapagos Islands. This is not surprising since the recent airplane equatorial neutron survey by Simpson[18] has shown that the neutron counting rate over the Galapagos Islands is substantially greater than the counting rate obtained at Guam.

The proton flux value measured in this experiment is much lower than that measured by other observers. This disagreement is too large to be accounted for by the higher geomagnetic cutoff at Guam. However, the present experiment would seem to be the first one that could directly distinguish fast downward moving particles from slow secondaries and splash albedo and which could accurately be extrapolated to zero atmospheric depth. It must also be emphasized that in every case the magnitude of the corrections applied to measured counting rates is smaller for protons than for alphas. The lower proton counting rate should have important consequences regarding the cosmic-ray energy balance.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the Office of Naval Research for the excellent Skyhook balloon flights and to Commander R. C. Cochoran and Lieutenant Commander S. C. Daubin who made the arrangements for the equatorial expedition.

[18] J. A. Simpson, University of Chicago (private communication).