VARIATION OF PROTON FLUX WITH ATMOSPHERIC DEPTH BETWEEN 10 AND 50 G/CM^2 AT $\lambda = 47°$ S. GEOMAGNETIC

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Summary

Proton fluxes at atmospheric depths between 10 and 50 g/cm^2 have been measured using nuclear emulsions during a series of balloon flights over Melbourne ($\lambda = 47°$ S. geomagnetic) in the period November 1961–April 1962. The proton flux $J(x)$ decreases with increasing depth within this region. It can be represented by the relation $\log J(x) = (3\cdot 05 \pm 0\cdot 02) - (2\cdot 36 \pm 0\cdot 66) \times 10^{-3}x$ and, when extrapolated, gives the flux at the top of the atmosphere to be 1120 ± 50 protons m^{-2} steradian^{-1} s^{-1}.

Introduction

In the last decade, measurements of the proton flux have been attempted at various geomagnetic locations with a variety of balloon-borne electronic counters, but owing to the uncertainty in the magnitude of the splash albedo most earlier results are subject to error. McDonald and Webber (1959) made a series of flights during the period 1955–1959 employing directional sensitive Čerenkov scintillator arrays. Their measurements on the proton flux are almost entirely responsible for our present knowledge of these particles.

An alternative method of measuring proton flux, which can also discriminate against the albedo particles, has been suggested by Waddington (1960). The proton flux is determined by observing the nuclear interaction stars that the protons produce while passing through nuclear emulsions. This method is valuable since it enables us to compare the proton flux with fluxes of multiply charged nuclei, all flux values being measured by the same device.

In order to extrapolate the proton flux values observed in emulsions to the top of the atmosphere, it is necessary to establish a growth curve for these particles. Because the values obtained by the emulsion technique refer to singly charged interacting particles, we do not expect the growth curve, determined by counter devices which will respond to all fast singly charged particles, to apply directly to emulsion data. In view of this we have determined a growth curve for the emulsion technique by exposing emulsions to cosmic radiation at different atmospheric depths.

Experimental Details

Exposure of Emulsions

The data for the present study were obtained from Ilford G5 emulsions which were exposed to the primary cosmic radiation at atmospheric depths between 10 and 50 g/cm^2 at Melbourne ($\lambda = 47°$ S. geomagnetic) during the period November 1961–April 1962 on days when the sea-level neutron counts varied less than 1%.

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The emulsions were exposed simultaneously at two different altitudes by the method described by Hopper *et al.* (1963). Two packets of emulsions were carried by the balloon to its ceiling altitude, then one packet, attached by approximately 6 km of string, was dropped to a lower altitude. The two packets were thus exposed with this constant separation between them. In some cases simultaneous flights were made at two levels.

Every exposed packet was developed with corresponding background plates from the same batch in order to correct for stars produced during storage. Also, to correct for stars produced during ascent and descent, emulsions were sent up to various altitudes and then allowed to descend immediately. The sets of emulsions used in this study are listed in Table 1. The value of x g/cm^2 represents the mean total amount of matter present above the emulsions at the altitude of exposure for zenith angles between 0° and 30°.

Table 1

LIST OF EMULSIONS USED FOR THE PRESENT INVESTIGATION

Set	Date of Exposure	Residual Pressure x (g/cm^2)
JU	November 3, 1961	49·7
JW	November 3, 1961	16·1
JU, W test	—	—
LA	February 15, 1962	36·0
LC	February 15, 1962	10·2
LA, C test	—	—
MA	April 5, 1962	12·7
MD	April 5, 1962	27·8
MB	April 5, 1962	Up to 31·0, descent immediately
MF	April 5, 1962	Up to 12·7, descent immediately
MA, B, D, F test	—	—
MH	April 5, 1962	21·3
MJ	April 5, 1962	Up to 19·4, descent immediately
MH, J test	—	—

Scanning Criteria

The emulsions were area scanned for all stars with $N_h \geqslant 3$, excluding stars lying within 15 μ from either surface of the processed emulsions. Thorium stars were also excluded. The scanning efficiency was found using the method described by Wu *et al.* (1964). Each star was then carefully examined under higher magnification for the presence of minimum ionization tracks left by fast singly charged particles. The efficiency in finding these tracks was found to be 100%.

With particles arriving at large zenith angles the reduction in the average flux due to geomagnetic effects is not sufficiently well known; therefore the primary particles that would be accepted for flux calculation were limited to a zenith angle of $\theta = 30°$. The direction of the primary particle can, in certain cases, be determined by examining the configuration of the star. Following Waddington (1960), the stars were classified into seven groups having different degrees of certainty with which the primary can be selected. The identity of the primary particle of the stars of groups (*a*), (*c*), and (*d*) (see Waddington 1960, Fig. 3), which together occupy 64·3% of the total, is well determined. Group (*f*), which occupies 2·1%, can be identified as produced by albedo particles. However, the primary particle of the stars in groups (*b*), 21·8%, (*e*), 7·0%, and (*g*), 4·8%, cannot be definitely identified; therefore each was given an appropriate fractional weight to obtain the number of stars with primary particle having $\theta \leqslant 30°$. Corrections were then made to the selected stars for the number produced during times other than the period of level flight of the balloon.

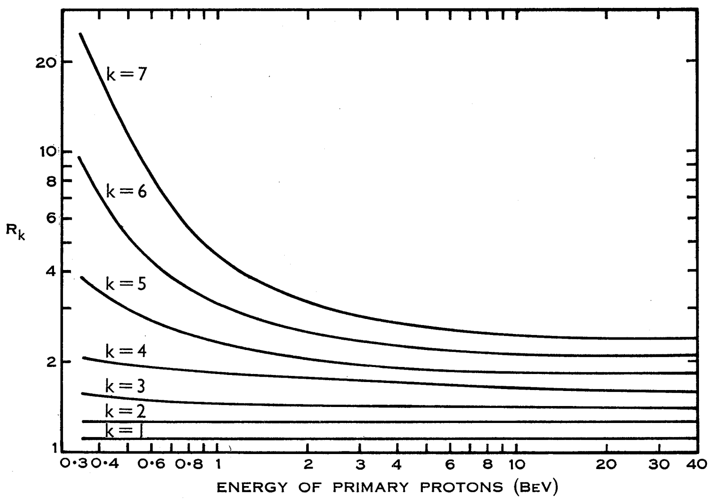

Fig. 1.—Energy dependence of the ratio R_k of the number of stars with $N_h \geqslant 0$ to the number of stars with $N_h \geqslant k$ for $k = 1$–7.

Estimation of Total Number of Interactions from the Determined Number of Interactions with $N_h \geqslant k$

In order to obtain all the interactions recorded in the emulsion during its exposure, it is necessary to know the ratio R_k, defined as the number $N(0)$ of stars in the emulsion with $N_h \geqslant 0$, to the number $N(k)$ of stars with $N_h \geqslant k$. The experimental data available on the interactions produced in nuclear emulsions by artificially accelerated protons of various energies (Sprague *et al.* 1954; Lock and March 1955*a*, 1955*b*; Rajopadhye 1960; Winzeler *et al.* 1960; Cvijanovich *et al.* 1961; Lim 1962) have been used to construct the energy dependence of R_k for values of k from 1 to 7 (Fig. 1).

The average number of shower particles produced during each interaction, or the mean multiplicity $\bar{n}_s$, has been found to be a function of the energy E of the primary particles. An empirical curve (Fig. 2) for the energy dependence of $\bar{n}_s$ was constructed using the data published by various authors (Camerini *et al.* 1951;

Bogachev *et al.* 1958; Rajopadhye 1960; Winzeler *et al.* 1960; Barbaro-Galtieri *et al.* 1961; Bricman *et al.* 1961; Lim 1962; Marzari-Chiesa *et al.* 1963). The stars selected during the present study have a mean multiplicity of $1 \cdot 80 \pm 0 \cdot 14$. From Figure 2 this yields a median energy of $3 \cdot 8 \pm 0 \cdot 5$ BeV for the primary protons. Therefore, from Figure 1 we obtain the values $1 \cdot 4 \pm 0 \cdot 1$, $1 \cdot 7 \pm 0 \cdot 1$, $1 \cdot 9 \pm 0 \cdot 1$, $2 \cdot 3 \pm 0 \cdot 1$, and $2 \cdot 7 \pm 0 \cdot 2$ for R_3, R_4, R_5, R_6, and R_7 respectively. A good estimation of $N(0)$ may thus be found from the known $N(k)$ values with values of k from 3 to 7.

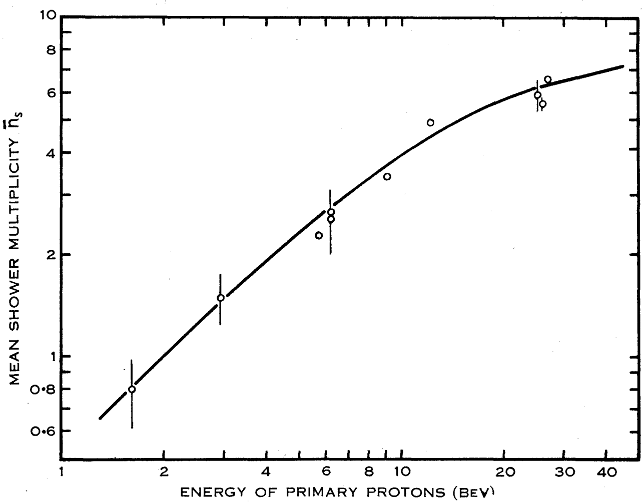

Fig. 2.—Variation of the mean multiplicity $\bar{n}_s$ with the energy of the primary protons.

Results

Calculation of Proton Flux

The proton flux under x g/cm^2 of residual material $J(x)$ is given by the relation

$$J(x) = \frac{\lambda N(0)}{Vt\Omega} \qquad (\text{protons m}^{-2}\,\text{sr}^{-1}\,\text{s}^{-1}),$$

where λ is the interaction mean free path of fast protons in the emulsion in metres; $N(0)$ is the estimated total number of interactions in the emulsion; V is the volume of emulsion scanned in cubic metres; Ω is the solid angle subtended by the protons (in the present case $\Omega = 0 \cdot 27$ sr corresponding to $\theta = 30°$); and t is the duration of exposure in seconds. A number of workers have determined the interaction mean free paths of protons of various energies in emulsion and all values are energy independent (Bogachev *et al.* 1958; Rajopadhye 1960; Winzeler *et al.* 1960; Barbaro-Galtieri *et al.* 1961; Cvijanovich *et al.* 1961; Abraham and Kalbach 1962). The average value of $37 \cdot 1 \pm 1 \cdot 5$ cm was adopted for the present calculations of proton fluxes.

The proton fluxes obtained with various amounts of residual material are listed in Table 2 and are plotted on a semi-logarithmic scale in Figure 3. The errors quoted are statistical. Assuming a relation of the type $\log J(x) = a + bx$, a straight line was therefore fitted through these experimental points using the least square method, which gave $a = 3 \cdot 05 \pm 0 \cdot 02$ and $b = -(2 \cdot 35 \pm 0 \cdot 66) \times 10^{-3}$ cm^2/g. The line was extrapolated to determine the flux at the top of the atmosphere, $J(0)$; the value obtained was 1120 ± 50 protons m^{-2} sr^{-1} s^{-1}.

TABLE 2

PROTON FLUX AT DIFFERENT ATMOSPHERIC DEPTHS

x (g/cm^2)	$J(x)$ (protons m^{-2} sr^{-1} s^{-1})	x (g/cm^2)	$J(x)$ (protons m^{-2} sr^{-1} s^{-1})
10·2	1030 ± 165	27·8	990 ± 115
12·7	1040 ± 100	36·0	930 ± 100
16·1	1140 ± 120	49·7	855 ± 165
21·3	930 ± 110		

Energy Spectrum of the Protons

The integral energy spectrum of the protons (Fig. 4) was obtained using the n_s frequency distribution of all the $N_h \geqslant 3$ stars with the aid of Figure 2. It can be fitted by a power law with $\gamma = 1 \cdot 37 \pm 0 \cdot 10$. No attempt has been made to correct the n_s distribution to include stars with $N_h < 3$. Because the mean multiplicity $\bar{n}_s$ increases with N_h (Daniel *et al.* 1960; Barbaro-Galtieri *et al.* 1961) we expect the energy spectrum obtained from the corrected n_s distribution to agree better with the power law at the low energy end and also to give a greater value of γ.

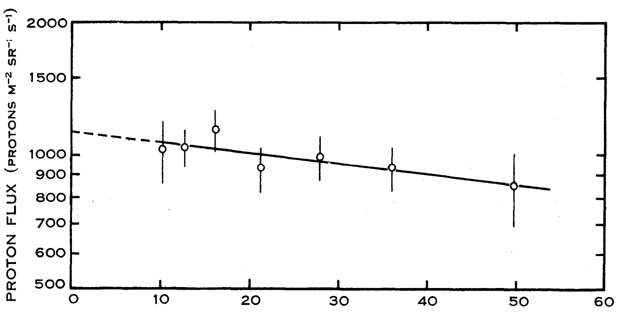

Fig. 3.—Variation of the proton flux at $\lambda = 47°$ S. with atmospheric depth determined by emulsions.

DISCUSSION

Although there is a large margin of error associated with the experimental points of Figure 3, we can still conclude that the proton flux *v.* atmospheric depth curve at $\lambda = 47°$ S. has a negative slope in the range of atmospheric depth from 10 to 50 g/cm^2. More results are being analysed and measurements at higher altitudes are planned to improve the accuracy of the result. On the other hand, the curves determined by McDonald and Webber (1959) using Čerenkov scintillator arrays for proton energy intervals $E \geqslant 750$ MeV, $100 \leqslant E \leqslant 750$ MeV, and $100 \leqslant E \leqslant 350$

MeV at various geomagnetic latitudes have positive slope near the top of the atmosphere and reach a peak between 50 and 100 g/cm^2. However, this difference may be explained as follows.

The shape of the proton growth curve in the atmosphere depends on the number of secondary protons which are emitted during each interaction of the primary proton (and, to a lesser extent, of α-particles) with the air nuclei, and registered by the detector. Suppose that during an interaction of a primary proton of energy E, n secondary protons are emitted and, of these, a number $n' \leqslant n$ can be

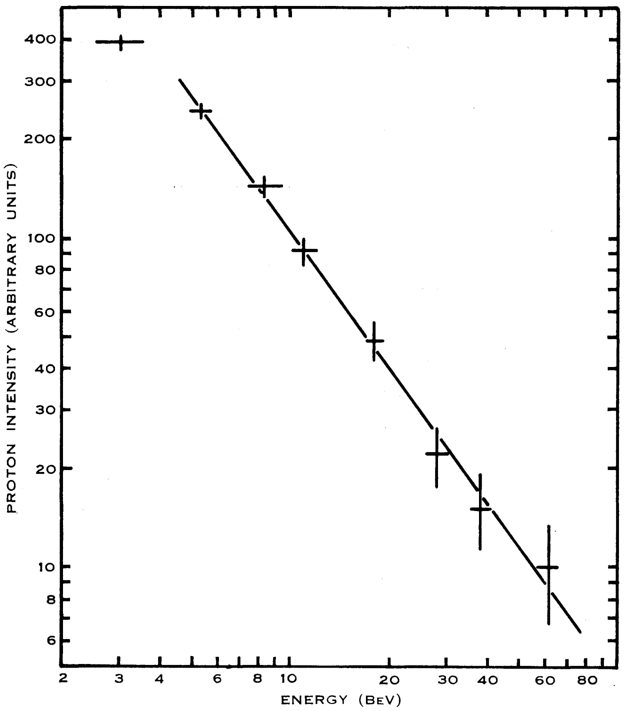

Fig. 4.—Integral energy spectrum of protons fitted by a power law: intensity $\propto (1+E)^{-1\cdot 37\pm 0\cdot 10}$.

detected by the detector which will respond to protons with energy greater than E'. When n' is sufficiently large so that during the passage of the protons through the atmosphere more protons are produced than are absorbed, we would expect the proton flux to increase to a peak and then start to decrease when absorption becomes dominant.

If an increase in the energy E results in an increase in the number n, or in the proportion of n with energy greater than E', then in either case an increase in n' will result. Therefore, when E is increased the position of the peak will be shifted towards greater atmospheric depth. This feature has been derived by Messel (1954) from his nucleon cascade theory and is in agreement with the results of McDonald and Webber (1959, Figs. 7 and 8). On the other hand when E is decreased, the value of n' may also decrease. Consequently we would expect the proton flux to be continually decreasing during its passage through the atmosphere.

For the case when the energy of the primary particles is fixed, the value of n' will then depend on the properties of the detector, namely, the value of E' and the overall efficiency in detecting the secondary protons. Therefore, the number n' will be greater for a detector with a lower value of E' and higher efficiency. In the present experiment, nuclear emulsions were used as the detector and protons were detected only if they interacted with the emulsion nuclei. This requirement meant that only protons of sufficiently high energy were capable of being detected. This could be the reason why the growth curve determined in this experiment at $\lambda = 47°$ using nuclear emulsions does not have a peak, in contrast to the curve determined by McDonald and Webber (1959) using Čerenkov scintillator arrays.

TABLE 3
COMPARISON OF PRESENT RESULTS AND THOSE OF MCDONALD AND WEBBER FOR THE PROTON FLUX AT THE TOP OF THE ATMOSPHERE

Flux at the Top of the Atmosphere $J(0)$ (protons m^{-2} sr^{-1} s^{-1})	Cut-off Kinetic Energy (BeV)	Reference
1800±50	0·38	McDonald and Webber (1959)
2190±50	0·5	McDonald and Webber (1959)
1770±50	0·55	McDonald and Webber (1959)
1670±50	0·67	McDonald and Webber (1959)
1550±50	0·8	McDonald and Webber (1959)
1120±50	2·1	Present Work
610±40	3·5	McDonald and Webber (1959)
590±40	3·8	McDonald and Webber (1959)

According to the results reported by Rajopadhye (1960) on the interactions of 5·7 BeV protons with emulsion nuclei, the average number of energetic protons emitted during each interaction is approximately 24% of the total number of shower particles produced. The stars selected for the present study have a mean shower multiplicity $\bar{n}_s = 1 \cdot 8$. If we assume the same percentage of the shower particles to be energetic protons, it would give the mean energetic proton multiplicity a value of 0·43. The results of Camerini *et al.* (1951) indicated that the percentage of protons among the shower particles emitted from each star was greater for stars with greater N_h, and the increase was in a ratio of approximately 1·15 for stars with $N_h = 3$–8 to all stars with $N_h \geqslant 3$. Therefore, if we only consider the interactions with the light nuclei of the emulsions (that is, $N_h = 3$ to $N_h = 8$) which bear a closer resemblance to the air nuclei, the average number of energetic protons emitted per star for the present study would be approximately 0·5. Thus we expect the growth curve to have a negative slope.

The experimental growth curve has been used to extrapolate the proton flux to the top of the atmosphere. It gives the value $J(0) = 1120 \pm 50$ protons m^{-2} sr^{-1} s^{-1}. It can be compared with the values reported by McDonald and Webber (1959) determined during 1955 and 1956—a period of comparable solar activity to the period when the present measurements were made (Table 3). Corrections for the re-entrant albedo have been made to the values given by McDonald and Webber. The results are in agreement.

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References

Abraham, F. F., and Kalbach, R. M. (1962).—*Nuovo Cim.* **26**: 717.

Barbaro-Galtieri, A., *et al.* (1961).—*Nuovo Cim.* **21**: 469.

Bogachev, N. P., *et al.* (1958).—*Sov. J. Atomic Energy* **4**: 373.

Bricman, C., Csejthey-Barth, M., Lagnaux, J. P., and Sacton, J. (1961).—*Nuovo Cim.* **20**: 1017.

Camerini, U., *et al.* (1951).—*Phil. Mag.* **42**: 1241.

Cvijanovich, G., *et al.* (1961).—*Nuovo Cim.* **20**: 1012.

Daniel, R. R., Kameswara Rao, N., Malhotra, P. K., and Tsuzuki, Y. (1960).—*Nuovo Cim.* **16**: 1.

Hopper, V. D., Laby, J. E., Sparrow, J. G., and Unthank, E. L. (1963).—*Nature* **119**: 271.

Lim, Y. K. (1962).—*Nuovo Cim.* **26**: 1221.

Lock, W. O., and March, P. V. (1955*a*).—*Proc. Roy. Soc.* A **230**: 222.

Lock, W. O., and March, P. V. (1955*b*).—*Proc. Roy. Soc.* A **231**: 368.

McDonald, F. B., and Webber, W. R. (1959).—*Phys. Rev.* **115**: 194.

Marzari-Chiesa, A., Rinaudo, G., Ciurlo, S., Picasso, E., and Cartacci, A. M. (1963).—*Nuovo Cim.* **27**: 155.

Messel, H. (1954).—"Progress in Cosmic Ray Physics." Vol. 2, p. 135.

Rajopadhye, V. Y. (1960).—*Phil. Mag.* **5**: 537.

Sprague, A. D., Glasser, R. G., Schein, M., and Haskin, D. M. (1954).—*Phys. Rev.* **94**: 994.

Waddington, C. J. (1960).—*Phil. Mag.* **5**: 1105.

Winzeler, H., Klaiber, B., Koch, W., Nikolic, M., and Schneeberger, M. (1960).—*Nuovo Cim.* **17**: 8.

Wu, K. K. M., Chow, B. S. K., Lim, R., and Hopper, V. D. (1964).—*Nucl. Instrum. Meth.* **25**: 343.