MEASUREMENTS OF THE COSMIC RAY NEUTRON RATE IN THE HIMALAYAS AND AUSTRALIAN ALPS

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[*Manuscript received August 30, 1954*]

Summary

The variation of α-track density in boron-loaded emulsions and the star rate in C2 emulsions have been measured at the same sites at mountain altitudes at two latitudes. The α-count is proportional to the slow neutron density in the atmosphere while the stars arise chiefly from fast neutrons. The variation with altitude can be represented in each case by a simple exponential of the form: $I=I_0e^{-x/L}$. Values were derived for the attenuation length L for each latitude:

geomagnetic lat. 21 °N., $L=148$ (slow neutrons), 139 (stars);

geomagnetic lat. 45 °S., $L=141$ (slow neutrons), 130 (stars).

The close resemblance and direction of variation of L values for neutron flux and star rates is evidence for their generic connexion. The latitude variation of L is less than observed in the upper half of the atmosphere. L values are also somewhat smaller than measured at higher altitudes, consistent with a degradation of the nucleon component with increasing atmospheric depth. The star rate in the atmosphere has been calculated to be $\sim 1 \cdot 3$ stars cm^{-2} sec^{-1} at geomagnetic latitude 45 °S.

I. INTRODUCTION

It has been recognized since soon after the discovery of the neutron that the cosmic ray flux through the atmosphere includes a neutron component. Because of its lack of charge (and hence immunity from accelerating mechanisms) together with its instability it cannot constitute an appreciable part of the primary radiation. However, it is plausible that neutrons comparable in energy to the primary radiation could be produced as disintegration and exchange products of high energy primaries interacting with oxygen and nitrogen nuclei in the top layers of the atmosphere. Interactions of this kind are observed as large stars in photographic emulsions exposed by balloons at $\sim$100,000 ft and it seems reasonable to expect neutrons to be released comparable in energy and abundance with the observed proton tracks.

High energy ($\sim$BeV) product nucleons (both protons and neutrons) from primary interactions give rise to collision cascades reaching down through the atmosphere, the average energy being degraded by successive collisions which give rise to stars and release more, but lower energy, nucleons. At $\sim$100 MeV star production ceases, energy loss by ionization for protons and slowing by elastic and inelastic scattering for neutrons being the predominant processes. The final product of the neutron component which escapes capture comprises slow neutrons ($\sim$1 eV) in random diffusion in the atmosphere.

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This picture of the secondary origin of cosmic neutrons has been confirmed by the determination of a primary transition maximum near the top of the atmosphere both for neutron star rates (Camerini *et al.* 1949 ; Freier, Ney, and Oppenheimer 1949) and the slow neutron intensity (Yuan 1948, 1950).

The present report is concerned with fast and slow neutron fluxes at ground level in the lower half of the atmosphere. Experiments were set up to determine the variation of neutron intensity with altitude at two different latitudes. From the altitude studies the attenuation length of the neutron-producing radiation and related quantities have been derived.

II. Location and Method

The measurements were made in the Garhwal Himalayas during September and October 1951 and in the Australian Alps during January and February 1953. Ilford Nuclear Research emulsions, type C2, 100–200 μ thick were used as detectors. Conditions encountered and the suitability of the Garhwal Himalayas for cosmic ray measurements* have been described (Mather 1952).

The plates were used to make two kinds of measurements :

(*A*) Determination of relative slow neutron flux by measuring the density of α-tracks from the $^{10}B(n,\alpha)^{7}Li$ reaction, using Ilford C2 plates loaded with $0\cdot023$ g cm^{-3} of boron. This reaction generally proceeds to the first excited state of ^{7}Li leading to an α-track of $1\cdot48$ MeV colinear with a recoil of $0\cdot85$ MeV giving a track $\sim$7 μ long. A small correction has to be applied for the capture of slow neutrons in nitrogen present in the gelatin, $^{14}N(n,p)^{14}C$ (cross section $1\cdot7$ barns compared with $\sim$740 for the boron reaction), which gives rise to $\sim$6 μ protons not readily distinguished from the α-tracks. This was determined experimentally by exposing unloaded C2 plates under the same conditions.

(*B*) Direct determination of the high energy flux by observing the production rate of stars per c.c. of emulsion. The majority of evaporation stars at mountain altitudes are due to neutrons of several hundred MeV energy which are themselves products of interactions at higher levels of the collision chain.

Plates were exposed in the Himalayas as follows :

Satpuli.. ..	2,100 ft, residual atmosphere	955 g cm^{-2}
Pauri ..	5,300	849
Hanuman Chatti	8,400	757
Badrinath ..	10,400	701
Saraswati Camp	15,800	565
Mana Pass ..	18,400	508

Exposures, including allowance for ascending and descending times, ranged from 1200 to 540 hr. Geomagnetic latitudes were between 19° 30′ and 21° 9′ N.

* A 17 kW diesel-electric generator is now installed at the town of Badrinath (10,400 ft, geomagnetic lat. $20\cdot5$ °N.) so that electrical equipment can be operated there.

The same quantities were measured in the Australian Alps, except that some boron-loaded plates were shielded with 0·5 mm of cadmium which absorbs all neutrons $\lesssim 0 \cdot 4$ eV energy. The Australian positions were :

Melbourne	sea-level, residual atmosphere	1,030 g cm^{-2}
Mt. Kosciusko area	5,200 ft	853
	7,300	788

Exposures were ~1300 hr, geomagnetic latitude 45° 4′ S. In all cases exposures were long enough to provide good time averages of neutron intensity. Moreover, as an obvious precaution against local variations of slow neutron flux (Section III), several groups of plates were placed about each site in the hope of averaging out differences.

Very little control could be exercised over temperature in these experiments. At the higher Himalayan sites day-time temperatures in the direct blaze of the Sun were uncomfortably high and would have led to severe fogging of the emulsions. On the other hand night temperatures were below zero. Some obvious precautions were followed. The emulsions were prepared by Ilford Ltd. with extra plasticiser. At the lower altitudes boxes of plates were left in villages under a light covering. At higher altitudes they were given shade by covering with an outer highly reflecting tin cover. In spite of this some of the emulsions showed signs of deterioration, generally in the form of background fog.

To minimize fading of the latent image (which can be troublesome in long exposures) the plates were sealed in containers with silica gel. In addition a number of vacuum-tight aluminium boxes were constructed to contain plates. These were pumped and sealed before leaving Colombo.

III. Origin of Slow Neutrons at Ground Level

First consider the case of neutron measurements in free space (strictly speaking only balloon flights in which a lightly covered detector is suspended well below the balloon). The average neutron energy from evaporation stars is probably ~15 MeV. These fast neutrons will be moderated by inelastic and elastic scattering by air atoms, those which survive capture being reduced to ~1 eV in ~130 collisions in a r.m.s. distance of ~150 g cm^{-2}. The neutron intensity changes by only a factor of ~2·5 in this depth so the slow neutron measurements essentially reflect the local neutron production rate in nitrogen and oxygen (Bethe, Korff, and Placzek 1940 ; Davis 1950).

At the surface of the Earth the situation is considerably modified for two reasons. Firstly, neutrons originating in air within 150 g cm^{-2} from the ground may diffuse into the ground where they are moderated and may then escape back to air. Secondly, neutron production occurs in the ground. Neutrons of ~15 MeV require perhaps 200 collisions in the ground to slow them and they may then return into air from production depths up to ~200 g cm^{-2}. Both effects will modify (to a degree depending on the atomic composition of the ground surface, and very difficult to estimate) the neutron spectrum and the slow neutron intensity so that the counting rate of a slow neutron detector cannot be related simply to free space measurements.

However, this does not invalidate ground neutron measurements of altitude behaviour provided conditions remain constant. It is well established that neutron production rate measurements in local condensed materials of light elements lead to the same attenuation length values as free space experiments (Simpson 1951 ; Simpson and Uretz 1953). In the present work the boron-loaded plates were exposed at ground level in topographical settings as comparable as possible. At higher Himalayan sites they were located on extensive outcrops of windswept rock which, during the summer, remained essentially snow-free.

The basic assumption had to be made that the atomic composition of the underlying ground was the same at all sites, which did not appear unreasonable for selected sites in the same mountain range. We believe this assumption has been vindicated by the comparatively small scatter of the results. This is in line with the remarkable uniformity of elemental composition of the lithosphere so far as major constituents are concerned.*

In view of the belief that slow neutrons are final products of star neutrons a direct measurement of star rates (B) can be expected to display approximately the same attenuation with altitude. " Back-streaming " of neutrons of $\sim$200 MeV is much less probable and it may reasonably be assumed that most stars will arise from fast neutrons proceeding downwards, making the result less dependent on the proximity of ground.

On the other hand a proportion of emulsion stars are disintegrations of heavy nuclei (silver and bromine) for which anomalous absorption lengths have been reported (e.g. in lead, Simpson and Uretz 1953).

IV. Slow Neutron Measurements

We shall consider the altitude study in two parts, the present section dealing with slow neutron production in local ground and air.

Boron-loaded emulsions were scanned at 450 $\times$ using a C.T.S. microscope with a 45 $\times$ fluorite objective of N.A. 0·95 which revealed the α-tracks clearly. However, extremely careful scanning was necessary to detect the steeply inclined tracks. The possibility of a small loss is unimportant for relative flux measurements of the kind being reported here but for absolute determinations (for instance, to correlate the α-count with counting rates of boron trifluoride counters) it must be determined. The problem is considered further in Appendix I.

Tracks were counted only if both ends lay inside the emulsion, which resulted in a certain loss from tracks beginning within distance R of either face of the emulsion, where R is the α-range. This factor can be calculated ;

$$F=\frac{\text{tracks counted}}{\text{true number of tracks}}=1-\int_0^R\int_0^{\cos^{-1}x/R}\frac{4\pi}{t}\,.\,\sin\theta\,.\,d\theta\,.\,dx$$

$$=1-\frac{R}{2t},$$

where t is the emulsion thickness. For a 100 μ emulsion with $R=7\ \mu$, $F=0\cdot97$.

* Most rocks are dominated by the light elements oxygen, silicon, and aluminium in the following proportions : 48, 28, and 8 per cent.

Figure 1 shows the counting rates for α-tracks from experiments at the two latitudes *v.* residual atmospheric pressure in g cm^{-2}. Assuming that the intensities I may be fitted by an exponential of the form

$$I = I_0 e^{-x/L},$$

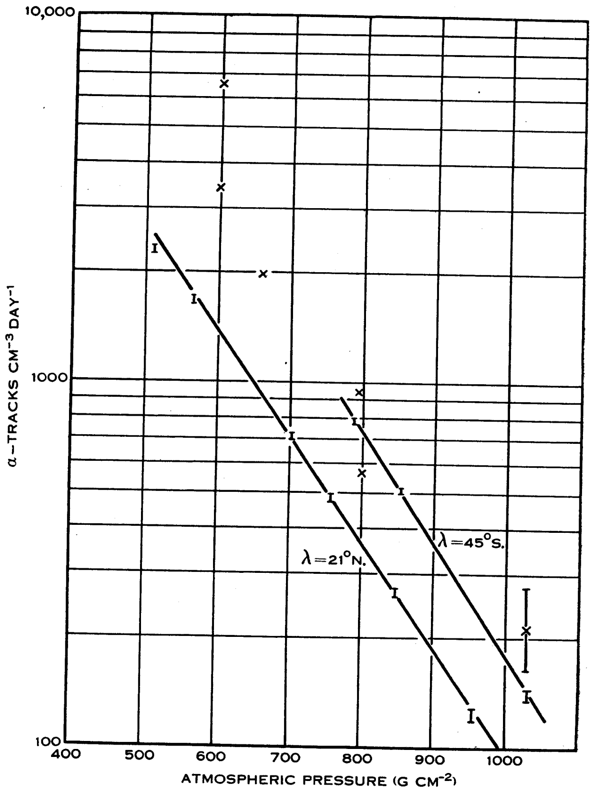

Fig. 1.—Altitude variation of α-tracks in boron-loaded emulsions due to slow neutrons. The upper curve is for $\lambda = 45$ °S., the lower for $\lambda = 21$ °N. Points $\times$ are taken from Kaplan and Yagoda (1952) for $\lambda = 50$ °N.

where x is the atmospheric depth and L the characteristic attenuation length, values of L were obtained as follows:

geomagnetic lat. 21° N., $L = 148 \pm 5$ g cm^{-2};

45 °S., $L = 141 \pm 6$ g cm^{-2}.

In view of the estimated experimental errors the difference between these is hardly significant although the small increase in L would be consistent with reduced average primary energy at higher latitudes leading to shorter collision chains of the nucleon component in the atmosphere and probably also to a smaller multiplicity of secondary events. Table 1 lists L values measured in the lower atmosphere by several other workers.

There is a tendency in the Himalayan data for the slope to decrease (L increase) for $x \gtrsim 600$ g cm^{-2}, implying a degradation of the average energy of the neutron-producing radiation as x increases, although the accuracy of the present work is insufficient to prove this. Unfortunately the boron-loaded plates located at the Mana Pass were disturbed several days before the end of the exposure by a band of Tibetan shepherds. They were thrown into snow some distance away and although many of them were still wrapped and proved usable the effect of the change on the local neutron flux is not known. The value for 508 g cm^{-2} is therefore uncertain to this extent.

TABLE 1

SOME CONTEMPORARY L VALUES AT VARIOUS LATITUDES FROM SIMILAR METHODS

Magnetic Latitude (deg.)	L	Method	Reference
0	145	S.n. (C)*	Simpson, Fonger, and Treiman (1953)
21	148	S.n.†	Present paper
21	139	Stars	Present paper
41	144	S.n. (C)	Simpson and Fagot (1953)
45	135	Stars	Bernadini, Cortini, and Manfredini (1950)
45	141	S.n.	Present paper
45	130	Stars	Present paper
46	190	Stars	Lattimore (1949)
46	150	Stars	George and Jason (1949)
50	143	Stars	Yagoda and Kaplan (1949) ; Yagoda, Kaplan, and Conner (1949)
51	160−	S.n.	Kaplan and Yagoda (1952)
52	<148	S.n. (C)	Simpson and Fagot (1953)

* S.n. (C) means detection of slow neutrons produced in local carbon.

† S.n. means detection of slow neutrons.

Nevertheless there is reason to believe that intensity *v.* altitude curves are not strictly exponentials. The value of L probably decreases slowly with increase in x. Simpson and Fagot (1953) reported a $\sim$17 per cent. fall in L from $x \simeq 300$ to 700 g cm^{-2} and concluded that L is a function of depth, decreasing with increase in x from a high altitude value depending on the magnetic latitude λ towards an approximately constant value for all λ, $L \rightarrow 140$ g cm^{-2} for $x \gtrsim 600$ g cm^{-2}. The present work is not inconsistent with this result. From the latitude measurements of Simpson (1951) and Yuan (1949) at aircraft altitudes (200–500 g cm^{-2}) L values of 190 and 170 can be interpolated for latitudes 21 and 45° respectively compared with our measured values of 148 and 141. The evidence from the present work is that L is rather insensitive to λ and tends to a value between 140 and 150 g cm^{-2}.

Boron-loaded plates shielded with cadmium (cut-off $\sim 0 \cdot 4$ eV) showed track densities $\sim 0 \cdot 2$ of the unshielded, corresponding to a cadmium ratio of ~ 5 which is considerably greater than observed in free space ($\sim 2 \cdot 1$, Yuan

1948 ; Simpson 1949 ; and others) indicating, as expected, a greater proportion of slow neutrons due to the presence of the ground. The slow neutron flux (unshielded—cadmium shielded) showed the same exponential absorption with altitude.

The only published data which we can compare directly with our absolute values are those of Kaplan and Yagoda (1952) who used boron and lithium loading in plates on mountains ($\lambda=50$ °N.). Their boron data are shown on Figure 1 (reconverted to α-counts using $\sigma=715$ barns, as adopted by them). Lithium data are not strictly comparable, choice of average cross sections being involved. The conditions of exposure of their plates is not known and precautions may not have been taken against variation in local ground material, which may account for the greater scatter of their points. However, the slope of the intensity-altitude relationship is not inconsistent with ours. Moreover it will be seen that $I_{50}>I_{45}>I_{21}$ in accordance with the well-established latitude variation. No detailed latitude comparison can be effected because of the different longitudes involved.*

Sea-level values over ground have special interest as controls for flux measurements underground and will be referred to in detail. For direct comparison with certain other measurements which have been published we have converted the α-counts to thermal neutron flux φ ($=\dot{n}v$) as follows :

$$\varphi=I(\alpha)/\Sigma,$$

where $I(\alpha)$ is the number of α-tracks cm^{-3} day^{-1} and Σ the macroscopic cross section $=N_{cc}\,.\,\sigma$, N_{cc} being the number of boron atoms per cm^3 in the emulsion ($1\cdot28\times10^{21}$) and σ the cross section for natural boron (18·8 per cent. ^{10}B) is 718 barns for thermal neutrons (2200 m sec^{-1}). If one assumes the neutron spectrum to be thoroughly thermalized and also that the surrounding medium obeys a $1/v$ law, the effective average cross section is $\frac{1}{2}\sqrt{\pi}\,.\,\sigma\simeq600$ barns, giving $\Sigma=0\cdot77$ cm^{-1}. In view of the large cadmium ratio found this may not be too bad an approximation for ground measurements although the shortcomings of the procedure are obvious.

Doing this we obtain as best sea-level flux values $\sim$95 (extrapolated) and $\sim$180 n cm^{-2} day^{-1} at 21 °N. and 45 °S. respectively, which may be compared with $\sim$270 (corrected to $\sigma=600$ barns) at 50 °N. due to Kaplan and Yagoda (1952). These are at least qualitatively consistent with latitude and longitude differences expected for the regions.

Eugster (1954) reported a value of 23 n cm^{-2} day^{-1} at Berne, Switzerland, at an altitude of 560 m, equivalent to 966 g cm^{-2}. Correction to sea-level reduces this to $\sim$15 which is some 18 times lower than the Kaplan and Yagoda† (1952) value for the same latitude (and the longitude difference should not be

* A neutron minimum probably occurs in the direction in which the equivalent dipole representing the Earth's field is off-centre, viz. $\sim$160 °E. long. A correction for longitude difference is expected to be in such a direction as to elevate the Himalayan and Australian data somewhat relative to the North American (Fig. 1).

† An earlier value of $\sim$20 published by Yagoda and Kaplan (1949) has been stated by Yagoda (personal communication) to be wrong.

large in this case). Eugster employed boron-loaded emulsions, so his results should be strictly comparable. Local ground fluctuations might account for some of the difference but an order of magnitude effect is highly improbable. Latent image fading during the long exposure he used (116 days) may have been responsible for the low result. This can cause serious loss of tracks unless stringent precautions are taken to minimize it; for instance, exposing the plates in vacuum or a well-desiccated atmosphere. The Swiss experiment was performed at 29 °C and $\sim$60 per cent. R.H., the high temperature in particular suggesting severe fading over quite modest periods of time. A not-unrealistic value for the mean life of tracks against fading under these conditions would be $\sim$30 days. It would therefore be more appropriate to divide the observed track density not by the exposure period but by the mean life, which would increase the flux estimate by a factor of $\sim$4—at least nearer the mark. It seems probable therefore that sea-level thermal rates for neutrons are in the region 100–300n cm^{-2} day^{-1} depending on the latitude.

V. Star Rates

Ilford C2 plates exposed at the above-mentioned sites (Section II) were scanned for stars using a $20\times$ objective. Only stars originating in the emulsion and having three or more prongs were recorded. At least one prong must exceed 50 μ to exclude natural α-decay of thorium impurities in the emulsion.

The results are shown in Figure 2 as star population cm^{-3} day^{-1} *v.* altitude for both latitudes. The star rate in the lower half of the atmosphere can be represented satisfactorily by an exponential as in Section IV. Attenuation lengths were calculated to be the following:

$$\lambda=21\ °\text{N.},\qquad L=139\pm\ 8\ \text{g cm}^{-2};$$

$$\lambda=45\ °\text{S.},\qquad L=126\pm15\ \text{g cm}^{-2}.$$

There are not enough values from the mountain work at 45° to secure an accurate value for L. The dotted line drawn in Figure 2 attempts to connect the mountain results with a preliminary value (600 stars cm^{-3} day^{-1})* for 43,000 ft (170 g cm^{-2}) obtained by exposing plates for $\sim$30 hr in a Canberra jet aircraft flying over the Melbourne area. This is a dubious procedure which we have not yet fully investigated. Star production on mountains may be more influenced by the surrounding material. Moreover, it is clear from Simpson's work referred to in Section IV that the radiation-attenuation is not a simple exponential from sea-level to 200 g cm^{-2}. The mountain data alone (λ=45 °N.) would favour $L\simeq133$ g cm^{-2} (full line, Fig. 2).

However, the results generally are consistent with three observations:

(1) To within experimental uncertainties L values from star rates agree with those from slow neutron fluxes.

(2) L_{star} tends to be somewhat shorter than L_{neutron}.

(3) L_{21} is probably larger than L_{45} for stars, as in the case of slow neutrons.

* This value is based on the total time spent over 40,000 ft. The time spent at lower altitudes is not known for this flight so the present value must be regarded as an upper limit.

These facts together confirm the view that stars produced in the atmosphere are the source of the slow neutron component of cosmic radiation. A longer absorption length in each case nearer the equator suggests a higher average energy for the primaries of stars (and hence also the slow neutrons) which is in line with a higher primary cut-off imposed at the equator by the Earth's field. The latitude difference is, however, considerably smaller than observed in the upper half of the atmosphere.

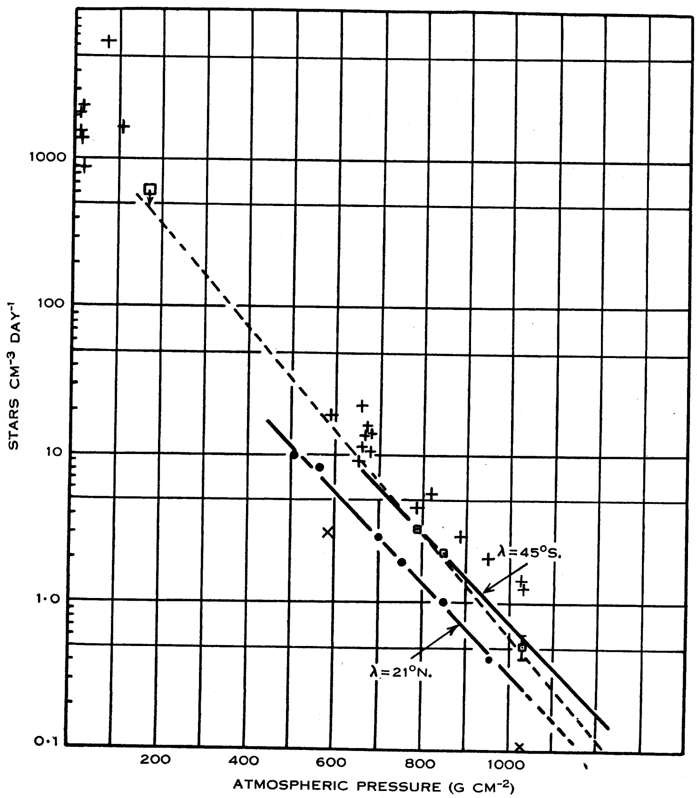

Fig. 2.—Altitude variation of star rates in photographic emulsions. Points □ for $\lambda=45$ °S., ● for $\lambda=21$ °N. Points + are from other workers in the 48–55 °N. latitude range and points × in the vicinity of $\lambda=0°$.

On Figure 2 we have also plotted for comparison a selection of star rates observed at other magnetic latitudes. The data between 48 and 54 °N. are seen to lie above our 45° line, the difference in absolute star rate being due as much to longitude as latitude difference. This again resembles the regional behaviour of slow neutrons, emphasizing a generic connection.

It is probable that star rates reflect the high energy neutron flux for the following reasons :

(1) The majority of evaporation stars observed had no apparent initiating primary. For C2 emulsions protons of energy $\gtrsim 100$ MeV were not recorded, so

this argument is inconclusive. However, the same thing is observed when G5 emulsions are used, and these are sensitive to minimum ionization tracks.

(2) The average evaporation star energy is $\sim$200 MeV excitation energy and a proton of this energy has a range in air of only 20 g cm^{-2} and would therefore be absorbed by ionization loss rather than nuclear collision.

(3) Competing star-producing processes are: $\pi\rightarrow$star, $\mu\rightarrow$star, and $\gamma\rightarrow$star. In the lower half of the atmosphere these are all improbable processes. They have been estimated and discussed by Bernadini, Cortini, and Manfredini (1949, 1950) and Simpson (1951). Not more than 10 per cent. of the stars can arise from these processes.

We now consider the total star rate in a vertical column of atmosphere of unit cross section. As a first approximation we represent the star rate (stars cm^{-3} day^{-1}) over the whole depth of the atmosphere at $\lambda=45$ °S. by

$$I=2000\mathrm{e}^{-x/130}$$

(where $L=130$ has been adopted as probably a close figure for this latitude). We can then calculate the star rate in air from the above rate in emulsion by assuming that the effective cross sections for star production are proportional to the geometric cross sections of the elements involved ($\sigma\propto A^{2/3}$ where A is the atomic weight):

$$I_a\ (\text{stars g}^{-1}\ \text{day}^{-1})=\frac{\bar{A}_e\bar{\sigma}_a}{\rho_e\bar{A}_a\bar{\sigma}_e}\,.\,I_e\ (\text{stars cm}^{-3}\ \text{day}^{-1}).$$

From the known composition of air and emulsion we find $I_a=0\cdot41I_e$, whence

$$I_a=820\mathrm{e}^{-x/130}.$$

Integrating this expression from 0 to 1030 g cm^{-2} gives the total rate of stars occurring in a vertical column of 1 cm^2. This leads to: $I_a\simeq1\cdot1\times10^5$ stars cm^{-2} day^{-1} or $1\cdot3$ cm^{-2} sec^{-1}, which is somewhat lower than generally assumed, the difference probably being due to the latitude and longitude of the location. However, for other reasons this value may be somewhat low. The exponential representation ignores the transition effect in star production near the top of the atmosphere. However, taking this figure as an average for the whole atmosphere (the star rate at $\lambda=45°$ will again be slightly lower than average which probably occurs nearer 50° but the error should be less than $\sim$10 per cent.) we can calculate the total star production in the atmosphere of the Earth$=4\pi R^2\times1\cdot3\simeq6\cdot5\times10^{18}$ stars sec^{-1} or $\sim1\cdot4\times10^{21}$ MeV sec^{-1} allotting 220 MeV per average star (R being the Earth's radius).

We can also estimate the intensity of the nucleon radiation responsible for stars at $\lambda=45°$ on the assumption that the cross section for star production is the geometric one $\sigma=\pi(r_0.A^{\frac{1}{3}})^2$. For an emulsion the weighted average of A is $\bar{A}_e=30$ and of σ is $\bar{\sigma}_e=4\cdot5\times10^{-25}$ cm^2 giving $0\cdot65$ nucleons cm^{-2} sec^{-1} at the top of the atmosphere (based on 2000 stars cm^{-3} day^{-1}) and therefore $0\cdot65\mathrm{e}^{-x/130}$ at depth x. This formula will certainly not be true in the transition region but is probably a reasonable approximation below $\sim$150 g cm^{-2}. Moreover, the true cross sections will be somewhat lower than geometric. There is some evidence to indicate that nuclear transparency is most pronounced for heavy elements such as dominate the emulsion. This makes the present result a lower limit for the true flux. Similar calculations can of course be carried through for the lower latitude, $\lambda=21$ °N. from the data of Figure 2.

The mean geometric cross section $\bar{\sigma}_a=3\cdot5\times10^{-25}$ cm^{-2} for air corresponds to a mean free path $\sim$70 g cm^{-2} or rather more if allowance is made for transparency. Since the observed attenuation length is $\sim$130 g cm^{-2} the primary nucleons of the nucleon component must make on the average rather less than two collisions in air.

VI. Star Multiplicity

If for any one latitude L values are shorter in the lower atmosphere than the upper and if the transition is gradual (as is presumably the case, corresponding to a degradation of the average energy of the nucleon component) then there should be an accompanying decrease in average star size and energy with atmospheric depth. An analysis is being conducted of star multiplicity at $\lambda=45$ °S. at mountain, aircraft, and balloon altitudes. This is at present incomplete but tentative data seem to bear out the supposition (see Table 2).

Table 2

VARIATION OF STAR MULTIPLICITY WITH ALTITUDE

Only evaporation stars are included

Altitude (ft)	Residual Atmosphere (g cm^{-2})	2–4 Prongs (%)	5–9 Prongs (%)	10 and more Prongs (%)
7,300	788	68·6	27·6	3·8
43,000	170	67	28	5
70,000	46	60·1	33·2	6·7

The mountain data are taken from plates exposed on Mt. Kosciusko, 7300 ft. The values for 43,000 ft are tentative but seem to confirm a relative increase in number of larger stars at the expense of stars in the 2–4 prong class (prong number here includes recoil track if observed). However, the possibility of the difference being due to the presence of ground must be admitted. This might cause an increase in the number of small stars due to back-streaming of secondary neutrons ($\sim$100 to 150 MeV) from stars produced in the ground. The data for 70,000 ft were kindly supplied by Dr. V. D. Hopper from plates exposed by him in balloon flights. The stars used were all of the evaporation kind having black tracks with some grey tracks but no shower particles.

The 70,000 ft data correspond to the region of the transition maximum and a marked shift from $\sim$3 prong ($\sim$150 MeV) to $\sim$7 prong ($\sim$300 MeV) and larger stars occurs. While considerably more data are required (especially free-space data in the lower atmosphere) the evidence is generally in favour of a decrease in average star energy with atmospheric depth, consistent with Simpson's conclusions on the trend in L (Simpson and Fagot 1953).

VII. Acknowledgments

The measurements carried out in the Himalayas were sponsored by the University of Ceylon with the assistance and cooperation of the High Commission for Ceylon in India and many Indian officials to whom the writer acknowledges his gratitude. Professor A. W. Mailvaganam and Dr. V. Appapillai of the University of Ceylon assisted with the planning of the experiment.

The interest of Professor L. H. Martin of the University of Melbourne in the continuation of the work in Australia has been appreciated. Part of the plate scanning was done by Mrs. S. Ovenden.

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Appendix I

Correction for Scanning Loss

When searching for short tracks there is more chance of failing to observe tracks which are steeply inclined in the emulsion. However, because of the dependence of solid angle on cos δ, where δ is the dip angle, most tracks appear fairly flat and the chance of loss applies only to the relatively small proportion of very steep tracks. The following measurements were made to determine the actual loss.

In order to obtain a high track density and improve statistics of counting, two boron-loaded C2 200 μ plates were exposed in a bucket of water surrounded by paraffin blocks (both of which served to moderate the neutrons) close to the beryllium target of a 500 keV deuteron electrostatic generator. Emulsion thicknesses were measured just prior to exposure and again after processing and drying to give the shrinkage factor $S=2\cdot69\pm2$ per cent.

(i) *Measurement of Track Density.*—The same region of one plate was scanned with a 45 × and a 95 × objective and a track count made with each using a calibrated eyepiece graticule. The results, based on ~2250 tracks at each magnification, were :

$$95\times \quad 6\cdot28\pm0\cdot13\times10^{5}\text{ tracks cm}^{-2},$$
$$45\times \quad 6\cdot34\pm0\cdot13\times10^{5}\text{ tracks cm}^{-2},$$

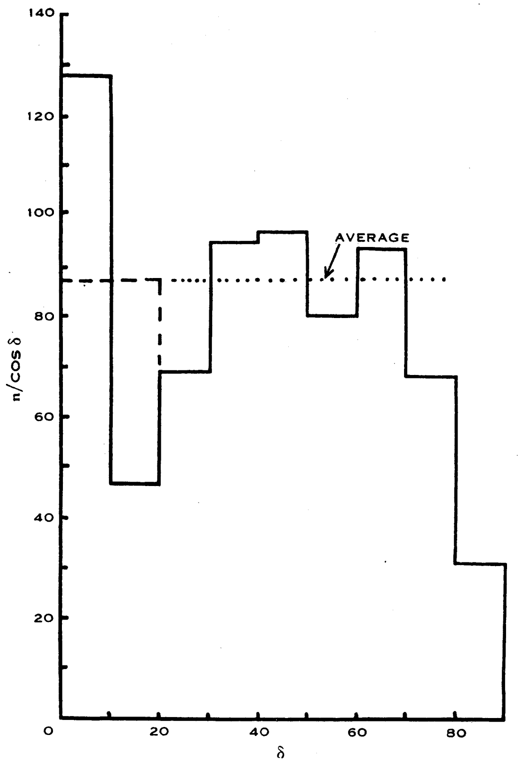

Fig. 3.—Distribution of dip angle δ for α-tracks from $^{10}B(n,\alpha)^{7}Li$ reaction in emulsion.

which agree to within the limits of counting. There is no suggestion of greater loss at 45 × than at 95 ×.

(ii) *Distribution of Dip Angles.*—Within a selected area the horizontal and vertical range of every recognizable track was measured using the 45 × objective under exactly the same conditions as adopted for the cosmic ray plates. Vertical ranges were corrected for shrinkage (×2·69) and the dip angles calculated (i.e. δ, the angle of dip formed in the original emulsion). Assuming the distribution of α-tracks to be isotropic in space a plot of $n(\delta)/\cos\delta$ *v.* δ should be isotropic if no tracks are neglected in scanning. If steep tracks are missed this should be revealed by a fall-off at large δ. The result obtained is shown in Figure 3 based on 500 tracks plotted in 10° blocks. The sharp peak in the first blocks followed by relatively few tracks from 10–20° arises from the large depth of field which is a feature of the 45 × fluorite objective. A check on this showed that a single grain could be focused sharply over $\sim 0 \cdot 7\ \mu$ movement of the fine focus. Now a 7 μ track having $0 \cdot 7\ \mu$ vertical dip would have a δ value of 15°. Hence tracks up to ~15° appear flat in the field of view and would be recorded with zero dip which would emphasize the 0–10° block at the expense of the 10–20° block. It is probably a better representation to average over 0–20° and this is shown dotted in Figure 3.

The result is a histogram consistent with isotropy from 0 to ~70°. There is some suggestion of an increase in ordinate from 0 to 50° which has been confirmed by more accurate range-depth measurements with the 95 × objective which has a more restricted depth of field. However, this effect, which is probably linked with the choice of S, is not important to the present discussion and will be reported separately.

A decline occurs beyond 70° which has been interpreted as a loss of tracks. The loss factor may be deduced by comparing blocks 70–90° with the average (87·1) of the range 0–70° (Table 3). The proportion of tracks which should be between δ_1 and δ_2 is $\int_{\delta_1}^{\delta_2} \cos \delta \, . \, d\delta$.

TABLE 3

LOSS FACTOR AT DIP ANGLES GREATER THAN 70°

Angle Range (deg)	Tracks Expected (%)	Loss Factor (%)	Absolute Loss of Tracks (%)
70–80	4·5	10·4	0·47
80–90	1·5	64·4	0·97

Hence the total absolute loss of tracks due to scanning by the method used is ~1·4 per cent. This correction was applied to the α-density (Fig. 1).