COSMIC RAY NUCLEI OF CHARGE $Z \geqslant 3$ DURING THE PERIOD OF LOW SOLAR ACTIVITY

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Received April 28, 1969

(Communicated by Prof. R. R. Daniel, F.A.Sc.)

Abstract

A detailed study of the composition and energy spectra of heavy nuclei of charge $Z \geqslant 3$ in the primary cosmic rays has been made during the period of low solar activity, using two stacks of nuclear emulsions exposed in balloon flights from Fort Churchill, Canada, in June 1963. Each of the stacks was composed of 120 nuclear emulsions of three different sensitivities and was exposed at about $3 \cdot 5$ g. cm.$^{-2}$ of residual air for about 11.1 hr. Reliable resolution of charges of nuclei from lithium to oxygen was obtained; for heavier nuclei, charge groups were determined. From the analysis of 793 tracks of nuclei with $Z \geqslant 3$, results on the following aspects were obtained:

(1) The differential energy spectra of L ($Z = 3$-5), M ($Z = 6$–9) and H ($Z = 10$–28) nuclei were measured in the energy interval 150–600 MeV/nucleon; integral fluxes were obtained for energy >600 MeV/nucleon;

(2) The energy dependence of the L/M ratio at the top of the atmosphere was determined; the ratios were obtained as $0 \cdot 45 \pm 0 \cdot 06$ and $0 \cdot 29 \pm 0 \cdot 03$ in the energy intervals of 200–575, and >575 MeV/nucleon respectively;

(3) Relative abundances of individual nuclei of Li, Be, B, C, N and O at the top of the atmosphere were determined as 36, 29, 55, 100, 60 and 106 respectively in the energy interval 150–600 MeV/nucleon; corresponding values were also obtained for energy >600 MeV/nucleon.

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(4) The differential fluxes of multiply charged nuclei measured by us and by other investigators were used to determine the solar modulation between solar maximum to solar minimum. It was found that solar modulation of the fluxes of M and He nuclei were consistent with $R\beta$ dependence and that the modulation parameter $\Delta\eta$ between 1965 and 1957 was about 1·1.

The implications of these results are discussed.

I. INTRODUCTION

IT is well known that a detailed study of the primary cosmic ray nuclei in the vicinity of the earth can provide important information in the understanding of the propagation, acceleration and origin of cosmic rays. A number of experiments have been made so far with the object of understanding these aspects of cosmic rays (for summary and references, *see*, *e.g.*, Webber, 1967; Biswas, 1968). The present investigation was undertaken to study in detail the charge composition, fluxes and energy spectra of the heavy nuclei of charge $Z \geqslant 3$ and of energy $\geqslant$ 200 MeV/nucleon during the period of low solar activity. For this purpose two large stacks of nuclear emulsions were exposed to cosmic rays in two high altitude balloon flights from Fort Churchill, Canada, in June 1963.

The two emulsion stacks were flown to altitudes of 3 to 4 g. cm.$^{-2}$ of residual atmosphere, so that the correction for the loss by fragmentation of nuclei in the overlying atmosphere was rather small. Nuclear emulsions of varying sensitivities such as Ilford G-5, G-2 and G-0 were used for resolving individual charges of $Z = 3$ to 8 and for charge groups of higher charges. In addition, the present analysis is based on a fairly large sample of 793 nuclei of charge $Z \geqslant 3$ so that statistically meaningful results were obtained.

In the present paper we discuss first the experimental procedure for determining the charge and energy of heavy nuclei and then obtain the relative abundances, fluxes and the energy spectra of these nuclei (or groups of nuclei) incident at the top of the atmosphere. The energy spectra measured in this experiment were used together with those of other investigators to study the solar modulation of the fluxes of multiply charged nuclei from solar maximum (1957) to solar minimum (1965). The implications of some of these results are discussed.

A brief report of the experimental results of this investigation was published earlier in the form of a letter (Anand *et al.*, 1966).

2. Experimental Procedure

Emulsion stack and flight details.—Two identical nuclear emulsion stacks were exposed on two balloon flights from Fort Churchill, Canada (geomagnetic latitude 73·5° N). The first stack (Stack A) was exposed on 15th June 1963 for 11.2 hr. at a ceiling altitude of 3·1 g. cm.$^{-2}$ while the second (Stack B) was exposed on 18th June 1963 for 11·1 hr. at an altitude of 4·3 g. cm.$^{-2}$. The flight curves for the two exposures are shown in Fig. 1. The amount of packing material above the Stacks A and B was negligibly small and consisted of styrofoam and black tape. During the balloon flights, the plane of the emulsions in each case was kept horizontal until the balloon reached ceiling altitude and was then flipped through 90° so that it became vertical.

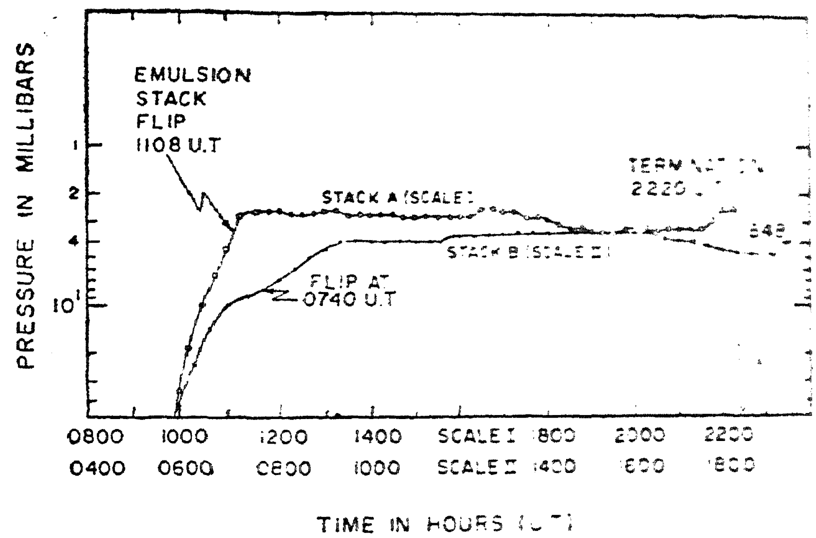

FIG. 1. Time-altitude curves of Stack A and Stack B in balloon flights on June 15, 1963 and June 18, 1963 respectively.

Each stack consisted of 120 Ilford nuclear emulsion pellicles each of size $10 \times 20 \times 0{\cdot}06$ cm. At ceiling altitude the 10 cm. side was vertical. The central 90 emulsions consisted of most sensitive (G-5) and less sensitive emulsions (G-2 and G-0) arranged in a sequence G-5, G-2, G-5, G-2, G-5, G-0 which was repeated 15 times. These were flanked by fifteen G-5 emulsions on either side. After the exposures, the stacks were processed in the conventional manner. Stack A was analysed by the Bombay group while Stack B was analysed by the Chandigarh group in an identical manner.

Scanning and acceptance criteria.—Only the G-5 emulsions from the middle portion of the stack were scanned systematically. Using a total magnification of 15 × 10, a line scan was made along the 20 cm. side at a distance of 5 mm. below the top edge of the emulsion. Tracks satisfying the following criteria were accepted:

(1) Projected zenith angle $\leqslant 45°$; (2) dip angle $\leqslant 11{\cdot}2°$; (3) ionisation > 8 times that of a singly charged minimum ionising particle; and (4) enter the stack from the top edge.

All particle tracks satisfying the above criteria were then followed into the stack until the particles either came to rest, interacted, or left the stack. In order to make suitable measurements on the interacting particles, it was necessary to impose additional condition for their acceptance, namely, the interacting particle tracks should have a length of at least 5 cm. available in the stack before they produced nuclear interactions.

In order to carefully determine the sanning efficiency of various observers, about 40% of the total scanning was rescanned by different observers. The scanning efficiency was almost 100% for particles of ionisation greater than 16 times minimum and about 90–95% in the case of particles having about 9–16 times minimum ionisation. Appropriate corrections for scanning loss have been very carefully made wherever necessary.

Heavy nuclei of the primary cosmic rays have been classified into the following groups: L-Nuclei, $Z = 3$ to 5; M-nuclei, $Z = 6$ to 9 ; H_1-nuclei, $Z = 10$ to 15; H_2-nuclei, $Z = 16$ to 19; H_3-nuclei, $Z = 20$ to 28; S-nuclei, $Z \geqslant 6$; H-nuclei, $Z \geqslant 10$.

Charge and Energy Determinations of the Heavy Primaries

The identification of charge and the subsequent energy determination was done by using a combination of the following methods:

(i) Grain-density *versus* residual range,

(ii) Change of grain-density with range,

(iii) Grain-density *versus* multiple coulomb scattering,

(iv) Delta-ray density *versus* residual range,

(v) Change of delta-ray density with range, and

(vi) Delta-ray density *versus* multiple coulomb scattering.

Since these methods are standard ones and are already discussed in literature (*e.g.*, Powell *et al.*, 1959; Aizu *et al.*, 1960), only some details relevant to the present analysis are included here. (For further details, *see* Sreenivasan, 1967; Bhatia, 1967.)

Grain-density measurements were done mainly in G-2 and G-0 emulsions whereas delta-ray measurements were done only in G-5 emulsions. The delta-ray density method was used only when the tracks did not pass through a G-2 or a G-0 plate or when the grain-density was too high to permit a reliable measurement.

Grain-density calibration.—All measurements of grain-density were restricted to emulsion depths $0 \cdot 15\, Z_0 - 0 \cdot 65\, Z_0$ from glass (Z_0 is the total thickness of emulsions) where there was no measurable change of sensitivity with depth. The calibration of measured grain-densities in terms of primary ionisation of the particle was made by using particles which were known to be relativistic either from the nature of interactions they produced or from measurements of multiple coulomb scattering. The comparison of these grain-density measurements with those of relativistic nuclei showing charge indicating interactions, *e.g.*, $C^{12} \rightarrow 3\alpha$, $O^{16} \rightarrow 4\alpha$, etc., was used to determine the calibration. In most cases plate calibration could be made by using, on an average, 5 to 6 tracks of relativistic particles in the G-2 and G-0 plates. Typical calibration curves of G-5, G-2 and G-0 emulsions are shown in Fig. 2. It is seen from the figure that ionisations up to about 6 times minimum ionisation could be measured reliably in a normal G-5 emulsion, up to about 150 times in a G-2 and up to about 250 times in a G-0 emulsion. Each observer set up his own calibration curves for each emulsion plate used for ionisation measurement. Thus, we have avoided any uncertainty which might arise due to plate-to-plate variation of grain-density.

Delta-ray density calibration.—The delta-ray density calibration as a function of the ionisation produced by heavy primaries in G-5 emulsions was done by making measurements on relativistic heavy nuclei selected in the same manner as for grain-density calibrations. For relativistic particles of charge Z the delta-ray density n_δ was thus obtained by using the relation, $n_\delta = aZ^2 + b$, where a and b are constants over a certain charge interval.

In order to determine the variation of delta-ray density with kinetic energy for a given charge it is necessary to construct calibration curves, using particles of known energy. This is so, because for a given charge, observed variation may differ from the theoretically predicted relation, $n_\delta \propto 1/\beta^2$ where βc is the velocity of the particle. Such calibration was done by measuring n_δ on the tracks of stopping α-particles at different residual ranges as well as on alpha-particles whose energies were determined from multiple scattering measurements. Thus from the measured variation of n_δ with kinetic energy for alpha-particles, n_δ *vs.* kinetic energy per nucleon (or residual range) curves for other charges were obtained.

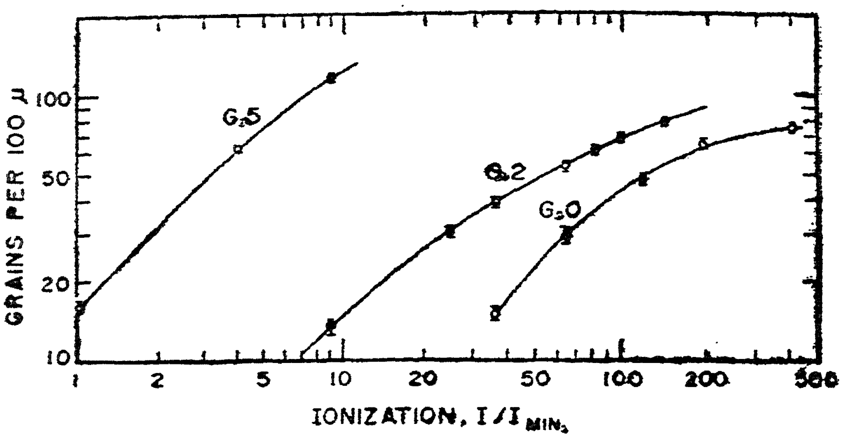

FIG. 2. Calibration curves of grain-density *vs.* ionisation for some typical G-5, G-2 and G-0 emulsions.

The delta-ray density measurements were made using two conventions, namely, the usual 4-grain delta-ray counting and the 'long delta-ray' criterion in which only those delta-rays having projected range greater than 5 μ were accepted. The latter criterion was used when the delta-ray density was too high for reliable measurements with the 4-grain delta-ray method.

Identification of particles.—From the sample of particles which satisfied the scanning and acceptance criteria, we separated out singly and doubly charged particles by following the tracks into the stack and by using one of the methods of identification as noted above. Particular care was taken to separate out alpha-particles of ionisation 8 to 10 $\times$ I min. from relativistic Li-nuclei. Thus a total of 793 nuclei of charge $Z \geqslant 3$ were obtained for further analysis (335 nuclei in Stack A and 458 in Stack B). In order to analyse these multiply charged nuclei we have grouped them into three different categories:

(*a*) Stopping particles (S-particles),

(*b*) Particles producing interaction after a range of 5 cm. in the stack ('interacting' particles), and

(*c*) Particles traversing the entire stack ('through' particles).

The identification of the stopping multiply charged particles was established by using either method (i) or (iv) mentioned earlier. For method (i), we first used the calibration curve of grain-density *vs.* ionisation of the particular emulsion plate (for example, as shown in Fig. 2) and determined the ionisation of the particle. Then the ionisation *vs.* residual range curves for charges Z = 1 to 28 were used. These curves were derived from the restricted energy loss *vs.* kinetic energy and the range-energy relation for protons as given by Barkas (1965). For method (iv), n_s *vs.* residual range curves, for different charges, were constructed according to the procedure mentioned above. The charge identification of 'interacting' and 'through' particles was made using one or more of the methods (ii), (iii), (v) and (vi) mentioned above. Among these groups, we had a class of particle tracks which showed large change of ionisation ($\gtrsim 20\%$) in traversing 5 to 10 cm. of emulsions; identification of these nuclei could be easily made using method (ii) or (v). The other class of nuclei were those which showed very little change of ionization in traversing 5 to 10 cm. of emulsion. In these cases it was sometimes found that method (ii) or (v) was unable to identify whether it was a relativistic particle of charge Z or a non-relativistic particle of charge Z-1. In all such cases unambiguous identification was made by multiple coulomb scattering measurements [method (iii) or (vi)]. Multiple scattering measurements were made on a Koristka microscope and energies as high as ~ 3 BeV/nucleon could be measured by this method. Fractional charges were assigned, using the methods of ionisation *vs.* residual range, change of ionisation with range or ionisation *vs.* multiple scattering. The charge spectrum for nuclei of Z = 3 to 9 and of energy < 575 MeV/nucleon is shown in Fig. 3. In the same figure we have also fitted the expected Gaussian distribution for an experimentally determined standard deviation of 0·25 unit of charge for the Medium nuclei assuming the relative abundances of C, N and O nuclei to be 100, 60 and 106 respectively. Similar fit was made in the case of L-nuclei, with a standard deviation of 0·2 unit of charge and a relative abundance of Li, Be and B as 36, 29 and 50 respectively. Appropriate corrections for extrapolation of the two charge groups to the top of the atmosphere have been made. For resolving the component like F which has rather small relative abundance higher degree of charge resolution is necessary.

For nuclei of energy > 575 MeV/nucleon, a large number of particle tracks traverse the stack without significant change of ionisation. In order to obtain reliable identification of these individual nuclei of $Z \leqslant 10$, two independent measurements of charge were made when necessary. This was so for roughly 10% in the case of M group and 15% in the case of L group nuclei. Thus the charge of these relativistic or near relativistic nuclei were determined unambiguously and their energy was known to be greater than 575 MeV/nucleon. For these nuclei fractional charge was not assigned as only the lower limit of energy is known.

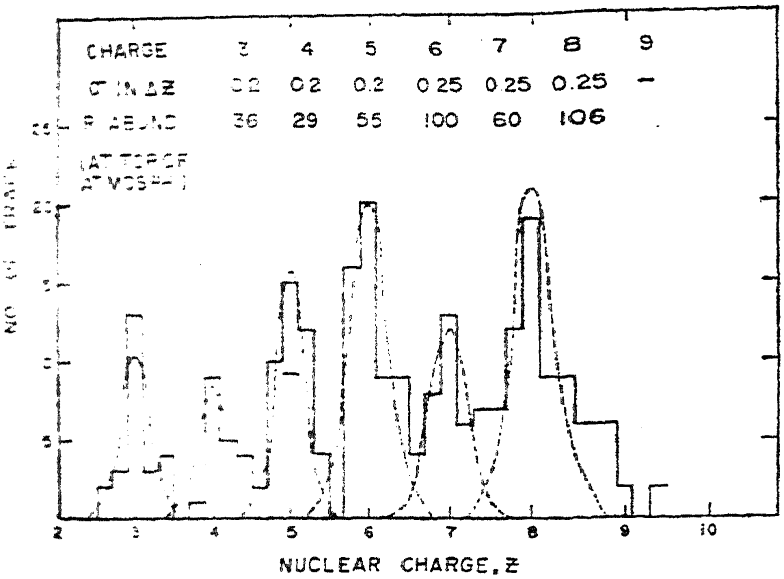

FIG. 3. The measured charge distribution for nuclei of $Z = 3$ to 8 of energy 150–600 MeV/nucleon. The measured standard deviations in the charge determination are shown. The dotted lines indicate the normalised gaussian distributions for the measured standard deviations. The relative abundances of these nuclei at the top of the atmosphere are shown (*see* text).

The nuclei with charge $Z > 10$ were assigned charges so that they could be classified into H_1, H_2 and H_3 groups of nuclei.

The energies of all the multiply charged stopping particles at the point of entry in the emulsion stack were determined using the range energy relation curves in emulsion (Barkas, 1965). The energies of the interacting particles and the 'through' particles were determined either by the scattering measurement or by using the method of change of ionisation with range. In order to determine the flux values of different groups of nuclei at the top of the stack, each accepted particle of $Z \geqslant 3$ crossing the scan line was given weight factors to correct for the loss due to interaction in the stack and that due to scanning efficiency. Thus a stopping particle with a residual range $R \leqslant 5$ cm. in the stack was given a weight factor $e^{R/\lambda}$ and those particles having total ranges in the stack greater than 5 cm. were each given a weight factor $e^{5/\lambda}$ where λ is the interaction mean free path in cm. for a particular group of nuclei in the nuclear emulsions. The corrections for scanning loss were made by using the scanning efficiencies determined for different ionisation groups.

Extrapolation to the top of the atmosphere.—For extrapolating the observed fluxes and energy spectra to the top of the atmosphere it is necessary to take into account certain corrections due to the overlying atmosphere. Firstly, the ionisation loss in the air is taken into account by using range energy relation in air. For our stacks this air-cut-off energy is about 125 MeV/nucleon for L-group nuclei, 150 MeV/nucleon for M-group nuclei and $\sim$ 250 MeV/nucleon for the H-group nuclei. Hence, flux values could be determined only above these air-cut-off energy values. Secondly, as a result of interaction and fragmentation of the cosmic ray nuclei in collision with the air nuclei, there will be a certain amount of diffusion of one group of nuclei into another. This can be corrected either by using the growth curves in air or by solving the one-dimensional diffusion equations (*see* Daniel and Durgaprasad, 1962). In this work, we adopted the following procedure. We extrapolated the measured flux of M-nuclei at the top of the stack $J_M(x)$ to the top of atmosphere $J_M(o)$, by means of diffusion extrapolation using interaction length of M-nuclei in air as 23·9 g./cm.[2] (Durgaprasad, 1964), and fragmentation parameter, P_{MM} as 0·14, which is the weighed mean of values for air-like media, graphite, teflon, celluloid and polythene (*see* Durgaprasad, 1964; Friedlander *et al.*, 1963 and references therein). Then the H/M and L/S *ratios* observed at the flight altitude were extrapolated to the top of the atmosphere using the slopes of the best fitting experimental growth curves of these ratios in air as summarised by Webber (1967). Thus knowing the flux of M-nuclei, L/S and H/M ratios at the top of atmosphere, the fluxes of L, M and H-nuclei at the top of the atmosphere were obtained. The flux of H-nuclei, $J_H(o)$ was further subdivided into those of H_1, H_2 and H_3 groups according to the following procedure. The fluxes of H_1, H_2 and H_3 nuclei at the top of the stack were extrapolated to the top of the atmosphere using the diffusion equations and fragmentation parameters (Durgaprasad, 1964). It was found that the fluxes of H_1, H_2 and H_3 nuclei at the top of atmosphere were in the ratios of 1 : 0·21 : 0·36. The sum of the fluxes of these three groups was normalized to the flux $J_H(o)$. We believe that the above procedure of extrapolation to the top of the atmosphere yields satisfactory results, since this is based on the measured growth curves of the ratios in the atmosphere as well as the best estimates of the fragmentation parameters in air. So far there is no evidence of any significant energy dependence of the interaction and fragmentation parameters in the energy region of relevance here; hence the effect has been ignored. We wish to emphasise here that since the fluxes were measured under small atmospheric depths, the uncertainties in the parameters used do not significantly affect the extrapolated values. The procedure of extrapolation was carried out separately for groups of nuclei in each stack, there was good agreement between the results obtained from the two stacks. The final results at the top of the atmosphere were then obtained by combining the data from the two stacks according to their statistical weights.

In order to determine the relative abundances of individual elements in a particular charge group we have assumed that while extrapolating to the top of the atmosphere these relative abundances remain the same since the residual atmosphere is only about 4 g./cm.^{2} and the differences in the mean free paths are negligibly small. For example, the carbon to oxygen ratio at the top of the atmosphere will be only about 1·5% higher than that measured by us at the flight altitude.

3. RESULTS AND DISCUSSION

Using the above-mentioned methods of charge identification, energy determination and extrapolation to the top of the atmosphere we have obtained the results concerning the differential and integral spectra of L, M and H-nuclei for the period of mid-1963, the energy dependence of the L/M ratio and the relative abundances of individual elements.

Some features of these observations have already been discussed earlier (Anand *et al.*, 1966; Biswas *et al.*, 1966) and in the present analysis we will confine our detailed discussion only to the interpretation of these results in terms of solar modulation.

(i) *Differential energy spectra of light, medium and heavy nuclei.*— The differential and integral energy spectra of L, M and H-nuclei are shown in Fig. 4 and Table I. For comparison we have also included the results of other investigators obtained during the same period of solar activity as indicated by the Mt. Washington Neutron Monitor Rate (2320) (Webber *et al.*, 1966; Fichtel *et al.*, 1966). It is clear from these data that the results obtained by these groups are in good agreement with each other and the mean curve drawn here represents the best shape of the spectra in mid-1963. The maxima in the spectra of L, M and H-nuclei occur at 400 $\pm$ 50 MeV/nucleon, 450 $\pm$ 50 MeV/nucleon, 450 $\pm$ 50 MeV/nucleon respectively. The position of the maximum in the case of helium nuclei occurs at 250 $\pm$ 50

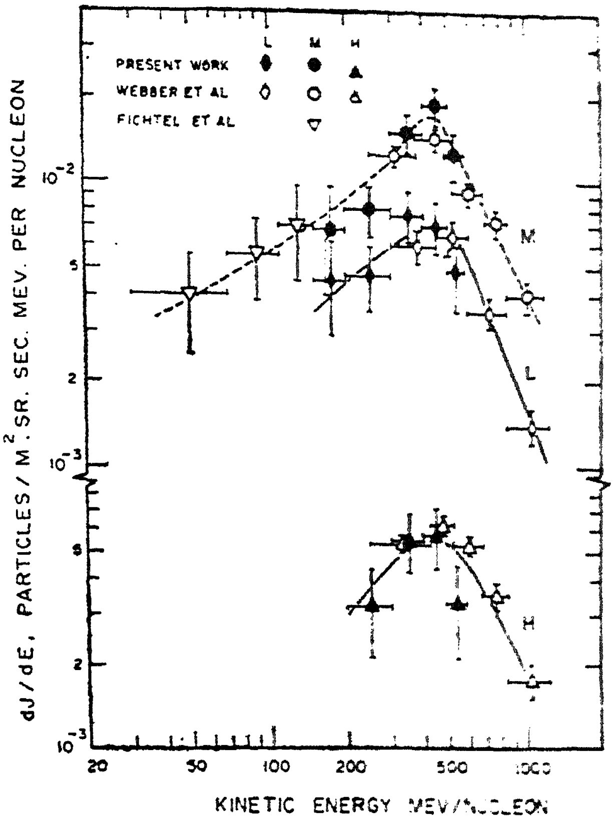

FIG. 4. Differential energy spectra of L, M and H-nuclei measured in the present work together with other measurements during the middle of 1963. The Mt. Washington neutron monitor rate corresponding to these data are: Present work; 2320 (Stack A, 2330, Stack B, 2310); Webber *et al.* (1966) 2310; Fichtel *et al.* (1966) 2320.

TABLE I

Differential and Integral fluxes of L, M and H-nuclei at the top of atmosphere

Kinetic energy, MeV/nucleon	Differential flux, dJ/dE, in nuclei (M^2 Sr. Sec. MeV per nucleon)$^{-1}$		
	L (3<Z<5)	M (6<Z<9)	H (Z > 10)
150–200	0·0046±0·0017	0·0069±0·0029	..
200–300	0·0047±0·0012	0·0081±0·0016	0·0032±0·0011
300–400	0·0077±0·0015	0·0152±0·0024	0·0055±0·0013
400–500	0·0071±0·0015	0·0190±0·0029	0·0058±0·0014
500–575	0·0050±0·0015	0·0126±0·0025	0·0033±0·0012
	Integral flux, in nuclei (M^2. Sr. Sec.)$^{-1}$		
>150	5·67±0·42	16·39±0·79	..
>200	5·44±0·41	16·04±0·78	6·01±0·48
>300	4·97±0·40	15·23±0·75	5·69±0·46
>400	4·20±0·36	13·71±0·72	5·14±0·44
>575	3·11±0·31	10·86±0·64	4·30±0·41

MeV/nucleon, lower than in the case of L, M and H-nuclei. The implications of these in terms of propagation and solar modulation effects have been discussed by Biswas *et al.* (1967, 1968).

Recent experiment by Von Rosenvinge *et al.* (1969), performed at a time when the neutron monitor rate (2350) was more or less at the same level shows a large discrepancy as compared to the mean spectra of L and M-nuclei determined in the present experiment. This discrepancy has been discussed by Biswas (1969). The results of Lim and Fukui (1965) which seem to give anomalous flux values have not also been included in the present analysis (*see* Anand *et al.*, 1966).

(ii) *The energy dependence of L/M ratio.*—The ratios of L/M, L/S and H/M at the top of the atmosphere obtained in our experiment are shown in Table II. It is seen from this table that in the energy interval 200–575 MeV/nucleon the ratio L/M is increasing with decreasiug energy. Using the recently determined L/M ratios and energy-dependent spallation cross-sections (Bernas *et al.*, 1967; Yiou *et al.*, 1967, 1968) the amount of matter traversed in space by cosmic ray nuclei as a function of energy was determined by several investigators (*see* for summary Biswas, 1968). These results indicate that at energy greater than 1·5 BeV/nucleon, the mean path length of cosmic ray nuclei is about 4 ± 1 g./cm.^{2} of hydrogen and at 200–400 MeV/nucleon it is higher by a factor of about two.

TABLE II

L/M, L/S and H/M ratios at the top of the atmosphere

Ratios \ K. Energy MeV/n.	200–300	300–400	400–500	500–575	200–575	>575
L/M	0·58±0·19	0·51±0·13	0·37±0·10	0·40±0·14	0·45±0·06	0·29±0·03
L/S	0·42±0·13	0·37±0·09	0·29±0·07	0·31±0·11	0·34±0·05	0·21±0·02
H/M	..	..	..	..	0·33±0·04	0·40±0·04

(iii) *Relative abundances of individual elements.*—In this work we obtained good charge resolution for nuclei of $Z = 3$ to 8 as described earlier and intensities of Li, Be, B, C, N and O nuclei were determined. These are shown in Table III in two energy intervals, E = 150–575 MeV/nucleon and E > 575 MeV/nucleon. The fluorine abundance is an upper limit since it includes the tail of the distribution of the oxygen nuclei and also of Ne.

TABLE III

Fluxes and relative abundances of nuclei as percentage of the total

Nuclei	Kinetic Energy 150–575 MeV/nucleon		Kinetic Energy >575 MeV/nucleon		Kinetic Energy >1·5 BeV/nucleon (O'Dell *et al.*, 1962)
	P/M². Sr. Sec.	Relative abundance	P/M². Sr. Sec.	Relative abundance	Relative abundance
Li	0·74±0·15	7·2	1·05±0·19	5·8	5·3
Be	0·60±0·14	5·9	0·41±0·11	2·2	2·3
B	1·14±0·18	11·1	1·65±0·22	9·0	7·4
L	2·48±0·28	24·2	3·11±0·31	17·0	15·[illegible]
C	2·07±0·30	20·1	4·39±0·41	24·0	30·1
N	1·24±0·22	12·1	2·39±0·30	13·1	9·7
O	2·20±0·32	21·4	3·21±0·35	17·5	19·4
F	0·48±0·12	4·6	0·87±0·18	4·8	2·4
M	5·97±0·42	58·2	10·86±0·64	59·4	61·6
H_1	1·11±0·20	10·8	2·72±0·32	14·9	..
H_2	0·37±0·12	3·6	0·68±0·16	3·7	..
H_3	0·30±0·11	2·9	0·91±0·21	5·0	..
H	1·79±0·27	17·5	4·30±0·41	23·5	23·4
Z⩾3	10·24±0·62	100·0	18·27±0·81	100·0	100·0

Next we examine the relative abundance of carbon, nitrogen and oxygen nuclei in the primary cosmic rays. The ratio of carbon to oxygen nuclei measured at different energy intervals by various investigators with fairly satisfactory charge resolution are shown in Fig. 5. The C/O ratio is independent of solar modulation. Although the experimental errors on the ratio are fairly large, it is seen in Fig. 5, that the general trend of results indicate that C/O ratio is about 0·90 at energy about 100 MeV/nucleon and it increases to a value of about 1·5 at energy > 1·5 BeV/nucleon. The value of the C/O ratio at E > 1·5 BeV/nucleon obtained by various investigators, *e.g.*, von

Rosenvinge *et al.* (1969) and O'Dell *et al.* (1962) are in disagreement with each other. This discrepancy needs further examination.*

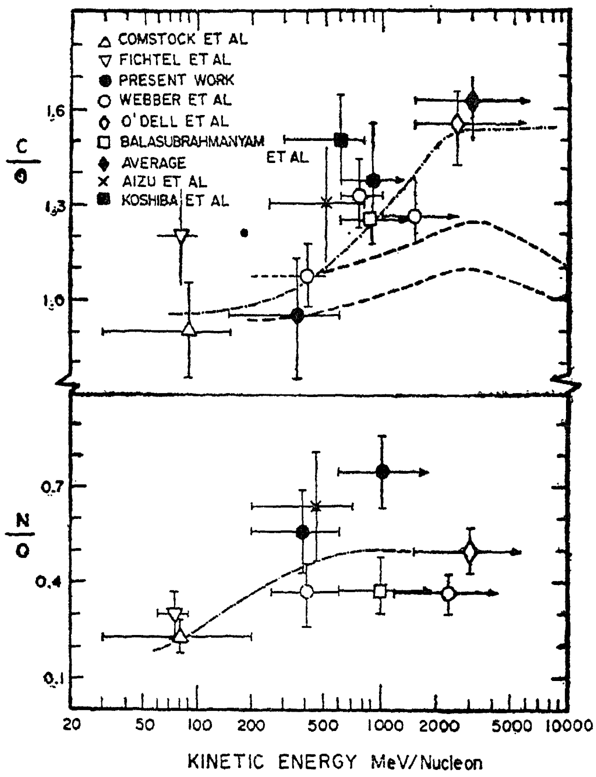

FIG. 5. Carbon to oxygen and nitrogen to oxygen ratios as a function of energy obtained from the present work and other investigations 'Average' denotes the average calculated by Webber (1967). The dashed lines indicate range of C/O ratios determined by von Rosenvinge *et al.* (1968). The dot dashed lines indicate the approximate variations of the ratios from other data. (The reference Fichtel *et al.* should read as Hagge *et al., Can. J. Phys.*, 1968, **46**, S539.)

The N/O ratios measured in this investigation and by others are also shown in Fig. 5. In this case also there is considerable scatter of data points. In the lowest energy interval, 90 MeV/nucleon, N/O is about 0·25 whereas at relativistic energies, > 1·5 BeV/nucleon its value is ~0·50, indicating N/O ratio changes by a factor of about two in this energy interval.

Detailed calculation of the energy dependence of the C/O and N/O ratios taking into account ionisation loss and the most recent spallation cross-section measurements have been made by Bhatia *et al.* (1969). These results indicate that the measured C/O and N/O ratios in cosmic rays at low and high energies are incompatible with the conventional one component

* Note added in proof: In recent experiments, Dayton *et al.* (*Proc. Int. Conf. Cosmic Rays*, Budapest, 1969, to be published) and O'Dell *et al.* (1969, *ibid.*) reported the C/O ratio at E > 1·5 BeV/nucleon as ~ 1·1.

model of cosmic rays and supports the hypothesis of two component model of cosmic rays proposed in recent years (Comstock *et al.*, 1967; Biswas *et al.*, 1966, 1968; Comstock, 1968; Burbidge *et al.*, 1967).

(iv) *Solar modulation energy spectra of medium and helium nuclei between solar maximum and minimum.*– In this work we have studied the changes in the intensity and the spectral shape of medium nuclei and helium nuclei during the solar maximum (mid-1957) to near solar minimum (1963-65) to investigate the solar modulation during the last solar cycle. Many studies have been made on the changes of P and He fluxes during last solar cycle (For summary, *see, e.g.*, Webber, 1968). But this represents an attempt to use the M-nuclei and He spectra for this purpose.

The best estimate of the differential energy spectrum of medium nuclei during mid-1963, obtained from the present data as well as that of Webber *et al.* (1966) and Fichtel *et al.* (1966) is shown in Fig. 4 as discussed earlier. The differential spectrum of M-nuclei during solar maximum was measured by Aizu *et al.* (1960) in September 1957. Since helium and medium nuclei have same mass to charge ratio they are expected to be modulated in the same manner and hence it is useful to compare the changes of helium and medium nuclei fluxes over the same period. The differential spectrum of helium nuclei during the middle of 1963 is obtained from the data of several investigators and is summarised in Fig. 3 of Biswas *et al.* (1967 a). The He spectrum measured during mid-1957 is obtained from the results of Aizu *et al.* (1960), Engler *et al.* (1958) and Freier *et al.* (1959), measured during May–September 1957.

Recent studies of the changes of fluxes of protons and alpha-particles during 1963–66 showed that solar modulation during this period could be represented by the Parker's theory of modulation by solar wind (Parker, 1963) in the following form

$$\frac{J_i^e(E, t)}{J_i^\infty(E)} = e^{-\eta(t) \cdot R^n \beta}$$

where $J_i^e(E, t)$ is the differential flux of i^{th} type of nuclei at kinetic energy, E MeV/nucleon, $J_i^\infty(E)$ the correspnding flux outside the solar system, $\eta(t)$ a constant depending only on time, t, R and β, rigidity and velocity of the nuclei and $n \approx 1$ for rigidity $R \gtrsim 0{\cdot}8$ BV, and $n \approx 0$ for $R < 0{\cdot}8$ BV (Gloeckler and Jokipii, 1967; Jokipii, 1968; O'Gallagher, 1968; Webber, 1968).

To study the solar modulation of medium and helium nuclei from mid-1957 to mid-1963 we plotted $\log_e$ [J (E, 1963)/J (E, 1957)] *vs.* Rβ for medium and helium nuclei in Fig. 6. It is seen that changes in M and He nuclei are consistent with one another and hence both the components are used to obtain the best fitting line given by $R^{-1.15}$. This was obtained by re-plotting the data in the form $\beta \log_e$ J (E, 1963)/J (E, 1957) *vs.* R (not shown), and the best fitting line is found to be $R^{-1.15}$. Thus the present analysis indicates in the rigidity interval 1·2 to 2·7 BV rigidity dependence as close to Rβ. In Fig. 6 we have shown the lines corresponding to β, Rβ and $R^2\beta$ dependence; it is seen that although $R^2\beta$ dependence cannot be ruled out, Rβ dependence gives a better fit.

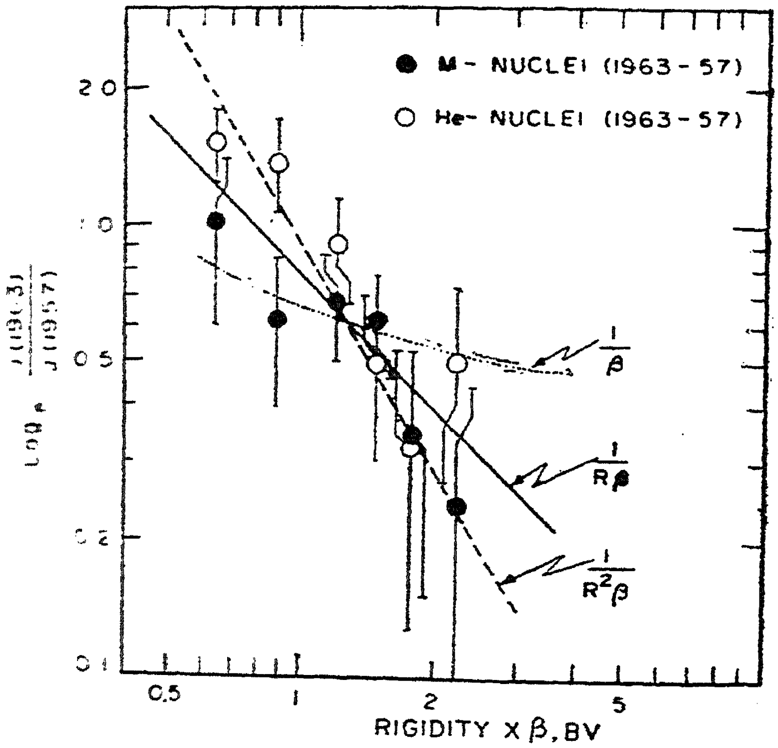

FIG. 6. $\log_e$ [J(1963)/J(1957)] *vs.* Rigidity$\times\beta$ plotted for M-nuclei and He-nuclei. The lines corresponding to $1/\beta$, $1/R\beta$ and $1/R^2\beta$ dependence of solar modulation are shown. The best fit line is given by Rβ dependence.

On the basis of Rβ dependence it is found from Fig. 6 that the change in η from 1963 to 1957 ($\triangle\eta$) is 0·8 BV. The value of $\triangle\eta$ for 1963–65 was found to be about 0·25 (Biswas *et al.*, 1967, Gloeckler and Jokipii, 1967). Hence, $\triangle\eta$ for 1965–57 is obtained as 1·05 BV. The residual modulation at solar minimum 1965 was determined as 0·65 BV by Biswas *et al.* (1967 *b*). Therefore the value of modulation parameter η at solar maximum in 1967 is obtained as 1·70 BV.

In Table IV we have summarised the data of this work and those of other investigators on the change of solar modulation during 1957–65 on the basis of $R\beta$ dependence of solar modulation, as well as the residual modulation in 1965, estimated by different methods. It seems that these observations would be consistent with the value of solar modulation parameter η (1965) at solar minimum as $0 \cdot 65 \pm 0 \cdot 10$, $\Delta\eta$ (1957–65) as about $1 \cdot 4 \pm 0 \cdot 4$ and η (1957) at solar maximum as $2 \cdot 0 \pm 0 \cdot 4$, indicating a change in η by a factor of about three between solar maximum and minimum during the last solar cycle.

TABLE IV

(*a*) *Solar modulation during* 1957–65

Authors	Method	Period	$\Delta\eta$ (BV)
Present work and Biswas *et al.* (1967 *a*, *b*)	M and He-nuclei	1957–65	1·[illegible]5
Lockwood and Webber (1968)	Neutron Monitor and P and He-nuclei	1959–65	1·40
O'Gallaghar (1968)	P and He nuclei	1958–65	1·[illegible]

(*b*) *Residual solar modulation in* 1965

Authors	Method	η (1965) (BV)
Biswas *et al.* (1967 *b*)	He^3/He ratios and He-energy spectrum	$0 \cdot 65 \pm 0 \cdot 05$
Gloeckler and Jokipii (1967)	Cosmic ray energy density	$\lesssim 1$
Ramaty and Lingenfelter (1968)	He^3/He^4 and H^2/He^4 ratios	$0 \cdot 4 \pm 0 \cdot 1$
Anand, Daniel and Stephens (1968)	Non-thermal radio emission and cosmic ray electron spectrum	$\approx 0 \cdot 65$
Webber (1968)	do.	0·75

ACKNOWLEDGEMENT

The authors are grateful to Indian National Committee on Space Research (INCOSPAR) and National Aeronautics and Space Administration (NASA) of U.S.A. for providing us the emulsion stacks and to Drs. F. B. McDonald and C. E. Fichtel of NASA Goddard Space Flight Center for the exposure of the stacks in balloon flights from Fort Churchill, Canada. We are thankful to Professor R. R. Daniel for helpful discussions. The authors, VSB, VSC and SDP, are thankful to the Cosmic Ray Committee of the Department of Atomic Energy, Government of India, for the financial support for the work done at Panjab University.

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