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III-1-8. Relative Abundances of the Heavy Nuclei of the Galactic Cosmic Radiation

F. W. O'DELL, M. M. SHAPIRO and B. STILLER
U. S. Naval Research Laboratory
Washington 25, D.C., U.S.A.

For a decade, controversy has persisted over the question: does the galactic cosmic radiation incident upon the top of the atmosphere contain a significant fraction of Li, Be, and B? This question has an important bearing on the "age" of the cosmic radiation and on its propagation through interstellar space. To resolve the problem, an emulsion experiment was designed to provide (a) higher statistical weight, (b) exposure at greater altitude, and (c) verifiable charge identification by employing several independent methods of ionization measurement in emulsions of different sensitivities. The balloon, launched at geomagnetic latitude 41°N, on March 9, 1958, floated at an atmospheric depth of 2.7 g/cm² for $7\frac{1}{2}$ hours. Over 900 tracks were analyzed, and the L tracks (due to Li, Be, and B) were well resolved from the heavier (S) tracks. The ratio $(L/S)_0$ at the top of the atmosphere was found to be 0.18 ± 0.04, and $(H/M)_0=0.38\pm0.04$. The value 0.14 is considered a lower limit for $(L/S)_0$ since it was obtained by using the extremely large Rochester fragmentation coefficients P_{HL} and P_{ML} in extrapolating to the top of the atmosphere. The results demonstrate conclusively that Li, Be, and B comprise a significant proportion of the heavy primary nuclei, and that their relative *cosmic-ray* abundance is approximately 2×10^5 times their relative "universal" abundance. Relative to carbon or oxygen, cosmic-ray nitrogen was found to be about one-half as abundant as previously supposed.

The "universal" abundance of lithium, beryllium, and boron is known to be exceedingly low—about two atoms to a billion hydrogen atoms. At balloon altitudes one certainly finds some Li, Be, and B in the cosmic ray stream. For a decade, controversy has persisted over the question: does the *primary* cosmic radiation contain a *significant* fraction of these light elements? This question has an important bearing on the "age" of the cosmic radiation and on its propagation through interstellar space. For the lithium-boron group, various investigators have reported conflicting intensities, all the way from zero to fluxes approaching those of the heavier atoms.

The difficulties have been mainly of two kinds-identification and extrapolation. The former is a question of resolution of charge, while the second problem is: What actually came in at the top of the atmosphere?, *i.e.*, what proportion of the observed light nuclei are secondaries, generated as collision products in the overlying atmosphere?

Although, in the last four years, several balloon flights have been achieved at altitudes of less than 10 grams per sq. cm, complete agreement (in their conclusions) has not been reached among all of the leading groups.

For example, three years ago the Bombay group had a flight at 6.6 g/cm² of residual pressures; and the Minnesota group at 3.8 g/cm². Yet the former group concluded that the primary flux of light elements is 5.7±6 per cent of the flux of heavier nuclei—an answer consistent with zero. On the other hand, the Minnesota group concluded that the ratio L/S of the three light elements to everything heavier is about 0.28. Now, in the same balloon flight with Bombay there were exposures by Rochester and Sydney. The Sydney group obtained a considerably larger answer than Minnesota. The Rochester group reported two possible answers—quite different from one another—derived by using two sets of constants in extrapolating to the top of the atmosphere.

In attempting to resolve the differences, we have investigated this problem in a stack of plates flown at an altitude even higher than that of the Minnesota group, *i.e.*, 2.7 gm/cm². We gave a preliminary report at the Moscow Conference. Subsequently our statistics were enhanced by a factor of 6.

Our balloon flight took place March 9, 1958, in Texas at geomagnetic latitude 41 degrees. The balloon floated at "ceiling" altitude for about 7 hours. Our detector stack consisted of 220 layers of 600μ Ilford emulsions of several sensitivities. These stripped emulsions included not only the very sensitive G.5 but also the less sensitive G. Special and G.O layers as well. An idea of the enormous range of sensitivities covered by these three types can be obtained from the following fact: The grain density-or blob density-of a relativistic nitrogen track in G.O is about 18 grains/100μ, almost exactly the grain density of a singly-charged, minimally ionizing particle in the G.5 emulsion.

The search was carried out in the G.5 emulsions, employing a "line scan," 4.5 mm below the top of the stack. Tracks longer than 4 mm per layer were traced through the stack until they terminated in some fashion or left the emulsion stack. This enabled us to weed out tracks due to slow particles of charge 1 or 2. For particles that passed the preliminary criteria, we made several types of ionization measurements, at least 2 independent ones, and where possible, 3 or 4. We relied heavily on gap measurements. Delta-ray counts were made on all tracks, as this provides a measure of ionization rather independent of the density in the core of the track. Finally we made *blob* counts in the G.O emulsion.

On tracks whose apparent ionization and total path in emulsion tentatively marked them as HN, we made ionization measurements of several kinds. At this latitude and altitude the primary nuclei are relativistic, so ionization measurements suffice.

A summary of our independent ionization measurements is shown in Table I. For more than half of the heavy nuclei in the L and M groups, three or four independent types of ionization measurements were made.

Table I.

Number of Indep't Charge Determinations	Tracks Measured			
	L+M		H*	
	N	%	N	%
≥1	724	100	58	100
≥2	674	93	40	69
≥3	387	53	12	21
4	126	17	0	0

* Having $N_\delta < 100$/mm ($Z<12$) 137 tracks have $N_\delta \geq 100$/mm ($Z \geq 12$).

Table II.

"Charge-Revealing" Collisions

Break-Up				Charge					Remarks
Frag.	N_α	N_S	N_H	From Break-Up	From Track Meas.				
					Delta-Ray	G.5	G.Sp	G.O	
		3	1*	3	3.0	3.0			*Recoil
	2		1*	4	4.1	4.1			*Black Track at~90°
	2	1		5	4.6	5.0			
	2	1		5	4.9	4.8			
	2	2*		5	4.8	4.8	5.1	4.8	*One S-Track at~10°
Be	1			6	6.0	5.8			
	2	2		6	5.8	6.0	5.8	6.1	
	3	2		8	7.8	7.8		8.1	
Be	2			8	7.7	8.2			
B	2	1		10	9.8		10.0	10.2	

For 93 per cent of the tracks in this group, at least two independent methods were used.

To establish a charge calibration for a given ionization parameter, a frequency distribution was plotted for that parameter. Primary reliance was placed on the peaks of these "raw data" histograms. However, measurements on certain "charge-revealing" collisions enabled us to verify the charge assignments (see Table II). These collisions are fragmentations in which the total charge of the fast breakup products gives an extra "handle" on the charge of the incident nucleus. We found 10 excellent charge revealing fragmentations (selected out of 433 collisions) in which a fast nucleus splits up into alpha particles, into fragments up to Be and B, and into 1 or 2 singly-charged particles in a narrow forward cone of directions. An exception is the Li nucleus, whose charge emerges as 3 singly-charged particles. Note the absence of slow fragments, except for the recoil nuclei in two instances.

These charge-revealing collisions helped in identification, and in verifying the charge calibration.

Fig. 1 displays the apparent charges deduced from gap and delta-ray measurements in G.5 emulsion, plotted against each other. Each point represents a track. In distinguishing between L and S particles, the two parameters tell much the same story; otherwise we should have more points in the quadrants at upper left and lower right. The large circles refer to the parent heavy nucleus in the "charge-revealing" collisions.

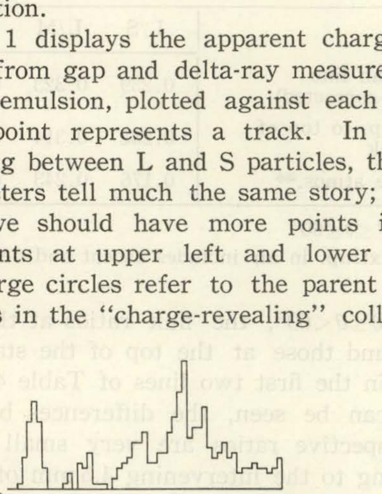

Fig. 1.

Histograms for each parameter are shown.

Fig. 2 shows the apparent charge deduced from delta-ray densities in G.5 emulsion plotted against the apparent charge deduced from blob densities in G.0. The lightest element visible in G.0 was boron (Li and Be were readily visible in G.5 and G. Special, but not in G.0. They were adequately identified in the more sensitive emulsions.) Grain count (or blob count) for relativistic boron was only $\sim$9 blobs per 100μ in G.0.

A suitably weighted "best experimental charge" Z was deduced for each heavy nucleus, from the apparent charge values obtained by the several methods in the various emulsions. The frequency distribution of these charges is shown in Fig. 3 for 746 tracks with $3 \leq Z \leq 11$. It is evident that the resolution between B and C is good. (136 tracks with apparent charge ≥ 12 are omitted from this histogram).

From this frequency distribution, a split between L and M nuclei was arbitrarily

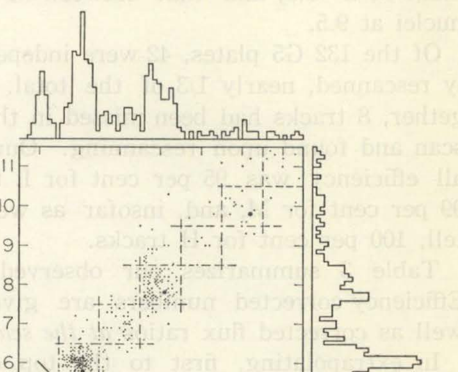

Fig. 2.

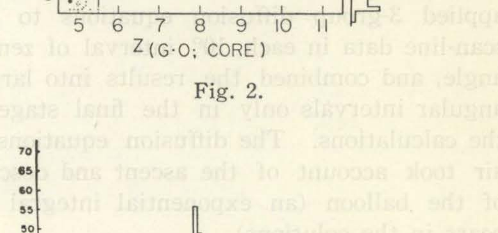

Fig. 3.

Table III. Numbers of L, M, and H Tracks* at the Scan Line in the Emulsion Stack

Zenith Angle Interval	Observed Numbers			Efficiency-corrected Numbers				Efficiency-corrected Ratios		
	L′	M′	H′	L	M	H	S=M+H	L/S	L/M	H/M
$0 \le\theta\le 10°$	21	72	32	22.2	72.7	32	104.7	0.212	0.305	0.440
$10° <\theta\le 20°$	27	91	29	28.5	91.9	29	120.9	0.236	0.310	0.316
$20° <\theta\le 30°$	33	103	25	34.8	104.0	25	129.0	0.270	0.335	0.240
$30° <\theta\le 40°$	20	85	36	21.1	85.9	36	121.9	0.173	0.246	0.419
$40° <\theta\le 50°$	23	59	24	24.3	59.6	24	83.6	0.291	0.408	0.403
$50° <\theta\le 60°$	21	59	21	22.2	59.6	21	80.6	0.275	0.372	0.352
$0 \le\theta\le 30°$	81	266	86	85.5	268.7	86	354.7	0.241	0.318	0.320
$30° \le\theta\le 60°$	64	203	81	67.5	205.0	81	286.0	0.236	0.329	0.395
$0 \le\theta\le 60°$	145	469	167	153.0	473.7	167	640.7	0.239	0.323	0.353
$60° <\theta\le 70°$	21	32	10	22.2	32.3	10	42.3			
$70° <\theta\le 80°$	7	19	4	7.4	19.2	4	23.2			
$80° <\theta\le 90°$	1	4	3	1.1	4.0	3	7.0			
$0 \le\theta\le 90°$	174	524	184	183.6	529.2	184	713.2			

* Having a projected length ≥ 4.2 mm per emulsion layer.

made at $Z=5.5$, and that between M and H nuclei at 9.5.

Of the 132 G5 plates, 42 were independently rescanned, nearly 1/3 of the total. Altogether, 8 tracks had been missed in the first scan and found upon rescanning. Our overall efficiency was 95 per cent for L tracks, 99 per cent for M, and, insofar as we could tell, 100 per cent for H tracks.

Table 3 summarizes our observed data. Efficiency-corrected numbers are given, as well as corrected flux ratios *at the scan line.*

In extrapolating, first to the top of the stack, then to the top of the atmosphere, we applied 3-group diffusion equations to the scan-line data in each 10° interval of zenith angle, and combined the results into larger angular intervals only in the final stage of the calculations. The diffusion equations in air took account of the ascent and descent of the balloon (an exponential integral appears in the solutions).

In the solutions to the diffusion equations we used the following values of the collision parameters: for interaction mean free paths we employed values, both for emulsion and air, based on the Bradt-Peters semi-empirical relation. We also used the values for emulsion adopted by Waddington (1) for the fragmentation coefficients, denoted by P_{ij}.

Table IV. Calculated flux ratios* (using diffusion equations)

	L/S	L/M	H/M
At scan line (effic.-corrected)	0.239	0.323	0.353
Extrap. to top of stack	0.232	0.314	0.357
Above atmos.**	0.176	0.243	0.381

* $0° \le\theta\le 60°$

** Extrap. in air includes ascent and descent.

For $0\le\theta<60°$, the flux ratios at the scan lines, and those at the top of the stack are given in the first two lines of Table 4.

As can be seen, the differences between the respective ratios are very small (corresponding to the intervening 4.5 mm of emulsion—up to 9 mm, of course, at $\theta=60°$). In our experiment the emulsion correction is minute for any reasonable set of P_{ij} values.

For the extrapolation in air, we searched the literature on fragmentation stars of the *l*-type ($N_h\le 7$) as well as fragmentation by air-like target materials, *e.g.*, carbon.

In addition to the results reported in the papers listed in Table 7 of reference (1), we felt it worthwhile to include values of fragmentation coefficients from seven other papers, and particularly from three papers in which air-like target materials were sandwiched between emulsions, despite the small statistical weight of the latter experiments. Some of the *l* stars are actually due to collisions with silver and bromine nuclei involving large impact parameters, and the correction for this effect in uncertain at best. The investigations in which the fragmentations definitely occurred in air-like targets are capable of yielding data of more direct relevance to air nuclei. For this reason we arbitrarily doubled the statistical weight of these data relative to the rest, although this doubling had only a very slight effect on the final set of P_{ij} values.

Table 5 shows the number of *l* stars, and of air-like-target stars that were used in arriving at our final P_{ij} values. Table 6, in the first column of figures, gives the set of fragmentation coefficients for air that we adopted. The notation (*l*, 2A) signifies that the statistical weight assigned to the A stars and *l* stars respectively, were in the ratio 412/1367, rather than 206/1367. The last

Table V.

Fragmentation Parameters for Air from Collisions of Heavy Nuclei

Type of Observation	Number of Fragmentations
l Stars ($N_h \leq 7$) (10 investigations)	1367
C, F, N, O, H Targets (3 investigations)	206
Total	1573

Sources: Bristol (2), Turin, Chicago (2), Gottingen (3), Rochester (2), Sydney, Melbourne, Tokyo.

Table VI. Fragmentation Coefficients for Air (×100)

	"NRL" (*l*, 2A)	W (Rev.)	A	*l*	*l*, A
P_{HH}	24	31	19	27	25
P_{MM}	14	16	6	16	15
P_{HM}	31	33	23	34	32
P_{LL}	15	13	13	15	15
P_{HL}	28	14	43	23	26
P_{ML}	27	21	33	26	26

l=" *l*-Stars " ($N_h \leq 7$); A=air-like targets

column in Table 6 shows the values obtained when normal statistical weight (206) is assigned to the A stars. The column in Table 6 headed "W(Rev.)" contains the values adopted by Waddington (1). The columns headed "A" and "*l*", respectively, are the values we computed from the raw data for the A stars and *l* stars, respectively.

By applying the "NRL" set of fragmentation coefficients to the solutions of the diffusion equations in air, we obtain flux ratios above the atmosphere, $(L/S)_0$, $(L/M)_0$, and $(H/M)_0$. These are given in the last line of Table 4, and in the first line of Table 7.

In order to see how the values of these ratios would be affected by making other assumptions about fragmentation (*i.e.*, using other P_{ij}), we calculated the ratios for the sets of P_{ij} given in the columns of Table 6 labeled "W(Rev.) and "A", respectively. The results are shown in the second and third rows of Table 7.

Table VII. Calculated Flux Ratios above Atmosphere under Various Assumptions about Fragmentation

	$(L/M)_0$	$(H/M)_0$	$(L/S)_0$
P_{ij} set from:			
"NRL:	0.243	0.381	0.176
Waddington Rev.:	0.269	0.377	0.195
Air-like targets:	0.216	0.377	0.157
Excluding secondary production of HN:	0.306	0.371	0.223
Rochester	0.195	0.381	0.141

Although certain of the P_{ij} differ considerably among the three sets, it can be seen that, at our atmospheric depth, these differences do not have a large effect upon $(L/S)_0$ or $(L/M)_0$. The ratio $(H/M)_0$ is very insensitive to these three sets of coefficients; it remains 0.38.

The remaining two rows in Table 7 provide more extreme upper and lower limits, respectively, on the $(L/S)_0$ and $(L/M)_0$ ratios. The row labeled "Excluding secondary production of HN" was computed under the assumption (patently false) that *no* secondary L or M nuclei were generated in collisions above the stack, and that the L, M, and H nuclei were attenuated in a simple exponential manner in the atmosphere above the stack. This should place rather severe upper limits upon $(L/S)_0$ and $(L/M)_0$. The last row in the table, labeled "Rochester", uses the Rochester fragmentation coefficients, with their extremely large values of P_{HL} and P_{ML}. The use of these coefficients may be expected to yield a rather severe lower limit to the $(L/S)_0$ and $(L/M)_0$ values. The lower limit to $(L/S)_0$ computed in this way turns out to be 0.14. Interestingly enough, the ratio $(H/M)_0$ still remains 0.58.

Using our data and the calculations described above, we arrive at a best value for $(L/S)_0$ of 0.18 ± 0.04.

Table 8 gives our calculated values of the relative abundances of individual elements

Table VIII. Relative abundances of the elements ($Z \geq 3$) in the primary cosmic radiation

Relative to all HPN (%)		Z	Relative to carbon (%)	
NRL	Others		NRL	Others
5.3	5.2	3	17.6	21.4
2.3	4.3	4	7.6	17.1
7.4	11.9	5	24.6	47.4
30.1	25.1	6	100.0	100.0
9.7	14.9	7	32.2	59.3
19.4	14.5	8	64.4	57.8
2.4	4.0	9	8.0	15.9
15.0	21.4	L	49.8	85.2
61.6	58.5	M	205.0	233.0
23.4	20.1	H	77.7	80.0

at the top of the atmosphere.

Among the elements above helium in the cosmic radiation, it is generally agreed that carbon is the most abundant element, and oxygen the next most abundant. (In the "universal abundances", oxygen is more frequent than carbon.) Since the latter predominates in the cosmic ray abundances of the heavy nuclei, it is sometimes useful to express the various individual element abundances relative to carbon.

Also, it is interesting to compare our results with the mean values (from 6 papers) published in reference (1).

We *agree* on the following ratios:

Li/total; Li/C; O/C; H nuclei/C;

We also agree on the following ratios between *groups* of nuclei:

H/S; H nuclei/M nuclei; H nuclei/total; M nuclei/total

("total" signifies all heavy nuclei, $Z \geq 3$).

We *differ* in the following:

Be/C; B/C; N/C; N/O; L nuclei/C.

The main result of our experiment is this: we believe there is no more room for doubt as to the presence in the primary cosmic ray beam of a sizeable intensity of the light elements-nearly 20 per cent as much as all the heavier ones. Relative to hydrogen, they occur in an abundance roughly 2×10^5 times greater than the universal abundance.

References

1) C. J. Waddington: Progress Nucl. Physics **8** (1960) 1.

Discussion

Powell, C.F.: The corrections used by Dr. Shapiro have positive values while that obtained by the Bombay group is negative. It will be a good idea if the workers associated with these investigations come to some general agreement regarding the slope of the line H/M vs. atm. depth.

Daniel, R.R.: The seriousness of this situation has been realized by many workers in this field. Investigations have now been undertaken by many groups to get the fragmentation parameters in air like nuclei so that the corrections obtained from the experimental growth curves (Bombay group) can be compared with confidence with the calculated growth curves using interaction mean free paths and fragmentation parameters. Preliminary results from such investigations will be presented by various groups to-morrow.

Shapiro, M.M.: Further experimental work on fragmentation against air-like targets is certainly needed. Conceivably, it may show that none of the present values of fragmentation coefficients that affect the $(H/M)_0$ ratio is valid. Meanwhile, however, it is noteworthy that in his recent review at Varenna (1961) of several works in addition to ours, Dr. Waddington arrived at an $(H/M)_0$ value of 0.38, the same as ours.

Zhdanov, G.B.: There is an obvious contradiction between the data of your work and previous one as to the sign of correction for the fragmentation in the atmosphere to the H/M ratio.

Shapiro: Our present slope (in H/M versus atmospheric depth) is quite small; and the uncertainty in it, as can be seen from the error assigned to our $(H/M)_0$ value, leaves open the question whether the true slope may be close to zero, or even positive. However, the method employed by the Bombay group in arriving at their growth curves is unfortunately capable of giving rise to serious error. This is evident from the enormous difference between the $(L/S)_0$ value they originally obtained (which was already based on over 600 tracks), and the value they now report for this ratio, which is based in large part on the original data.

Peters, B.: You all will agree that Dr. Shapiro and his group have presented a most valuable paper. Perhaps only those who have themselves been involved in the Li, Be, B problem can fully appreciate the amount of labour, care and patience which lies behind this detailed analysis of nearly 1000 primary particle tracks. This work and that presented in the preceding paper by Dr. Daniel of the Bombay Group are by far the statistically most extensive investigations of the ratio of light nuclei to heavier nuclei in the primary radiation. It is a particular satisfaction to me that these two investigations agree in their conclusion and that after many years of uncertainty there exists a number for the important L/S ratio, which is, I think, acceptable to all those who have worked on this difficult problem. The flux values presented by Dr. Shapiro come from emulsions exposed at greater altitude than any other previous stacks used for such investigations and need therefore only little extrapolation to the top of the atmosphere. The corresponding reduction in errors and uncertainties make the value $L/S=18\pm4\%$ which Dr. Shapiro's group has obtained the best value available now for this important ratio. Similarly the work gives convincing confirmation to the minimum in the abundance curves at Nitrogen, which some investigators have reported and others have found difficult to verify. Of course much remains to be done experimentally. The L/S ratio has been measured with high precision so far only at one particular geomagnetic latitude. To study its value in different energy regions is urgent because it is one of the best methods available for finding out whether primary cosmic ray nuclei of different energy have different trajections and therefore traverse different amounts of interstellar matter. Some of the following papers may throw some light on this question.

Historically the L/S studies were begun to find out whether the composition of the primary radiation represents the composition of a source region containing both hydrogen and complex nuclei or whether the primary proton and helium components are fragments produced in interstellar space by a beam consisting initially of heavier elements only. A value $L/S=18\%$ strongly favours the first hypothesis, but the second one cannot be ruled out with safety until careful experiments on spallation reactions at different energies have actually established that break up in interstellar space would lead to a much higher L/S ratio than that actually observed.

There can be no doubt, however, that we are now in a better position to find answers to the question of source composition and to the interstellar history of accelerated primaries of different energy, then we were at the time of the Moscow Conference.