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NUCLEAR EMULSION RECORDINGS OF HEAVY PRIMARIES ON APOLLO VII AND VIII*

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SUMMARY PAGE

THE PROBLEM

Fluxes and energy spectra of galactic heavy primaries encountered on a lunar mission are greatly different from those on a near-Earth orbital mission. Data from Apollo VII and VIII, the former a 10.8-day orbital mission and the latter a 6.1-day lunar mission, are ideal for identifying the indicated difference through measurements in the nuclear emulsions carried by the astronauts in their garments.

FINDINGS

Since the "microbeam" effects of heavy nuclei center upon the highest Z numbers, the Ilford G.5 emulsions from the two missions were scanned for nuclei of $Z \geq 20$. The microscopic scanning was carried out under low power, comparing the visual appearance of the tracks to the same standard track of $Z = 20$ used in an earlier evaluation of the same kind on Gemini VII.

A total of 84 track segments of $Z \geq 20$ was counted in 5.99 cm^2 emulsion area for Apollo VII and of 76 segments in 1.82 cm^2 for Apollo VIII. This represents a flux of 1.3 nuclei/(cm^2 24 hours) for Apollo VII and of 6.86/(cm^2 24 hours) for Apollo VIII. By applying QF factors as recommended by the ICRP to the absorbed doses of 0.42 millirad for Apollo VII and 1.5 millirads for Apollo VIII, the corresponding dose equivalents of 6.5 and 23.9 millirems, respectively, were obtained. These contributions constitute 4 per cent of the total mission dose equivalent for Apollo VII and 12 per cent for Apollo VIII. The results indicate that heavy nuclei contribute sizeably to the astronaut's radiation exposure on deep-space missions outside the magnetosphere. The fact that the "microbeam" effects of heavy nuclei, especially in long-term total body exposures, have not been investigated at all makes the assessment of the exposure status of an astronaut for accumulated time on deep-space missions a problematic issue.

INTRODUCTION

On a lunar mission the parameters of the galactic radiation environment in space are substantially different from those on a near-Earth satellite mission with a conventional orbit of about 30° inclination. The missions Apollo VII and VIII, the former a preparatory mission with a conventional near-Earth satellite orbit and the latter the first manned lunar mission, were pre-eminently suited for collecting accurate quantitative information on how the indicated difference makes itself felt within the Apollo Command Module in the radiation sensors carried by the astronauts in their space suits. The following report is an interim account of scans of galactic heavy nuclei in selected nuclear emulsions from the radiation packs of the two missions.

To be sure, the bulk of the radiation exposure on both missions resulted from trapped protons picked up, on the Earth-satellite mission Apollo VII, in repeated passes through the South Atlantic Anomaly, and on the lunar mission Apollo VIII, in two complete traversals of the radiation belt on the outbound and inbound transfer ellipses.

Contrary to the radiation exposure from trapped protons which poses no particular problem in its radiobiological interpretation, the "microbeam" effects of heavy nuclei on living matter are at present incompletely understood. Pilot experiments in balloons and satellites have demonstrated the effectiveness of single traversals of heavy nuclei for shrimp eggs (1), hair follicles of the black mouse (2), and maize embryos (3); yet no data on long-term effects of total body exposure to galactic heavy primaries on test animals or man are available. Speculative reasoning by induction from effects of conventional high LET radiations is expressly cautioned against by the RBE Committee of the International Commission on Radiological Protection (ICRP). As stated in the report of this committee (4), the basic dosimetric concepts underlying the definition of the rad unit cannot be applied to microbeam irradiation.

Despite the just-indicated lack of precise knowledge, radiobiologists seem in general agreement that the particular conditions of heavy nuclei exposure as they prevail in near-Earth orbits of low inclination would not pose any problems since, in such orbits, the free-space flux is substantially reduced and the nuclei with peak values of Linear Energy Transfer (LET) are completely excluded due to the screening effect of the Earth's magnetic field. This assurance would seem in need of re-examination after man, on the three successful deep-space missions Apollo VIII, X, and XI, left the magnetosphere and travelled for days at a time in regions where substantially larger fluxes of galactic particles prevail, with LET spectra extending to substantially higher peak values.

The present report does not endeavor to resume the discussion of the controversial heavy nuclei issue. It merely furnishes the dosimetric data for such a discussion by presenting comparative flux data on heavy primaries for the two missions Apollo VII and VIII. Although recordings of heavy nuclei on manned near-Earth satellite missions have been reported before by Benton and Collver (5) for the mission Gemini VI and by the present authors (6) for Gemini VII, it should be realized that these earlier data do not lend themselves to a direct comparison with those of the lunar mission because of the substantially lighter shielding of the Gemini vehicle. Due to the small depth of penetration of heavy nuclei, the difference in shielding would introduce an additional variable into the comparison. It is for this particular reason that we have carried out a combined scan for heavy nuclei in emulsions of Apollo VII and VIII with the same observer alternatingly scanning emulsions of the two missions.

EXPERIMENTAL PROCEDURE

Accurate determination of the Z number of a heavy track in emulsion requires large emulsion volumes that will allow the pursuit of individual tracks over considerable lengths. In the small emulsion volumes available in the radiation packs presently in use for the Apollo astronauts, only semiquantitative estimates are possible by comparing the visual appearance of the tracks under the microscope with a standard track from a large emulsion stack whose Z number is accurately established.

Although the Z spectrum of the primary galactic radiation is a continuum extending from protons (Z = 1) to Ni nuclei (Z = 28) and, with very low fluxes, to even heavier elements, tracks in the group from Z = 20 to 28, usually called the $Z \geq 20$ group, stand out, in G.5 emulsion, in their visual appearance under the microscope because of their broad black silver core and their dense delta ray aura. The time requirements for sorting out, from a population of tracks of heavy primaries, those belonging to the $Z \geq 20$ by comparing the visual appearance with a standard track of Z = 20 are considerably less than for individual Z matching of the entire population of heavy tracks. Moreover, accuracy and consistency of the former method are greatly superior to the latter, since the observer refers, in his rating, always to one and the same track.

As mentioned before, we have tackled the same task already on an earlier occasion when the heavy flux of the emulsions flown on the 14-day mission Gemini VII was evaluated. In the present investigation, we have followed essentially the same method. In the interest of consistency throughout our entire effort of radiation monitoring on all manned space missions, we have used, in the present analysis, the same track which served as standard in the earlier study (l.c., 6, Figure 2, p. 9). For the reader's convenience, the earlier illustration is reproduced as Figure 1.* Comparing this track to the standards in Powell, Fowler, and Perkins' classic atlas (7), we rate the track as produced by a relativistic nucleus of Z = 20.

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*In order not to break the continuity of the text, all tables and illustrations appear at the end.

The tracks in the G.5 emulsions of Apollo VII and VIII were compared with this standard and were accepted as belonging to the $Z \geq 20$ group if they appeared at least as heavy as the standard. A special problem in identifying Z numbers by visual comparison is posed by tracks with steep dip angles. Due to projective image compression in the longitudinal direction, such tracks appear heavier and their Z numbers are easily overestimated. We have tried to allow for this phenomenon by requiring an increasingly heavier appearance for increasingly steeper angles. For tracks accepted as $Z \geq 20$, a further resolution of the Z number was attempted by interpolating between Powell, Fowler, and Perkins' standard tracks for $Z = 20$ and 26. In these comparisons we have tried to judge the visual appearance of the tracks conservatively in the sense that their Z numbers were slightly over-rated rather than exactly matched to the standards. Figure 2 shows two selected tracks heavier than $Z = 20$. Applying the indicated criteria, we classed them as $Z = 22 \pm 2$ and 28 ± 2.

While we are entirely aware that the described method of matching the overall appearance of tracks furnishes, at best, a semiquantitative estimate of the flux, we should like to point out that, in our particular case, main emphasis rests on the comparison of emulsions from two different missions. Even if our evaluation should contain a major systematic error, it is likely to affect the data for the two missions Apollo VII and VIII in the same way since identical criteria were applied, by the same observer, to all tracks. In other words, any systematic error of our method should not influence the ratio of the fluxes for the two missions.

RESULTS

Table I shows the results of comparative scans for nuclei of $Z \geq 20$ in 100 micra G.5 emulsions from Apollo VII and Apollo VIII. By adding the numbers of segments and dividing by the scanned area, one sees that the fluxes on the two missions are indeed strikingly different. The 260-hour Apollo VII mission shows a flux of 14 nuclei/cm^2 whereas the 146-hour mission Apollo VIII shows a flux of 42 nuclei/cm^2. This means that the fluxes per unit time differ by a factor of more than 5.

The assessment of absorbed tissue doses and dose equivalents was carried out by the method which we always use in evaluating absorbed energy from flux data. We visualize the scanned emulsion volume replaced by an equal volume of tissue. Division of the total track length by this volume furnishes the equivalent unidirectional flux. Multiplication of that flux by the LET furnishes absorbed energy. LET values for heavy nuclei were obtained by multiplying the minimum LET of protons by Z^2. Dose equivalents were determined by using the QF values set forth in Publication 9 of the International Commission on Radiological Protection (8). Intermediate QF values not listed in the tabulation of the ICRP were obtained by curvilinear interpolation. Table II shows a detailed breakdown of the absorbed doses and dose equivalents for all nuclei on Apollo VII. Table III lists the corresponding values for Apollo VIII. Again, if the respective mission durations are taken into consideration, the 24-hour dose equivalent of 3.9 millirem/day for the lunar mission Apollo VIII is greater by a factor of 6.5 than the corresponding dose of 0.6 millirem/day for the Earth-orbital mission Apollo VII. Taking further into consideration that the total exposure from trapped protons on Apollo VIII was found to be about 180 millirads and on Apollo VII about 150 millirads, one sees that the $Z \geq 20$ class of heavy nuclei contributed, for the Earth-orbital mission, about 4 per cent to the total dose equivalent, whereas the corresponding contribution for the lunar mission is about 12 per cent. These data demonstrate very clearly the greatly different make-up of the total radiation load on a deep-space mission outside the magnetosphere as compared to a near-Earth satellite mission. The fact that the nature of tissue damage from heavy nuclei, especially for long-term exposures at low dose rates, is not clearly understood at present adds another note of discomfort to this finding.

DISCUSSION

It seems of interest to investigate more closely how the flux values reported above compare to the flux data on heavy primaries available in the literature. Since we are dealing with the local flux within the vehicle, the shielding influence of the Apollo ship needs to be assessed beforehand.

Quite differently from primary protons of the galactic radiation which have a collision mean free path of about 100 g/cm^2, mean free path values for heavy primaries range from 28 g/cm^2 for the $Z = 6\text{-}9$ class down to 12 g/cm^2 for the $Z = 20\text{-}26$ class. That means a substantial fraction of the incident flux undergoes nuclear collisions in the materials of vehicle frame and equipment, breaking up into fragments before entering the astronauts' bodies. A detailed analysis of the shield distribution of the Command and Service Module of the Apollo vehicle has been carried out by North American Aviation, Inc. A simplified version of it, lumping the several hundred fractional solid angles of the original study together into larger classes using mean shield thicknesses, has been presented in an earlier report (9). Table IV shows the attenuation of the heavy galactic flux from $Z = 6$ to 28 as it would occur in the simplified Apollo shield system for the collision mean free path values listed in column 2. Concentrating again on the heaviest class with Z numbers of 20 and greater, one sees that, for an order of magnitude type estimate, an attenuation of 50 per cent can be assumed. It should be mentioned that the shield distribution in question holds for the center seat in the Command Module, yet does not take into consideration the additional shielding due to the astronauts' bodies. Therefore, the attenuation is underestimated; i.e., the residual flux values represent upper-limit estimates.

Existing data on the free-space flux of galactic heavy primaries are not very abundant. Especially poor is the resolution of the Z spectrum which, in turn, produces a large margin of uncertainty for the LET distribution and, to a still higher degree, for the dose equivalents because of the steep increase of QF values with increasing LET.

It is usually assumed that the energy spectra of the various Z components of the primary galactic radiation show the same basic configuration as galactic alpha particles. In other words, the energy spectra, if plotted over a common Mev/nucleon scale, become identical, with merely the ordinate scales differing by constant factors. A very comprehensive review of available data on the galactic alpha spectrum at solar minimum and maximum has been given by Webber (10). A more recent survey has been published by Balasubrahmanyan and co-authors (11). There is a major discrepancy between the two studies in the spectra for solar maximum. Since the Apollo VIII mission took place very close to the maximum of solar cycle 20, the indicated discrepancy very directly affects the present analysis. As a balanced approach, we have established the mean between the energy spectra of Webber and Balasubrahmanyan. The resulting spectrum was shown in an earlier report (12). For the reader's convenience, it is reproduced as Figure 3. For the flux ratio of $Z \geq 20$ nuclei to alpha particles, we followed Waddington's synoptic analysis (13) and assumed the value of 0.006. In other words, by multiplying the ordinate values in Figure 3 by 0.006 without any other changes in the abscissa or ordinate units, the spectra in Figure 3 hold for the $Z \geq 20$ group.

Numerical integration of the spectrum for solar maximum in Figure 3, for a target area of 1 cm^2 and 4 pi incidence, leads to a flux of 37.0 nuclei/(cm^2 24 hours) penetrating the area from all directions from both sides. The attenuation of 50 per cent in the hardware of the Apollo vehicle reduces this flux to 18.5 nuclei/(cm^2 24 hours). This value compares to a value of 6.9 nuclei/(cm^2 24 hours) as it follows from our recordings if we remember that Table I lists, for the 6.1-day mission Apollo VIII, a total of 76 tracks traversing 1.82 cm^2. If we realize that 4 pi incidence holds actually only for the transit time during which both the planetary bodies of Earth and Moon cover a small fraction of 4 pi and that, furthermore, the sizeable self-shielding due to the astronauts' bodies was neglected, the agreement must be termed surprisingly good in view of the large margins of basic uncertainties and errors in existing information on the heavy spectrum and our crude method of "guestimating" Z values.

Again, we attach main importance to the more than five times larger heavy flux per unit time on the deep-space mission. This finding certainly is not subjected to the just-indicated limitations of accuracy and strongly suggests that the heavy nuclei exposure should be considered as a separate entity in the account of an astronaut's accumulated career dose. It also emphasizes the need for early and determined efforts toward elucidation of the radiobiological significance of this novel type of radiation injury to man in deep space.

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Table I

Heavy Flux $Z \geq 20$ on Apollo VII and VIII

	Apollo VII		Apollo VIII	
Estimated Z	Number of Track Segments	Combined Length, micra Em	Number of Track Segments	Combined Length, micra Em
22	40	6,804	24	5,575
23	23	4,309	30	4,352
24	12	2,374	7	1,215
25	8	971	8	969
26	1	103	3	554
27	--	--	3	1,037
30	--	--	1	307
Scanned Area, cm^2	5.99		1.82	
Scanned Volume, cm^3	0.0599		0.0182	
Position	Command Module Pilot, Thigh		Command Module Pilot, Thigh	

Table II

Mission Dose from Nuclei Z ≥ 20 on Apollo VII

Estimated Z	Equiv. Flux, Particles/cm^2	LET, Mev/(g/cm^{2}T)	Abs. Dose, millirad	QF	Dose Equiv., millirem
22	9.69	968	0.167	14.5	2.41
23	7.19	1,058	0.135	15.5	2.09
24	3.92	1,152	0.080	16.2	1.30
25	1.62	1,250	0.036	16.9	0.61
26	0.172	1,352	0.0041	17.6	0.073
		Total	0.422	Total	6.48*

*Mission duration was 260 hours leading to a dose rate of 0.6 millirem/day.

Table III

Mission Dose from Nuclei Z ≥ 20 on Apollo VIII

Estimated Z	Equiv. Flux, Particles/cm^2	LET, Mev/(g/cm^{2}T)	Abs. Dose, millirad	QF	Dose Equiv., millirem
22	30.7	968	0.527	14.5	7.64
23	23.9	1,058	0.447	15.5	6.97
24	6.68	1,152	0.137	16.2	2.21
25	5.33	1,250	0.118	16.9	2.00
26	3.05	1,352	0.073	17.6	1.29
27	5.70	1,458	0.148	18.3	2.70
30	1.69	1,800	0.054	20.0	1.08
		Total	1.504	Total	23.89*

*Mission duration was 146 hours leading to a dose rate of 3.9 millirem/day or 6.5 times the dose rate for Apollo VII.

Table IV

Estimated Attenuation of Heavy Nuclei in Apollo Vehicle*

Z Class	Collision Mean Free Path, g/cm^2	Residual Flux Anterior Half Space	 Posterior Half Space
6-9	28	0.67	0.60
10-19	20	0.58	0.51
20-28	14	0.48	0.41

*Computation based on shield distribution of North American Aviation, Inc. Additional shielding due to astronauts' bodies not taken into consideration.

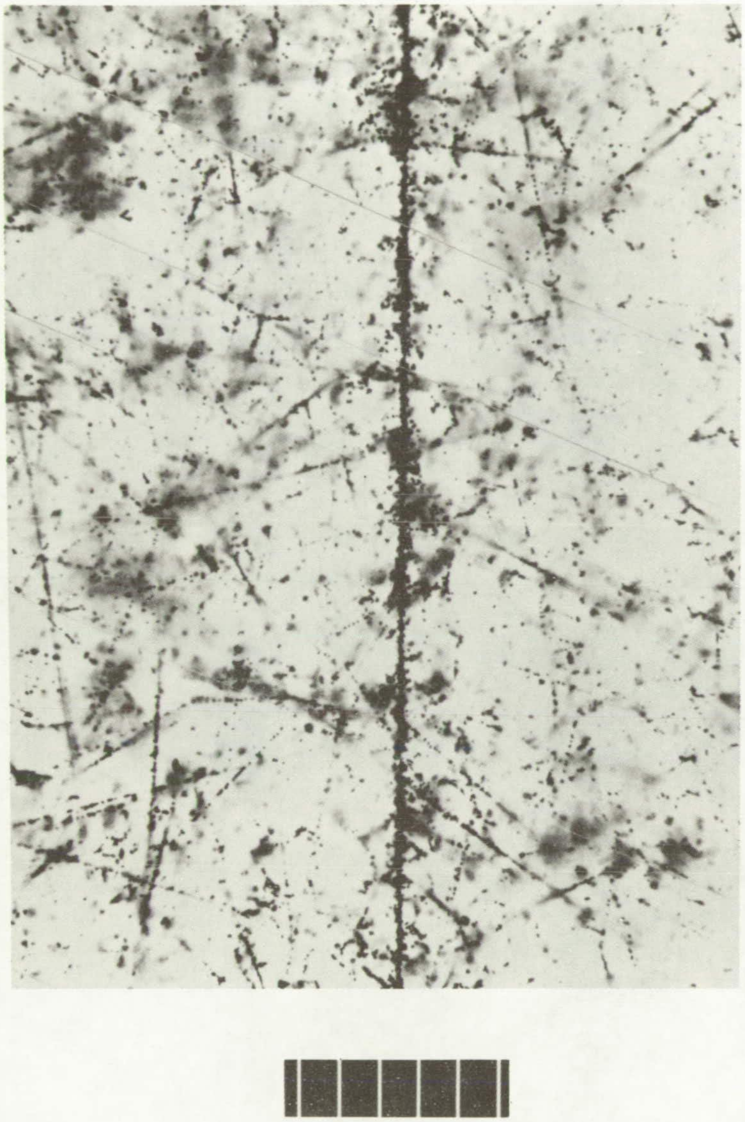

Figure 1

Heavy Nucleus Track of Estimated $Z = 20$ in Ilford G.5 Emulsion Used as Minimum Standard in Scanning for Nuclei of $Z \geq 20$

1 Scale Division = 10 micra

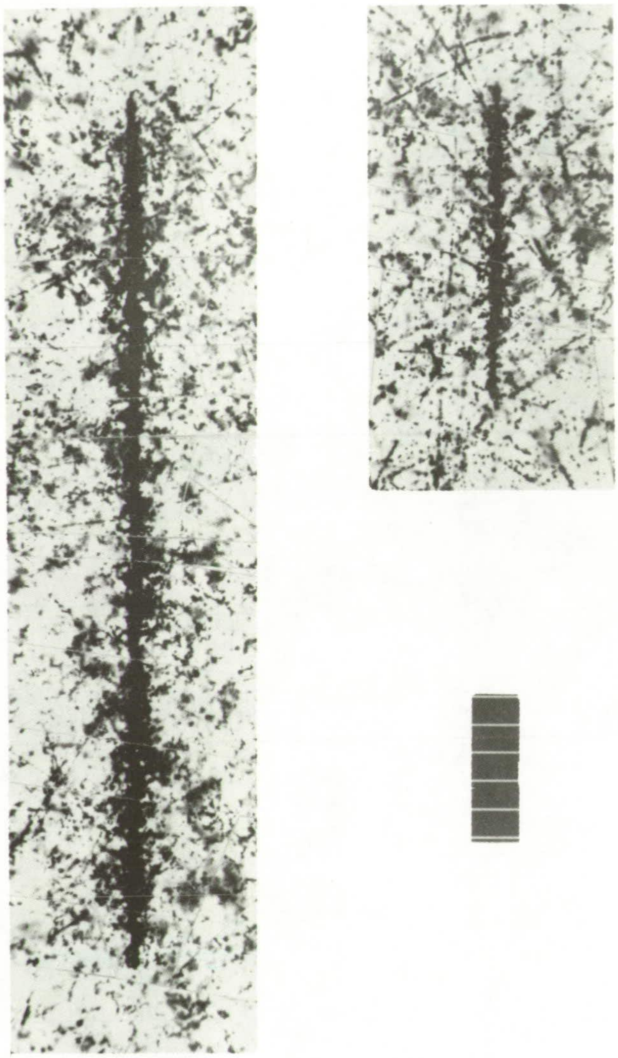

Figure 2

Two Selected Heavy Tracks in Ilford G.5 Emulsion of Apollo VIII
Estimated Z Numbers: 28 ± 2 (left) and 22 ± 2 (right)

1 Scale Division = 10 micra

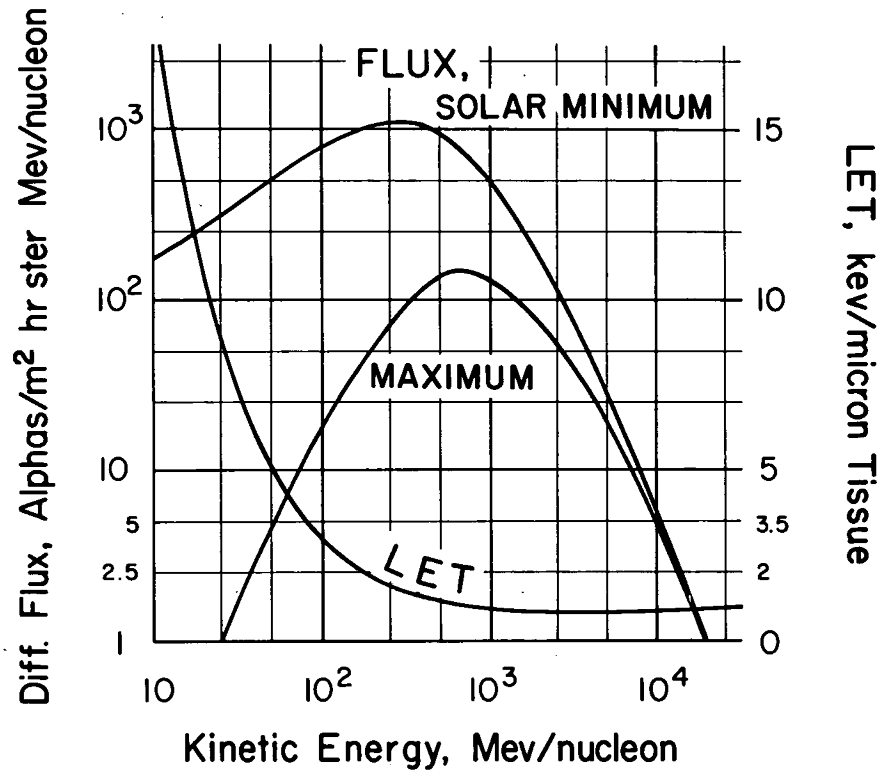

Figure 3

Differential Energy Spectra of Galactic Alpha Particles at Solar Minimum and Maximum

For corresponding spectra for nuclei $Z \geq 20$, multiply ordinate values by 0.006.

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13. ABSTRACT

Ilford G.5 emulsions in radiation packs carried by the astronauts in their space suits on the Earth-orbital mission Apollo VII and the first lunar mission Apollo VIII were scanned for tracks of heavy nuclei. Since the "microbeam" effects of heavy nuclei in living tissue center upon the high Z numbers, the scan was limited to Z numbers of 20 and higher. Greatly different fluxes are found on the two missions: 1.3 nuclei/(cm^2 24 hours) on Apollo VII and 6.86/(cm^2 24 hours) on Apollo VIII. Absorbed mission doses and dose equivalents are 0.42 and 1.5 millirads and 6.5 and 23.9 millirems, respectively. The dose equivalents constitute 4 per cent of the total exposure on Apollo VII and 12 per cent on Apollo VIII. The findings demonstrate the great difference in the make-up of the radiation environment in a near-Earth orbital and a deep-space mission and point out the need for a better understanding of the radiobiological significance of total body irradiation with heavy nuclei if the exposure status of an astronaut from accumulated exposures to the deep-space radiation environment is to be assessed accurately.

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