Reports

Apollo 14 and Apollo 16 Heavy-Particle Dosimetry Experiments

Abstract. *Doses of heavy particles at positions inside the command modules of Apollo missions 8, 12, 14, and 16 correlate well with the calculated effects of solar modulation of the primary cosmic radiation. Differences in doses at different stowage positions indicate that the redistribution of mass within the spacecraft could enhance safety from the biological damage that would otherwise be expected on manned, deep-space missions.*

Densely ionizing, heavy atomic nuclei are the most individually damaging form of cosmic radiation encountered by space personnel on missions outside the earth's atmosphere. For example, an iron nucleus leaves a cytologically lethal swath of damage as it crosses cell nuclei through its last ~3 mm of range. Earlier measurements in which Apollo helmets were used as dosimeters have indicated that a significant fraction (~1 percent) of certain nonregenerative motor-control cells would be killed in a Mars-length mission with the present Apollo spacecraft shielding (*1*). As an extension of the dosimetry work for Apollo 8 and Apollo 12 (*1*), we have used a number of the parts from the Apollo 14 electrophoresis experiment (*2*) and tracks formed after stowage of the Apollo 16 cosmic-ray experiment (*3*) to measure the doses of heavy nuclei that penetrated the interiors of the command modules during these two missions. During most of the Apollo 14 mission the equipment for the electrophoresis experiment was located in a compartment just beneath astronaut Edgar D. Mitchell.

First, we discuss the Apollo 14 experiment. In this experiment we etched and examined the tracks produced by the heavy particles that entered the Lexan polycarbonate parts forming the main body of the electrophoresis experimental device. The ionization threshold for particle registration of this material [if untreated by ultraviolet (UV) radiation] is that for single-hit inactivation of human kidney cells (*4*) and hence is appropriate for assessing the biological effects of heavily ionizing particles. The experimental procedures were essentially identical to those used in our earlier work, except that the largest piece of Lexan was re-etched for an extra 31.4 days after its original 8-day treatment in order to enlarge the tracks for photography and ready viewing with the naked eye. Figure 1 shows a track at low magnification, illustrating the geometrical variation that allows individual particles to be identified (*5*). As noted earlier (*1*), most of the nuclei observed are either iron, or its near neighbors in the periodic chart, or spallation products of iron, and all are of atomic number ≥ 10. The particle shown here has been identified according to the analytical technique described earlier (*6*) as argon. Because the nucleus was not observed as it stopped, with lower probability it could be potassium or calcium. More extensive calibration data than now exist for the etchant used could readily resolve such an uncertainty.

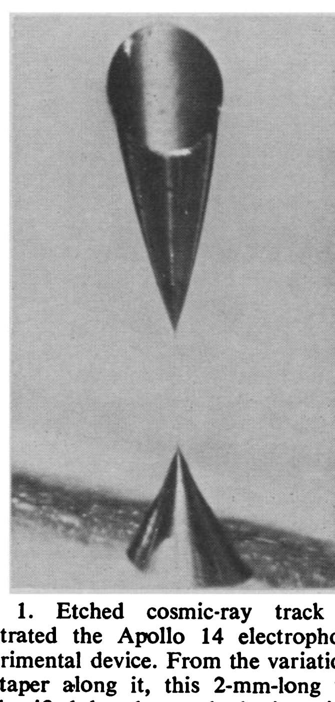


Fig. 1. Etched cosmic-ray track that penetrated the Apollo 14 electrophoresis experimental device. From the variation of the taper along it, this 2-mm-long track is identified by the method given in (*6*) as caused by an argon ion. The track intersected two etched surfaces, giving rise to two separate cones.

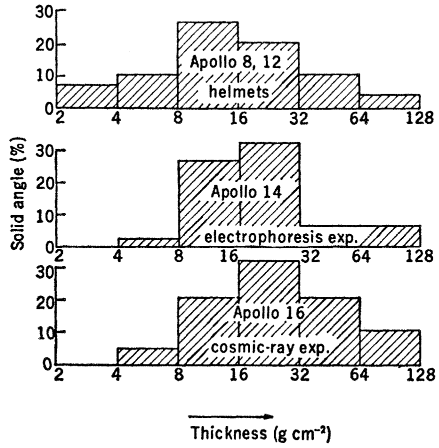
The equipment for the Apollo 16 cosmic-ray experiment was exposed on the lunar surface and later folded and stowed just prior to lift-off. The Lexan detectors that made up a major portion of the experimental device were held in such a manner that each sheet was displaced relative to its neighbor as the device was folded (*3*). By counting particle tracks that line up in the shifted position, we have a measure of particles that registered after the shift and therefore penetrated the spacecraft walls before entering the detectors. This fluence describes a particular position in the command module, since for most of the time after the shift the experimental device was stored in the same location. These samples were etched with 6.25*N* NaOH saturated with etch products (*7*). Since with this etchant the detector is less sensitive than with the NaOH-ethanol etchant that was used previously (*1*), track counts for the cosmic-ray experiment must be increased (by an estimated 80 percent) to make them comparable with the track counts of the helmet (*1*) and electrophoresis experiments. The numbers we will quote here are so corrected.

We observed 0.608 ($\pm$ 0.041) track cm^{-2} in the Apollo 14 command module and 0.334 ($\pm$ 0.041), corrected to 0.594, in the Apollo 16 command module, as compared to 0.56 ($\pm$ 0.053) and 1.41 ($\pm$ 0.146) in the Apollo 8 and Apollo 12 command modules, respectively. If we allow for the different lengths of the four missions and the time when the experimental devices were partially shielded by the moon, the four flux values for Apollo missions 8, 12, 14, and 16 are 1.53×10^{-7}, 3.12×10^{-7}, 1.92×10^{-7}, and 3.42×10^{-7} particle cm^{-2} sec^{-1} $ster^{-1}$, respectively (*8*). These values may be compared with those expected from solar modulation of the primary cosmic radiation and with the results of Benton and Henke (*9*), who used somewhat different procedures. As the entries in column 5 of Table 1 indicate, the sun became decreasingly active in the sequence of Apollo missions 8, 12, 14, and 16; fewer of the penetrating galactic cosmic rays were deflected away from the inner solar system in the Apollo 16 mission as compared with the

Apollo 8 mission, and the calculated (*1*) relative track density therefore rises from 0.66 for Apollo 8 to 1.00 for Apollo 12, 1.43 for Apollo 14, and 2.50 for Apollo 16. For Apollo 8 both our measurements ("≥ neon") and those of Henke and Benton ("≥ carbon") are consistent with the effects of solar modulation; for Apollo 14 and Apollo 16 Benton and Henke's measurements are roughly consistent with the calculations carried out by the method described in (*1*) giving the results summarized in Table 1, but the results presented here appear to be lower for both the Apollo 14 and the Apollo 16 missions.

The discrepancies between the two sets of observations could, in principle, be related to three possibilities: (i) differences in the fluxes of the different nuclei observed by the two groups of experimenters ("≥ carbon" by Henke and Benton and "≥ neon" by ourselves), (ii) differences in the Lexan detectors used in the helmet (type 111 or 112) and in the Lexan detectors used in the electrophoresis experiment (type 100), or (iii) different thicknesses of shielding at different positions in the spacecraft. As noted by the column headings in Table 1, the two groups measured particles of different mass. Benton and Henke used an intense UV irradiation (producing more etchable tracks, presumably to enhance statistics) to give very different registration properties (*10*), allowing nuclei as light as helium to register (*11*) although only nuclei at least as heavy as carbon were counted. Depending on the extent of the UV irradiation, track densities for the Apollo 8 mission ranged from 0.56 track cm^{-2} [no UV (*1*)] to 0.62 track cm^{-2} [some UV (*12*)] to 2.64 track cm^{-2} [intense UV (*9*)]. In our experiments UV was excluded to produce, as noted earlier, a biologically meaningful registration threshold as well as to allow valid intercomparison of the four missions. The first possibility—that the (≥ carbon/≥ neon) ratio was higher by a factor of ~ 3 during the Apollo 14 and Apollo 16 missions—is highly unlikely, since fluctuations in this ratio of greater than 30 percent would be inconsistent with measurements of galactic cosmic rays (*13*). The second possibility—that the two detectors we intercompare on the Apollo 12 mission and on the Apollo 14 mission were different—we ruled out on the basis of calibration measurements of etching rates for full-energy and low-energy fission fragments. For helmet Lexan, electrophoresis Lexan, and the usual 112 Lexan used for particle identification (*5*) the etching rates were identical within the experimental uncertainty (± 1.5 percent for full-energy particles and ± 7 percent for low-energy particles). The final possibility is the preferred one—that the storage positions of the Apollo 14 and Apollo 16 experimental devices were close to some thicker-than-average shielding in the command module, so that the effective solid angle through which cosmic rays could approach was reduced. Figure 2 shows the fractions of the solid angle occupied by shielding of different thickness intervals, as seen by the detectors in the helmet, electrophoresis, and cosmic-ray experiments we are considering. These calculations, which were carried out for the positions in the spacecraft for which the period of exposure of the apparatus for each experiment was the greatest, show clearly that the Apollo 8 and Apollo 12 helmets had some shielding thinner than 4 g cm^{-2} (1.5 cm of aluminum) and that the Lexan for the other experiments had, on the average, thicker shielding.

Since the calculated relative fluxes given in Table 1 were derived for the position of the helmets used on the Apollo 8 and Apollo 12 missions, we calculated corrections for the Apollo 14 and Apollo 16 experiments, using the distributions of matter given in Fig. 2 and calculations of flux versus depth as observed in meteorites (*14*) corrected for the average difference in density



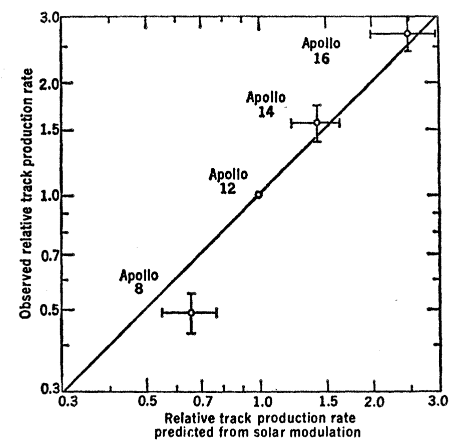


Fig. 2 (left). Distribution of mass around the three experiments considered in this report: Apollo helmets on Apollo 8 and Apollo 12 missions, the electrophoresis demonstration on Apollo 14 mission, and the cosmic-ray detector on Apollo 16 mission. We calculated these distributions from the known positions of storage of mass in the spacecraft, using a computerized description of the mass distribution of the command module. The distributions are used as described in (*1*) to derive track production rates for the three missions. For each experiment 10 percent of the solid angle was obscured by thicknesses greater than 128 g cm^{-2}, which allow negligible contributions to the observed track density. Fig. 3 (right). Observed track production rates, corrected for shielding thicknesses, plotted against the production rates calculated from solar modulation, corrected for shielding thicknesses. In all cases the rates are given relative to those for the Apollo 12 mission.

Table 1. Heavy-particle fluxes relative to the Apollo 12 mission.

Mission	Observed in command modules			Calculated from solar modulation*
	≥ Neon		≥ Carbon [Benton and Henke (*9*)]	
	Directly observed	Corrected for position in spacecraft		
Apollo 8	0.49 ± 0.06 (*1*)	0.49 ± 0.06	0.54 ± 0.14	0.66 ± 0.11 (*1*)
Apollo 12	1.00† (*1*)	1.00†	1.00†	1.00†
Apollo 14	0.60 ± 0.07	1.57 ± 0.18	2.00 ± 0.39	1.43 ± 0.21
			1.47 ± .28‡	
Apollo 16	1.10 ± .12	2.68 ± .29	3.25 ± .14	2.5 ± .5

* We calculated the fluxes listed in this column as described in (*1*), using the counting rates of the neutron monitor at Climax, Colorado, as a measure of solar activity; these fluxes include the effects of ionization and spallation loss of nuclei in passing through the spacecraft walls. † The directly observed track densities of each experiment were normalized to those of the Apollo 12 experiments. ‡ Film badge on E. D. Mitchell, crew member closest to the electrophoresis experiment.

between meteorites and aluminum. Column 3 of Table 1 gives the results of these corrections (factors of ~2.5 for each), and Fig. 3 presents a comparison of theory and experiment. We see from Table 1 that solar modulation has been responsible for variations from the Apollo 8 mission to the Apollo 16 mission by a factor of 5; shielding differences at different positions caused differences of a factor of ~2.5. These two factors thus explain the apparent discrepancy between our results and those of Benton and Henke (*9*).

The total doses of particles in the Apollo 14 and Apollo 16 command modules are higher but comparable to that in the Apollo 8 command module and presumably would cause the killing of a number of cells comparable to our calculation (*1*) for that mission. Even for the giant cells, the fraction killed is probably trivial, less than 500 cells per 10^6. However, relevant to a Mars-like mission (of ~ 2 years in duration), cellular damage would be extensive—as great as ~ 3 percent for the Apollo 16 flux level. The inadvertent reductions by a factor of ~ 2.5 in flux as a result of differences in shielding presumably could be enhanced by judicious planning and rearrangement of needed mass to provide optimum shielding at particular positions which the crew would occupy during most of a long voyage.

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Temporal Constancy of Zodiacal Light

Abstract. *Measurements over a 4-year period from the satellite OSO-5 have failed to show any temporal variations in the surface brightness and polarization of zodiacal light.*

The zodiacal light is a faint glow of light along the zodiac (or ecliptic) produced by the scattering of sunlight by particles in the solar system. Our satellite observations undertaken to search for temporal changes in the brightness have revealed a remarkable constancy of the phenomenon. Observations of the surface brightness and polarization of the zodiacal light had been made for many years without apparent convergence between the results obtained by different workers (*1*). An evaluation of ground-based measurements of the surface brightness of zodiacal light at the north ecliptic pole shows a range of more than a factor of 3 in the values obtained by different observers (*2*), and variations of a factor of 2 sometimes occur in the results of a single group (*1*). It is therefore difficult, and virtually meaningless, to intercompare the observations for an indication of temporal changes in zodiacal light, while the magnitude of the variations in a single set of data makes it difficult to credit small changes reported from such results. Nevertheless, many papers have been written on the variations of zodiacal light intensity, at constant ecliptic coordinates, over periods of days and years; these purport to show evidence for a correlation between the surface brightness and magnetic storms, lunar phase, the position of Comet Encke, an annual cycle, and the 11-year solar activity cycle.

During the last few years measurements from balloons (*3, 4*), rockets (*5, 6*), and satellites (*7–10*) have begun to reduce the inconsistency between different observations of zodiacal light. Balloon observations eliminate the need to subtract the contribution to the measured light made by the tropospheric scattered component; a comparison of satellite and ground-based measurements indicates that the latter generally suffer from a systematic positive error, perhaps due to incorrect subtraction of the component scattered in the earth's atmosphere (*8*). Measurements above about 150 km further eliminate most of the problems of airglow subtraction, although airglow cannot be entirely discounted above this altitude (*2, 7*), and it has been measured during one zodiacal light experiment from a satellite (*11*). A single rocket (or balloon) experiment cannot attempt to define temporal changes in the zodiacal light; however, an experiment on a satellite is in a unique position to do so.

The Minnesota experiment on the Orbiting Solar Observatory satellite OSO-5 has made it possible to compare measurements of the surface brightness and polarization of the zodiacal light with a single instrument over a time span of years. The satellite was launched in January 1969 and turned off in January 1973. During that 4-year period observations were taken throughout most of the new moon periods until the moon, if risen, was within 50° of the field of view of the photometers. A description of the experiment has been published (*12*).

Several observers have reported changes in the zodiacal light associated with magnetic activity. A measure of the magnetic disturbances at the earth are the geomagnetic indexes Kp and ΣKp. Blackwell and Ingham (*13*) correlated an increase in the surface brightness of the zodiacal light with Kp (the planetary 3-hour range index) during a strong magnetic storm in July 1958; Asaad (*14*) found a decrease in the surface