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LUNAR SURFACE COSMIC RAY EXPERIMENT
S-152, APOLLO 16

GENERAL ELECTRIC EXPERIMENT
FINAL REPORT

June 29, 1973

R. L. Fleischer, H. R. Hart, Jr., M. Carter, G. M. Comstock,

A. Renshaw, and R. T. Woods

Principal Investigator: R. L. Fleischer

Prepared under Contract No. NAS 9-11468

by

GENERAL ELECTRIC COMPANY

Physics and Electrical Engineering Laboratory
Corporate Research and Development
P.O. Box 8, Schenectady, New York 12301

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Manned Spacecraft Center
Houston, Texas

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ABSTRACT

This report presents the work done and reported under contract NAS 9-11468. The investigation was directed at determining the energy spectra and abundances of low energy heavy cosmic rays ($0.03 \leq E \leq 150$ MeV/amu) during the Apollo 16 mission. The cosmic rays were detected using passive, solid particle track detectors. Particles emitted during the 17 April 1972 solar flare dominated the spectra for energies below about 70 MeV/nucleon. Two conclusions emerge from the low energy data: 1.) The differential energy spectra for solar particles vary rapidly (roughly E^{-3}) for energies as low as 0.05 MeV/nucleon for iron-group nuclei. 2.) The abundance ratio of heavy elements changes with energy at low energies; heavy elements are enhanced relative to higher elements increasingly as the energy decreases. Galactic particle fluxes recorded within the spacecraft are in agreement with those predicted taking into account solar modulation and spacecraft shielding.

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SUMMARY AND GUIDE TO APPENDED PAPERS

The relative abundances and energy spectra of heavy solar and cosmic ray particles contain a wealth of information about the sun and other particle sources, and about the acceleration and propagation of the particles. At the time of the Apollo 16 experiment the lowest energy range, from a few million electron volts per nuclear mass unit (MeV/nucleon or MeV/amu) to a few kiloelectron volts per nucleon, was largely unexplored. The present cosmic ray experiment was designed to examine this energy range using passive, solid particle track detectors.

At the time of the Apollo 16 flight, April 1972, the solar activity was approaching the 1975 minimum in its 11 year cycle. There was thus the possibility that the experiment would allow resolution of the question of the source of low energy heavy cosmic ray particles during a period when the sun was quiet.

The experiment was designed with this low particle flux in mind. If, on the other hand, a solar particle event occurred during the exposure, the experiment would yield valuable information about the energy spectra and composition of low energy, heavy solar particles. Because a solar flare occurred during the translunar portion of the flight, our low energy results characterize solar flare particles.

This report describes the results obtained in the General Electric experiment; separate reports describe the results of the Washington University and University of California experiments flown in the same experimental package. The report is based primarily upon five appended publications, the Apollo 16 Preliminary Science Report(1), a Physical Review Letter (2), a paper to be published in the forthcoming Proceedings of the 13th International Cosmic Ray Conference (3), a paper soon to appear in Science (4), and an abstract for the Fourth Annual Lunar Science Conference.

The results presented in Figure 1 of this report are based on our most recent data and analyses. Two main points emerge: 1.) The differential energy spectra for solar particles are rapidly varying functions of energy down to very low energies, well into the new energy range made available by the Apollo 16 experiment. Thus, for the iron group cosmic rays (points labeled "Heavy Cosmic Rays"), the differential fluence varies roughly as E^{-3} between 0.05 MeV/nucleon and 30 MeV/nucleon. 2.) At low energies the spectral shape changes. Thus, below 0.05 MeV/nucleon the iron group spectrum flattens. This break, with its characteristic flattening, also occurs for the spectra of other elements, but at energies which depend inversely on atomic number; thus for carbon-and-heavier cosmic rays (labeled "Lexan + UV" in Fig. 1) the break occurs at ~1MeV/nucleon, and for the satellite proton data the break occurs at ~10 MeV/nucleon. This sequence of changes in spectral shape yields the impressive result displayed in Table I; the elemental abundance ratios for solar cosmic rays change as the energies decrease. At higher energies the ratio of iron group to carbon-and-heavier nuclei is essentially equivalent to that of the solar photosphere, 0.04; at lower energies the heavier elements are enhanced relative to the lighter elements.

The data imply that heavy nuclei in solar cosmic rays are appreciably more abundant than in the solar photosphere. As early as 1958 Korchak and Syrovatskii predicted preferential enhancement, at low energies, of heavier nuclei during the acceleration process. This enhancement of heavier nuclei would occur because of their lower effective change-to-mass ratios (5). More recent explanations involve not only the acceleration processes but also possible variations in the composition of the solar atmosphere in the vicinity of solar flares (6).

The heavy cosmic rays above about 70 MeV/amu, where the curve in Figure 1 has again flattened, are galactic, not solar, in origin. These data were obtained from interior Lexan sheets, after UV irradiation, by measuring etching rate as a function of residual range in the manner described by Price and Fleischer (7).

Other galactic cosmic rays, recorded while the experiment was stowed within the command module in its folded or shifted mode (1), allow us to determine the effects of solar modulation and spacecraft shielding on the flux of heavy galactic cosmic rays (4). The results are important to manned space missions because of the lethal damage to biological cells caused by these highly ionizing particles. This experiment, together with earlier experiments using Apollo 8 and 12 helmets (8) and our results (4) from the Apollo 14 electrophoresis experiment (9), yield two conclusions: 1.) Extended space missions (e.g., a two years flight to Mars and back) would be safest during times of peak solar activity, since the solar modulation from an active sun decreases the flux of highly penetrating galactic heavy cosmic rays. (The much higher flux of solar particles is relatively easily shielded because of their lower energies.) 2.) The shielding of galactic cosmic rays due to the mass of the space-craft and its contents could be considerably enhanced by judicious planning of the distribution of the mass.

The analysis of these valuable detectors continues. Mr. R. T. Woods, a doctoral candidate at the State University of New York at Albany, is analyzing the particle tracks in the glasses for his Ph.D. thesis. This work is being done at General Electric under the guidance of R. L. Fleischer. The different glasses, with their differing sensitivities or thresholds, allow the determination of elemental abundances at very low energies. As an illustration of the differences in sensitivity of these glasses, the track densities observed in the GE 1457 phosphate glass, the GE 1484 uranium phosphate glass, and the tektite glass (1), are in the ratio 50: 20: 1 for surface removals of 0.5, 0.3, and 3.7 μm, respectively. For the uranium phosphate glass exposed under the Teflon thermal shield, roughly one in ten of the tracks are multipronged, presumably the result of scattering events in which uranium was the target. The analysis of the interior Lexan sheets will shortly be completed; the elemental abundances of the higher energy cosmic rays have yet to be determined.

Finally, the appropriate reports, publications, and data will shortly be forwarded to the National Space Science Data Center for archiving.

Acknowledgments

We are indebted to W. R. Giard, M. McConnell, and G. E. Nichols for experimental assistance, and to C. Bostrom, W. F. Dietrich, G. Paulekas, J. A. Simpson, and S. Singer for permission to quote their preliminary satellite data.

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TABLE I

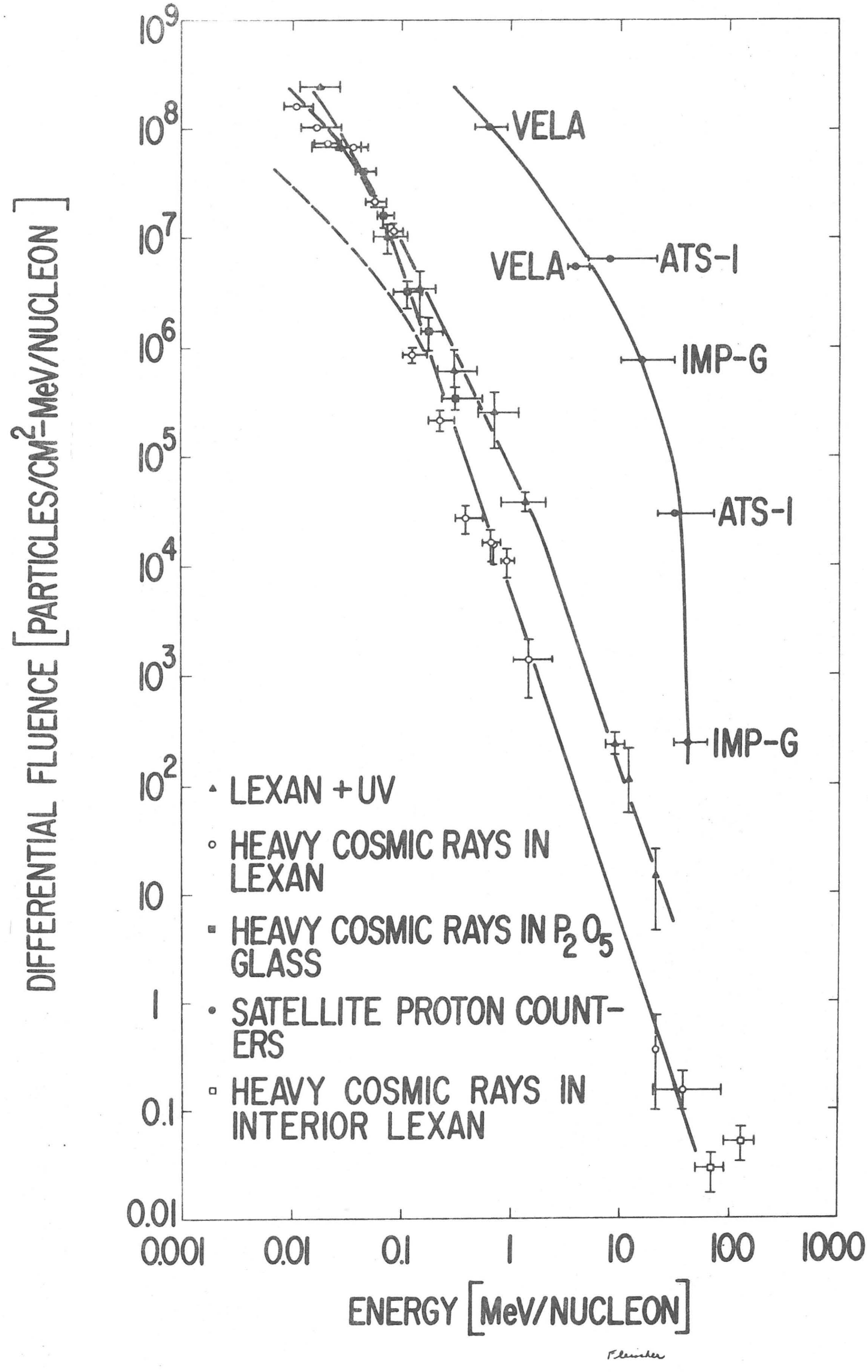
Abundance Ratios

Energy MeV/Nucleon	Iron/(Carbon + Heavier)	Iron/Proton
10	0.04	2.5×10^{-6}
3	0.03	1.5×10^{-5}
1	0.025	0.8×10^{-4}
0.3	0.11	0.8×10^{-3}
0.1	~0.5	-
0.03	~1	-
Photospheric	.04	4×10^{-5}

FIGURE 1.

CAPTION

Differential energy spectra for heavy cosmic rays during the period 16-23 April 1972 compared to the spectrum derived from various satellite proton counters. Fluence is given in particles /cm^2 MeV per nucleon integrated over a 2π solid angle. See reference 1 for a detailed schedule of exposure solid angle. The dashed line represents P_2O_5 glass data reanalyzed assuming a zero range deficit instead of the 0.85 micron range deficit assumed for the square points. The "Interior Lexan" points were obtained using the methods described in reference 7. The proton results are from preliminary data from satellite proton counters operated by C. Bostrom (IMP), G. Paulikas (ATS), and S. Singer (Vela).


DIFFERENTIAL FLUENCE [PARTICLES/CM²-MeV/NUCLEON]
ENERGY [MeV/NUCLEON]
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
10³
10²
10
1
0.1
0.01
0.001
0.01
0.1
1
10
100
1000
VELA
VELA
ATS-I
IMP-G
ATS-I
IMP-G
LEXAN + UV
HEAVY COSMIC RAYS IN LEXAN
HEAVY COSMIC RAYS IN P2O5 GLASS
SATELLITE PROTON COUNTERS
HEAVY COSMIC RAYS IN INTERIOR LEXAN
Fleischer

APPENDIX I

15. Cosmic Ray Experiment

INTRODUCTION

The relative abundances and energy spectra of heavy solar and cosmic ray particles convey much information about the Sun and other galactic particle sources and about the acceleration and propagation of the particles. In particular, the lowest energy range, from a few million electron volts per nuclear mass unit (nucleon) to a kiloelectron volt per nucleon (a solar wind energy), is largely unexplored. The cosmic ray experiment contained a variety of detectors designed to examine this energy range.

It is not known whether, in times of solar quiet, the low-energy nuclei are primarily solar or galactic in origin. One objective of this study was to resolve that question by measuring the chemical composition of the particles. Alternatively, if the Sun were active during the mission, it was expected that the flood of solar particles would provide an abundance of detailed compositional information about the Sun and solar acceleration processes. Because a solar flare occurred during the translunar portion of the flight, the latter objective was served.

The cosmic ray experiment equipment consists of a four-panel array of passive particle track detectors to observe cosmic ray and solar wind nuclei and thermal neutrons, and also includes metal foils to trap light solar wind gases. The materials in the panels were chosen for experiments performed by groups at General Electric (GE), the University of California, and Washington University. Preliminary results of the experiments being performed by the GE group are described in part A of this section; the other experiments are described in parts B and C. The experiment equipment is shown mounted on the descent stage of the lunar module (LM) in figure 15-1(a). During the first extravehicular activity (EVA), the equipment was placed on the minus Y footpad of the LM (fig. 15-1(b)).

The detection basis of nearly all of the experiments is that particles passing through solids can form trails of damage, revealable by preferential chemical attack, which allow the particles to be counted and identified. Much of this work is reviewed in references 15-1 to 15-4. An example of an etched track

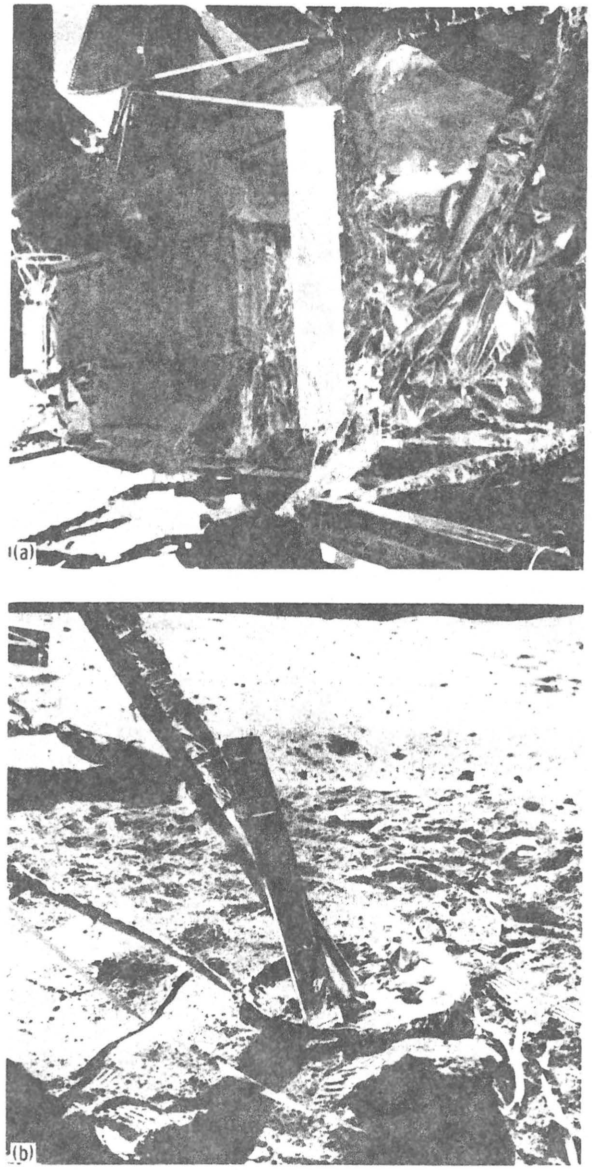


FIGURE 15-1.—The cosmic ray experiment (a) on the descent stage of the lunar module, of Apollo 16, where originally mounted, and (b) on the LM minus Y footpad (on the left footpad, looking down-Sun), where it was placed during EVA 1. Panel 2 and the bottom of panel 3 were used for the GE experiment; panel 1 (the lowermost panel) and panel 4 (the topmost panel) were used for experiments by the University of California and Washington University, respectively. Solar elevation was 35.8°.

that was identified as a zinc ion is shown in figure 15-2 (ref. 15-5).

The detector array was mounted on the LM before launch and was first exposed to space at the time just after translunar injection when the LM was withdrawn from the service module/LM adapter (the panels that, during launch, enclose the LM with aluminum equivalent to 0.3-cm-thick Lexan polycarbonate plastic). Exposure ended just before the termination of the third EVA on the Moon, at which time the four-panel array was pulled out of its frame and folded into a compact 5- by 18.4- by 30-cm package (fig. 15-3) for return to Earth. Because the folding and stowing of the device ended the period of useful exposure of the detectors, provision was made to distinguish particles detected during the useful period from those that subsequently penetrated the spacecraft and entered the detectors.

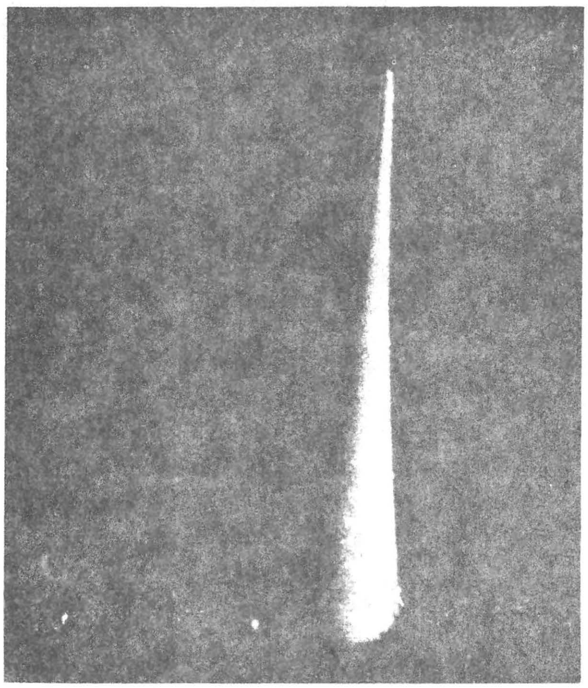


FIGURE 15-2.–Replica of a 0.07-cm etched track in an Apollo space helmet. From the shape, the track can be inferred to have been caused by a zinc ion.

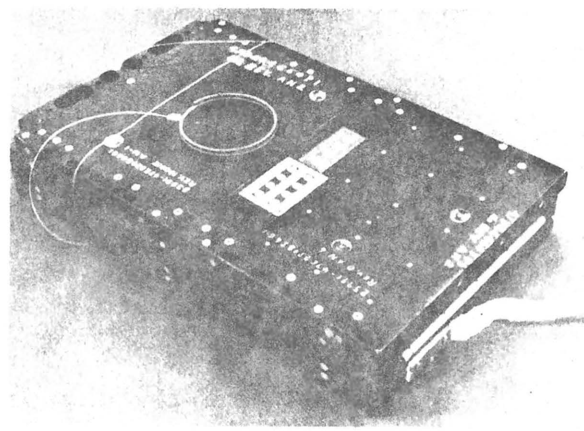


FIGURE 15-3.–Folded detector array. After exposure, the array was folded into the configuration shown to form a convenient package for return to Earth. Temperature labels are visible.

PART A

COMPOSITION AND ENERGY SPECTRA OF SOLAR COSMIC RAY NUCLEI

R. L. Fleischer[a] *and H. R. Hart, Jr.*[a]

The GE experiment consisted of two types of detectors: plastics and glasses located in panel 2 and the lower half of panel 3. In panel 2, the entire exposed detector area of 14.7 by 22.6 cm was composed of 31 sheets of 0.025-cm Lexan polycarbonate plastic 9070-112. In panel 3, 39 sheets of 0.02-cm Eastman Kodacel cellulose triacetate TA-401 with no plasticizer made up the major volume fraction. The lower part of panel 3 contained five types of glass detectors: 2.5- by 1.3- by 0.1-cm GE phosphate-uranium glass 1484 (ref. 15-6), 2.5- by 2.5- by 0.1-cm GE phosphate glass 1457 (ref. 15-7), 2.5- by 2.5- by 0.1-cm Corning alumina-silicate glass 1720, 2.5- by 2.5- by 0.1-cm silicon dioxide (Suprasil 2 silica glass from Amersil, Inc.), and a nearly elliptical tektite slab (Santiago, Philippines, tektite 1, supplied

[a]General Electric Research and Development Center.

by D. Chapman, NASA Ames Research Center) that fit within a 2.5- by 3.8- by 0.1-cm space.

Particles that entered the array after it was folded were recognized, if they crossed from one sheet to another, by means of a 2-mm relative shift of alternate sheets (fig. 15-4). This shift was produced automatically by the folding of the array at the end of EVA 3 just before the array was stowed in the LM. The designed full 2-mm shift occurred in panel 2, and a lesser shift occurred in panel 3.

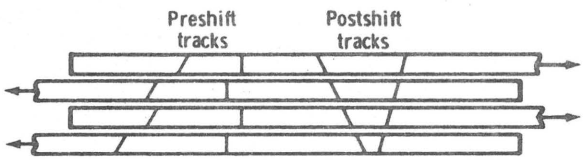


FIGURE 15-4.–Shifting procedure. A 2-mm relative shift of alternate plastic sheets allowed the preshift and postshift tracks to be distinguished. Postshift tracks are interesting only for personnel dosimetry purposes because the tracks represent particles that penetrated the spacecraft before entering the detectors.

Detector temperatures are important because thermal effects can be observed in the plastics and in some of the glasses used in panel 3 after the materials were exposed at temperatures above 328° K. Although tracks are retained to much higher temperatures in all the detectors, the quantitative relation between the ionization rate of the particle and the track etching rate is disturbed. Consequently, for particle identification to be possible, all tracks must have identical thermal histories above 328° K (ideally no exposure above that temperature). To keep temperatures less than 328° K in full sunlight during both translunar flight and the time on the Moon, panels 1, 2, and 3 were covered with a perforated thermal control material, 0.005-cm Teflon backed with thin silver and Inconel coatings (a composite that has a high reflectivity in the visible region of the solar spectrum and a high emissivity at infrared wavelengths). The space-exposed surfaces of the detectors also were coated with a 210-nm aluminum film to avoid ultraviolet (UV) exposure of the plastics, which is known to affect track etching rates (refs. 15-8 and 15-9). Because of the slowing down of cosmic ray nuclei in the silver-backed Teflon, particles of less than 5 to 6 MeV/nucleon are registered in the plastic detectors only through the perforations in the Teflon. There were sixty 0.3-cm-diameter perforations above the Lexan detectors (4.26 cm^2 total area) and 15 above the Kodacel (1.06 cm^2 total). Similarly for the glasses (fig. 15-5), nuclei of less than 10 to 20 MeV/nucleon are registered only beneath the single 0.5-cm-diameter hole that was positioned over the center of each glass plate.

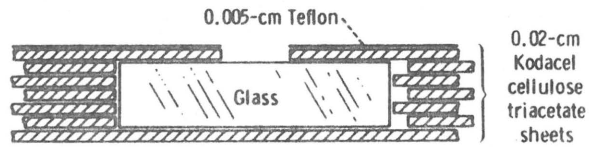


FIGURE 15-5.–Exposure of glass detectors. Glass plates were recessed within the triacetate sheets as sketched. Except for the single 0.5-cm-diameter perforation, the aluminized glass was covered by a 0.005-cm Teflon sheet and a 0.02-cm triacetate sheet. The 0.3-cm-diameter perforations allowed portions of the top Lexan and Kodacel sheets to be directly exposed. The Teflon was backed by a 165 ± 15 nm silver coating covered with an 85 ± 15 nm Inconel layer.

Consequently, for the low-energy nuclei that are of primary interest, the Teflon constitutes a shield, the quantitative effect of which on the observed track density can be calculated. For an isotropic bombardment with φ nuclei/[(area) X (solid angle)], the track density ρ is given by $\int \varphi \cos\theta \, d\Omega$ where θ is the angle of incidence and the integration is over the solid angle Ω permitted by the Teflon shield and the cone angle of the etched tracks. The Teflon is approximated by a straight-edged semi-infinite sheet spaced a distance h from the detector. For this case, the ratio ρ/φ depends only on the track cone angle θ_c and the ratio u of the distance x along the detector under the shield to the spacing h. The result

$$\rho/\varphi = \cos^2\theta_c \cos^{-1}\left(u \tan\theta_c\right) - \left(1 + u^{-2}\right)^{-1/2} \tan^{-1}\left(\left[1 - \left(u \tan\theta_c\right)^2\right]^{1/2} \Big/ \left[\tan\theta_c\left(1 + u^2\right)^{1/2}\right]\right) \qquad (15\text{-}1)$$

is plotted in figure 15-6 for various values of θ_c. The figure illustrates how increasing the cone angle decreases the observable track density and increases the abruptness of the transition from maximum to zero track density near the edge of the shield. These same results are useful for computing effective solid angle of detection for particles of all energies in the case of a thick shield such as the Moon was while the experiment was located close to the lunar surface.

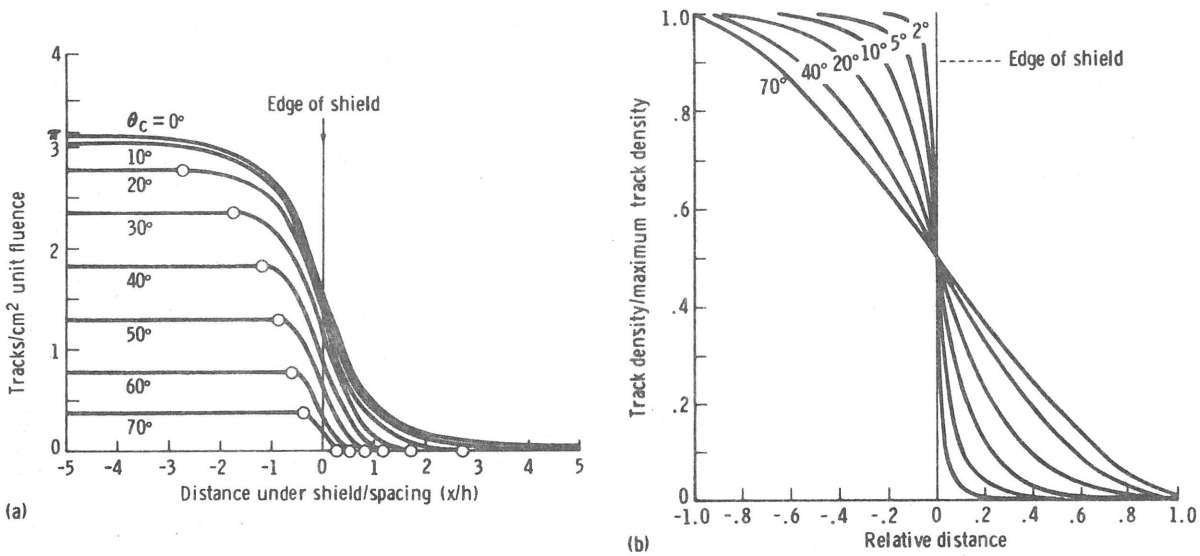


FIGURE 15-6.—Effect of a shield on the etchable tracks per unit fluence as a function of track cone angle. (a) The x is the distance under a parallel, semi-infinite shield a distance h from the detector surface. (b) Normalized data relative to the position where the etched track density goes to zero.

Operation of the Experiment

The experiment was exposed during the mission for nearly 1 week, distributed in time and possible solid angle as listed in table 15-I. The solid angle restrictions listed are merely the shadowing effects of the Moon. The degree of obstruction caused by struts, the scientific equipment bay, and other portions of the spacecraft varies with different positions in the array. For panels 2 and 3, the obstruction is such that the best solid angle factors for $\theta_c < 20°$ are probably those calculated for $\theta_c = 20°$. The LM orientation distribution during lunar orbit prior to landing has been averaged for the appropriate 30.1-hr period. As noted in table 15-I, the last part of the exposure occurred on the LM minus Y footpad with the apparatus leaning against the strut with its face in the down-Sun direction and tilted upward at an angle of 69° to the horizontal, as inferred from a pair of up-Sun and cross-Sun photographs. This shift of the experiment from the LM was a contingency procedure designed to minimize solar heating by exposing to the direct Sun only the multilayer insulation at the back of the experiment.

Although the clean equipment should not have overheated, a deposit of as much as a 10-percent cover of lunar dust or other deposit with similar

TABLE 15-I.—Cosmic Ray Exposure of the Cosmic Ray Experiment

Mission segment	*Time, hr*	*Relative solid angle*	*Tracks per unit flux*		
			$\theta_c = 0°$	$\theta_c = 20°$	$\theta_c = 70°$
En route to Moon	71.4	1.0	3.14	2.76	0.164
In lunar orbit	30.1	0 to [a]1.0	.726	.541	.030
On LM on Moon	20.7	.5	1.57	1.38	.082
On LM footpad (69° to horizontal)	44.9	.64	1.95	1.70	~0
Weighted averages	–	.75	2.19	1.87	.085
Total	167.1	–	–	–	–

[a]Variable with time; 0.5-hr averages used.

optical and infrared properties would have produced excessive heating before the end of EVA 3. Temperature labels designed to sense the approach to the permitted upper limit were located on the outboard face of the frame. Near the end of EVA 1, all these labels were observed by the commander to have been affected, signaling that the polycarbonate temperature had exceeded 318° K; therefore, the contingency procedure was followed at that time. After retrieval, temperature labels within the plastic stacks indicated temperatures of 339° ± 6° K within panel 3 and a part of panel 2, and 350° ± 6° K in another part of panel 2. The temperatures observed in panels 1 to 3 correlate with the dust (or contamination) found on the retrieved panels, the highest temperature (>355° K) occurring in panel 1 and the lowest (<344° K) in panel 3. It is presently not known whether the "dust" cover occurred from rocket exhaust at the time of LM withdrawal from the service module/LM adapter or from ricocheting lunar dust at the time of lunar landing. This is a matter of some consequence because, in the latter case, tracks formed before landing will have had a common thermal history above 328° K.

Solar Flare

During the translunar part of the mission, a medium-size solar flare occurred that contained $\approx 10^8$ protons/cm^2 of energies greater than 5 MeV. Preliminary data, for the flux in various energy intervals, from several satellites are shown in figure 15-7. (The data are from the following satellites: Applied Technology Satellite (ATS), Interplanetary Monitoring Platform (IMP), Pioneer, and Vela.) No extra particles were observed beyond the general steady background at energies greater than 60 MeV. Most of the flare particles arrived before lunar landing; only a few percent greater than 5 MeV arrived after landing, and, even for the slowest particles for which data are available (0.46 to 0.90 MeV), less than 10 percent arrived after landing. If the dust were deposited on the experiment during landing, virtually all the flare tracks recorded will have had the same subsequent thermal history. Even if this were not the case, the highest temperatures to which the detectors were exposed were experienced during the 20.7 hr when the experiment was facing the Sun while on the lunar surface. As a result, most of the thermal effects on solar flare tracks were concentrated in that period and were common to virtually all of the solar particles.

Procedure

Etching and read-out have been performed on Lexan sheets from panel 2 and on glass 1457 from panel 3. For glasses, the final steps in the preflight preparation were annealing (for the tektite and glass 1484, removing preexisting tracks), polishing, etching, inspecting, and coating with an evaporated aluminum reflective coating approximately 210 nm thick. The 210-nm aluminum coating was also present on the top Lexan and Kodacel sheets. After the flight, before the panels were disassembled, the outlines of the 0.5-cm-diameter openings above the glasses and the 0.3-cm-diameter holes above the plastics were scribed into the detector surfaces.

The track etching rates of the detectors can be altered by thermal annealing, the glasses to a lesser extent than the plastics. In figure 15-8, the changes in the track etching rates caused by 1-hr anneals are shown for several glasses. In figure 15-8, V_T is the average track etching rate for californium-252 fission fragments, and V_G is the general etching rate for unirradiated regions. The extreme cases, GE phosphate glass 1457 and Corning glass 1720, are two of the glasses flown on this experiment.

After the panels were disassembled, the glass samples were carefully sectioned by sawing from the underside through most of the thickness and then fracturing the remaining near-upper-surface thickness to avoid the loss of valuable surface material.

One portion of each glass was then etched in room-temperature sodium hydroxide for 1 to 2 min to remove the aluminum coating. The same part was then etched in 50 percent hydrofluoric acid to remove approximately 0.5 μm of glass from each surface to reveal cosmic ray tracks. The etched glasses were scanned at 1000X in an optical microscope, then were replicated (cellulose acetate, gold coated), and scanned at 5000X in a scanning electron microscope (SEM). Parts of the top sheet of Lexan, after removal of the aluminum by a 296° K sodium hydroxide solution, were etched for 3 or 6 hr in 313° K 6.25N sodium hydroxide solution saturated with etch products (ref. 15-10). In one case, a preirradiation with UV was used to accelerate etching attack

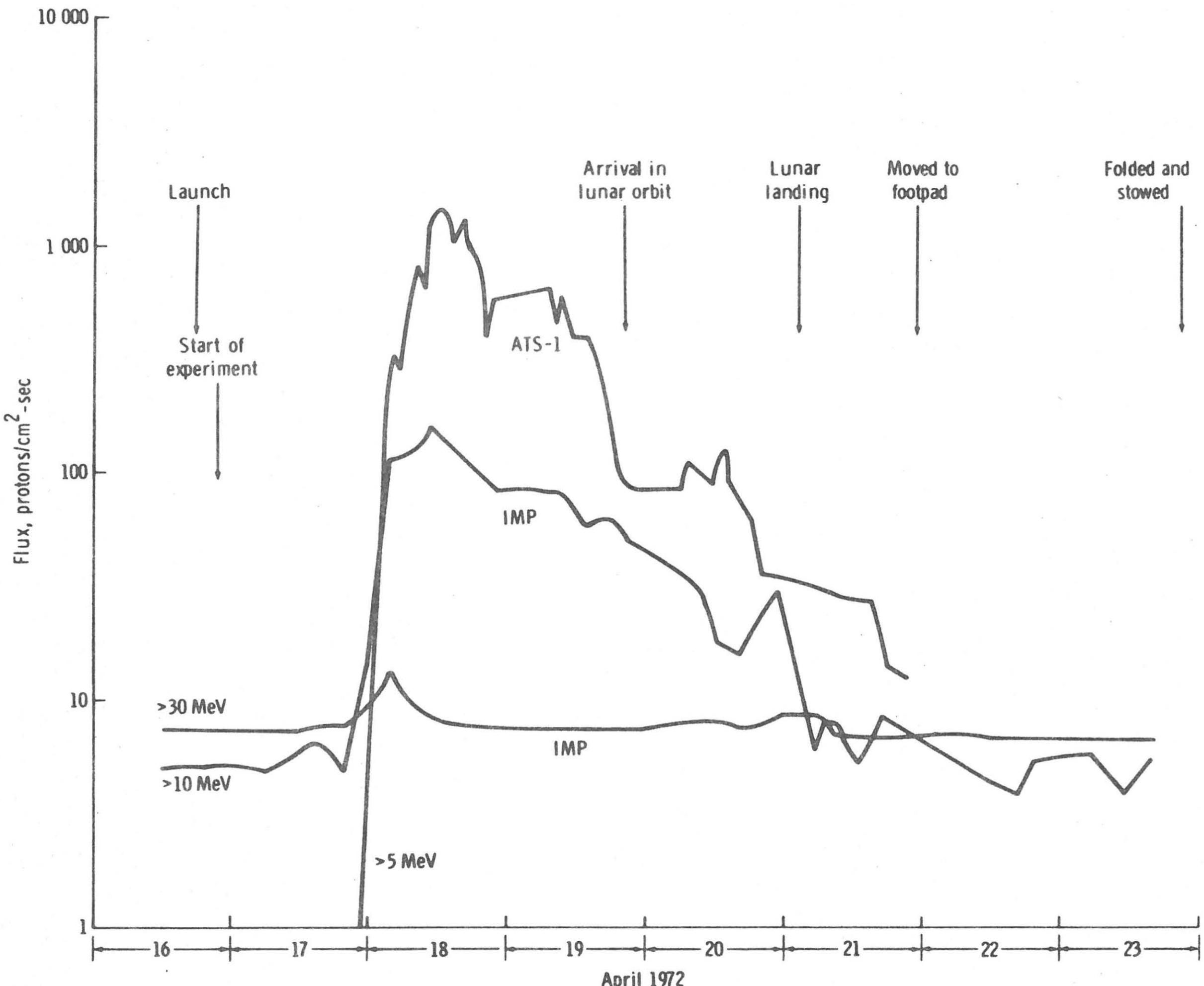


FIGURE 15-7.–Proton flux observed by various satellites during the first week of the Apollo 16 mission. The relevant operations affecting the cosmic ray experiment are noted at the top of each part of the figure. In all cases, the data are preliminary and subject to change. Data courtesy of C. Bostrom (IMP), G. Paulikas (ATS), and S. Singer (Vela). (a) Flux >5, >10, and >30 MeV.

along the tracks (refs. 15-8 and 15-9). Results are given in this subsection for a 6-hr etch of a sheet from the lower left part of panel 2 (hole 2) and a 6-hr etch of a UV-treated sheet from the upper right corner of panel 2 (hole 59). These parts are thought to correspond to the warmest and coolest parts of panel 2, respectively, as judged from the distribution of dust cover and temperature label readings. Sheets 2 to 11 below hole 2 were etched 40 hr under the etching conditions described previously. Solar flare tracks on the exposed surfaces of the phosphate glass and Lexan are shown in figure 15-9. From the optical scans in the central open regions of the different detectors, the track length distributions given in table 15-II were obtained. The differential energy spectrum is derived from these track lengths using range-energy relations (ref. 15-11) for iron nuclei, allowing for the thicknesses of the aluminum layer and the layer etched away and assuming that the aluminum is crossed at 45° incidence.

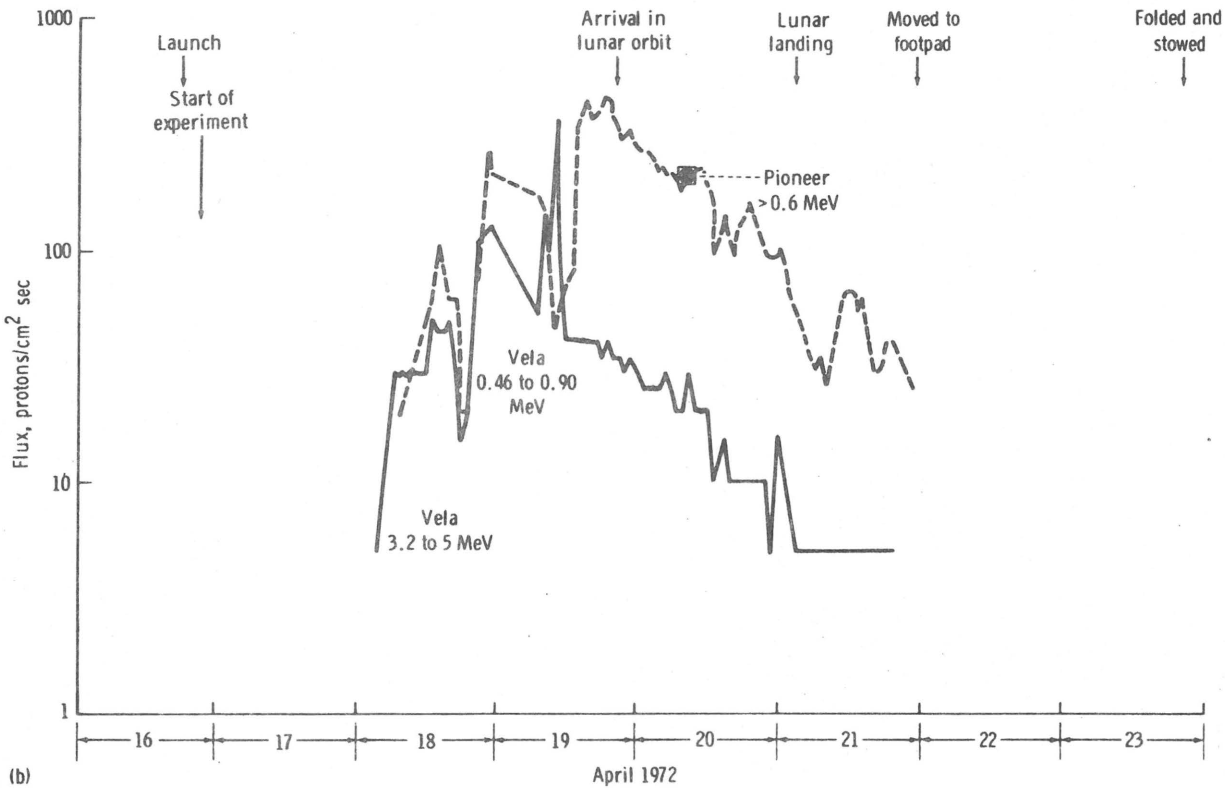


FIGURE 15-7.–Concluded. (b) Flux in the intervals 0.46 to 0.90 MeV and 3.2 to 5.0 MeV.

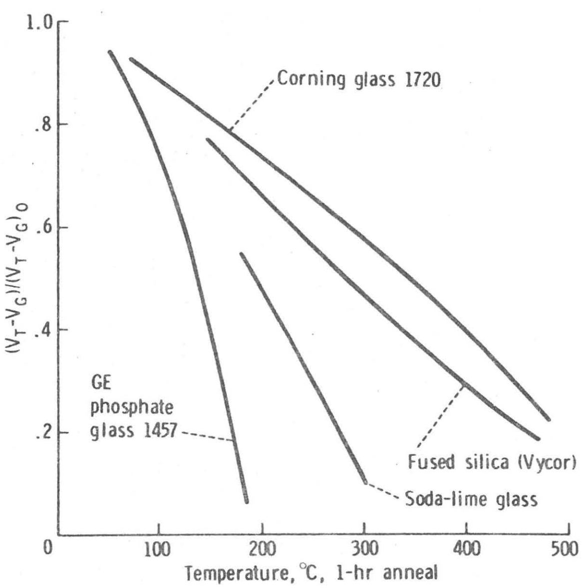


FIGURE 15-8.–Annealing of the track etching rate for californium-252 fission fragments in several glasses. The V_T is the average track etching rate, and V_G is the general etching rate for an unirradiated region. The reference V_T is that obtained after a long time at room temperature.

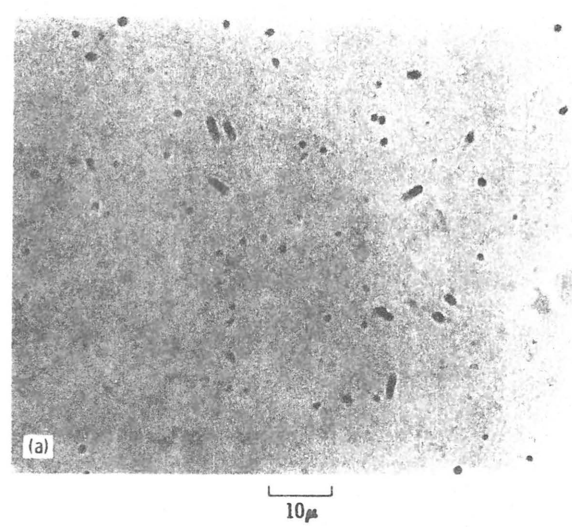


FIGURE 15-9.–Heavy solar cosmic ray tracks in plastic and glass detectors. The surface removal is 5 × 10^{-5} cm for the glass and 10^{-4} cm for the plastic. (a) Glass 1457 viewed optically.

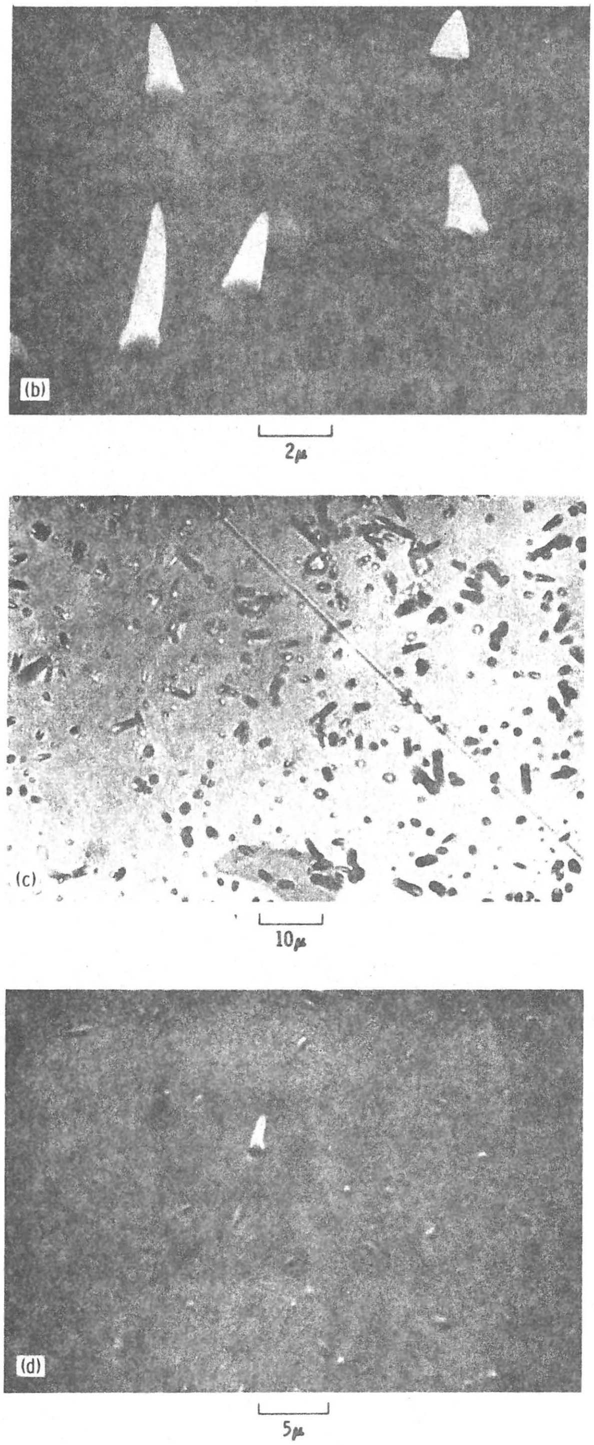


FIGURE 15-9.–Concluded. (b) Glass 1457 viewed in a scanning electron microscope. The SEM replica is cellulose acetate. (c) Lexan polycarbonate hole 4 viewed optically. (d) Lexan polycarbonate viewed in a scanning electron microscope. The SEM replica is silicone rubber.

TABLE 15-II.–Track Length Distributions at Detector Surfaces

(a) Track length

Length, cm	*Number*	*Tracks/cm²*
Phosphate glass 1457		
(0 to 0.5) × 10^{-4}	82	0.92 × 10^6
(.5 to 1.0)	26	.29
(1 to 2)	19	.21
(2 to 3)	10	.11
(3 to 6)	10	.11
Lexan (hole 2, 6-hr etch)		
(0.1 to 0.5) × 10^{-4}	108	1.1 × 10^6
(.3 to 1)	127	1.3
(.5 to 1)	65	.65
(1 to 2)	~50	1.5
(2 to 3)	51	.52
(3 to 4)	34	.35
(4 to 6)	25	.064
(6 to 8)	20	.034
(8 to 11)	9	.0066
(11 to 14)	9	.0042
(14 to 17)	6	.0028
(17 to 30)	3	.0014
Lexan (hole 59, UV + 6-hr etch)		
(0.5 to 1.5) × 10^{-4}	22	1.34 × 10^6
(.5 to 2.0)	79	2.07
(1.5 to 2.5)	8	.49
(2.4 to 4.5)	10	.61
(4.5 to 6.5)	5	.31
(6.5 to 10.5)	3	.18
(10.5 to 18.5)	3	.18

(b) Track density at exterior surface

Phosphate glass 1457	1.8 (±0.1)
Lexan (hole 2, 6-hr etch)	6.10 (±0.35) optical
Lexan (hole 59, UV + 6-hr etch) . .	7.5 (±0.3)

The justification for assuming that all particles are iron in computing the energies derives from the plot given in figure 15-10. For GE phosphate glass 1457, neon ions give tracks having an average cone angle of 30° to 35° over a distance of approximately 15 μm. The SEM photographs of cosmic ray tracks give the cone angle distribution for the >1-μm tracks shown in figure 15-10. This cone angle distribution indicates that the tracks are predominantly from particles much heavier than neon. Separate experiments by the

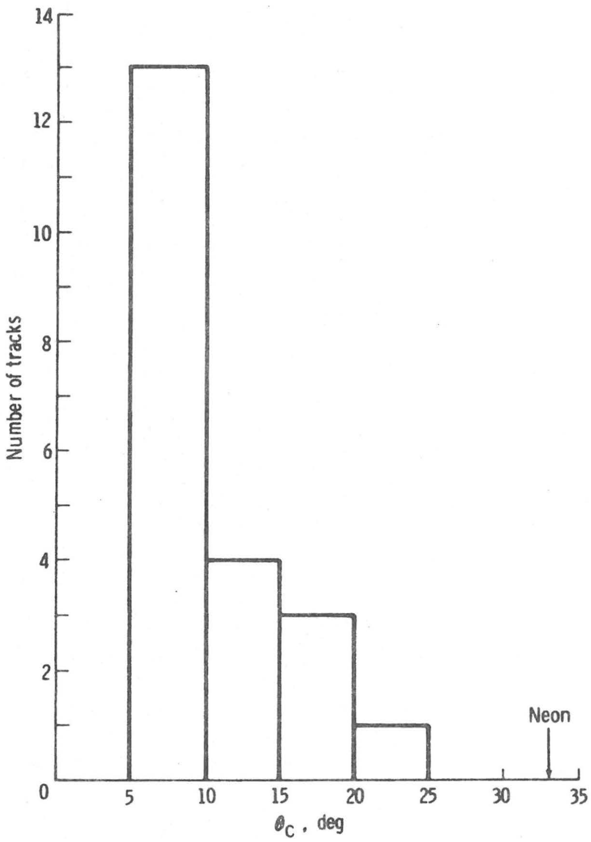


FIGURE 15-10.–Distribution of projected cone angles measured for solar flare tracks in phosphate glass 1457. The angles are obtained from SEM photographs of a cellulose acetate replica after a 12-min etch of the glass in 50 percent hydrofluoric acid.

authors with M. Saltmarsh and A. E. van der Woude of argon-40 and iron-56 beams indicate that the tracks were made by ions heavier than argon and close to iron in atomic number. From known solar abundances (ref. 15-12), it is expected that iron is dominant and that most of the nuclei observed have range-energy relations that are adequately approximated by that of iron. The justification in using iron for the 6-hr etch of hole 2 is that the results there agree with the phosphate glass. For hole 59 (UV treatment before a 6-hr etch), this assumption will be shown to be useful but quantitatively wrong.

Particles stopping at greater depths than were observed at the exposed Lexan surface could be counted on the same surface but beneath the silver-backed Teflon, at the back of the top sheet, and in sheets 2 to 11. These data lead to spectral information at ≈10 MeV/nucleon and above.

One interesting anomaly was the observation beneath the silver-backed Teflon of a high density (≈3000 tracks/cm^2 in the non-UV-irradiated Lexan and ≈10 000 tracks/cm^2 in the UV-irradiated Lexan) of short tracks ranging to ≈10^{-3} cm long with rapidly decreasing numbers of tracks with increasing length. Such tracks were fewer at the opposite side of the Lexan sheet (depth 0.035 to 0.050 cm rather than 0.010 to 0.014 cm). The falloff with depth is too rapid to be consistent with direct effects in the plastic of the appreciable proton irradiation from trapped particles encountered while leaving the vicinity of the Earth. A proton flux of ≈3 X 10^9 protons/cm^2, >3 MeV, and ≈8 X 10^6 protons/cm^2, >30 MeV, is inferred from reference 15-13, extrapolating to greater distances from the Earth on the basis of reference 15-14. The most likely source of the short tracks is the aluminum-Inconel-silver-Teflon composite adjacent to the surface where these short tracks were found. Whether these are reaction products, compound nuclei, or recoil nuclei has not been determined. The cosmic ray flux at 0.010- to 0.014-cm depth was inferred from the abundance of tracks >15 X 10^{-4}-cm length, which appear to form a distinctly separate population.

Energy Spectra

The energy spectra inferred for heavy particles and that derived for protons from the satellite data in figure 15-7 are shown in figure 15-11. The non-UV-irradiated Lexan gives results that are indistinguishable from those of the phosphate glass. Because those tracks have been identified as from iron nuclei or those close to iron in atomic number, the composite curve (the lowest of the three in figure 15-11) applies to the iron group nuclei.

The curve for the UV-irradiated Lexan lies generally above that for the non-UV-irradiated samples; examination of additional samples has shown that this difference is primarily caused by the effect of the UV in lowering the effective threshold for particle track registration (ref. 15-9). The approximate 10-to-1 ratio of differential fluence in the 20- to 60-MeV/nucleon range would be consistent with nuclei down to carbon-12 being revealed in the Lexan, as judged by neon-20 calibration tracks and as is consistent with the solar flare composition observed by Mogro-Campero and Simpson (ref. 15-15). Recalculation of the energy spectrum to include the carbon-nitrogen-oxygen (CNO) group for the UV-

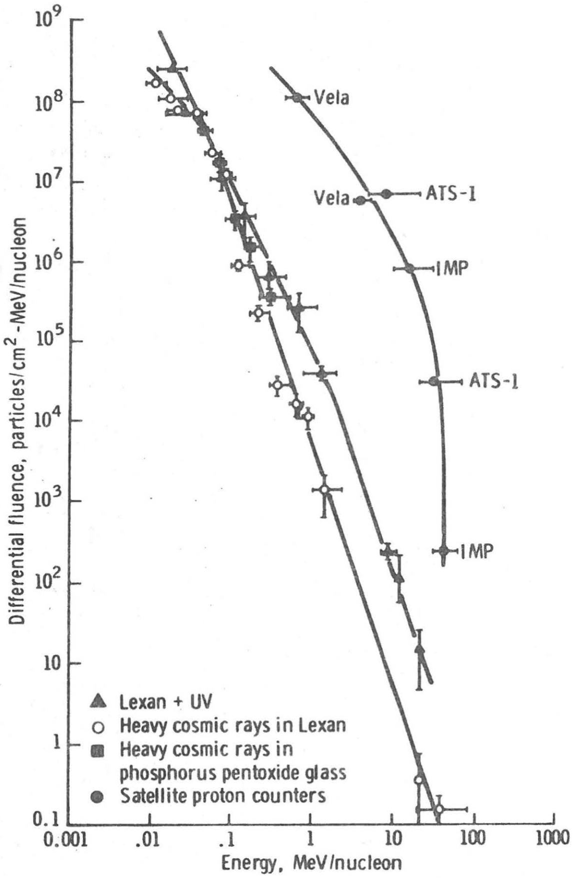


FIGURE 15-11.—Differential energy spectra for heavy cosmic rays during the period April 16 to 23, 1972, compared to the spectrum derived from various satellite proton counters. Fluence is given in protons/cm^2-MeV/nucleon integrated over a 2π solid angle. Proton data are derived from those given in figure 15-7.

irradiated sample would steepen the curve slightly but would not alter its qualitative character significantly.

Discussion

The spectrum for iron group cosmic ray is given by an energy$^{-\gamma}$ $E^{-\gamma}$ relation, where the spectral index γ is 3 (±0.3) from 30 MeV/nucleon down to 0.04 MeV/nucleon and flattens to γ = 1 (±0.5) from 0.04 to 0.01 MeV/nucleon. The γ = 3 result is identical to a previous conclusion (ref. 15-16) in the energy range 1 to 100 MeV/nucleon from examination of Surveyor III filter glass and with that of Mogro-Campero and Simpson from their counter telescope in the range 3 to 60 MeV/nucleon (ref. 15-15). The result is also similar to the results of two other studies of the Surveyor glass (refs. 15-17 and 15-18) although the spectrum was not expressed as E^{-3} in those papers.

The proton-to-iron ratios listed in table 15-III were derived from this result. With decreasing energy, the ratio decreases from 15 times the photospheric value at 10 MeV/nucleon to 0.05 times that value at 0.3 MeV/nucleon (ref. 15-19). Although proton data are lacking at the lower energy, the trends in the curves in figure 15-11 suggest that this enrichment in the heavy nuclei continues at least another order of magnitude in energy down to the break in the slope of the iron group curve. The existence of increasing enhancement of iron towards lower energies is in agreement with previous results by Price et al. (ref. 15-18) and Mogro-Campero and Simpson (ref. 15-15) but is quantitatively less at the same energies. The present results, however, extend to much lower energies.

TABLE 15-III.—Ratios[a] of Proton Flux to Iron Flux

Energy, MeV/nucleon	*Proton flux/iron flux*
10	4×10^5
3	6.5×10^4
1	1.2×10^4
.3	1.2×10^3

[a]Abundance ratio in photosphere = 2.5×10^4.

If the UV-irradiated data are recalculated on the assumption that oxygen-16 is the most abundant species present (approximating CNO plus all heavies by using oxygen range-energy curves), ⩾ carbon/⩾ iron ratios can be estimated: 25 (10 MeV/nucleon), 35 (3 MeV/nucleon), 40 (1 MeV/nucleon), 9 (0.3 MeV/nucleon), approximately 2 (0.1 MeV/nucleon), and approximately 1 (0.03 MeV/nucleon). A strong relative enrichment of iron relative to the lighter nuclei is apparent at low energies. These ratios are to be compared with values of 8 found by Mogro-Campero and Simpson (ref. 15-15) near 20 MeV/nucleon and 84 found by Bertsch et al. (ref. 15-20) near 60 MeV/nucleon, both these results being averages for groups of flares. The trend of relative enrichment of iron towards lower energies is again clear.

The relative heavy element enrichment at low energies is associated with the position of the decrease in the magnitude of slope of the energy spectra, which occurs at progressively higher energies from iron ($\approx$0.04 MeV/nucleon) to "$\geqslant$ carbon" ($\approx$1 MeV/nucleon) to hydrogen ($\approx$10 MeV).

Total iron down to $\approx$0.01 MeV/nucleon is $\approx 4 \times 10^6$ particles/cm^2 per 2π solid angle as compared to $\approx 2.2 \times 10^8$ protons/cm^2 (as derived from fig. 15-11); these numbers give an enrichment by a factor $\approx$450 relative to the photospheric value. However, because the proton fluence below 0.3 MeV is unknown, the quantitative meaning of this value is not clear. It does, however, strongly suggest that the heavies in the solar flares are in fact appreciably more abundant than in the surface of the Sun. The preferential enhancement at low energies of the heavier nuclei because of their low charge-to-mass ratio was predicted in 1958 by Korchak and Syrovatskii (ref. 15-21).

Summary

Solid-state track detectors were exposed to the solar flare of April 18, 1972, during the Apollo 16 mission and etched to reveal tracks of cosmic ray nuclei. Iron group nuclei were observed in phosphate glass and desensitized Lexan polycarbonate detectors, and their spectrum was measured down to $\approx$0.02 MeV/nucleon, nearly two orders of magnitude lower in energy than had previously been observed in such nuclei. The relative enrichment of iron relative to lighter nuclei previously seen at higher energies continues to increase into the new low-energy region. The energy spectrum of particles equal to or greater than carbon is inferred from sensitized Lexan polycarbonate and allows the relative enrichment of iron relative to the medium and heavy nuclei to be estimated down to 0.03 MeV/nucleon.

Acknowledgments

The authors are indebted to C. Bostrum (Johns Hopkins U.), G. Paulikas (Aerospace Corp.), and S. Singer (Los Alamos) for permission to quote their satellite proton results; to W. R. Giard, M. McConnell, and G. E. Nichols (General Electric Research and Development Center) for experimental assistance; and to M. Saltmarsh and A. van der Woude (Oak Ridge National Laboratory) for permission to quote joint work prior to publication.

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APPENDIX II

Enrichment of Heavy Nuclei in the 17 April 1972 Solar Flare*

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(Received 31 July 1972)

Polycarbonate and glass detectors exposed on Apollo 16 to the 17 April 1972 solar flare were used to measure the spectrum of iron-group cosmic-ray nuclei down to ~ 0.02 MeV/nucleon. The enrichment of iron relative to lighter nuclei previously seen at higher energies increases markedly in this new, very-low-energy region. The energy spectrum of carbon and heavier nuclei inferred from sensitized Lexan polycarbonate reveals the enrichment of iron relative to carbon and heavier nuclei down to ~ 0.03 MeV/nucleon.

The relative abundances and energy spectra of heavy solar and cosmic-ray particles contain a wealth of information about the sun and other galactic particle sources, and about the acceleration and propagation of the particles. In particular, the lowest-energy range from a few million electron volts per nuclear mass unit (MeV/nucleon) down to a keV/nucleon (a solar wind energy) has been largely unexplored. On Apollo 16 there were three cosmic-ray experiments which contained track detectors designed to examine this energy range.[1] We report here energy spectra and relative abundances for heavy solar cosmic rays from the flare of 17 April 1972.

A four-panel detector array was mounted on the lunar module at launch and first exposed to space just after translunar injection when the lunar module was withdrawn from the adapter panels which enclosed it during launch. Exposure ended just before the termination of the third extravehicular activity on the moon, at which time the array was pulled out of its frame and folded into a compact package for return to Earth. The portion of the experiment considered here consisted of two types of detectors: In panel 2 the entire exposed detector area of 14.7 by 22.6 cm was composed of sheets of 0.010-in. Lexan polycarbonate type 9070-112 plastic; panel 3 included a 1-in. $\times$ 1-in. $\times$ 1-mm plate of General Electric phosphate glass 1457.[2] Portions of each of these detectors were exposed to space protected only by 2100-Å evaporated aluminum films. Other portions were covered by 0.002-in. silver- and Inconel-backed Teflon thermal control material.

Particle tracks in solids are affected by elevated temperature[3] and, in particular, both the polycarbonate films and the glass plate used in this experiment are affected by temperatures above 55°C. Since the temperature labels present in the experiment showed temperatures ~ 70°C, some desensitization did occur through track annealing. Consequently, it was found helpful in some cases to use uv irradiation of the polycarbonate to enhance sensitivity.[4,5] We refer to the as-received and uv-irradiated samples as *densensitized* and *sensitized,* respectively.

Satellite measurements by C. Bostrum, G. Paulikas, and S. Singer (unpublished) showed that late on 17 April during the translunar portion of the mission, a medium-sized solar flare occurred that contained ~ 10^8 protons/cm^2 of energies > 5 MeV, but included no extra particles beyond the general steady background above 60 MeV. It will be noted that the major portion of the flare particles arrived prior to lunar landing; at > 5 MeV only a few percent arrived after landing, and even for the slowest particles for which data are available (0.46–0.90 MeV) less than 10% arrived after that time. Since the period of most intense heating of the experiment occurred 20 h after landing, the significant heat effects for all of the solar tracks were identical. For the uppermost detector sheets, which we consider here, the flood of solar-flare particles gives an abundance that is many times the expected galactic fluence. Consequently, the results we report here are essentially solely for the 17 April flare.

Samples were treated in room-temperature NaOH for 1 to 2 min to remove the aluminum coating. The glass was then etched in HF in order to remove roughly $\frac{1}{2}$ μm of glass from each surface and reveal cosmic-ray tracks. The etched glass was scanned at 1000× in an optical microscope, then replicated (cellulose acetate, gold coated) and scanned at 5000× in a scanning electron microscope. Portions of the top sheet of Lexan polycarbonate, after removal of the aluminum, were etched for 6 h in 40°C 6.25 *N* NaOH solution saturated with etch products.[6] The preirradiation with uv used conditions described earlier.[4] Results are given here for a sheet from the lower-left portion of panel 2 and a uv-treated sheet from the upper-right corner of panel 2. Examination of duplicate samples has shown that the presence or absence of the uv treatment is the significant difference between these two samples. From optical scans of the different detectors we obtained the track-length distributions given in Ref. 1. From these track lengths the differential energy spectrum is derived using range-energy relations[7] for iron nuclei, allowing for the thicknesses of the aluminum layer and the layer etched away, and assuming for simplicity that the aluminum is crossed at 45° incidence.

The justification for assuming that all particles are iron in computing the energies derives from comparing the observed cone angles in the glass with those from accelerator irradiations with ^{20}Ne, ^{40}Ar, and ^{56}Fe. For the range 0 to 2 MeV/nucleon, in General Electric 1457 phosphate glass, neon ions give tracks having an average cone angle of 30–35° and argon ions give a value of ~10°.[8] The scanning electron-microscope photographs of cosmic-ray tracks give a cone-angle distribution for >1-μm tracks that are mostly below 10°, with decreasing abundance at larger angles. This cone-angle distribution indicates that the tracks are predominantly from particles appreciably heavier than neon. From known solar abundances[9] we expect iron to be dominant and that most of the nuclei observed have range-energy relations that are adequately approximated by that of iron. The justification in using iron for the desensitized Lexan is that the results there agree with the phosphate glass. For the sensitized Lexan the ^{20}Ne calibrations reveal that nuclei down through ^{12}C should be readily detectible. This result is in contrast to that in the desensitized Lexan, where Ne is undetectible for the etching time that was used. Particles at depths greater than were observed at the exposed Lexan surface could be counted on the same surface but beneath the silver-backed Teflon, and also at the back of the top sheet.

One interesting anomaly was the observation, just beneath the silver-backed Teflon, of a high density (~3000/cm^2 in the desensitized and ~10 000/cm^2 in the sensitized Lexan) of short tracks ranging up to ~10^{-3} cm long with rapidly decreasing numbers toward greater lengths. Since we infer that these short tracks are reaction products, as yet unidentified, from the metallic coating, we ignore them in deriving the cosmic-ray flux at 12- to 17-mg/cm^2 depth. This cosmic-ray flux was inferred from the abundance of tracks of length >15×10^{-4} cm, which appear to form a distinctly separate population.

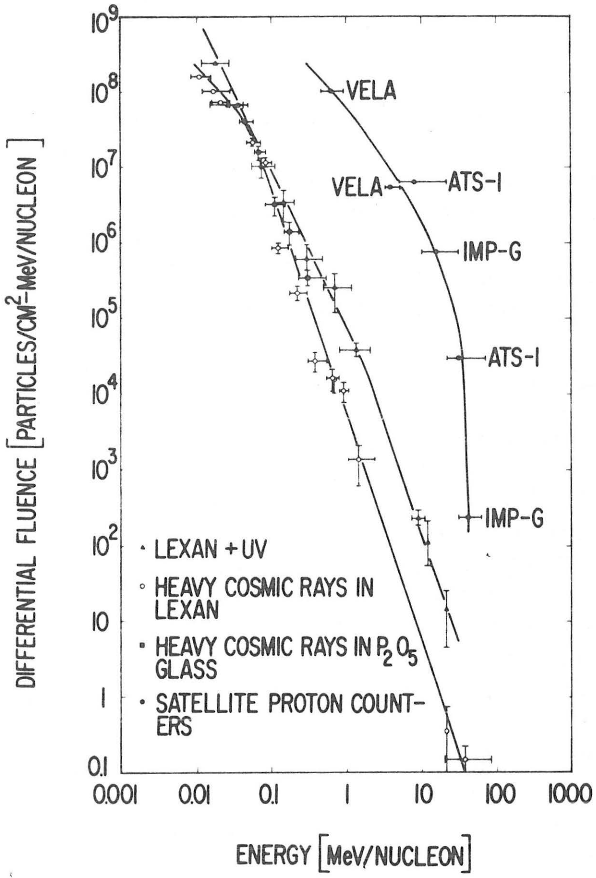

FIG. 1. Differential energy spectra for heavy cosmic rays during the period 16–23 April 1972 compared to the spectrum derived from various satellite proton counters. Fluence is given in particles/cm^2 MeV per nucleon integrated over a 2π solid angle. The "Lexan + uv" is referred to as "sensitized" Lexan in the text. The proton results are from preliminary data from satellite proton counters operated by C. Bostrom (IMP), G. Paulikas (ATS), and S. Singer (Vela).

Figure 1 gives the energy spectra inferred for heavy particles and that derived for protons from preliminary satellite data from several groups. As is obvious in Fig. 1, the desensitized Lexan gives results that are indistinguishable from those of the phosphate glass; since we have identified those tracks as being from iron nuclei or nuclei close to iron in atomic number, the composite curve (the lowest of the three in Fig. 1) applies to the iron-group nuclei.

The curve for the sensitized Lexan, which we noted records carbon and heavier nuclei, lies generally above that for the non-uv-irradiated Lexan because of the effect of uv radiation in lowering the effective threshold for particle track registration.[5] Recalculation of the energy spectrum using the range-energy relations of the CNO group for the sensitized Lexan would steepen the curve very slightly, but would not alter its qualitative character significantly. In using these curves to derive ratios of CNO and greater to the iron group, we recalculated the higher of our two spectra using the ^{16}O range energy curve as an approximation of the range energy curves of CNO plus all heavy nuclei.

The spectrum for iron-group cosmic rays in Fig. 1 is given by a relation $(\text{energy})^{-\gamma}$, where the spectral index γ is 3 (± 0.3) from 30 MeV/nucleon down to 0.04 MeV/nucleon and flattens to $\gamma = 1$ (± 0.5) from 0.04 to 0.01 MeV/nucleon. The $\gamma = 3$ result is identical to our previous conclusion[10] in the energy range 1 to 100 MeV/nucleon from examination of Surveyor-III filter glass and with that of Mogro-Campero and Simpson from their counter telescope in the range 3–60 MeV/nucleon[11]; it is also roughly consistent with the results of two other studies of the Surveyor glass,[12,13] although the spectrum was not expressed as E^{-3} in those papers.

From the spectra just given a striking result can be inferred, namely, the sequence of ratios of iron nuclei to carbon and heavier nuclei listed in Table I. With decreasing energy the ratio increases from roughly $\frac{2}{3}$ of the photospheric value of 0.04 in the range 1–10 MeV per nucleon to ~25 times that value of 0.03 MeV/nucleon. The statistics allow a factor-of-2 error in the cosmic-ray ratios. The values are to be compared with ratios of iron-group nuclei to carbon and heavier nuclei of 0.08 and 0.13 above 10 MeV/nucleon by Teegarden, van Rosenvinge, and McDonald[14] for two flares, of 0.3 found by Mogro-Campero and Simpson[11] near 20 MeV/nucleon (average of several flares with spectral index 3), and of 0.015 to 0.03 above 20 MeV/nucleon by Bertsch *et al.*[15,16]

TABLE I. Abundance ratio of iron group to carbon and heavier nuclei.

Energy MeV/nucleon	Relative abundance
10	0.04
3	0.03
1	0.025
0.3	0.11
0.1	~0.5
0.03	~1

near 60 MeV/nucleon averaged for several flares. None of these results included the 17 April event. There appears to be a rough trend of relative enrichment of iron towards lower energies in this higher-energy region also.

The relative heavy-element enrichment at low energies is associated with the change of slope of the energy spectra, which occurs at progressively higher energies in Fig. 1 as one goes from iron (~0.04 MeV/nucleon) to carbon and heavier nuclei (~1 MeV/nucleon) to hydrogen (~10 MeV). The observed increasing enhancement of iron towards lower energies is in agreement with previous results by Price *et al.*[13] and Mogro-Campero and Simpson,[11] but is quantitatively less at the same energies. The present results, however, extend to much lower energies.

α-particle spectra are not available through enough of the energy region of interest to give iron-to-α ratios. Dietrich and Simpson (personal communication) obtain an $E^{-5.5\,(\pm 1.3)}$ spectrum in the region 8.5 to ~15 MeV/nucleon where we have E^{-3}. If taken literally, these results too imply an ascending Fe/He ratio with decreasing energy. However the spectral index 5.5 is subject to a slight downward correction because the counting procedure used gave diminished weight to the early portion of the flare, when the proton spectral index was lower (4.5 as compared to 5.5 later). Consequently, any inference on Fe/He should await more complete data. Although proton data are lacking at the lower energies, proton-to-iron ratios can be quoted. They range downward from 4×10^5 at 10 MeV/nucleon (15 times the photospheric value[17]) to 6.5×10^4, 1.2×10^4, and 1.2×10^3 at 3, 1, and 0.3 MeV/nucleon. Similar variations in proton-to-α ratios have often been observed.[18]

The integrated fluence of iron down to ~0.01 MeV/nucleon is $\sim 4\times10^6$ particles/cm^2 per 2π solid angle as compared to $\sim 2.2\times10^8$ protons/cm^2 down to 0.3 MeV; these numbers could give an enrichment of at most a factor of 450 relative to the photospheric value. Since the proton fluence below 0.3 MeV is unknown, the quantitative meaning of this value is by no means clear. It does, however, strongly suggest that the heavy nuclei in the solar flare are in fact appreciably more abundant than in the surface of the sun. The preferential enhancement at low energies of the heavier nuclei because of their low charge-to-mass ratio was predicted in 1958 by Korchak and Syrovatskii.[9]

We are indebted to C. Bostrum, W. F. Dietrich,

G. Paulikas, J. A. Simpson, and S. Singer for permission to quote their preliminary satellite proton and α results, to W. R. Giard, M. McConnell, and G. E. Nichols for experimental assistance, and to M. Saltmarsh and A. van der Woude for permission to quote joint work prior to publication.

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[1]More detailed descriptions of the experiments are given by R. L. Fleischer and H. R. Hart, Jr., in National Aeronautics and Space Administration Apollo-16 Preliminary Science Report, 1972 (unpublished); P. B. Price *et al.*, *ibid.*; R. M. Walker *et al.*, *ibid.*

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APPENDIX III

ENRICHMENT OF HEAVY NUCLEI IN THE APRIL 17, 1972 SOLAR FLARE

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Cosmic ray nuclei from the April 17, 1972 solar flare were recorded in polycarbonate plastic and phosphate glass track detectors exposed on the Apollo 16 flight. The energy spectra of iron group nuclei and of carbon and heavier nuclei were measured down to ~0.02 MeV/nucleon, revealing that the enrichment of iron relative to carbon and heavier nuclei increases markedly in this very low energy region.

1. Introduction. The relative abundances and energy spectra of heavy solar cosmic ray particles contain a wealth of information about the sun as a source body and about the acceleration and propagation of the particles. It is only recently that the very low energy range from a few MeV/nucleon to a few keV/nucleon has been studied. We report here very low energy spectra and relative abundances for heavy solar cosmic rays from the flare of April 17, 1972, as determined from track detectors flown on Apollo 16. There are in print two detailed descriptions of our experiment (1,2).

2. Experimental. A multi-institutional detector array was mounted on the Apollo 16 lunar module and first exposed to space just after translunar injection; the exposure was ended just before the end of the third extravehicular activity on the moon, for a total exposure of 167 hours. The portions of our experiment considered here consisted of two types of detectors: sheets of Lexan polycarbonate plastic, and a small plate of GE phosphate glass 1457 (3). Portions of these detectors were protected only by 2100Å aluminum deposited films; other portions were covered by 50 μm silver-and-Inconel-backed Teflon thermal control material.

A dust coating on the thermal control material led to some overheating of the detectors on the moon's surface, changing the calibration of the plastic detector. This calibration change was measured using preirradiated plastic tabs which had been mounted in the array.

During the translunar portion of the mission, a small solar flare (~10^8 protons/cm^2, E>5 MeV) was recorded by several satellites (Figure 1). In Figure 1 we see that the major portion of the flare

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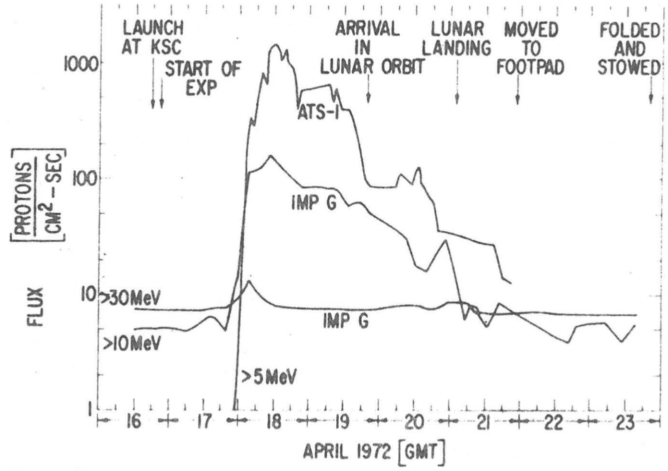

Figure 1. Proton fluxes (preliminary), at energies greater than 5 MeV, observed during the exposure period. The data are courtesy of C. Bostrom (IMP) and G. Paulikas (ATS). Lower energy fluxes (VELA, S. Singer) are displayed in reference 1.

particles arrived before the lunar landing; thus the heating episode on the lunar surface affected virtually all flare particle tracks in the same way.

The glass was etched in HF to remove ½ μm. The Lexan plastic was divided into two groups; one was irradiated with UV to enhance its sensitivity, and the other was studied as received. Both Lexans were etched for 6 hours in 40°C 6.25N NaOH solution saturated with etch products (4).

Optical scans at 1000X yielded track length distributions which could be converted into differential energy spectra. On the basis of calibration data (2) and track counting criteria we made the following elemental assignments for the various detectors: The phosphate glass and as-received Lexan yield the fluence of iron group nuclei; the UV-sensitized Lexan yields the fluence for carbon-nitrogen-oxygen and heavier nuclei. Work in progress should help us identify with more precision the elemental assignments, especially at the lower energies.

3. <u>Results.</u> The resulting differential energy spectra for heavy cosmic rays, calculated using range-energy relations for iron (5), and that derived for protons from preliminary satellite data, are shown in Figure 2. Work in progress will extend the data to 150 MeV/nucleon.

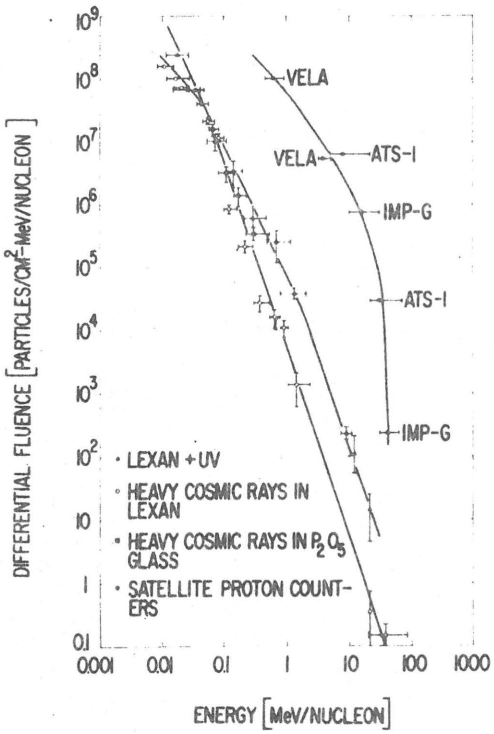

Figure 2. Differential energy spectra for heavy cosmic rays during the period 16-23 April 1972, compared to proton spectra from satellite counters. Fluence is given in particles/cm^2 MeV per nucleon integrated over a 2π solid angle.

A recalculation of the UV-sensitized Lexan data using ^{16}O range-energy relations would steepen the curve very slightly but would not alter its character significantly. Such a recalculation was used in calculating the abundance ratios presented below. The spectrum for iron group cosmic rays is steep, flattening out at lower energies:

$E^{-3\ (\pm\ 0.3)}$ for $0.04 < E < 30$ MeV/nucleon, flattening to $E^{-1\ (\pm\ 0.5)}$ in the energy range 0.04 to 0.01 MeV/nucleon.

The spectra of Figure 1 yield the elemental abundance ratios shown in Table I. For iron nuclei to carbon-plus-heavier the ratio increases with decreasing energy from the photospheric value of 0.04 at 10 MeV/nucleon to roughly 25 times that value at 0.03 MeV/nucleon. The statistics allow a factor of two error in the ratios.

Table I. Abundance Ratio of Iron Group to Carbon and Heavier Nuclei

Energy (MeV/nucleon)	Relative Abundance
10	0.04
3	0.03
1	0.025
0.3	0.11
0.1	~0.5
0.03	~1

Likewise, the data of Figure 1 yield an enhancement of iron group nuclei relative to protons, and of carbon and heavier nuclei relative to protons (2).

4. Discussion and Conclusions. As described above, the differential energy spectrum for iron group cosmic rays shows the now familiar roughly E^{-3} energy dependence (6,7,8,9). The present results show that this behavior extends to energies as low as 0.03 MeV/nucleon.

The ratios of iron relative to carbon and heavier elements indicated in Table I are to be compared with ratios of 0.08 and 0.13 above 10 MeV/nucleon found by Teegarden, et al (10) for two flares, of 0.3 found by Mogro-Campero and Simpson (7) near 20 MeV/nucleon for the average of several flares, and of 0.015 to 0.03 at higher energies found by Bertsch et al (11). None of these results include the 17 April flare. Mogro-Campero and Simpson (7) have emphasized the variations in elemental ratios from flare to flare.

The relative heavy-element enrichment at low energies is associated with the changes of slope of the energy spectra which occur at progressively higher energies (in Figure 2) as one goes from iron to carbon plus heavier nuclei to hydrogen. This increasing enhancement of iron towards lower energies is in agreement with previous results of Price et al (12) and Mogro-Campero and Simpson (7), but is quantitatively less at the same energies; the present results extend to lower energies. Energy-dependent abundance ratios for individual elements, rather than for groups of elements, have been reported by Braddy, et al (8) and Price, et al (9) for several flares, including the 17 April flare.

The data presented in Figure 2 imply that the heavy nuclei in the solar flare are appreciably more abundant than in the solar photosphere (2). As early as 1958 Korchak and Syrovatskii predicted preferential enhancement at low energies of heavier nuclei during the acceleration process because of their lower effective charge-to-mass ratios (13). More recent explanations involve not only acceleration processes but also possible variations in the composition of the solar atmosphere in the vicinity of solar flares (9).

Acknowledgments. We are indebted to C. Bostrom, W. F. Dietrich, G. Paulikas, J. A. Simpson, and S. Singer for permission to quote their preliminary satellite data, to W. R. Giard, M. McConnell, and G. E. Nichols for experimental assistance. The work has been supported by The National Aeronautics and Space Administration under Contract No. NAS 9-11468.

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APPENDIX IV

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APOLLO 14 AND 16 HEAVY PARTICLE DOSIMETRY EXPERIMENTS

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SUMMARY Doses of heavy particles at positions inside the command molecules of four Apollo missions correlate well with the calculated effects of solar modulation. Differences at different stowage positions indicate that redistribution of mass within the spacecraft could enhance safety from the biological damage that would otherwise be expected on manned, deep-space missions.

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**NASA Manned Spacecraft Center Houston, Texas

Subject - particle tracks

Key Words - particle tracks, cosmic rays, personnel dosimetry, space flights, solar activity

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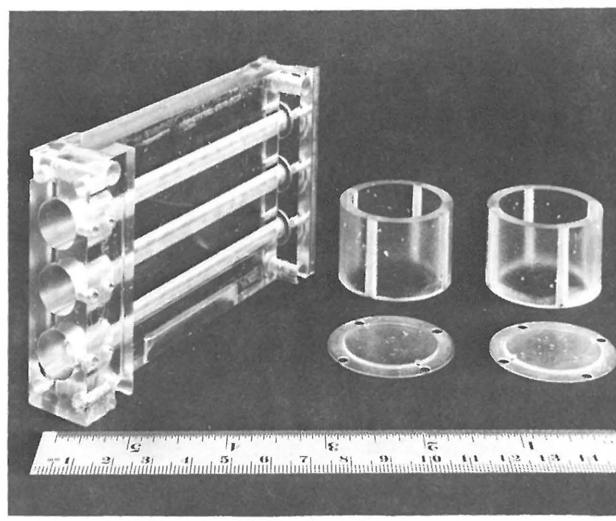
APOLLO 14 AND 16 HEAVY PARTICLE DOSIMETRY EXPERIMENTS

R. L. Fleischer, H. R. Hart, Jr., G. M. Comstock,* M. Carter,† A. Renshaw, A. Hardy**

Highly 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. Previous measurements using Apollo helmets as dosimeters indicated that a significant fraction (~1 percent) of certain nonregenerative cells would be killed in a Mars-length mission using the present Apollo spacecraft shielding.[(1)] As an extension of the dosimetry work for Apollos 8 and 12,[(1)] we have used a number of the parts from the Electrophoresis Experiment from Apollo 14[(2)] and tracks formed after stowage of the Apollo 16 Cosmic Ray Experiment[(3)] to measure the dose of heavy nuclei that penetrated the interior of the command module. During most of the mission the electrophoresis experiment was located in a compartment just beneath Astronaut Edgar D. Mitchell.

First we discuss the Apollo 14 experiment. In that case we etched and examined the tracks produced by the heavy particles that entered the Lexan® polycarbonate parts forming the main body of the electrophoresis experiment, the plastic pieces shown in Fig. 1(a). The ionization threshold for particle registration of this material (if untreated by UV radiation) is that for inactivation of human kidney cells[(4)] and hence is appropriate for assessing the biological effects of heavily ionizing particles. Experimental procedures were essentially identical to those used in our previous work, except that the largest piece 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(b) shows four tracks at low magnification, illustrating the geometrical variations along individual tracks that allow individual particles to be identified.[(5)] As noted earlier,[(1)] most of the nuclei observed are iron, its near neighbors in the periodic chart, or spallation products of iron, and all are of atomic number ≥ 10. The particles shown were identified by the analytical technique described earlier[(6)] as Fe, Ar, Ca, and Ti. Because only the iron was observed as it stopped, it is the only elementally certain identification. With lower probability "Ti" could be Sc or Cr, "Ca" could be Sc or Ti, and "Ar" could be Ti or Ca. More extensive calibration data than now exist for the etchant used could readily resolve these uncertainties.

The Apollo 16 Cosmic Ray Experiment was exposed on the lunar surface and was later folded and stowed just prior to lift-off. The Lexan detectors that made up a major portion of the experiment were held in such a manner that each sheet was displaced relative to its neighbor as the experiment 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 most of the subsequent time was spent there. Etching of these samples was done using the normal solution for particle identification, 6.25N NaOH saturated with etch products.[(7)] Since this etch is less sensitive than the NaOH-ethanol etch that was used previously [(5)], track counts must be raised (by an estimated 80%) to make them comparable with the helmet[(1)] and electrophoresis experiments. The numbers we will quote are so corrected.



(a)

Fig. 1 Apollo 14 Electrophoresis Experiment: 1(a) etched polycarbonate parts of the experiment. The white lines and dots are the etched tracks of cosmic rays that penetrated the command module. 1(b) etched cosmic ray tracks in the experiment can be identified by the variation of the track taper with position along the track. Clockwise from the upper right, the identifications and lengths are Fe(0.8 mm), Ca(0.7 mm), Ti(0.9 mm), and Ar(2.0 mm). As photographed here, the track curvatures show that the Fe, Ti, and Ar were moving upward, and the Ca downward.

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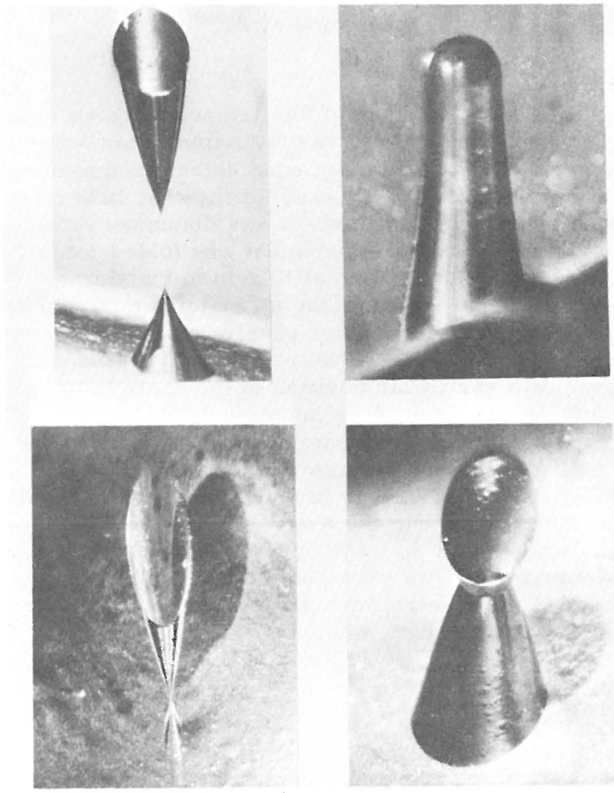

(b)

Fig. 1 (concluded)

We observed 0.608 (±0.041) tracks/cm^2 in Apollo 14 and 0.334 (± 0.041), corrected to 0.594, in Apollo 16, as compared to 0.56 (± 0.053) and 1.41 (±0.146) in the command modules of Apollos 8 and 12, respectively. Allowing for the different lengths of the four missions and the time when the experiments were partially shielded by the moon, the four flux values for missions 8, 12, 14, and 16 are 1.53 x 10^{-7}, 3.12 x 10^{-7}, 1.92 x 10^{-7}, and 3.42 x 10^{-7} particles/cm^2-sec-steradian.[8] These values may be compared with those expected from solar modulation and with the results of Benton and Henke,[9] who used somewhat different procedures. As the right-hand column of Table I indicates, the sun became decreasingly active in the sequence Apollos 8 to 12, 14, and 16; fewer of the penetrating galactic cosmic rays were deflected away from the earth, and the calculated[1] track density therefore rises from 0.66 to 1.00, 1.43, and 2.50. For Apollo 8, both our measurements ("≥Ne") and those of Henke and Benton ("≥C") are consistent with the effects of solar modulation; for Apollos 14 and 16, Benton and Henke's measurements are roughly consistent with the calculations, but our present results appear to be lower for both Apollos 14 and 16.

TABLE I

Heavy Particle Fluxes Relative to the Apollo 12 Mission

	Observed in Command Modules			
	≥Neon			
Mission	Directly Observed	Corrected for Position in Spacecraft	≥Carbon	Calculated From Solar Modulation
Apollo 8	0.49±0.06 (Ref. 1)	0.49 ±0.06	0.54 ±0.14(Ref. 9)	0.66 ±0.11 (Ref. 1)
Apollo 12	1.00* (Ref. 1)	1.00*	1.00* (Ref. 9)	1.00*
Apollo 14	0.60 ± .07	1.57 ± .18	2.00 ±.39(Ref. 9)† 1.47 ±.28(Ref. 9)	1.43 ±.21
Apollo 16	1.10 ±.12	2.68 ±.29	3.25 ±.14(Ref. 9)	2.5 ±.5

*Reference level.

†Film badge on E. D. Mitchell, crew member closest to electrophoresis experiment.

The discrepancies between the two sets of observations could in principle have to do with (a) differences in the fluxes, (b) different properties of the Lexan in the helmet (type 111 or 112) and that in the electrophoresis experiment (type 100), or (c) different shielding at different positions in the spacecraft. As noted by the column headings in the table, 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 Apollo 8 ranged from 0.56/cm^2 [no UV[1]] to 0.62/cm^2 [some UV[12]] to 2.64/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 possibility that the (≥carbon/≥neon) ratio was higher by a factor of ~3 during Apollos 14 and 16 is highly unlikely since fluctuations in this ratio of greater than 30% would be inconsistent with measurements of galactic cosmic rays.[13-16]

The second possibility--that the two detectors we intercompare on Apollos 12 and 14 were different--was eliminated by calibration measurements of etching rates for full-energy and low-energy fission fragments. For helmet Lexan, electrophoresis Lexan, and for the usual 112 Lexan used for particle identification,[5] the rates were identical within the experimental uncertainty of ±7% and ±1.5% for the two energies used. The final possibility is the preferred one--that the storage positions of the Apollo 14 and 16 experiments 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 three experiments we are considering. These calculations, which were done for the positions in the spacecraft where each experiment spent the largest part of its exposure, show clearly that the Apollo 8 and 12 helmets had some shielding thinner than 4 g/cm^2 (1.5 cm of aluminum) and that the other experiments had on the average thicker shielding.

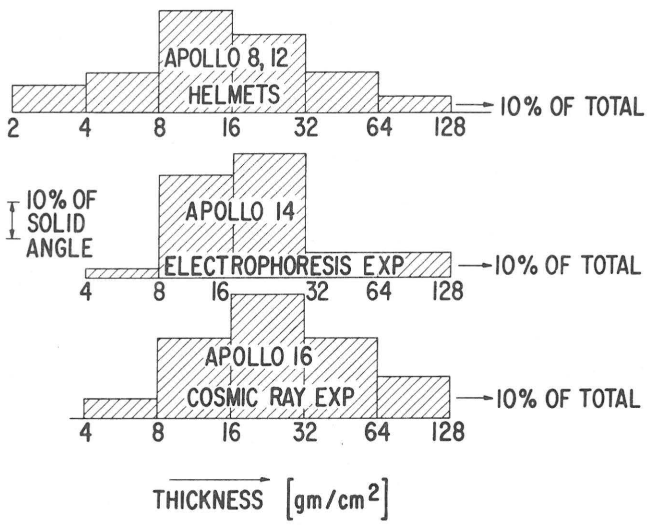

Fig. 2 Distribution of mass around the three experiments considered in this report: Apollo helmets on Apollos 8 and 12, the Electrophoresis Demonstration on Apollo 14, and the Cosmic Ray Detector on Apollo 16.

Since the calculated relative fluxes given in Table I were derived for the position of the helmets used on Apollos 8 and 12, corrections were calculated for the Apollo 14 and 16 experiments using the distributions of matter given in Fig. 2 and calculations for meteorites of cosmic ray flux vs depth(17) corrected for the average difference in density between meteorites and aluminum. The third column of the table gives the results of these corrections (factors of ~2.5 for each) and Fig. 3 compares theory and corrected experiment. Solar modulation has been responsible for a factor of five variations from Apollo 8 to Apollo 16, shielding differences at different positions caused a factor of ~2.5 differences, and the apparent discrepancy with Ref. 9 is removed.

The total doses of particles in the Apollo 14 and 16 command modules are higher but comparable to that in Apollo 8, and lead to similar numbers of cells killed to those we calculated(1) for that mission. Even for the giant cells the fraction killed is probably trivial, less than 500 cells per million. The interesting conclusion, however, is relevant to a Mars-like mission (of ~2 years' duration), where cellular damage would be extensive--as great as ~3% for the Apollo 16 flux level. The results here, showing inadvertant reductions by a factor of ~2 1/2 in dose as a result of differences in shielding, presumably could be considerably 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.

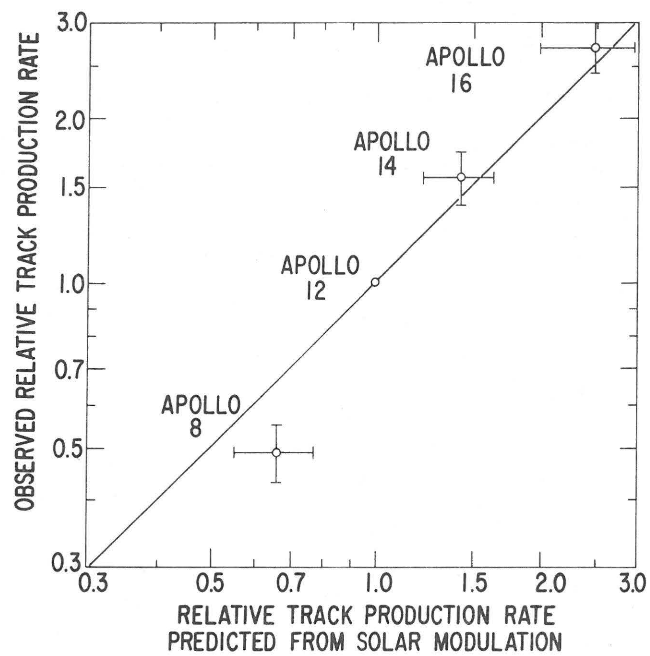

Fig. 3 Observed track production rates, corrected for shielding thicknesses, plotted against the production rates calculated from solar modulation, corrected for shielding thicknesses. In all cases the rates are given relative to those for Apollo 12.

ACKNOWLEDGMENTS

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APPENDIX V

ABSTRACT FORM

FOURTH ANNUAL LUNAR SCIENCE CONFERENCE

INSTRUCTIONS FOR PREPARATION OF ABSTRACT TO BE REDUCED AND REPRODUCED BY PHOTO-OFFSET PROCESS: Type Single Space (Pica preferred) within margins only. Indent 10 spaces on first line and begin with the TITLE IN CAPS; follow with Author(s) and Affiliation, e.g., D. J. Jones, Geophysics Corp. of America, Bedford, Mass., 01730 (abbreviate where appropriate). Start Abstract on new line, indent 5 spaces. Mail Abstract to ABSTRACTS, The Lunar Science Institute, 3303 NASA Road 1, Houston, Texas 77058.

APOLLO 16 COSMIC RAY EXPERIMENT--SOLAR FLARE ENERGY SPECTRUM AND HEAVY ELEMENT ENRICHMENT AT LOW ENERGY,

Howard R. Hart, Jr. and Robert L. Fleischer, General Electric Research and Development Center, Schenectady, New York.

The relative abundances and energy spectra of solar flare particles contain detailed information about the sun as a cosmic ray source and about the acceleration and propagation of solar particles. The low energy range from a few MeV per nucleon down to a keV per nucleon (a solar wind energy) has been largely unexplored. On Apollo 16 there were three cosmic ray experiments which contained track detectors designed to examine this energy range [1]. We report here energy spectra and relative abundances for heavy solar cosmic rays from the flare of April 17, 1972.

A detector array was mounted on the lunar module at launch and exposed to space from translunar injection until the end of the third EVA on the moon. As indicated by the satellite proton fluxes recorded in Fig. 1, a medium sized solar flare occurred during the translunar portion of the mission [2]; more than 90% of the flare particles recorded arrived before the lunar landing. The portion of the experiment considered here consisted of two types of detectors: sheets of .010 inch Lexan polycarbonate plastic and a 1 mm thick plate of GE phosphate glass 1457. Portions of each of these detectors were exposed to space protected only by a 2100Å film of aluminum; other portions were covered by .002 inch silver-and-Inconel backed Teflon thermal control material. For the uppermost portions of the detectors the flood of solar particles gave an abundance many times the expected galactic fluence; the results we report are essentially therefore only those for the April 17 flare. While on the lunar surface the detectors, particularly the Lexan, were heated by an amount sufficient to cause some desensitization through track annealing. Since this heating occurred after the end of the solar flare particle flux, the heat effects for all of the solar particles were identical.

Portions of the glass were etched in HF to reveal cosmic ray tracks. Segments of the Lexan sheets were etched in NaOH, some in the as-received, thermally desensitized condition and some after UV-sensitization. From measured track length distributions we derive differential energy spectra using range-energy relations for iron nuclei. The use of the iron range-energy

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relations is justified for the glass and the desensitized Lexan, which record predominately iron group cosmic rays; it is slightly in error for the UV-sensitized Lexan which records particles as light as ^{12}C[1]. In Fig. 2 we plot three energy spectra (integrated over a 2π solid angle): The upper-most curve gives preliminary satellite data for protons [2]; the lowest curve is a composite of the data from the glass and the desensitized Lexan, i.e. the iron group nuclei; the intermediate curve, the data from the sensitized Lexan, represents carbon and heavier nuclei. If the data are represented by a relation $(\text{energy})^{-m}$, the spectral index m is 3 (± 0.3) at higher energies and flattens to m=1(± 0.5) at lower energies. The energy at which the flattening occurs differs for the different curves, going from ~.04 MeV/nucleon for iron to ~1 MeV/nucleon for carbon and heavier nuclei to ~10 MeV/nucleon for hydrogen. The resulting striking increases in relative heavy element enrichment are summarized in Table I. Here the "carbon and heavier nuclei" values have been recalculated using range energy curves for ^{16}O. The observed increasing enhancement of iron towards lower energies is in agreement with previous results by Price, et al [3], and Mogro-Campero and Simpson [4], but is qualitatively less at the same energies; the present results, however, extend to much lower energies. Though it would be desirable to compare our results to proton and helium fluxes in the lower energy region, these data do not exist. Subject to this limitation our results strongly suggest that the heavy nuclei in the solar flare particle flux are appreciably more abundant than in the surface of the sun. The preferential enhancement at low energies of the heavier nuclei because of their low charge-to-mass ratio was predicted in 1958 by Korchak and Syrovatskii [5].

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(1) More detailed descriptions are given in: FLEISCHER R.L. and HART H.R. JR. (1973) NASA Apollo 16 Preliminary Science Report (to be published); PRICE P.B., BRADDY D., O'SULLIVAN D., and SULLIVAN J.D., ibid.; BURNETT D., HOHENBERG C., MAURETTE M., MONNIN M., WALKER R. and WOLLUM D., ibid. More detailed references and discussion are in: FLEISCHER R.L. and HART H.R. JR. (1973) Phys. Rev. Lett. 30, 31-34.

(2) Preliminary satellite proton fluxes are from: BOSTROM C. (IMP-G), PAULIKAS G. (ATS-1), and SINGER S. (Vela).

BRIEF TITLE APOLLO 16 COSMIC RAY
(Abbreviated Title – All Capital Letters)

INITIAL AUTHOR Hart, H. R., Jr. et al.
(Initial author: e.g., Smith, A. B. et al.)

Type within margins only

(3) PRICE P.B., HUTCHEON I., COWSIK, R. AND BARBER D.J. (1971) Phys. Rev. Lett. 26, 916-919.
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TABLE I Abundance Ratios

Energy MeV/Nucleon	Iron/Carbon + Heavier	Iron/Proton
10	0.04	2.5×10^{-6}
3	0.03	1.5×10^{-5}
1	0.025	0.8×10^{-4}
0.3	0.11	0.8×10^{-3}
0.1	~0.5	-
0.03	~1	-
Photospheric	.04	4×10^{-5}

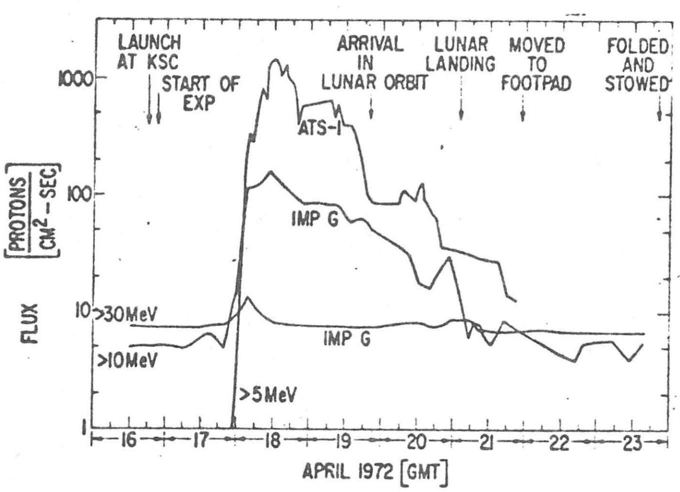

Fig. 1

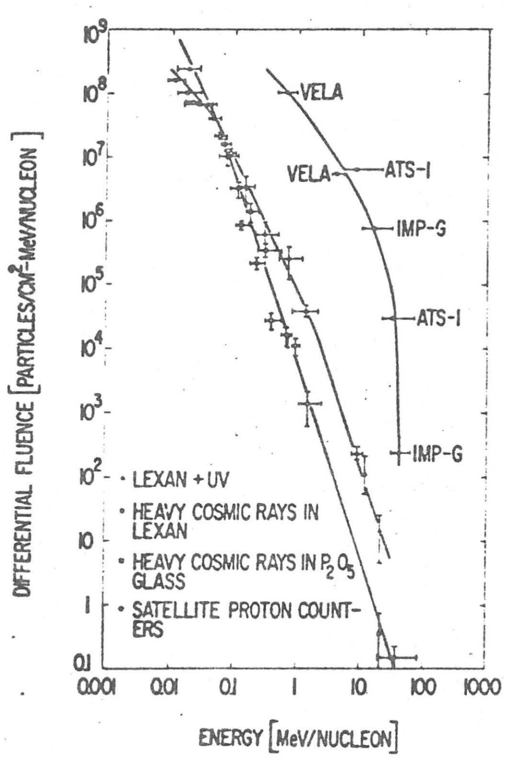

Fig. 2